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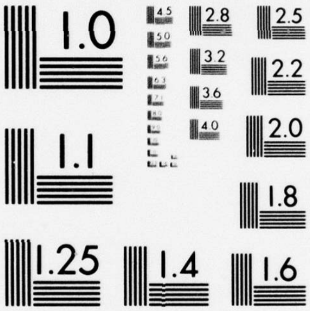

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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM ①

1. REPORT NUMBER ⑭ AFIT-CI-79-11	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) ⑥ A Study of Failure Mode and Effect Analysis and its Role in Air Force Program Management.		5. TYPE OF REPORT & PERIOD COVERED Thesis
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) ⑩ Frederick Charles Potts, Captain		8. CONTRACT OR GRANT NUMBER(s) ⑨ Master's thesis,
9. PERFORMING ORGANIZATION NAME AND ADDRESS AFIT Student at University of Missouri-Rolla		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS ⑫ 93p.
11. CONTROLLING OFFICE NAME AND ADDRESS AFIT/CI WPAFB OH 45433		12. REPORT DATE ⑪ 1977
		13. NUMBER OF PAGES 81
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

DDC
RECEIVED
NOV 27 1978
F

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release; Distribution Unlimited

LEVEL II

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

APPROVED FOR PUBLIC RELEASE AFR 190-17.

NOV 1 1978

JOSEPH P. HIPPS, Major, USAF
Director of Information, AFIT

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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79-11

A STUDY OF FAILURE MODE AND EFFECT ANALYSIS AND ITS ROLE IN AIR FORCE PROGRAM MANAGEMENT

BY

FREDERICK CHARLES POTTS, 1944-

A THESIS

Presented to the Faculty of the Graduate School of the

UNIVERSITY OF MISSOURI-ROLLA

In Partial Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE IN ENGINEERING MANAGEMENT

1977

Approved by

Daniel L. Babcock (Advisor) Henry Metzner

William H. Tranter

ABSTRACT

Failure Mode and Effect Analysis (FMEA) is a systematic approach which evaluates a system with respect to its most possible failures. This is accomplished by first making the basic assumption that the system has failed and then hypothesizing specific failure modes, failure causes and failure effects. Also included is a determination of some measure of failure probability and the assignment of a criticality classification. The study examines this process through the formulation of a FMEA on a hypothetical system. The way in which FMEA is currently employed in Air Force defense system procurements is reviewed and the potential benefits of the expanded utilization are explored. The study concludes that the lack of understanding of the basic concepts and the reliability oriented use of FMEA precludes much of its potential benefit to the Air Force Program Manager. Certain benefits are emphasized if the recommended changes to the philosophy surrounding the FMEA process should be adopted.

EXECUTIVE SUMMARY

Failure Mode and Effect Analysis (FMEA) is a systematic approach to the analysis of the capabilities and performance of a system with respect to the areas of its possible failure. In contrast, a reliability analysis is concerned with the probability that a system will operate successfully within defined specifications over a specified period of time. Essentially, the FMEA is a deterministic analysis because it makes the basic assumption that the system has failed, regardless of the results of the reliability analysis. Then, the FMEA proceeds with a hypothetical determination of how the system failed, known as the Failure Mode, and the effect that this failure will have on the system capabilities and performance, known as the Failure Effect. Currently, this analysis is carried out through the entire system structure from the overall system level to the lowest level of individual components.

The purpose of this study is to analyze the important aspects of Failure Mode and Effect Analysis. This analysis is limited to the relationship of FMEA to defense system procurement in the Air Force and the role it can play in Air Force Program Management. The study builds a 'failure model' of a hypothetical system and fits its use into the procurement system. Then, it examines the ways in which this concept can be employed in streamlining the procurement process and in providing the Air Force Program Manager with an effective management tool.

Failure Mode and Effect Analysis is a potentially valuable tool for the Air Force Program Manager. However, an extensive study of the current role of FMEA in Air Force Program Management has shown that the use of FMEA as a management tool is hindered by the current philosophy which surrounds the process. This philosophy has resulted in procedures which tend to continue to limit the scope of FMEA

utilization and which contribute to the development of FMEA as a process which becomes increasingly separated from management.

A study of Air Force procurement effort shows that the procedures for formulating and evaluating a FMEA are not well defined. This study has found that little documentation, either in the form of Air Force Manuals or Pamphlets, exists to aid the Program Manager in his efforts to understand and employ the FMEA process. In addition, it has been found that the potential benefits which result from a comprehensive use of FMEA are sacrificed because of the lack of emphasis placed upon the process. Consequently, such benefits as the early assessment of program feasibility, visibility of the dollar impact of design changes, efficient evaluation of the dollar impact of trade-offs to the parameters of cost, schedule and performance, and the quick assessment of the progress and maturity of the system development become lost. Primarily, this is due to the lack of information available, and the small amount of training available, on FMEA.

Currently, FMEA is primarily a reiteration of the quantitative determinations of the reliability analysis. In order for the full benefit of the FMEA process to be realized, this study has found that FMEA must become divorced from the numerics of the reliability analysis because its full potential lies in its ability to provide information for qualitative management decisions. This study recommends that the FMEA make use of a technique which associates failure probability and failure rate data with a predetermined set of ranges. These ranges allow more flexibility in the decision making process because the dependency of the FMEA upon specific numbers is reduced.

A major factor found by this study which hinders the wide use of FMEA is its current dependency upon a rather well developed design of the system. This is yet another aspect of the current philosophy which must be changed in order to derive expanded benefit from FMEA. The evaluation of a defense alternative while it is in the conceptual phase of development, before it becomes a definitive design and before the initiation of design reviews, can provide management with indications of its feasibility and emphasize problem areas early in the acquisition cycle when costs are lower.

In order to better enable Program Management to retain visibility of the progress of a system development the incorporation of the FMEA Transition Summary is recommended. This supplement to the FMEA is not a summary of the contents of the FMEA, but is a summary of the changes which have taken place to the FMEA, especially between design reviews and as design changes take place. The Summary provides real-time visibility over the progress of the system development because as design changes take place, and the contractor submits an amended Summary, Program Management can directly relate their impact to the system objectives. The Transition Summary also provides a vehicle for evaluating the dollar impact of trade-offs to cost, schedule and performance requirements.

Also recommended is the use of the Failure-Criticality Grid which provides a method for visualizing the relationships of failure and criticality classification. This can be especially beneficial to the Program Manager in his efforts in determining the capability of the system development to meet specific design goals and defense objectives, allocating resources to critical areas of the procurement effort, establishing the dollar impact of design changes, and in evaluating the progress and maturity of the system development. This study has found that, owing to its size and complexity, a FMEA accomplished with current techniques is extremely difficult to analyze with respect to the relative occurrence of any single criticality classification and the distribution of all criticality classifications over the entire system. The Failure-Criticality Grid clearly fulfills this need and provides the primary benefit of providing the Program Manager with visibility of the entire system development.

The true validity and cost effectiveness of the FMEA process lies in its capability to be applied to a diverse number of areas of the procurement effort. This study has found that the current structure of FMEA and the general philosophy surrounding its use have acted as deterents to its being employed to its full potential. This is especially true in the broad area of logistics support. A change in the current philosophy, and the subsequent change in the procedures, can result in a wider use and acceptance of FMEA. As the scope of FMEA use increases to cover more aspects of the procurement effort, its validity and cost effectiveness increase.

ACKNOWLEDGEMENTS

Many individuals gave enthusiastically of their valuable time in providing the personal interviews for this study. Their efforts contributed substantially to the accomplishment of this research. Special thanks are due to Major Francis Stump of NASA Headquarters, who gave willingly of his limited time to provide suggestions and valuable insights into the principles and problems involved with Failure Mode and Effect Analysis.

Acknowledgement is given to Dr. Daniel Babcock and Dr. Henry Metzner of the Engineering Management Department for their thorough review of the drafts and their cogent suggestions.

Special acknowledgement is accorded to Major Lyle Lockwood and Captain William Glover of the Air Force Business Research Management Center for their invaluable assistance in obtaining information and in developing the path for this research effort.

I also wish to acknowledge the support and assistance provided by Lieutenant Colonel R. L. Stoner and Captain Thomas Shuppe of the Special Engineering Branch of the Acquisition Logistics Division, who materially aided in drawing this work to its conclusion.

The patience, understanding and encouragement of my wife, Lynn, constitutes the single most significant contribution. To her I extend a most special, and heartfelt, note of thanks.

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I. INTRODUCTION

Failure Mode and Effect Analysis, known as FMEA, is a systematic process of analyzing the capabilities and performance of a system with respect to the areas of its possible failure. In contrast, a reliability analysis is concerned with the probability that a system will operate successfully within defined specifications over a specified period of time. Essentially, the FMEA is a deterministic analysis because it makes the basic assumption that the system has failed, regardless of the results of the reliability analysis. Then, the FMEA proceeds with a hypothetical determination of how the system failed, known as the Failure Mode, and the effect that this failure will have on the system capabilities and performance, known as the Failure Effect. Currently, this analysis is carried out through the entire system structure from the overall system level to the lowest level of individual components.

FMEA is required on all major defense system acquisitions made by the Department of Defense (DOD). A detailed study of the process as it is performed by all branches of the DOD would be too extensive for proper evaluation. Therefore, this study deals specifically with the role of FMEA in the management of defense system procurements by the United States Air Force.

Failure Mode and Effect Analysis is required on every major Air Force procurement effort, as established by Military Standard (MIL-STD) Number 785A. (1) This written requirement is minimal in scope in that it does not describe the basic concepts of FMEA or reference a MIL-STD that does, and no Air Force documentation is available to fully explain, or supplement, it. Therefore, the lack of information on this process is a significant problem to the Air Force Program Manager. It is not realistic to require the Program Manager to properly employ this potentially valuable tool if he is unaware of its basic concepts, its current and potential uses, and its capabilities.

A. PURPOSE OF THE STUDY

The purpose of this study is to analyze the important aspects of Failure Modes and Effects Analysis. This analysis will be limited to the relationship of FMEA to defense system procurement in the Air Force and the role it can play in Air Force Program Management. The study will endeavor to build a 'failure model' of a hypothetical system and fit its use into the procurement system, under current conditions. Then, it will be necessary to explore the ways in which this concept can be utilized in streamlining the procurement process and in providing the Air Force Program Manager with an effective management tool.

As previously mentioned, the major problem confronted in an attempt to contrast the effectiveness of various Failure Mode and Effect Analyses is the lack of information. There is no single guiding directive, relative to Air Force procurement procedures, which specifically delineates the required process or the minimum informational content necessary. Essentially, the company which accomplishes the FMEA applies their individual interpretation of MIL-STD-785A to their particular effort, and is correct in doing so as long as they satisfy that basic requirement. Consequently, there is no straight-forward manner in which these specific analyses can be contrasted since no documented rationale exists to explain their formulation. Therefore, no effort will be made here to directly compare a specific FMEA from some arbitrary Company A with that of one of Company B and point out the benefits and deficiencies. The objective of this study is to combine the important aspects of Failure Modes and Effects Analysis, present a model FMEA, and draw conclusions as to the current deficiencies and future benefits of the entire FMEA endeavor.

B. STATEMENT OF THE PROBLEM

Currently, Failure Mode and Effect Analysis is a requirement of every major Air Force defense system procurement as directed by Military Standard 785A. Funds and time are expended by civilian contractors in analyzing designs, compiling data and formulating reports to satisfy this requirement. Even after all this, little seems to be known about the process outside of the select few who are involved in its accomplishment. No Military Standard, Air Force Manual or Pamphlet exists to supplement the basic requirement. Few textbooks in reliability, quality control or project management approach the subject, and those which do describe it in a few superficial paragraphs. Much of the FMEA information and procedures available to, and utilized by, civilian contractors seems to be in the form of corporate Standard Practices which have gained their current status through a trial and error process. Essentially, FMEA seems to be an important process about which little indepth information is available.

The lack of information available on FMEA constitutes a significant problem. Consequently, the Air Force Program Manager is faced with the situation of being required to manage the FMEA effort on a continuing basis without the knowledge necessary to evaluate its validity or support its worth.

It is becoming increasingly important that the Air Force derive maximum dollar benefit from all procurement oriented efforts. The Air Force Program Manager is entrusted with the responsibility of assuring that all facets of a procurement process mesh efficiently and that all requirements are thoroughly and economically carried out. Clearly, it is difficult to determine if maximum benefit is being derived from FMEA with so little information available.

Therefore, the problem confronted here is one of building a detailed framework of the FMEA process. This framework consists not only of the foundations of the concept of FMEA but also how it relates to the procurement process.

II. RESEARCH INFORMATION

Research for this study was accomplished through an extensive literature review and through numerous personal interviews. The following is a discussion of the results of this effort which spanned a time frame of approximately 18 months. Involved in this was the review of over 700 articles, papers and books, and approximately 5000 miles of travel by the author for the interviews.

A. LITERATURE REVIEW

The basic requirement for the accomplishment of a Failure Mode and Effect Analysis in all major Air Force defense system procurements is given in Military Standard 785A (2) as follows:

> "The primary purpose of FMEA is to identify potential system weaknesses. Each potential failure shall be evaluated to determine its effect on mission accomplishment and ranked as to its criticality. Mission critical failures shall be further investigated as to failure mode to determine design improvements required to eliminate failure causes or reduce risks to acceptable levels. The FMEA should be planned as a continuing effort to give design guidance, and provide data for consideration in each design review."

In attempting to define how to fulfill this requirement, the Program Manager is immediately faced with the lack of indepth information on Failure Mode and Effect Analysis, especially that concerning the role of FMEA in the management of a system acquisition. In a review of the abstracts of over 600 articles and papers available through the Defense Logistics Studies Information Exchange (DLSIE) on the broad subject area of reliability and FMEA, only one article was found which addressed the basic concepts involved in formulating a FMEA. Although many authors refer to the purpose and potential uses of FMEA, their orientation is toward the design engineer and little emphasis is given to the management aspects of the process.

Blanchard (3) has shown some of the ways in which FMEA can be integrated into a management program through its use in logistics management. He mentions that FMEA can be used to gauge the supply supportability and maintainability of a system and that FMEA should be an important contributor to the maintenance analysis. Although other authors imply that it can be used in these areas, few state how.

Little insight is gained into the methods and procedures for formulating a FMEA. A majority of authors simply state, in a few sentences, the informational content required and show a sample FMEA format without detailing the significance of the individual entries or how they might impact upon the management of the program. Arnzen (4) describes the make-up of a FMEA in a logical and progressive manner. He employs a sample system to show the relationship of the system block diagram to the entries in the FMEA form and shows how improvements to the design can be itemized. However, the article is oriented toward the design engineer and only briefly mentions the role of FMEA in a management environment.

The scope of information necessary for a meaningful FMEA varies from author to author. Juran (5) suggests the use of an analysis which categorizes the probability of a failure occurrence, the likelihood of damage to surrounding elements, and the seriousness of the failure to the operation of the system. In addition, he recommends that the analysis should detail such items as the effect of the failure upon the productivity of the system, the units or items which must be removed to repair the failure, the special tools required and an estimate of the time required to repair the failure. Again, the emphasis is toward the design engineer with little emphasis placed upon the management aspects, and the description of the concepts involved is cursory. The analysis by Arnzen (6) is much more refined and presents information which emphasizes the "vital few" concept. Blanchard (7) leaves the form and content to the analyst, explaining the requirements in general terms and implying that the FMEA should be oriented toward the maintenance and logistics aspects of the system.

The ways in which FMEA is actually used in current programs is limited to a discussion of its primary use during design reviews and again the orientation is toward the use of FMEA by the corporate design engineer. In order to circumvent this situation, a number of interviews were held with people actively involved in the management of various aspects of defense system acquisition for the Air Force.

B. INTERVIEW SYNOPSES

The initial interview for this study was held on November 22, 1976 with Mr. W. P. Murden and Mr. A. S. Torgerson of the Reliability Division of the McDonnell-Douglas Aircraft Corporation in St. Louis, Missouri. (8) This gave the viewpoint of a civilian contractor toward FMEA. Mr. Torgerson reviewed the process and the procedures required by the McDonnell-Douglas regulations, or Standard Practices. (9) He stated that the analysis is conducted by a team composed of a design engineer and a reliability engineer and is quite extensive in scope. Mr. Murden stated that the process is valuable in the areas of reliability and logistics and would most probably be accomplished, to some extent, even if not required by the Air Force. Both gentlemen agreed that the FMEA process is an extensive one requiring many man-hours to complete and could possibly be simplified. Since FMEA is accomplished throughout the acquisition effort and is not specifically itemized in the contract, no information was available as to the specific costs involved. Also, the close relationship between FMEA and a definitive design of the system was verified. Generally, the involvement of FMEA in the operations of the McDonnell-Douglas Corporation is quite extensive. Many of the departments involved in the design effort have exposure to the FMEA and make use of it. The significant problem seemed to be with the various subcontractors in that many are not familiar with the FMEA process and have to be educated on it by McDonnell-Douglas personnel. As in a majority of the references reviewed by this study, the emphasis and orientation of the FMEA still remains toward the design of the system. Therefore, it became necessary to conduct more interviews to determine the extent of its use by Air Force Program Management.

Captain Francis Stump, of the Directorate of Engineering Services of the Air Force Acquisition Logistics Division, Wright-Patterson Air Force Base, was contacted on April 4, 1977. (10) His previous involvement with the National Aeronautics and Space Administration (NASA) and his current assignment with the Air Force Logistics Command have given him extensive knowledge of the concepts of FMEA. He also served on numerous occasions as a guest lecturer on FMEA to the Air Force Institute of Technology School of Systems and Logistics Management. Essentially, Captain Stump presented his lectures on FMEA (11) (12) which introduced the basic concepts, showed the applications and uses of FMEA, defined the terms used in the analysis, and showed the common purpose of the several approaches which are taken. Also, he thoroughly outlined the formulation of a FMEA through the analysis of a sample system. Most important, however, was the emphasis which Captain Stump placed on the need for the increased involvement of FMEA in Air Force Program Management and the need for documentation on FMEA which would be readily available to the Program Manager.

An interview with Major James Wessell (13) of the directorate of Systems Engineering of the F-15 Joint Engine Project Office (JEPO), Wright-Patterson Air Force Base, on April 6, 1977, established the fact that, in this particular program, the use of FMEA in the later stages of system development is minimal. Also in the F-15 Program, the FMEA is not required to be delivered to the Air Force by the contractor, McDonnell-Douglas, and is retained by the contractor for evaluation during design reviews. Data items which show significant changes to the FMEA or the distribution of failures were also not required. Major Wessell stated that the significant use of the FMEA in the F-15 Program was in the area of safety.

Mr. Charles Dorney, of the System Safety Office of the F-15 Joint Engine Project Office, was also interviewed on April 6, 1977 (14) because of his knowledge of FMEA and his involvement with the safety aspects of the F-15 acquisition effort. Mr. Dorney related that the FMEA constituted the major source for the Safety and Hazard Analysis conducted on the system. This analysis is essentially a contractor responsibility and that although the form may vary between contractors the content is the same.

Various aspects of the involvement of FMEA in the F-16 Aircraft Program were covered in an interview on April 7, 1977 with Lieutenant Thomas Landers, Wright-Patterson Air Force Base, (15), of the Analysis and Integration Branch of the F-16 Directorate of Systems Engineering. As in most other programs, the Failure Mode and Effect Analysis of the F-16 aircraft is a contractor responsibility and is retained by the contractor, Grumman Aircraft Engineering Corporation, for evaluation during design reviews. The analysis is not used by Program Management to any significant degree.

Mr. W. O. Detert, of the Aeronautical Systems Division Reliability and Maintainability Engineering Branch, in an interview on April 7, 1977 (16) verified information previously obtained. Generally, FMEA is a contractor responsibility and is not normally delivered to the Air Force but is retained by the contractor for Air Force evaluation during design reviews. FMEA is a required Design Review Agenda item and is evaluated for its basic content and for the occurrence of mission critical failure modes, or those listed in this report as Category III and IV criticality classifications. Also, Mr. Detert stated that the introduction of the FMEA into the Program Management is not a common practice. In addition, Mr. Detert stated that the reliability engineers who conduct the evaluation of the FMEA during design reviews are either familiar with the process from past experience or become familiar with the process in the course of their duties. No formalized training is conducted on FMEA.

On October 17, 1977, interviews were conducted at the National Aeronautics and Space Administration (NASA) Lyndon B. Johnson Space Center (JSC) in Houston, Texas. The individuals interviewed were: Mr. Henry L. Williams, Chief, Vehicle Reliability Engineering Branch, (17) and Mr. Marion E. Merrell, AST Reliability Engineer. (18) Primarily, these interviews were for the purpose of drawing a contrast between the FMEA process currently used by NASA in the Space Shuttle Program with that currently used by the Air Force. The Space Shuttle is a development which may change the nature of NASA operations. Heretofore, spacecraft were "one-shot" equipment items in that they were not recovered for reuse. The Space Shuttle represents the beginning of the development of reusable spacecraft and involves new problems in the areas of reliability and maintainability.

One of the most significant differences found between the two programs is that the FMEA used by NASA is strictly qualitative in nature as opposed to the quantitative basis of the Air Force process. Through the evolutionary nature of the FMEA development at NASA, it was found that the use of numerics was not beneficial to the smooth flow of the decision making process. Although this type of analysis is still somewhat controversial, the contrast between these two methods does substantiate the hypothesis made by this study that the use of a "middle ground" approach is feasible and practical. That is, the FMEA can be based upon numeric factors which are tailored to the particular development without an overwhelming reliance upon numerics which have become standard in all reliability and maintainability analyses, such as mean time between failures (MTBF), mean time to repair (MTTR) and failure rate or failure probability.

Another significant contrast exists in the area of documentation. In addition to the major directing document (19) the manager which has charge of the FMEA has a complete desk instruction (20) which details the FMEA process. This desk instruction is updated periodically as modifications to the FMEA requirements occur. No such document exists for the Air Force manager.

Although the responsibility for accomplishing the FMEA still rests with the civilian contractor, NASA requires that the entire FMEA be delivered to the NASA manager, who performs periodic reviews of the document and is responsible for evaluating the impact of changes through the use of the FMEA. In addition, Mr. Merrell stated that the availability of the complete FMEA expedites the design review process and generally benefits the decision making process. The contractor is required to provide interim updates to the FMEA as design changes occur. The complete FMEA is also distributed to other NASA offices, such as those concerned with testing and maintainability.

The depth of the information presented in these interviews is far too extensive for this report. However, it is important to note that the FMEA process used by NASA is evolutionary in nature in that it has been improved many times by using the results of previous programs; that it is nonnumeric in structure and is used to make qualitative management decisions; has definitized management control by requiring that the contractor deliver the entire analysis and provide interim updates; has widespread use in many areas of the system development; and is based upon well documented procedures through the use of a basic directive and a detailed supplement in the form of a desk instruction for the manager.

III. DISCUSSION, PROCEDURES AND RESULTS

The following is a discussion of the basic elements involved in formulating a Failure Mode and Effect Analysis. Through the use of a hypothetical system, the generalized procedures for formulating a FMEA are presented. It must be emphasized that these procedures do not represent those used in the FMEA for any specific program, but are the procedures used in deriving the model FMEA in Appendix A. Also included in the following sections are the results of this study as to the use of each aspect of the FMEA in the procurement process.

A. <u>FAILURE MODES AND EFFECTS ANALYSIS</u>

A system operates, or fails to operate, based upon the performance of certain critical components or subsystems. The key in evaluating the ability of the system to perform a required mission, or achieve a desired objective, is the identification of these critical areas. Many times, the design of a system is so complex that a simple examination is not sufficient for this identification process. The Failure Mode and Effect Analysis is a systematic method of identifying and classifying these critical areas. The title itself is an indication of the nature of the analysis.

1. <u>Elements of the FMEA</u>. The failure mode is the manner in which the component, subsystem or system has failed. For example, a power supply may fail to provide the required voltages to the various parts of the system, or a compressor may fail to provide the correct hydraulic pressure. There are four basic failure modes: premature operation, failure to operate at a prescribed time, failure to cease operation at a prescribed time, and failure during operation. (21) (22) Virtually every type of failure mode can be classified into one or more of these general categories. These general failure mode categories are, of course, too broad in scope for a definitive analysis.

Table I is a list of the specific failure modes. These 32 failure modes describe, in sufficiently specific terms, the failure of any component, subsystem, or system. When used in conjunction with the four basic categories, the complete failure mode can be defined. For example, the power supply previously mentioned may have a failure mode which falls under the general category of failure during operation and a specific failure mode of loss of output. The compressor may have a general failure mode of failure to operate at a prescribed time and a specific failure mode of internal leakage.

The analysis also involves a consideration of the failure cause, or that situation which results in the failure mode. The list of Table I, therefore, performs another purpose in also defining a list versatile enough to provide a failure cause. Again using the previous examples, the power supply has a general failure mode of failure during operation, the specific failure mode of loss of output, and a failure cause of the category OPEN (ELECTRICAL). The compressor has the general failure mode of failure to operate at a prescribed time, the specific failure mode of internal leakage, and the failure cause of structural failure (rupture); possibly related to internal valves.

Again, as indicated by the title, it is necessary to determine the effect which the failure mode has on the system, or on those components or subsystems directly related to the failed item. Again referring to Table I, it is possible to see that the failure effect which is the result of a failure mode of one unit may indicate the failure mode of the next item in a subsystem. For example, the loss of the output of the hypothetical power supply may have the effect of the inability of certain items to function. Correspondingly, these units would have a failure cause of 'loss of input' and the effect on the system may be a failure mode of 'fails to start'. Clearly, this somewhat precludes the effectiveness of the analysis because it does not make readily apparent the

TABLE I
FAILURE MODES

1. STRUCTURAL FAILURE (RUPTURE)
2. PHYSICAL BINDING OR JAMMING
3. VIBRATION
4. FAILS TO REMAIN (IN POSITION)
5. FAILS TO OPEN
6. FAILS TO CLOSE
7. FAILS OPEN
8. FAILS CLOSED
9. INTERNAL LEAKAGE
10. EXTERNAL LEAKAGE
11. FAILS OUT OF TOLERANCE (HIGH)
12. FAILS OUT OF TOLERANCE (LOW)
13. INADVERTANT OPERATION
14. INTERMITTENT OPERATION
15. ERRATIC OPERATION
16. ERRONEOUS INDICATION
17. RESTRICTED FLOW
18. FALSE ACTUATION
19. FAILS TO STOP
20. FAILS TO START
21. FAILS TO SWITCH
22. PREMATURE OPERATION
23. DELAYED OPERATION
24. ERRONEOUS INPUT (INCREASED)
25. ERRONEOUS INPUT (DECREASED)
26. ERRONEOUS OUTPUT (INCREASED)
27. ERRONEOUS OUTPUT (DECREASED)
28. LOSS OF INPUT
29. LOSS OF OUTPUT
30. SHORTED (ELECTRICAL)
31. OPEN (ELECTRICAL)
32. LEAKAGE (ELECTRICAL)

seriousness of any one particular failure mode. Therefore, each failure effect is classified by its criticality to the over-all system performance. This criticality classification is as follows:

CLASS IV: 'CATASTROPHIC.' Any single failure which could potentially cause the complete loss of the system, or cause injury to operational or other personnel.

CLASS III: 'CRITICAL.' Any failure which could potentially degrade the specified performance of the system to a point causing complete loss of the system without damage or danger to personnel; a condition which although enabling the system to function could potentially become more serious, or a hazardous condition which is reparable during operation.

CLASS II: 'NON-CRITICAL.' Any failure which degrades the performance of the system to a point which could potentially prevent the accomplishment of a specified function without the loss of associated equipment and without danger to any personnel, but not to a point which causes the complete loss of the system.

CLASS I: 'MINOR.' Any failure which does not degrade the performance of the system, or any type of failure requiring corrective action other than those of Class II, III, or IV.

It is important that the analyst use sound judgement in applying these criticality classifications shown in Table II. Any process which involves a judgement concerning the danger of human life naturally breeds a tendency to extend that judgement to compensate for all factors for the sake of safety; often to an illogical or extreme extent. Therefore, the extensive use of a Category IV classification just "to play it safe" would be inappropriate and would degrade the validity of the FMEA. The use of a Category I classification for the expediency of avoiding problems would also be unjustified. All factors must be taken into account in the application of these classifications because of their impact upon the evaluation of the success of the system development

TABLE II
CRITICALITY CLASSIFICATIONS

CLASS		
IV	CATASTROPHIC	Any single failure which could potentially cause the complete loss of the system, or cause death or injury to personnel.
III	CRITICAL	Any failure which could potentially cause any of the following: 1. The function or mission of the system to be aborted without loss of equipment or endangering personnel. 2. A condition which although enabling the system to function, could become more serious. 3. A hazardous condition which is reparable during system operation.
II	NON-CRITICAL	Any failure which degrades the performance of the system and results in the function or mission being aborted or the loss of any automatic control capabilities.
I	MINOR	Any failure which does not degrade the performance of the system, any type of failure other than those of Class I, II, or III, which requires corrective action.

with respect to the constraints of cost, performance and schedule.

2. A Hypothetical System. The value of the FMEA lies in its systematic approach, and by using the preceeding definitions it is possible to establish a sequence of events for the development of a FMEA, as shown in Table III. This sequence is presented here through the analysis of a hypothetical system. First, the system being analyzed must be fully identified as to its nomenclature, function and composition including a description of the associated subsystems. In addition, it is necessary to identify those associated subsystems which are to be excluded from the analysis. For our purposes, we shall identify the system being analyzed as a high pressure air compressor which will, hypothetically, be used to supply all the high pressure air for a varied number of operations. This system is a modification of that presented by Stump (23) in that it incorporates a more comprehensive indenture level identification scheme. The compressor will be an electric motor driven two cylinder, four stage piston type with closed, or recirculating, water cooling and self-contained lubrication. Excluded from the analysis will be the power controller and the high pressure storage tank. Figure 1 shows the block diagram for this system, which breaks the system into its functional areas, such as motor and compressor, and clearly shows the inputs and outputs of each functional area. Therefore, it can be easily seen that the motor supplies torque of 4610 revolutions per minute (rpm) to the compressor, the cooling and moisture separation, and lubrication stages and that the compressor supplies outputs of high pressure air and of pressure and temperature signals to the instrument and monitor stage. Although not included in the analysis, the relationship of the electrical control stage to the over-all system is also shown.

Each of the major functional areas may also consist of functional sub-areas, and in a complex system this chain of interrelationships may be quite complex. Therefore, the next

TABLE III

THE STEPS OF A FAILURE MODES AND EFFECTS ANALYSIS

1. COMPLETELY IDENTIFY THE SYSTEM BEING ANALYZED
2. BREAK DOWN THE SYSTEM INTO A FUNCTIONAL BLOCK DIAGRAM
3. ESTABLISH INDENTURE LEVEL IDENTIFICATION
4. DETERMINE THE FAILURE MODE(S)
5. DETERMINE THE FAILURE CAUSE(S)
6. ANALYZE THE SYMPTOMS AND THE METHODS OF DETECTION
7. DETERMINE THE EFFECT OF THE FAILURE(S)
8. DETERMINE THE COMPENSATING PROVISIONS
9. DETERMINE THE CRITICALITY FACTOR
10. EVALUATE THE FAILURE PROBABILITY
11. REMARKS AND RECOMMENDATIONS

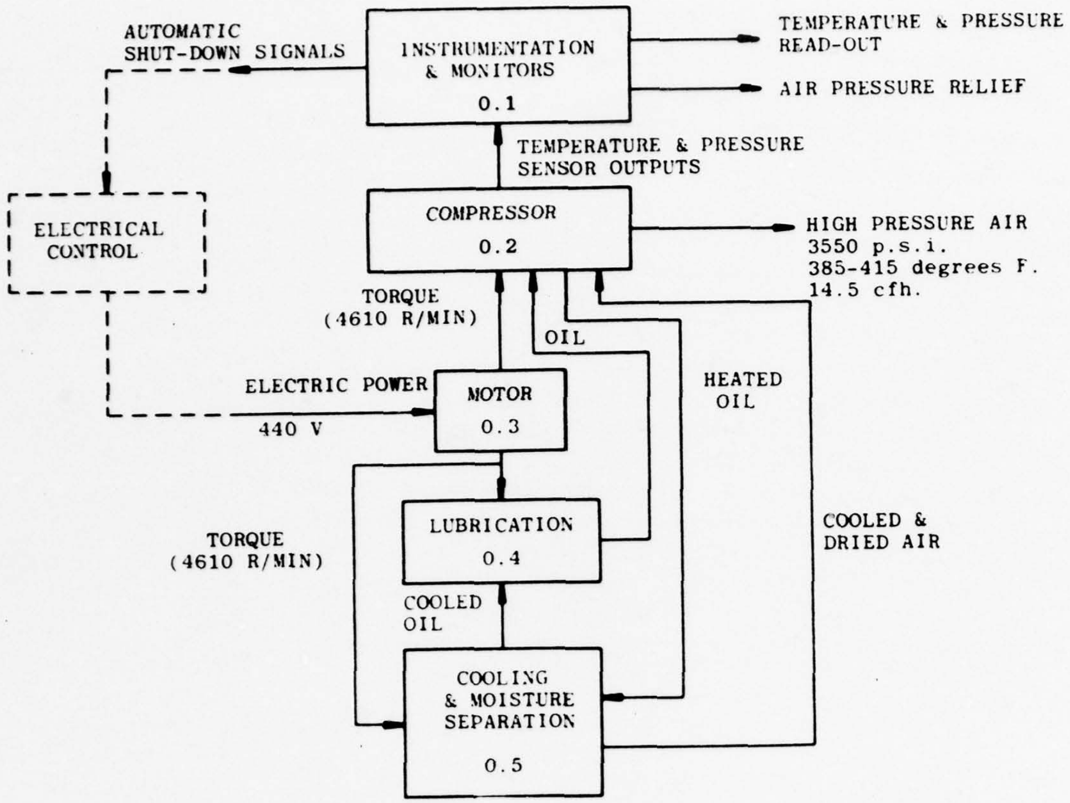

Figure 1. System Functional Block Diagram
Second Indenture Level

step of the analysis is to establish some means for the identification of the level of these relationships, or the indenture level. The first indenture level is that of the complete compressor system and will be indicated by '0'. The second level is that of the major functional areas, instrumentation and monitors, compressor, motor, lubrication, and cooling and moisture separation, and these will be numbered, respectively, 0.1, 0.2, 0.3, 0.4, 0.5, as shown in Figure 1. The third indenture level consists of those subsystems which comprise each of these major areas. The breakdown for the instrumentation and monitor stage is shown in Figure 2. Each of the subsidiary block diagrams follow the same concept in that they must completely identify the subsystem function, show the input and output relationships, and be clearly associated with the next higher level diagram. This system can be easily extended to the full depth of any system, as shown in Figure 3 which illustrates the breakdown of the temperature monitor subsystem numbered 0.1.4 in Figure 2. A unit designated by 0.1.4.1.4 can be readily identified, in a top-down analysis, as belonging to the major system 0., or the compressor system, major functional area 0.1, or the instrumentation and monitor stage, subsystem 0.1.4, or the temperature monitor, subunit 0.1.4.1, or the temperature sensor for the air inlet, and finally to unit 0.1.4.1.4, or the fourth stage air inlet temperature sensor. In addition, this indenture system allows each input or output signal or function to be precisely designated. The signals for each individual unit can be numbered consecutively and entered as a dashed number in the indenture level number. For example, the oil temperature signal shown in Figure 2 would be designated as 0.1.4-3, indicating that it is signal number three for unit 0.1.4. Although the system arrangement as shown in Figure 4 seems somewhat complicated, in practice it is quite simple to master and affords the analyst a brief and precise method of itemizing and accounting for each unit and signal within a complex system.

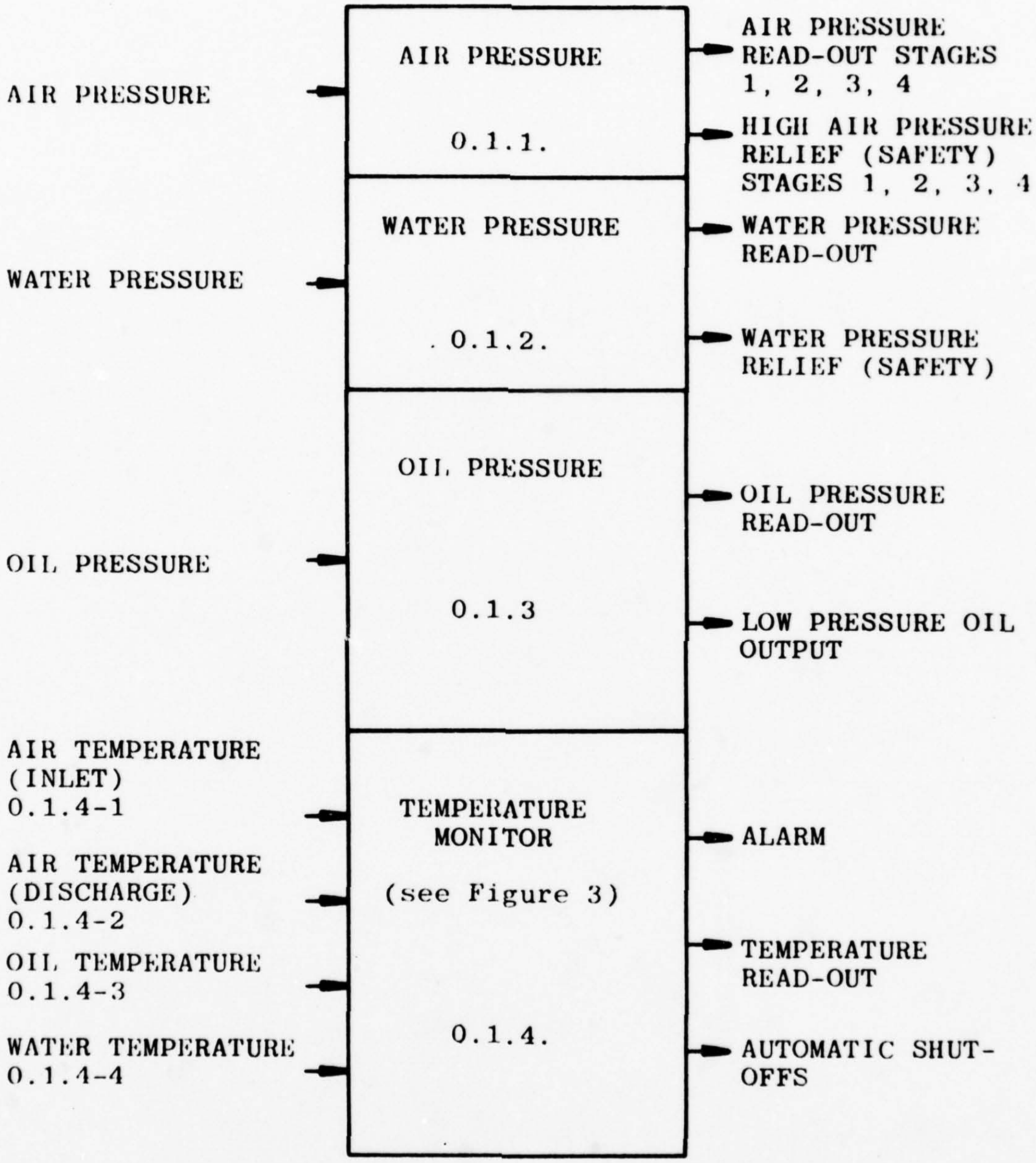

Figure 2. Instrumentation and Monitors
Third Indenture Level

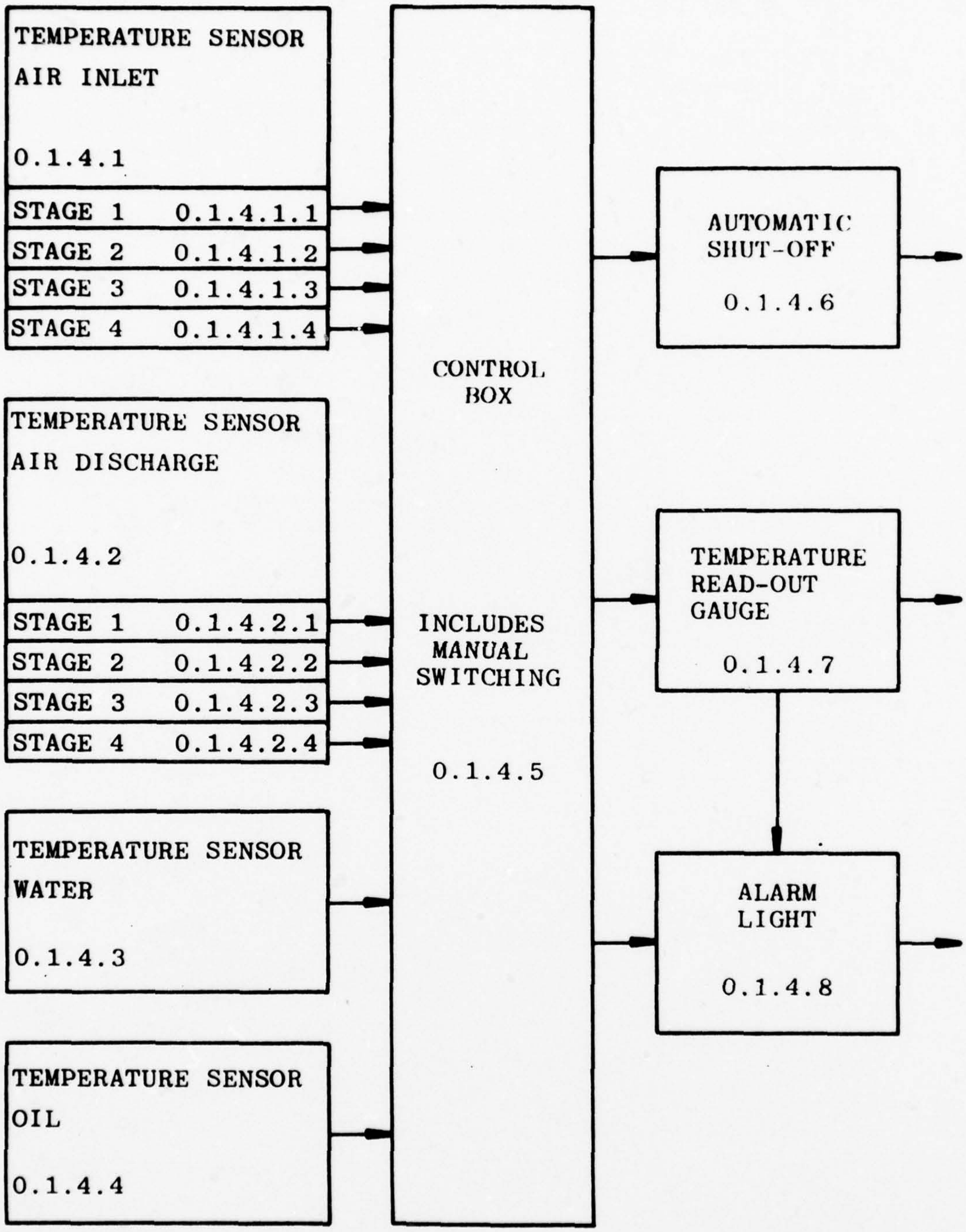

Figure 3. Temperature Monitor
Fourth Indenture Level

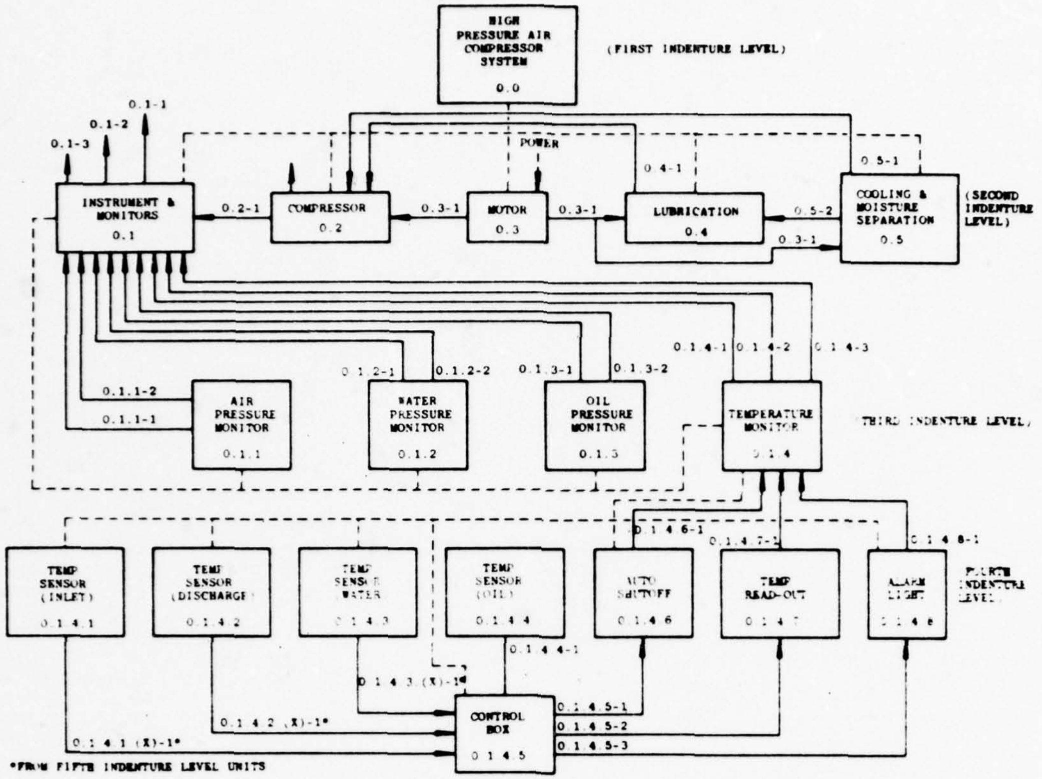

Figure 4. System Functional Block Diagram Signal Identification

3. The FMEA Form. The formulation of these system block diagrams constitutes one aspect of the construction of a system failure model. Another important facet of this initial stage in the building of a system failure model is the introduction of a method for systematically tabulating the results of the analysis through the use of a specified format. This FMEA form should be structured so that data can be easily entered and quickly read and should not contain irrelevant information. The value of the FMEA lies in its flexibility and its logical structure and too much data can negate this value just as can the lack of data. In addition, the FMEA form should be closely tied to the information presented in the system block diagrams previously described. Together, these items constitute the basic requirements of the analysis. When separated from the FMEA form, the block diagram does describe the structure of the system, but when united with the FMEA form its value is substantially increased. When separated from the block diagram, the FMEA does essentially describe the failure model of the system, but the interrelationships involved are readily apparent when it is used in conjunction with the system block diagrams. The actual format of the FMEA form should be left to the discretion of the analyst and tailored to the requirements of the customer. A review of the sources available to this study has resulted in the following comprehensive list of data items which should, as a minimum, be contained in the FMEA:

1. Item Description and Specification
2. Failure Mode
3. Failure Cause
4. Symptoms and Detectability
5. Failure Effect
6. Compensating Provisions
7. Failure Probability
8. Remarks and Recommendations
9. Criticality Classification

A significant amount of the succeeding discussion will, therefore, deal with the formulation of this FMEA form and the contribution made by each portion to the overall system failure model. The Failure Mode and Effect Analysis for the hypothetical high pressure air system is contained in Appendix A. The basic objective of this FMEA is to provide a working model which shows the relationship of the FMEA form to the system block diagrams, and provides examples of the procedures outlined in succeeding sections.

a. Failure Mode. Once the operational structure of the system has been described, it is possible to describe the system in terms of its failure. Utilizing the block diagram of Figure 1 and the list of failure modes in Table I, the system can be modeled in terms of its possible failure modes. This assignment of failure modes requires the analyst to apply a judgement based upon the stated requirements contained in the equipment specifications. The failure mode which is the result of this postulation is that which causes a deviation from the specified output function requirements. It must be emphasized that the analyst is not determining, at this point in the FMEA process, how well the subsystem under consideration meets the specifications, or attempting to determine which of the specifications are most likely not to be met. This is because the FMEA process is initiated after the basic assumption that the subsystem being considered has somehow failed. The judgement area for the analyst is in making a correlation between the specification and the failure mode. This assignment of failure modes proceeds through each indenture level, and the subsystems of which they are comprised. Essentially, this process of failure mode identification comprises the first stage of construction of the failure model of the entire system.

The high pressure air compressor system of Figure 1 has a specified output requirement of high pressure air at 3550 pounds-per-square-inch (psi), at a temperature of 385 to 415 degrees Fahrenheit, and at a rate of 14.5 cubic-feet-per-hour (cfh). Clearly, one failure mode for this first indenture level, or the level annotating the entire system, which must be analyzed is the complete loss of this required output. The specifications of pressure, temperature and rate of air-flow for this system also constitute failure areas which must be analyzed.

The Failure Mode and Effect Analysis for the hypothetical high pressure air system is shown in Appendix A. Generally, the assignment of failure modes to the individual subsystems is accomplished by examining the outputs of these subsystems. Therefore, the entries under the FAILURE MODE--DESCRIPTION column pertain to the outputs of the subsystems listed in the OUTPUT SPECIFICATION column. The entries under the FAILURE MODE--REF column refer to the indenture level numbers and signal designators shown in the system block diagram. This hypothetical system has been analyzed at the "black box" level, or that level of analysis which considers the inputs and outputs of the subsystem without regard to the individual units or components which comprise the subsystem. If more detail were required in the analysis, the subsystems could be broken down into their associated units and then into the individual components. Regardless of the depth required, the analysis follows the same general guideline of determining the failure mode through an examination of the outputs.

b. Failure Cause. As each failure mode is determined, the analysis proceeds to a consideration of the cause of that particular failure. In the analysis for the compressor, designated by reference number 0.2, the failure mode of LOSS OF OUTPUT has an associated failure cause of LOSS OF INPUT. Clearly, the failure cause which has been used can only be as specific as the indenture level will allow. The analyst must be cautious to curtail the tendency to carry the analysis to a depth greater than that necessary for the immediate task. It would be inappropriate to list a failure cause for the second indenture level analysis which specifies a unit or component in the fourth indenture level. For example, in the previously mentioned case, it would be an incorrect expansion of the scope of the analysis to relate the failure cause of LOSS OF INPUT to a bearing in the motor, since the bearing is not shown in the second level indenture diagram. What is shown, however, is the torque input from the motor and this input is related to the failure cause. Through this systematic approach, the analyst can assure a one-for-one correspondence to the analysis and the system structure as detailed in the block diagram.

As previously mentioned, the list of failure modes listed in Table I also constitutes a convenient source of possible failure causes. This is generally true since the output of one unit, analyzed by the assignment of a failure mode, often is the input to a succeeding unit, which is analyzed by the assignment of a failure cause. The actual manner in which the failure cause, or any other entry, is described should, of course, be a factor left to the judgement of the analyst. However, the analyst should follow the guideline of assuring that the entries are brief, concise, and most especially, clear. The analysis contained in Appendix A will, for a majority of entries, use the failure modes of Table I for continuity and to provide a standard base of information.

Generally, therefore, the assignment of possible failure causes involves a consideration of, and a direct relationship to, the inputs of the item being analyzed. The failure cause entry, in conjunction with the failure mode entry, describes the input-output relationship pertinent to the item being analyzed. The collection of these entries over the entire scope of the entire Failure Modes and Effects Analysis then describes the input-output relationships for the entire system over a wide range of specific and possible occurrences.

c. Symptoms and Detectability. The function of the SYMPTOMS-DETECTABILITY portion of the FMEA is to delineate those occurrences which might indicate a failure cause. This allows the analyst to indicate the natural effects related to a failure cause and the system design features which have been included to indicate the failure cause. For example, one of the natural effects resulting from the failure cause of vibration is noise. Therefore, the analyst can indicate this as a symptom of vibration, as has been done with the motor of the analysis in Appendix A. Also, this system has the design feature of system read-outs to indicate the physical conditions, such as temperature and pressure, which are related to the system performance. These system read-outs, therefore, indicate symptoms of failure causes and enable them to be detected.

This section of the analysis can also indicate areas of design deficiencies by indicating failure causes which may not be easily detectable. For example, if the motor of the compressor system stops running, this is a symptom of a failure. However, if the system were located in normally noisy surroundings, where no one could hear the motor stop, or if the operator for some other reason was not aware that the motor had stopped, then this symptom would go unheeded. Employing this information the analyst could then conclude that it might be necessary to include some means of monitoring the motor revolutions in the design.

The symptoms associated with a failure cause, and the ability to detect them, have an important influence on other aspects of any development. Those failure modes which have effects involving human safety must be easily and quickly detectable. This section can provide the safety engineer with valuable data on the detectability of a possible hazardous condition. The accomplishment of the task for which the system was designed can also be influenced. Clearly, if a relatively minor failure cause goes undetected, it has the potential of eventually causing the complete loss of the system. Therefore, the symptoms of these types of failures should be detectable. The FMEA provides this information. Finally, the maintainability of the system is influenced because the SYMPTOMS-DETECTABILITY portion of the analysis allows the analyst to provide information needed for maintenance instructions.

d. Failure Effect. The failure effect is simply the total effect on the system of a particular failure mode. As previously mentioned, the failure mode should be considered in relation to the particular indenture level being analyzed. The failure effect, however, may be related to higher indenture levels. For example, a resistor in a power supply may have a failure mode of the category SHORTED (ELECTRICAL) and have the failure effect of causing the loss of an output transistor. This all takes place on the same indenture level--that of the resistor. In contrast, the transistor failure may have the failure effect of causing the loss of the power supply output, which is on a higher indenture level. Any failure effect which individually and directly causes the complete loss of the system is known as a single point failure and is considered as a catastrophic failure.

The failure effect, therefore, can exist on two levels: the local level and the system level. The local level involves the indenture level of the unit being analyzed and, perhaps, the next higher level. The system level involves the consideration of that particular failure effect on the over-all system performance.

e. Compensating Provisions. This section is related to the failure effect in much the same way that the symptoms section related to the failure cause. The compensating provisions are those design features of the system which have been included to inhibit or prevent the influence of a specific failure effect. For example, if a system has been designed so that the failure of a unit automatically switches in another identical unit to take its place, then this redundancy feature is a compensating provision. A system could also include the compensating provision of alternate modes of operation, such as switching from an automatic mode to a manually controlled mode of operation. This part of the analysis should also consider those safety devices which have been included in the system. Smoke detectors, automatic fire extinguishers, electrical shock prevention devices and failure alarms are just a few.

As with the other sections of the analysis, this section can also provide the analyst with information which points out design deficiencies.

f. Failure Probability. The failure probability is a measure of the likelihood of failure of the item under consideration. At present, this information is obtained directly from the reliability analysis, performed on the system in parallel to the FMEA, or can be derived from the information in the reliability analysis through the following relationship:

FAILURE PROBABILITY = 1 - RELIABILITY ESTIMATION

When used in the FMEA, in conjunction with the criticality classification, it is possible to determine the probability of occurrence of a particular failure mode and its relative seriousness.

A detailed explanation of the basic concepts used in the reliability analysis is beyond the scope of this report. However, it must be emphasized that the reliability analysis is fundamentally probabilistic in nature. A 'bottom-up' analysis begins at the lowest indenture level of the system, involving individual components, and uses the reliability determinations at this level to establish the reliability calculations for the next higher level. This process proceeds up through the hierarchical structure of the system until reaching the highest indenture level, or that of the over-all system. A 'top-down' analysis begins at the highest indenture level and proceeds to the lowest. Regardless of the direction of the analysis, the end result is to assure that the design meets the requirement of the specified system reliability. In order to accomplish this task, the technique of reliability apportionment is also used.

Reliability apportionment is a 'top-down' process of subdividing a specified system reliability among the major subsystems. Each of these allocations are further subdivided among the units which comprise the major subsystems. This process establishes a set of design goals for each component, unit, and subsystem, and when taken together result in the satisfaction of the specified reliability requirement.

In assessing the failure probability, the FMEA analyst should be aware of the fact that the reliability analysis is an estimation. Regardless of the highly developed state-of-the-art, the probabilistic nature of the reliability analysis must be realized.

The analysis of the hypothetical compressor system employs a stratification technique, which is more fully explained in later sections. This somewhat changes the typical form of the FMEA because the FAILURE PROBABILITY becomes the FAILURE PROBABILITY RANGE. However, the basic intent of the information is the same. Regardless of the technique used for this information, the analyst must assure that accurate and meaningful data is presented. Approximations are relevant only when the person reading and using the FMEA realizes that they are approximations.

g. Remarks and Recommendations. This portion of the form is clearly self-explanatory. It is the area of the form set aside for the analyst to provide comments. Brevity and conciseness are, of course, necessary.

h. Criticality Classification. This portion of the form follows the definitions outlined in Table II. As previously stated, the criticality classification, when used with the FAILURE PROBABILITY RANGE, can provide the analyst information on the probability of occurrence of a particular failure mode and its relative seriousness.

B. FMEA AND THE PROGRAM MANAGER

The Department of Defense employs a structured process for the acquisition of defense and space systems. This acquisition process is cyclical in nature and is intended to present a systematic approach for the determination of specific defense objectives, the establishment of the management programs required, and the timely and efficient management of the research and development efforts required to accomplish these objectives. Also involved in this cycle is an iterative evaluation process which is intended to preclude the occurrence of commitments for the development and production of systems which may have been premature with respect to the full verification of these needs and goals. It is not within the scope of this report to present a detailed analysis of this procurement cycle. However, in order to analyze the role of Failure Mode and Effect Analysis in Air Force Program Management, it is necessary to briefly explore it in order to show the relationship of the Program Manager to the acquisition cycle.

1. The Acquisition Cycle. The acquisition cycle, as defined by current Department of Defense Directives (24) (25) consists of four major milestones, as designated by the outermost corner blocks in Figure 5. The inner area of Figure 5 indicates the name given to each milestone which is also the general classification for the events which occur from milestone to milestone. The other areas of Figure 5 indicate the general objectives and specific management considerations, respectively, which must be accomplished between milestones. The dividing line which occurs at each milestone represents a transition which consists of an evaluation of the need of the system being acquired with respect to the defense objectives to be accomplished. It is at this transition where the Program Manager must decide to either continue with the procurement effort and proceed with the actions leading to the next milestone, hold the cycle in abeyance and evaluate other alternatives, or to halt the cycle and recommend cancellation of the program. Just as each phase consumes more area as it moves from the center to the outer boundaries of the diagram, so the acquisition cycle as a

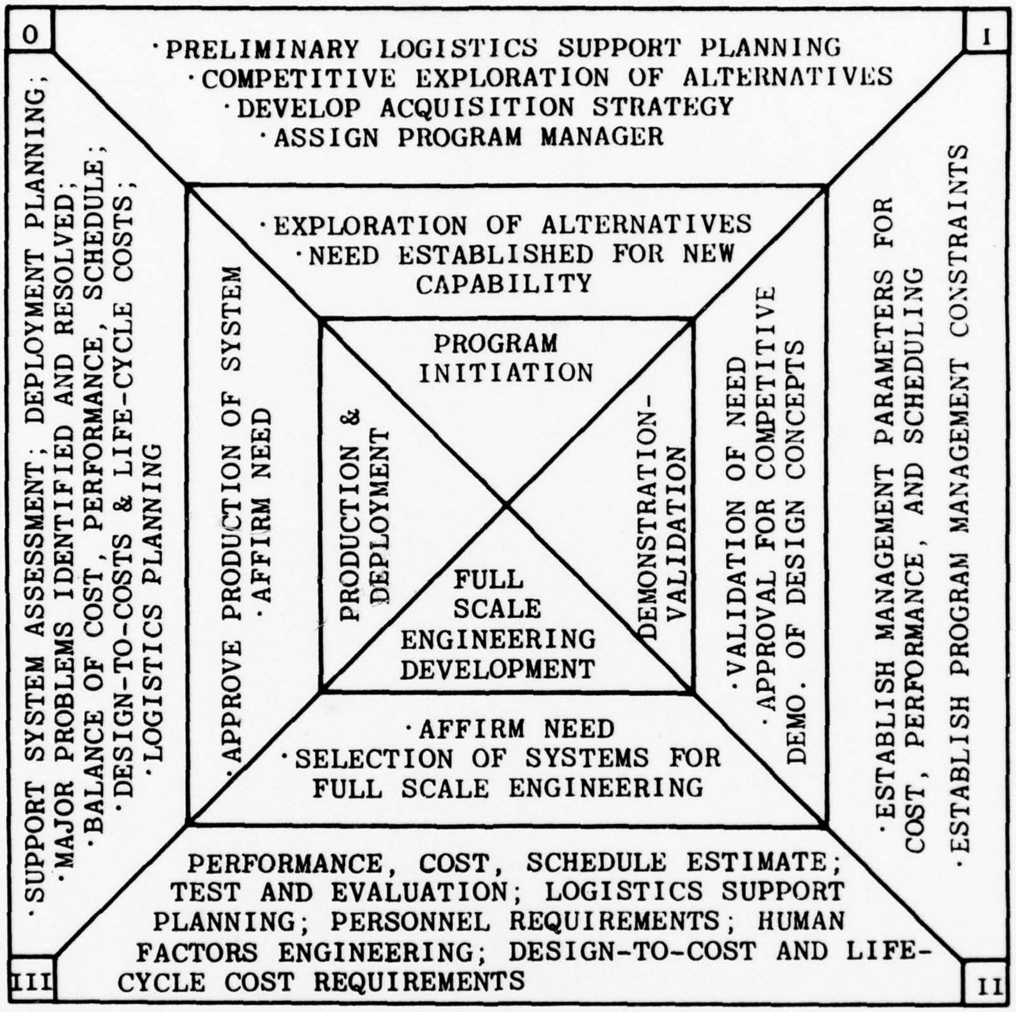

Figure 5. Acquisition Cycle

whole consumes resources as it proceeds. Consequently, the Program Manager must be sure that each effort involved in the acquisition cycle is valid and cost effective.

a. Milestone 0--Program Initiation. The acquisition cycle begins at Milestone 0. Prior to this decision point, actions have been taken which have resulted in the approval by the Secretary of Defense of the validity of the defense objective, or mission need. Certain key actions must take place during this phase of the cycle before the decision point of Milestone I can be reached.

Once the program has been approved and the cycle has begun, a Program Manager is assigned. The Program Manager is responsible for the establishment of a System Program Office (SPO) and the development of a sound acquisition strategy, or a plan for the effective management of the acquisition cycle.

A major emphasis of this phase is the competitive exploration by industry and designated research groups of the alternatives available in order to avoid the possibility of expending funds on unrealistic goals or those which are minimally cost effective. In addition, preliminary and formulative efforts are made for future logistics planning. This area of planning includes such topics as reliability, maintainability and supply supportability. Under current directives, FMEA is included in the reliability planning.

b. Milestone I--Demonstration and Validation. Before the cycle can transition from the Program Initiation Phase to the Demonstration and Validation Phase, the decision point of Milestone I must be passed. This requires that the original need be reaffirmed and that all activities of the Program Initiation Phase have been satisfactorily accomplished. During this Demonstration and Validation Phase, the feasibility and effectiveness of the alternatives in meeting the mission need must be demonstrated and proven. The Program Manager must establish the management constraints for each alternative and assess the problems and issues of the recommended actions. In addition, the Program Manager must establish projections for the management parameters involved in cost, performance and scheduling. Demonstration and validation test and evaluation data must also include the capability of each alternative to meet the logistics requirements of reliability, maintainability and supportability.

c. Milestone II--Full-Scale Engineering Development. The initial management action taken during this phase is a reaffirmation of the original need and an evaluation of the defense objective, or mission, to be accomplished. Then, a specific alternative is selected for full-scale engineering development based on the results of the demonstration and validation test and evaluation. Operational and logistical considerations are made which will produce the most effective balance in cost, performance and scheduling. Realistic design-to-cost and life-cycle cost requirements must be made in order to assure effective achievement of the cost objectives.

Logistics support planning is included in essentially every major action of this phase because of three paramount considerations. First, it is important to identify the uncertainties and risks involved in the selected alternative, and resolve them to an acceptable level. Whenever these uncertainties and risks cannot be determined to be acceptable, their impact upon the successful accomplishment of the procurement effort, and the satisfaction of the defense objective, must be determined. Second, the development must be logistically supportable and the requirements must be established to assure the availability of parts and material. Third, all aspects of reliability and maintainability must be evaluated in order to establish the accomplishment of design-to-cost and life-cycle cost requirements, to assure the identification of risk areas, to support the operational and logistical considerations, and to provide a foundation for the operational test and evaluation efforts which must be accomplished before the cycle can transition from this phase to the decision point of Milestone III.

d. Milestone III--Production and Deployment. As in all the previous portions of the cycle, this phase is initiated only after the need has been reevaluated and reaffirmed and all actions of the previous phase have been completed. Transition past Milestone III represents a decision to proceed with production and deployment efforts based upon this reaffirmation of the original need and the test and evaluation results. At this point in the acquisition cycle, all aspects and requirements of cost, performance, schedule, design-to-cost and life-cycle-cost factors, system support, reliability and maintainability must be valid and cost effective.

2. Utilization of FMEA. Currently, the utilization of Failure Modes and Effects Analysis is somewhat limited in scope due to the fact that FMEA is closely tied to a specific design. Although FMEA is a portion of the reliability planning effort, and is considered in the initial logistics planning effort, its use in the Program Initiation Phase is practically nonexistent.

The use of FMEA does not become significant until after Milestone II, in the Full-Scale Engineering Development Phase. Again, this is due to the fact that a firm design is not usually available until this time, and the current practice for formulating a FMEA is based upon the availability of this design. During this phase many important aspects of the acquisition begin to take shape. Reliability and maintainability determinations are made which will have a significant impact on the effectiveness of the chosen alternative to satisfy the defense objective. Other logistical considerations, such as procurement of parts and material requiring long order times and system spare parts support, are made which establish the foundations for a production decision. These, and numerous other considerations, are built upon the actions of the preceeding activities and vastly affect the succeeding ones. In addition, design reviews are held, the function of which is to review the effectiveness, validity and maturity of the design. The use of FMEA in the acquisition first becomes apparent at this time because it is a requirement, based upon current Department of Defense procurement directives, that these design reviews include an evaluation of the FMEA. Specifically, this evaluation must determine that the contractor involved has eliminated, or sufficiently resolved and compensated for, all category III and IV failure modes. Also, it is during the Full Scale Development Phase that the Safety and Hazard Analysis for the system begins to take shape. Currently, the FMEA is a major resource in the formulation of this analysis.

During the Production and Deployment Phase the FMEA again becomes dormant. Essentially, its purpose under current practices is fulfilled and it is used primarily as a design and reliability reference. This is not to slight the effort which is involved in formulating and compiling a FMEA for a system because, in a majority of cases, the effort involves a great deal of time and consumes a significant amount of resources in man-hours and money. For example, the FMEA for the hydraulics system of an aircraft can often occupy numerous volumes. The FMEA for the entire aircraft, covering all subsystems, can, and does in the case of the F-15 aircraft, present a significant storage problem because of its size.

This points out a significant road-block to the widespread utilization of the FMEA by Program Management. The areas of responsibility which must be assumed by the Program Manager are vast and wide in scope. The current procedures used by contractors in formulating a FMEA result in a document, or set of documents, which are quite voluminous. This is primarily due to the fact that a majority of Failure Mode and Effect Analyses are performed to cover every possible avenue of failure mode and to include every indenture level of the system. If one magnifies the scope of the hypothetical FMEA in Appendix A to include every possible failure mode of every individual subsystem, unit and component of the system, it is not difficult to realize that this analysis would quickly mushroom into a nearly unmanageable size.

Clearly, it becomes increasingly difficult for Program Management to be able to efficiently assimilate so much data carried to such an extreme depth. The FMEA process loses flexibility, ceases to become a management tool and becomes, instead, an exercise accomplished because the current directives require it. The process also loses validity because funds are expended for an effort with doubtful cost effectiveness. That is, one can question the validity of data that is so extensive that few are in a position to analyze it or take benefit from its formulation. What is clearly needed is a methodology for incorporating the experience gained from past Failure Mode and Effect Analyses, and the needs of the Program Manager for obtaining accurate data concerning the problems and issues of a particular system and procurement effort which can be quickly and effectively employed in the decision making process. Also, what is needed is a revision of the philosophy surrounding the formulation and use of such a document to preclude the current difficulties.

C. A REVISION OF PHILOSOPHY

Failure Mode and Effect Analysis can potentially be a valuable tool for the Air Force Program Manager. However, an extensive study of the current role of FMEA in Air Force Program Management has shown that the use of FMEA as a management tool is hindered by the current philosophy which surrounds the process. This philosophy has resulted in procedures which tend to continue to limit the scope of FMEA utilization and which contribute to the development of FMEA as a process which becomes increasingly separated from management. What seems to be happening is that FMEA is becoming more a reliability and design aid than a valuable resource easily visible to, and of direct and substantial use by, Air Force Program Management. The following sections are a discussion of the aspects of this current philosophy which should be readjusted if the Air Force Program Manager is to have the latitude to derive full benefit, within a management environment, from the effort expended in accomplishing a FMEA.

1. Education. The procedures for formulating and evaluating a FMEA are, based upon a study of Air Force procurement efforts, relatively ill-defined. Although Military Standard 785A stipulates the requirement for accomplishing a FMEA, it makes no reference to any formalized documentation which might explain the basic concepts involved. This study has found that no such documentation, either in the form of Air Force Manuals or Pamphlets, exists to aid the Program Manager. Few of the references reviewed by this study contain more than a superficial explanation of the need and use of FMEA. A majority of these works, dealing with reliability engineering, logistics engineering and program and systems management, contain only a few short paragraphs which deal with FMEA. A review of over 600 articles and papers on the broad subject area of reliability, available through the Defense Logistics Studies Information Exchange (DLSIE), produced only one article which specifically covered the procedures involved in formulating a FMEA. No articles have been found by this study to deal specifically with the role of FMEA in Program Management or how FMEA might be employed for the evaluation of the success of a procurement effort. Industrial standards which have been reviewed have been found to be rather limited in scope, primarily as "how-to" references, with little emphasis on the management aspects of the process.

The FMEA process is currently, and should continue to be, a contractor responsibility. However, the Program Manager has a basic responsibility to understand those endeavors undertaken by a contractor, in order to properly manage the resources which they consume. This study has found that FMEA is a process which is not fully understood by the Air Force

Program Manager, based on a number of interviews, and which is not currently employed to its full potential.

Current procurement practices call for the FMEA for a system development to be an agenda item at all design reviews. Reliability engineers evaluate the FMEA primarily to determine if the contractor has satisfactorily resolved all mission critical, or Category III and IV, failures. After fulfilling this requirement, the FMEA is retired to the contractors' files, updated as required, and produced at the next design review. Little Air Force documentation has been found by this study which details in depth the formulation, evaluation or potential use of FMEA. This study has found that a great number of those individuals involved in evaluating the FMEA accept the validity of the contractors' analytical procedures with little in-depth knowledge of the process. In addition, the formalized training conducted on FMEA is minimal in scope and a majority of individuals have either learned about the process by experience or by instruction on the job.

This is not to imply that FMEA should be removed from the realm of responsibility of the contractor. Quite the contrary, because the contractor has the best working knowledge of the system development and should be the originator of the FMEA. However, what is needed is a shift of the philosophy surrounding the FMEA in that management, and those who perform the evaluation during design reviews, should be more knowledgeable about the basic concepts involved. FMEA has more value than just being a scheme for the counting of mission critical failures. Formal Air Force documentation is needed which will constitute a baseline of knowledge for the proper utilization of FMEA.

Standardization of the format or content of a FMEA is just as undesirable as removing the responsibility for the FMEA from the contractor. Since the FMEA is also a contractor resource, any change which inflicts bureaucratic standardization retards the creativity of the contractor in effectively performing his function. However, there are certain aspects of a FMEA which will occur in nearly every system development, and Program Management should assure that they are contained in the FMEA. Such items as failure mode, failure cause, failure effect, criticality classification, and some measure of failure probability are, as previously described, clearly central to the FMEA process. The form and content requirement for other items, such as compensating provisions and remarks, should be a function of the Program Management of each separate development effort. Close cooperation between the contractor and Program Management is essential to the production of a meaningful analysis.

2. Early Program Assessment. A major factor which this study has found which hinders the wide use of FMEA is its current dependency upon a rather well developed design of the system. This design is not usually developed to a state which is easily analyzed until late in the Demonstration and Validation portion of the acquisition cycle, shown in Figure 5. This is yet another aspect of the current FMEA philosophy which should be changed in order to derive expanded benefit from the FMEA. The evaluation of a defense alternative while it is in the conceptual phase of development, before it becomes a definitive design and before the initiation of design reviews, can provide management with indications of its feasibility and emphasize problem areas early in the acquisition cycle when costs are generally lower.

Although somewhat simplistic in nature, the system diagram of Figure 1 represents a system in a conceptual phase. All of the specifications are involved and the subsystem interrelationships are evident. The FMEA contained in Appendix A is an analysis of this hypothetical design. Admittedly, a defense system may be more complex but nearly every design goes through the same conceptual phase-point as that of Figure 1. What is most important is that it is possible to quickly determine potential system weaknesses from an analysis accomplished at this early stage of system development. Unlike the situation caused by current procedures, the Program Manager has early visibility of the feasibility of the project, early knowledge of the general system structure, and without the complexity of succeeding levels of design detail it is possible for him to quickly isolate the areas of the procurement process which will require close managerial attention. When many alternatives are being considered for possible development, the accomplishment of this generalized FMEA offers a valid and cost effective vehicle by which the feasibility of each alternative can be assessed.

In the analysis in Appendix A, it can be seen that the Instrumentation section of the system, shown in Figure 1, has three areas which can cause serious problems. First, the read-outs of temperature and pressure, reference 0.1-1, can cause a Category III failure when the read-outs are normal and the inputs are abnormal. Second, the Automatic Shutdown, reference 0.1-2, can cause a Category IV failure if there should be a loss of output when the inputs are abnormal. Third, the Air Pressure Relief, reference 0.1-3, can cause a Category IV failure if there should be a loss of output when the inputs are abnormal. In addition, an analysis of this third entry has resulted in a specific safety recommendation. Each of these areas would, in an actual system development, require management attention. Their early assessment could potentially result in a more efficient allocation of resources and a more cost effective procurement effort.

It must be emphasized that these indications of potential system deficiencies are evident not because of an analysis of a detailed design but rather that of a conceptual block diagram. This type of diagram, in most cases, is available during the early phases following Milestone 0, when the various defense alternatives are being evaluated for future development. What is gained by this introduction of FMEA early in the acquisition cycle is an early indication of the existence of specific problem areas when the cost of redesign and evaluation are low. Also, this example points out that it is not a general requirement of all system procurement efforts to accomplish a FMEA based solely upon a detailed design in order to produce an analysis which is beneficial to Program Management.

As before, it is not considered prudent to remove the responsibility of this preliminary FMEA from the jurisdiction of the contractor. The Air Force Program Manager is not a system designer, but he does have a responsibility to provide design guidance. The accomplishment of a FMEA while the system is being conceptualized will enable him to accomplish this task on a continuing basis and provide a cost effective means of transitioning from milestone to milestone.

3. Increased Management Visibility. In order to properly manage the continuing effort of a defense system acquisition, the Program Manager must have full visibility of the progress and maturity of the system development. This is especially true when the acquisition cycle transitions to the point where a validation of the need of the defense objective is required. Under the current philosophy of FMEA use it is not possible to easily fit the FMEA into this context, primarily because of its size and complexity. Understandably, the least conceivable action that a Program Manager might take when arriving at this decision point would be to bury himself in the detail of a FMEA. However, the information which he most probably needs at this point is contained in the FMEA. Again, what is needed is a shift of philosophy.

Few programs require that the contractor deliver copies of the full scale FMEA to Program Management, which is logical when one considers its size and complexity. Instead, the contractor retains possession of the FMEA and produces copies only on demand. As each design review is held, the FMEA is made available for Air Force review and evaluation. The contractor then reclaims the FMEA and performs the update as requirements and design changes dictate. The question remains, however, of how Program Management can retain visibility of the progress of the system development when one of the primary source documents for this assessment remains with the contractor. Delivery of the FMEA by the contractor does not offer a plausible solution because it still burdens the Program Manager with the necessity of reviewing a sizeable document.

a. The FMEA Transition Summary. One answer may lie in the use of the FMEA Transition Summary, shown in Figure 6. This type of supplement to the FMEA is not a summary of the contents of the FMEA. Instead, it is a summary of the changes which have taken place to the FMEA, especially between design reviews and as design changes take place, and offers some immediate benefits over the current practice. The format presented here is an improvement of that offered by Arnzen (26) in that the Summary is directly related to the system block diagrams through the REFERENCE entry and the change in criticality classification is made clearer.

The FMEA Transition Summary provides a real-time visibility over the progress of the system development because as design changes occur, and the contractor submits an amended Summary, Program Management can directly relate their impact to the system objectives. This is not, in any way, to suggest that the current practice of filing an Engineering Change Proposal (ECP) is not effective, but the use of the FMEA Transition Summary draws direct correlations between the design change and the effect of that change upon the FMEA and the system development. The use of the Summary also offers the advantage of providing a reference to those individuals participating in the design review of the changes which have occurred since the last review. In this way, the design review process is expedited because each change can be directly and quickly related to the FMEA to determine the effect of the change. Therefore, the reviewer does not have to retrace areas already covered in a previous review and can efficiently proceed to the affected sections of the FMEA.

	ORIGINAL SYSTEM		REVISED SYSTEM		
REFERENCE	CRITICALITY CATEGORY	DESCRIPTION	CRITICALITY CATEGORY	DESCRIPTION	REMARKS RECOMMENDATIONS IMPROVEMENTS
0.1-1	III	Single system - Read-outs of temp. & pressure	I	Redundant system for read-outs. Dual system.	Reduces effect of single point failure. System can function on one leg of the redundant system.
0.1-2	IV	Single system - Automatic Shutdown	I	Dual redundancy for Automatic Shutdown	Reduces effect of single point failure. System can function on one leg of the redundant system.
0.1-3	IV	Single system - Air pressure relief	I	Dual redundancy for air pressure relief.	Reduces effect of single point failure. System can function on one leg of the redundant system.
					Safety warning added to compressor system control panel. Warning also included in operations manual.

Figure 6. FMEA Transition Summary

Another important responsibility of the Program Manager is to be able to quickly and efficiently evaluate the parameters of cost, performance and schedule requirements in order to assess the impact of trade-offs. In other words, he must be able to determine the cost-benefit relationships involved in each area of the system development. The FMEA Transition Summary offers a method for accomplishing this task because as each design change takes place, and is recorded on the Summary, the Program Manager can relate its implementation to the FMEA and evaluate its impact. The collection of the Summaries constitute a chain of events in the system development and the Program Manager can arrive at conclusions regarding the relative value of each change by reviewing the changes which preceeded it.

b. The Failure-Criticality Grid. The format and content of a FMEA done by one contractor differs in form and content from that of another. However, most contain either an entry for failure rate or failure probability. Both of these factors are derived from the information in the reliability analysis but have subtle differences. Failure probability is the probability that a failure will occur during a specified interval of time and failure rate is the frequency at which failures occur over a specified interval of time. Failure probability is usually expressed as a number between zero and one and failure rate is normally expressed as the number of failures occurring per unit operating hour. This type of information is generally beneficial because it provides some degree of correspondence to the likelihood of the occurrence of a failure mode. The question arises, however, of how a Program Manager can effectively employ this information in assessing the progress of the system development, establishing trade-offs with respect to the factors of cost, schedule and performance, or determining the dollar impact of changes.

The Failure-Criticality Grid, shown in Figure 7, is a modification of that used by Stump (27) in that it more

CRITICALITY CLASSIFICATION

IV	0.1-2 0.1-3 0.2-1 0.2-1 0.2-2 0.4 0.5 0.5 0.1.4-3			
III	0.2-1 0.3 0.3 0.3 0.4 0.5 0.5 0.1.4-2		0.1-1 0.1.4-1	
II	0.2-1 0.1.4-2 0.1.4-3	0.1-3		
I	0.1-1 0.2-2	0.2-1	0.1-2 0.1.4-1	
	1	2	3	4

FAILURE RANGE

Figure 7. Failure-Criticality Grid

effectively incorporates the definitions of Section III. The Failure-Criticality Grid is intended to provide a method which will allow the Program Manager to easily visualize the relationships of failure probability or failure rate and criticality classification. This can be especially beneficial for the Program Manager in his efforts in determining the capability of the system to meet specific design goals and defense objectives, allocating resources to critical areas of the procurement effort, establishing the impact of design changes, and in determining the progress and maturity of the system development. The Failure-Criticality Grid uses a technique of stratifying the failure probability or failure rate information into designated ranges. It must be emphasized that the following discussion employs failure ranges which are for example only.

Stratification, as used in the formulation of the Failure-Criticality Grid presented here, is the process of dividing the probability space into different ranges when using failure probability data. (28) For failure rate data, the area of stratification could, for example, cover from zero failures per unit time to the maximum specified failures per unit time. The ranges are flexible and can be adjusted in size and number according to the system specification and the requirements of Program Management. The stratification shown in Table IV is used for the hypothetical FMEA in Appendix A. Again, it must be emphasized that the failure ranges, failure probabilities and failure rates used herein are for example only. In actual use in a procurement effort, these factors would be based upon the specification and the requirements of the Program Management of that particular program.

The Failure-Criticality Grid is a method by which the Program Manager can quickly and efficiently determine the relationship of the criticality classification and the failure range, as determined by the stratification technique. As entries are made in the Grid, the distribution of the failure

TABLE IV

STRATIFICATION OF FAILURE RANGES USED IN THE PROGRAM DISTRIBUTION GRID

RANGE	
1	Failure probability which is less than or equal to 0.01; very low. Failure rate of one or less failures per year.
2	Failure probability which is greater than 0.01 and less than or equal to 0.10; low. Failure rate of more than one failure per year and two or less failures per year.
3	Failure probability which is greater than 0.10 and less than or equal to 0.20; medium. Failure rate of more than two failures per year and three or less failures per year.
4	Failure probability which is greater than 0.20; high. Failure rate of greater than three failures per year.

modes, specified by unit and signal reference number, become apparent. The Grid shown in Figure 7 is for the system shown in Figure 1 and the FMEA in Appendix A. The vertical axis represents the criticality classification, in descending order, and the horizontal axis represents the failure ranges obtained after stratification. Each failure mode is then assigned to its respective location in the matrix based upon these two factors, and is designated by the indenture level reference notation described in earlier sections.

This study has found that, owing to its size and complexity, a FMEA accomplished with current techniques is extremely difficult to analyze with respect to the relative occurrence of any single criticality classification and the distribution of all criticality classifications over the entire system. The Failure-Criticality Grid clearly fulfills this need. The primary benefit of this method is that the Air Force Program Manager has immediate visibility of the entire system development.

If a Program Manager should establish the goal of reducing the number of Category III and IV failures, as well he should, the Failure-Criticality Grid offers him a vehicle with which to measure the success of his efforts. In addition, he can determine the change in status of the failure modes for the entire system. For example, if a design change were implemented to eliminate the Category III-Range 3 failure mode, referenced by 0.1-1 in Figure 7, and this change resulted in a shift of this failure mode to Category IV-Range 1, the change would be obvious with the use of the Grid. Current FMEA procedures require that a large portion of the FMEA would have to be analyzed before such a change would be apparent. The Grid of Figure 7 shows a large cluster of failure modes in Category IV-Range 1. Perhaps a Program Manager might want to allocate resources to change this situation. Under current practices, this grouping of failure modes would be hidden in the complexity of the FMEA. Nearly every occurrence which changes the criticality classification or failure range of a specific failure mode is made clear through the use of the Failure-Criticality Grid. In addition, the impact of such a change upon the entire system configuration is readily apparent. Essentially, the Grid can provide the Air Force Program Manager with increased visibility of the procurement effort and result in increased managerial efficiency. The benefits to be derived from the use of the Failure-Criticality Grid are only limited by the Program Manager.

4. Increased Management Flexibility. A significant situation which has been found to exist is the lack of management flexibility in the formulation of the Failure Mode and Effect Analysis of a specific system. The Program Manager does not have the latitude to manage this resource because he cannot make determinations as to the scope of the FMEA for his program. For example, if a particular subsystem does not show the potential for causing significant problems in the system development the Program Manager cannot specify the level to which this subsystem will be analyzed. Current practices and requirements dictate that all portions of the system will be analyzed to the lowest, or component level. Of course, this assures that no possible contingency can occur which will degrade the system performance; however, it lessens the authority of the Program Manager. The formulation of a FMEA consumes time, funds and personnel. If the current depth of analysis is not needed, in the opinion of the authority responsible for the program, then the question remains whether these resources can be better spent in other areas. When the depth of the information precludes its use because of the time needed to assess it, then that information, and the resources spent to produce it, have reached a point where the return diminishes.

The FMEA presented in this study is a model upon which an actual FMEA can be based. However, with the practices in effect, the Program Manager does not have the latitude to stipulate the format which the contractor will use. This is especially true if the contractor does not supply all the information which the Program Manager might require. Essentially, the Program Manager is put in the situation of getting what he is given and being forced to be satisfied because to reaccomplish this effort may cost significantly more than the program plan and budget can bear.

5. Increased Logistic Supportability. The true validity and cost effectiveness of the FMEA process lies in its capability to be applied to a diverse number of areas of the procurement effort. This study has found that the current structure of Failure Mode and Effect Analysis and the general philosophy surrounding its use have acted as deterents to its being employed to its full potential. This is especially true in the broad area of logistics support, since it involves some key activities. A change in the current philosophy, and the subsequent change in the procedures, can result in a wider use and acceptance of FMEA. As the scope of FMEA use increases to cover more aspects of the procurement effort, its validity and cost effectiveness increase.

Logistics support is a term which may be applied to encompass a variety of subjects. For the purposes of this discussion, logistic support will include the areas of operational testing, supply support, maintainability, personnel and training, and technical data. Just as each portion of the model FMEA presented can benefit the Program Manager in his endeavor to manage the over-all system development, so they can benefit each of these subdivisions of the program.

The maintainability of the system, or the capability for the system to be effectively repaired and serviced, is a factor which must be considered throughout the entire acquisition cycle. Clearly, if the system is not maintainable then its feasibility for fulfilling the defense objective is negated. The impact of design changes, the types and distribution of failures, the causes and effects of failures, the symptoms and detectability of failures, and the interrelationships of subsystems are all factors which influence maintainability. Accordingly, the FMEA is a method by which each of these factors can be assessed. However, this study has found that little use is made of the FMEA in this context. A great deal of the information which is used to evaluate the maintainability of a system is drawn from the reliability analysis because of the numerical determinations made for such factors as mean-time-to-repair (MTTR), mean-time-between-failure (MTBF), mean-time-between-replacement (MTBR), maintenance downtime (MDT), and total turnaround time (TAT). The FMEA is not structured to provide the calculations for these factors, and it should not be. However, the FMEA can provide the information needed to make a qualitative evaluation of maintainability because it does show the relative impact of design changes, and emphasizes those areas of failure which can cause significant maintenance problems. The Failure Mode and Effect Analysis also shows the subsystem relationships involved in the system and can indicate the existence of problem areas which may not be apparent by the numbers alone.

Each failure which occurs will, in most cases, require some type of supply support in the form of a part used to repair it. Again, the FMEA is suited to provide the information necessary to accomplish the planning for this supply support. The types and distribution of failure modes for the entire system, and for specific subsystems, obviously give indications of the frequency with which the system will require parts. In addition, this information can be valuable in determining the priorities which will be involved. For example, Category I failures may not require as high a supply priority as Category II failures. A particular subsystem with a high incidence of failures in one area will likely require more spare parts than another. In addition, information presented in the FMEA can provide indications as to the relative costs involved in supplying the system throughout its life cycle. As design changes occur, or trade-offs are made which affect the system configuration, these changes can be reflected in the FMEA on real-time basis through the use of such sections of the FMEA as the Transition Summary and the Program Distribution Grid. The FMEA provides the supply analyst with a means of qualitatively evaluating the supply supportability of the system without attempting to derive the meaning of a numerical analysis.

Failure Mode and Effect Analysis can make an important contribution in the area of technical data. A FMEA structured such as the one in Appendix A shows not only the type of failure, or failure mode, but also the effect of the failure, the cause of the failure, the symptoms and means of detection of the failure, and those features of the design which compensate for the failure. In addition, the FMEA shows the structure of the system and the subsystem relationships involved. Essentially, the FMEA provides the information necessary to formulate a maintenance manual. Also, this information is central to the information required in preparing an operational manual.

General determinations as to the requirements for numbers and skill levels of personnel can be facilitated by use of the FMEA. A qualitative evaluation of the data on failure types and the effect which they have on system performance can provide indications of the skills needed or the type of training required. For example, if the FMEA of a system resulted in more failures in the electronic sections of the system, then more personnel trained in electronics would be needed than those with mechanical skills. The specific skills needed would require a more comprehensive evaluation of the data contained in the FMEA and that contained in the reliability analysis.

The formulation of plans for the operational test and evaluation is an exacting process requiring data from a variety of sources. Currently, this planning is done by combining the requirements of the specification with information obtained from the reliability analysis and technical information on the system performance and capabilities supplied by the contractor. This study has found that little use is made of the FMEA in this planning process. The operational test and evaluation results constitute a basis for a production decision, and the FMEA contains information which can significantly assist in this decision and in the formulation of the test plan. For example, by employing the information contained in the FMEA a specific subsystem performance can be evaluated in a failure environment. That is, if design features have been incorporated to compensate for a failure, then the ability of the system to survive that failure mode could be tested. The maintainability of a system can be tested by using the information in the FMEA to supply failure information to assist in determining the accuracy of the information contained in the reliability analysis.

IV. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The results of this study lead to the overall conclusion that Failure Mode and Effect Analysis is a resource which is not being employed to its full potential in Air Force defense system acquisitions. Most prevalent of the many factors which have contributed to this circumstance is the current philosophy which surrounds the use of the FMEA process. This philosophy has made FMEA another portion of the rather mystic science of reliability and hindered its development as a valuable management tool.

The model FMEA presented in Appendix A can be used as a guideline for the Air Program Manager in integrating FMEA into an acquisition effort. When it is combined with the system block diagrams and used in conjunction with the Transition Summary and the Failure-Criticality Grid, it offers a valid and cost effective method for evaluating the capability of the chosen alternative to meet the requirements of the defense objective and serves as a measure of the progress of the acquisition effort. In addition, it provides a concise history of the significant events which have occurred and indicates their impact on the overall system configuration. Armed with this type of information, the Program Manager can effectively evaluate trade-offs with respect to the requirements of cost, performance and schedule.

Further study is recommended below with suggestions on how to circumvent some of the problem areas highlighted here and suggestions on further areas of study.

B. RECOMMENDATIONS

FMEA can only be effective if the concepts involved in its formulation and the benefits to be derived from its use are understood by Air Force Program Managers. Education on the process is clearly necessary. Air Force documentation is needed which will provide the Program Manager an available reference on FMEA without requiring him to delve into the few books and articles available. Air Force management courses should be available which stress the value and validity of FMEA and delineate the wide scope of its potential use.

A measure of flexibility needs to be introduced into the directives which require the use of FMEA in the acquisition process. The Program Manager should have the latitude to structure the FMEA in the way which best benefits the program. The depth of the analysis should not be a requirement which encompasses more than what is needed for management objectives.

The slight modifications to the form and content which have been presented in this report should be included within the structure of the FMEA. This is not a recommendation that they be unilaterally required but that they should be made available to the Program Manager for use in the program and the FMEA.

This change in the current philosophy and the shift of FMEA from a strictly reliability oriented function to that of a process which can benefit the entire acquisition process should be made. Only in this way can the effective utilization of FMEA be realized.

C. AREAS OF FURTHER STUDY

The computerization of Failure Mode and Effect Analysis is an area worthy of further study. Although there are instances of where the computer has been used to generate the FMEA form from specific input data, no use has been made of the computer in the decision making processes involved in the FMEA. Essentially, the overall problem is three-fold in nature. First, a set of universal rules must be developed which can be applied to every FMEA. Then, a set of decision algorithms must be written which can incorporate these rules and the specifications for a particular defense system. Finally, a computer program must be generated which combines the rules and the decision algorithms, provides for such aspects as the FMEA Transition Summary and the Failure-Criticality Grid, and allows flexible requirements as specified by

Program Management. This type of computerized analysis can be of immediate benefit in reducing the workload of Program Management and in providing a centralized store of readily available FMEA information on a timely basis.

The use of FMEA in evaluating Reliability Improvement Warranties (RIW) offers another area of study. Simplistically, a RIW is much like the service agreement that a retailer makes with a customer covering a refrigerator. However, for a complex defense system, they are much more complicated and cover nearly all aspects of system operation and maintenance. Reliability Improvement Warranties are currently of increasing interest and importance in the Air Force and FMEA offers a potential method of determining their validity in specific programs.

Further amplification of this study is also possible. A case-by-case study encompassing the aerospace industry could provide information concerning the role of FMEA in that industry. The sample FMEA study questionnaire contained in Appendix B could be distributed to aerospace contractors and the results analyzed. In addition, the impact of FMEA on other areas of private industry, such as the automotive industry or the home appliance industry, could be examined.

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Sumerlin, W. T. Techniques of System Reliability Estimation, Including Failure Effect Analysis (Failure Consequence). Lecture Series Number 47 of the NATO Advisory Group for Aerospace Research and Development. Neuilly-Sur-Seine, France: North Atlantic Treaty Organization, 1969.

Von Alven, William H., ed. Reliability Engineering. Englewood Cliffs, New Jersey: Prentice-Hall, 1964.

Wessell, James, Major, USAF. Personal interview. Wright-Patterson Air Force Base, Ohio, April 6, 1977.

Williams, Henry L. Personal interview. Houston, Texas, October 17, 1977.

VITA

Frederick Charles Potts was born in Indianapolis, Indiana on September 3, 1944. He was raised in Florida and in 1962 was graduated from Robinson High School in Tampa, Florida. In 1965, he enlisted in the United States Air Force and served with the Strategic Air Command until 1971. At this time, he was accepted into the Airman Education and Commissioning Program and assigned to the Air Force Institute of Technology at the University of Missouri-Columbia. He graduated from the University of Missouri-Columbia in 1973 with a Bachelor of Science degree in Electrical Engineering. He was commissioned as an officer in the Air Force in September, 1973. Preceding his enrollment to the University of Missouri-Rolla, he served with the Air Force Communications Service as a Communications-Electronics Engineer. While assigned to the Headquarters of the Air Force Communications Service he served as a Project Officer and gained his experience in program management. He has also served as the Systems Manager for an isolated overseas communications site. In August 1976, he was assigned to the Air Force Institute of Technology and is currently enrolled in the University of Missouri-Rolla seeking a Master of Science degree in Engineering Management.

APPENDIX A
MODEL FAILURE MODE AND EFFECT ANALYSIS

Presented here is a model Failure Mode and Effect Analysis for the hypothetical high pressure air compressor system described in the body of the report. The FMEA consists of the system description, the system specifications, the system block diagrams, and the analysis forms. It must be emphasized that all factors are for example only and are not meant to specify, or form the basis for the specification of, any actual system. In actual use, these factors would be subject to the contractual negotiations of that particular procurement effort.

A. SYSTEM DESCRIPTION

The hypothetical system to be analyzed is a high pressure air compressor which will be used to supply all the high pressure air for a varied number of operations. The compressor is an electric motor driven two cylinder, four stage piston type with closed (recirculating) water cooling and self-contained lubrication. Excluded from the analysis is the power controller and the high pressure storage tank.

B. SYSTEM SPECIFICATION

The Instrumentation and Monitors Subsystem supplies signals representing air temperature and pressure to a readout device which is considered a portion of this subsystem. This subsystem also supplies a signal for the automatic relief of excessive high pressure air to an external automatic relief valve. This external high pressure relief valve will be activated by the Instrumentation and Monitor Subsystem when the pressure of the air produced by the compressor exceeds 3550 pounds-per-square-inch (psi). In addition, the Instrumentation and Monitor Subsystem will supply a signal to the power controller for the automatic shutdown of the entire system when the temperature of the high pressure air is less than 385 degrees Fahrenheit or exceeds 415 degrees Fahrenheit. This automatic shutdown signal will also be used to activate an audible alarm sufficient in volume to notify the operator that the system has been shut down.

The Compressor Subsystem supplies high pressure air at a pressure of 3550 p.s.i., at a temperature between 385 and 415 degrees Fahrenheit, and at a rate of 14.5 cubic-feet-per-hour (cfh).

The Motor Subsystem receives electric power from the power controller and operates on 440 volts, 60 cycle alternating current. The Motor Subsystem supplies torque to the compressor and operates at a constant speed of 4610 revolutions-per-minute (rpm). In addition, the Motor Subsystem supplies torque to the Lubrication Subsystem and the Cooling and Moisture Separation Subsystem.

The Lubrication Subsystem supplies lubricating oil to the Compressor Subsystem.

The Cooling and Moisture Separation Subsystem cools and dries outside air and supplies it to the Compressor Subsystem for compression and output. Moisture content of the air supplied by this subsystem must be less than ten parts-per-million (ppm). In addition, this subsystem receives heated oil from the Compressor Subsystem and cools it for redistribution to the Lubrication subsystem.

C. FUNCTIONAL BLOCK DIAGRAMS

The functional breakdown of the high pressure air compressor system is shown in Figures 1, 2, 3, and 4. The major subsystem relationships are shown in the second indenture level diagram of Figure 1. The Instrumentation and Monitors Subsystem is expanded to the third indenture level in Figure 2. The Temperature Monitor Subsection of the Instrumentation and Monitors Subsystem is shown in the fourth indenture level in Figure 3. Specific inputs and outputs are identified and the relationships existing through four indenture levels are shown in Figure 4.

D. MODEL FAILURE MODE AND EFFECT ANALYSIS

The actual FMEA is shown in Figure 8. The procedures for formulating and evaluating this analysis are contained in Section III of the report.

OUTPUT SPECIFICATION FUNCTIONAL DESCRIPTION	REF	FAILURE MODE DESCRIPTION	FAILURE CAUSE	SYMPTOMS-DETECTABILITY	FAILURE EFFECT	COMPENSATING PROVISIONS	FAILURE PROBABILITY RANGE	REMARKS RECOMMENDATION	CRITICALITY CLASS
INSTRUMENTATION	0.1								
READ-OUTS OF TEMPERATURE AND PRESSURE	0.1-1	ERRONEOUS INDICATION Read-out abnormal Inputs normal	ERRONEOUS INPUT Faulty instrument or sensor signal	OPERATIONS NORMAL	UNNECESSARY SHUTDOWN OF SYSTEM	NONE	1	- - - -	I
	0.1-1	ERRONEOUS INDICATION Read-out normal Inputs abnormal	ERRONEOUS INPUT Faulty instrument or sensor signal	NO OBVIOUS SYMPTOMS	LOSS OF OUTPUT Possible damage to compressor	NONE	1	- - - -	III
AUTOMATIC SHUTDOWN	0.1-2	FALSE ACTUATION Inputs normal	ERRONEOUS INPUT Faulty instrument or sensor signal	COMPRESSOR SHUTS DOWN	UNNECESSARY SHUTDOWN OF SYSTEM	NONE	3	- - - -	I
	0.1-2	LOSS OF OUTPUT Inputs abnormal	ERRATIC OPERATION	SYSTEM READ-OUTS may indicate abnormal operation	LOSS OF OUTPUT Possible damage to compressor	SYSTEM READ-OUTS	1	- - - -	IV
AIR PRESSURE RELIEF	0.1-3	FALSE ACTUATION Inputs normal	ERRONEOUS INPUT Faulty instrument or sensor signal	LOW AIR PRESSURE	FAILS OUT OF TOLERANCE (LOW) Low air pressure	NONE	2	- - - -	II
	0.1-3	LOSS OF OUTPUT Inputs abnormal	ERRONEOUS INPUT Faulty instrument or sensor signal	AUTO SHUTDOWN SYSTEM READ-OUTS	LOSS OF OUTPUT Possible damage or injury if pressure builds too high	AUTOMATIC SHUTDOWN	1	**Safety warning should be present. Normal operation has possible release of high pressure air.**	IV

Figure 8. Model Failure Mode and Effect Analysis

OUTPUT SPEC- IFICATION FUNCTIONAL DESCRIPTION	REF	FAILURE MODE DESCRIPTION	FAILURE CAUSE	SYMPTOMS- DETECTABILITY	FAILURE EFFECT	COMPENSATING PROVISIONS	FAILURE PROBABILITY RANGE	REMARKS RECOMMENDATION	CRITICALITY CLASS
COMPRESSOR 3550 psi 385-415 deg F. 14.5 cfh	0.2								
HIGH PRESSURE AIR	0.2-1	LOSS OF OUTPUT No high pressure air	LOSS OF INPUT No torque input from motor	SYSTEM READ-OUT shows low air pressure	LOSS OF OUTPUT No high pressure air	NONE	1	- - - -	III
	0.2-1	FAILS OUT OF TOLERANCE (LOW) Low air pressure	ERRONEOUS INPUT (LOW) Low torque from motor	SYSTEM READ-OUT shows low air pressure	ERRONEOUS OUTPUT (LOW) Low air pressure	NONE	1	- - - -	II
	0.2-1	LOSS OF OUTPUT No high pressure air	LOSS OF INPUT No input from cooling	SYSTEM READ-OUT shows no air pressure	LOSS OF OUTPUT Possible damage to compressor	NONE	1	- - - -	IV
	0.2-1	FAILS OUT OF TOLERANCE (LOW) Low air pressure	ERRONEOUS INPUT Low supply of air from cooling	SYSTEM READ-OUT shows low air pressure	ERRONEOUS OUTPUT (LOW) Low pressure	NONE	1	- - - -	II
	0.2-1	LOSS OF OUTPUT No air pressure	LOSS OF INPUT No oil input from lubrication	SYSTEM READ-OUT shows low oil pressure	LOSS OF OUTPUT Possible damage to compressor	NONE	1	AUTO SHUTDOWN may limit damage	IV
TEMPERATURE & PRESSURE SENSOR OUTPUTS	0.2-2	ERRONEOUS OUTPUT Signal abnormal Compressor normal	ERRATIC OPERATION Faulty device or sensor	OPERATIONS NORMAL	UNNECESSARY SHUT DOWN OF SYSTEM	NONE	1	- - - -	I
	0.2-2	ERRONEOUS OUTPUT Signal normal Compressor abnormal	ERRATIC OPERATION Faulty device or sensor	NO OBVIOUS SYMPTOMS	LOSS OF OUTPUT Possible damage to compressor	NONE	1	AUTO SHUTDOWN may limit damage	IV

Figure 8. (continued)

OUTPUT SPECIFICATION FUNCTIONAL DESCRIPTION	REF	FAILURE MODE DESCRIPTION	FAILURE CAUSE	SYMPTOMS-DETECTABILITY	FAILURE EFFECT	COMPENSATING PROVISIONS	FAILURE PROBABILITY RANGE	REMARKS RECOMMENDATIONS	CRITICALITY CLASS
MOTOR 4610 rev/min 60 hp	0.3	LOSS OF OUTPUT No rev/min Stops running	ERRATIC OPERATION Possible electrical malfunction	MOTOR stops running	LOSS OF OUTPUT No high pressure air	NONE	1	SYSTEM READ-OUTS should include motor current and rev/min indicators	III
TORQUE TO: **COMPRESSOR** **LUBRICATION** **COOLING AND** **MOISTURE** **SEPARATION**		FAILS OUT OF TOLLERANCE (LOW) Low rev/min	ERRATIC OPERATION Possible electrical malfunction	SYSTEM READ-OUTS indicate low air pressure	ERRONEOUS OUTPUT Low air pressure. Possible damage to compressor.	NONE	1		III
		VIBRATION Rough running	PHYSICAL BINDING OR JAMMING Possible mechanical malfunction	Vibration, varying rev/min, noise	ERRONEOUS OUTPUT Low air pressure. Low cooling. Reduced lubrication.	NONE	1	- - - -	III
LUBRICATION 36-85 psi	0.4	LOSS OF OUTPUT No oil output	LOSS OF INPUT No torque from motor	High temperature in compressor. No oil pressure read-out.	LOSS OF OUTPUT No high pressure air. Damage to compressor.	NONE	1	AUTO SHUTDOWN may limit damage	IV
		FAILS OUT OF TOLERANCE (LOW) Low oil pressure	INTERMITTENT OPERATION. Possible mechanical malfunction	High temperature in compressor. Low oil pressure read-out.	ERRONEOUS OUTPUT Low air pressure. Possible damage to compressor.	NONE	1	See third indenture level analysis; INSTRUMENTATION AND MONITORING: REF 0.1.3	III

Figure 8. (continued)

OUTPUT SPECIFICATION FUNCTIONAL DESCRIPTION	FAILURE MODE REF	FAILURE MODE DESCRIPTION	FAILURE CAUSE	SYMPTOMS-DETECTABILITY	FAILURE EFFECT	COMPENSATING PROVISIONS	FAILURE PROBABILITY RANGE	REMARKS RECOMMENDATION	CRITICALITY CLASS
COOLING AND MOISTURE SEPARATION 385-415 deg F MOISTURE: 10 ppm Standard Temp. and Pressure	0.5	LOSS OF OUTPUT No cool, dry air to compressor	LOSS OF INPUT No torque from motor	SYSTEM READOUTS show low air pressure	LOSS OF OUTPUT No high pressure air. Possible damage to compressor	NONE	1	**AUTO SHUTDOWN may limit damage when temp. builds in compressor**	IV
		FAILS OUT OF TOLERANCE (HIGH) High temperature air to compressor	ERRONEOUS INPUT (LOW) Low torque from motor	SYSTEM READOUTS show high temp. air	FAILS OUT OF TOLERANCE (HIGH) High temperature air	NONE	1		III
COOLED OIL TO: LUBRICATION		LOSS OF OUTPUT No cooled oil	LOSS OF INPUT No torque from motor	SYSTEM READOUTS show high temp. oil	LOSS OF OUTPUT No high pressure air. Damage to compressor.	NONE	1	AUTO SHUTDOWN may limit damage when temp. builds in compressor. Final	IV
		FAILS OUT OF TOLERANCE (HIGH) High temperature oil to lubrication	INTERMITTENT OPERATION. Possible PHYSICAL BINDING OR JAMMING	SYSTEM READOUTS show high temperature in compressor	Possible long-range damage to compressor.	NONE	1	system design should have loss of oil pressure included in AUTO SHUTDOWN subsystem	III

Figure 8. (continued)

OUTPUT SPECIFICATION FUNCTIONAL DESCRIPTION	FAILURE MODE REF	FAILURE MODE DESCRIPTION	FAILURE CAUSE	SYMPTOMS-DETECTABILITY	FAILURE EFFECT	COMPENSATING PROVISIONS	FAILURE PROBABILITY RANGE	REMARKS RECOMMENDATION	CRITICALITY CLASS
TEMPERATURE MONITOR Monitors air, oil and water temperatures Air: Oil: Water:	0.1.4								
ALARM	0.1.4-1	LOSS OF OUTPUT Inputs abnormal; Alarm does not sound	ERRATIC OPERATION Faulty device or sensor signal	AUTO SHUTDOWN. SYSTEM READ-OUTS may indicate abnormal operation	No audible indication to operator of AUTO SHUTDOWN	NONE	3	- - - -	I
	0.1.4-1	FALSE ACTUATION Inputs normal; Alarm sounds	ERRATIC OPERATION Faulty device or sensor signal	NORMAL OPERATION. SYSTEM READ-OUTS will show normal indications	INADVERTANT OPERATION. Operator may initiate unnecessary shutdown of system	SYSTEM READ-OUTS	3	Operator must check SYSTEM READ-OUTS	III
TEMPERATURE READ-OUT	0.1.4-2	LOSS OF OUTPUT Inputs abnormal	ERRATIC OPERATION Faulty device or sensor signal	SYSTEM READ-OUTS will show no temperature	No visible indication of system condition	NONE	1	AUTO SHUTDOWN may limit damage	II
	0.1.4-2	ERRONEOUS INDICATION Read-outs abnormal. Inputs normal	ERRATIC OPERATION Faulty monitor device	NORMAL OPERATION	INADVERTANT OPERATION. Operator may initiate unneeded shutdown of system	NONE	1	Loss of temperature read-out should indicate trouble	III
AUTOMATIC SHUTDOWN	0.1.4-3	LOSS OF OUTPUT Inputs abnormal	ERRATIC OPERATION Faulty monitor device	SYSTEM READ-OUTS will indicate abnormal operation	LOSS OF OUTPUT Possible damage to compressor	SYSTEM READ-OUTS	1	SYSTEM READ-OUTS may indicate trouble	IV
	0.1.4-3	FALSE ACTUATION Inputs normal	ERRATIC OPERATION Faulty monitor device	COMPRESSOR SHUTS DOWN	LOSS OF OUTPUT Unnecessary system shutdown of system	NONE	1	- - - -	II

Figure 8. (continued)

APPENDIX B
SAMPLE FMEA STUDY QUESTIONNAIRE

Presented here is a sample questionnaire which may have potential use in further studies of the FMEA process as it applies to contractors involved in DOD contracts. The objective of the questionnaire is to determine whether the contractor surveyed is on a prime contractor or subcontractor level, whether the contractor employs the FMEA process as required by DOD directives, and what procedures are used to specify the manner in which the analysis is performed. This information can be used as a basis from which to draw conclusions as to the impact of the changes recommended in this report. For example, questions six and seven indicate the references used by the surveyed company in formulating the procedures and show the factors involved in the FMEA. In addition, the use of the FMEA in the areas of testing and logistics can be determined by questions eleven through fifteen and can indicate whether the FMEA has widespread use in the company. The questionnaire also surveys those companies planning to introduce the FMEA process to determine the direction of that planning.

A. QUESTIONNAIRE INSTRUCTIONS

Please indicate your response to all applicable questions with an "X" in the space next to your answer. Certain questions will contain directions based upon your response. Primarily, these directions consist of PLEASE PROCEED with the questionnaire in a sequential manner. PLEASE PROCEED to a specified question number without answering intermediate questions, or PLEASE INDICATE additional information. If you do not wish to supply this additional information, please enter "N/R" in that area. If you do not wish to answer a question, please mark the numeral designating that question with an "X". No effort will be made to "interpret" your reasons for not supplying extra information or not answering a question. The markings requested are for ease in compiling the data.

Your name, position and company are optional. No use will be made of specific names, positions, or companies in the final report. This information will only be used to determine population and sample factors for statistical analysis of the questionnaire.

NAME:
POSITION:
COMPANY:

THANK YOU AND PLEASE PROCEED WITH THE QUESTIONNAIRE.

1. Is your company involved with defense contracts from the Department of Defense (DOD)?
   ______ YES - PLEASE CONTINUE
   ______ NO - THANK YOU. PLEASE RETURN THE QUESTIONNAIRE IN THE SUPPLIED RETURN ENVELOPE.
2. Is your company mainly involved on a prime contractor or subcontractor level?
   ______ PRIME CONTRACTOR
   ______ SUBCONTRACTOR
   ______ BOTH
3. Does your company employ the process of Failure Mode and Effect Analysis (FMEA) in connection with DOD contracts?
   ______ YES - PLEASE CONTINUE
   ______ NO - PLEASE PROCEED TO QUESTION 18
4. Does your company use the nomenclature Failure Mode and Effect Analysis?
   ______ YES
   ______ NO - PLEASE INDICATE THE NAME USED:
   ____
5. Does your company have its own corporate practices to direct the procedures used in this analysis?
   ______ YES
   ______ NO

6. PLEASE INDICATE if any of the following are used in conjunction with, or in place of, company requirements:

______ MIL-STD 785A
______ MIL-STD 756A
______ MIL-HDBK 217
______ RADC RELIABILITY HANDBOOK
______ QUALITY CONTROL HANDBOOK
______ MIL-STD 882
______ NONE OF THE ABOVE
______ OTHER: ____
____

7. PLEASE INDICATE which of the factors listed below are considered in this analysis:

______ OUTPUT SPECIFICATION/FUNCTIONAL DISCRIPTION
______ FAILURE MODE
______ FAILURE CAUSE
______ SYMPTOMS/DETECTABILITY
______ FAILURE EFFECT
______ EXISTING COMPENSATING PROVISIONS
______ CRITICALITY FACTOR/CLASSIFICATION
______ FAILURE PROBABILITY
______ FAILURE RATE
______ RECOMMENDATIONS
______ OTHER: ____
____

8. PLEASE INDICATE which of the following individuals are directly involved with the initial formulation of the FMEA:

______ RELIABILITY ENGINEER
______ DESIGN ENGINEER
______ OTHER: ____

9. Is this analysis updated as design changes occur or on a periodic basis?

______ YES, as design changes occur
______ YES, on a periodic basis
______ YES, based on both of the above
______ NO, updates are not accomplished

10. If a failure probability or failure rate is included in the analysis, is this information derived from the reliability analysis or derived solely as a part of the FMEA?

______ DERIVED FROM THE RELIABILITY ANALYSIS
______ DERIVED AS A PART OF THE FMEA
______ THIS INFORMATION IS NOT USED

11. Is the FMEA used by your company in deriving a Safety/Hazard Analysis of the system?

______ YES, directly
______ YES, indirectly
______ NO

12. Is the FMEA used by your company in a logistics context to determine such factors as optimum order quantities or spare parts requirements?

______ YES
______ NO

13. Is the information from the FMEA used by your company in preparing "in-house" testing plans?

______ YES
______ NO

14. PLEASE INDICATE if this analysis is used in the preparation of any of the following:

______ FLIGHT MANUALS
______ TROUBLESHOOTING GUIDES/MANUALS
______ MAINTENANCE MANUALS
______ TECHNICAL ORDERS
______ OPERATIONAL MANUALS
______ OTHER: ______________________________
____

15. Is the information from the FMEA used by your company for preparing testing plans for other than "in-house" purposes, such as those used for operational test and evaluation?

______ YES

______ NO

16. By what means is the FMEA prepared?

______ MANUALLY

______ COMPUTER

______ BOTH MANUALLY AND BY COMPUTER

17. If computerization of this analysis was shown to be feasible and practical, would there be sufficient interest in your company for the development of this software?

______ YES

______ DOUBTFUL

______ NO

THANK YOU. PLEASE RETURN THE QUESTIONNAIRE IN THE SUPPLIED RETURN ENVELOPE.

18. Is your company currently planning to implement a Failure Mode and Effect Analysis Program for application to DOD contracts?

______ YES - PLEASE CONTINUE

______ NO - THANK YOU. PLEASE RETURN THE QUESTIONNAIRE IN THE SUPPLIED RETURN ENVELOPE.

19. In implementing this program, how will your company prepare the analysis?

______ MANUALLY

______ COMPUTER

______ BOTH MANUALLY AND BY COMPUTER

20. In implementing this program, will your company have its own corporate practices to direct the procedures used?

______ YES

______ NO

21. Will any of the following be used in conjunction with, or in place of, company requirements for this analysis?

______ MIL-STD 785A
______ MIL-STD 756A
______ MIL-HDBK 217
______ RADC RELIABILITY HANDBOOK
______ QUALITY CONTROL HANDBOOK
______ MIL-STD 882
______ NONE OF THE ABOVE
______ OTHER: ____
____

THANK YOU. PLEASE RETURN THE QUESTIONNAIRE IN THE SUPPLIED RETURN ENVELOPE.

B. SUGGESTED LIST OF COMPANIES

TRW Systems, Inc.
Defense and Space Systems Group
Reliability Division
One Space Park
Redondo Beach, California 90278

IBM Corporation
Federal Systems Division
Reliability Group
Bethesda, Maryland 20034

Raytheon Company
Government Marketing
Reliability Division
141 Spring Street
Lexington, Massachusetts 02173

Hydraulic Research Textron
Department AF-1
25200 West Rye Canyon Road
Valencia, California 91355

System Development Corporation
Reliability Division
2500 Colorado Avenue
Santa Monica, California 90406

Northrup Corporation
Reliability Division
Ventura Division
1515 Rancho Conejo Blvd.
Newbury Park, California 91320

Motorola
Government Electronics Division
Reliability Group
P.O. Box 2606
Scottsdale, Arizona 85252

Rockwell International
Rocketdyne Division
Reliability Group
6633 Canoga Avenue
Canoga Park, California 91304

Cutler-Hammer
AIL Division
Reliability Group
Deer Park
Long Island, New York 11729

GTE Sylvannia, Inc.
Western Division
Reliability Group
P.O. Box 205
Mountain View, California 94042

Bell Aerospace-Textron
Reliability Division
Buffalo, New York 14240

Westinghouse Electric Corporation
Defense and Electronic Systems Center
Reliability Division
MS-129A
P.O. Box 746
Baltimore, Maryland 21203

Pratt & Whitney Aircraft Group
Government Products Division
Reliability Section
West Palm Beach, Florida 33402

General Dynamics
Pierre Laclede Center
St. Louis, Missouri 63105

Sanders Associates, Inc.
Federal Systems Group
Reliability Division
95 Canal Street
Nashua, NH 03061

Applied Technology
Reliability Division
645 Almanor Avenue
Sunnyvale, California 94086

The Bendix Corporation
Aerospace-Electronics Group
Reliability Division
Dept. 110-B
1911 North Fort Myer Drive
Arlington, Virginia 22209

Teledyne CAE
Reliability Division
1330 Laskey Road
Toledo, Ohio 43612

E-Systems, Inc.
Reliability Division
P.O. Box 6030
Dallas, Texas 75222

Hewlett-Packard
Reliability Division
16399 West Bernardo Drive
San Diego, CA 92127

Sikorsky Aircraft
Reliability Division
Stratford, Connecticut 06602

Guidance & Control Systems
Reliability Division
5500 Canoga Avenue
Woodland Hills, California 91364

Sierra Research Corporation
Reliability Division
P.O. Box 222
Buffalo, New York 14225

Sperry Vickers
Reliability Division
Jackson, Mississippi 39206

Ex-Cell-O Corporation
Aerospace Division
Reliability Group
2855 Coolidge
Troy, Michigan 48084

Tracor, Inc.
Applied Technology Division
Reliability Group
6500 Tracor Lane
Austin, Texas 78721

Government Avionics Marketing
Collins Radio Group
Rockwell International
Cedar Rapids, Iowa 52406

AiResearch Manufacturing Company
Reliability Division
P.O. Box 5217
Phoenix, Arizona 85010

Aero Products
Reliability Division
Woodland Hills, California 91364

ALKAN U.S.A., Inc.
Reliability Division
6020 Richmond Highway
Alexandria, VA 22303

Boeing Company
P.O. Box 3707
Seattle, WA 98124

APPENDIX C

ADDRESSES OF INDIVIDUALS INTERVIEWED FOR THIS STUDY

Presented here are the addresses for those individuals interviewed for this study. Throughout this listing, the abbreviation AFB will be used to indicate Air Force Base.

Mr. W. O. Detert
ASD/ENESR
Wright-Patterson AFB, Ohio 45433

Mr. Charles Dorney
ASD/YF
Wright-Patterson AFB, Ohio 45433

Lt. Thomas Landers
ASD/YPEX
Wright-Patterson AFB, Ohio 45433

Mr. Marion E. Merrell
NB-2
NASA Lyndon B. Johnson Space Center
Houston, Texas 77058

Mr. W. P. Murden
Reliability Division
McDonnell-Douglas Corporation
St. Louis, Missouri 63166

Captain Francis Stump
Headquarters NASA
Mail Code MOE
Washington, D.C. 20546

Mr. A. S. Torgerson
Reliability Division
McDonnell-Douglas Corporation
St. Louis, Missouri 63166

Major James Wessell
ASD/YF
Wright-Patterson AFB, Ohio 45433

Mr. Henry L. Williams
Chief, Vehicle Reliability Engineering Branch
NB-2
NASA Lyndon B. Johnson Space Center
Houston, Texas 77058