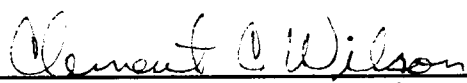
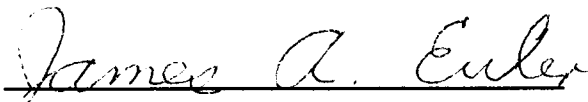
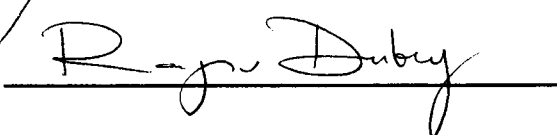


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Clement C. Wilson, Major Professor

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CREATING RELIABILITY IN THE DESIGN PROCESS:
AN EVALUATION APPROACH, DESIGN TOOL,
AND EXAMPLE APPLICATION

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

David A. Walker

August 1990

DEDICATION

This paper is dedicated to my family, Jack, Pat, and Daniel Walker, for their loving care, guidance, and friendship, and to my future wife, Elaine, for her abundant support, insight, companionship, and love.

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From JBF Associates, Inc., Dr. Jerry Fussell and David Montague have been instrumental in cultivating my interest in reliability aspects of engineering, and have provided my fundamental education in the subject through course work and personal discussions. Myron Casada has also contributed comments, in addition to the knowledge I gained while working for him on a major refinery FMEA project. Finally, Tim Mynatt has provided technical expertise concerning some programming issues.

The assistance from each of these individuals is appreciated, and will not be forgotten.

ABSTRACT

This research is conducted to provide insight into the current issue of implementing designer reliability analysis in the early stages of development and production for a truly superior product or process. Additionally, the research suggests a solution by providing a simplified reliability analysis approach and design tool for use by the designer in the early design stages, to enable more effective and efficient reliability improvements to be made to engineered systems. The reliability design tool is based on the universally accepted Failure Modes and Effects Analysis (FMEA) technique through an automated information management and reliability analysis calculation program. The software program is specifically created to provide easily interpreted results for making reliability improvement decisions through a simple, easy-to-use format. An example case study is provided to demonstrate the approach and the software, and to provide useful reliability assessment and improvement information. The subject of the case study is a current graduate research project at The University of Tennessee, Knoxville, aimed at developing and marketing a low-cost, cartesian co-ordinate robot.

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CHAPTER 1

INTRODUCTION

1.1 Project Background [College of Engineering, 1988]

The College of Engineering at the University of Tennessee, Knoxville has initiated **The Superior Engineering Design Program** as a major effort to enhance engineering education. The goal of the program is to improve engineering design skills of the next generation of engineers to develop more competitive U. S. products and processes for the world markets. The program focuses upon interdisciplinary education and actual design experiences with modern equipment. A sophisticated computer Engineering Design Center, testing and practice laboratories, and new courses have been developed in pursuit of the program's goals. These efforts have been well received, and supported, by industrial sponsors such as Westinghouse, International Business Machine, Northern Telecom, and Martin Marietta.

The program is headed by Dr. Clement C. Wilson, formerly with IBM. Dr. Wilson's 26 years of experience in industry have provided him with a range of assignments from technology development to manufacturing. A fundamental element of the program, based on Dr. Wilson's industrial experience, is the belief that excessive

specialization is detrimental to successful design projects because of the wide range of requirements imposed on new products and processes. One area which is particularly specialized, and alienated from many design projects, is reliability assessment and improvement. Dr. Wilson's extensive industrial experiences have demonstrated to him the critical influences of reliability and failure costs on products, often determining the success or failure of product lines, or entire business interests. Based on this experience, Dr. Wilson has supported, and funded, this research effort to provide an effective reliability assessment and improvement design tool for use in the engineering curriculum, and in the Engineering Design Center.

1.2 Project Goals

The goal of this research effort is to develop a reliability design tool capable of assessing the reliability and risk characteristics of engineered systems, and providing improvement information for the systems. In an effort to avoid specialized use by only reliability engineers, the approach will be based on an accepted, uncomplicated reliability analysis approach, with flexibility for use on many types of systems. The ambition is not to develop a "new" reliability analysis

methodology, but rather to make innovative use of existing approaches, and to "bridge the gap" between design engineering and reliability engineering. The primary goal is to contribute a tool capable of providing the designer opportunities to efficiently improve a product or process during design while changes are easily enacted. A secondary goal of the research is to provide useful reliability and risk improvement information for the UT Robot, a product currently under design at the University of Tennessee, Knoxville. The case study with the UT Robot is a contribution to the design efforts of the UT Robot and a demonstration of the reliability design tool's value.

1.3 Organization of the Presentation

The presentation of the research project is divided into six chapters as summarized below.

Chapter 1 is an introduction to the research effort describing the project initiation, sponsorship, and goals. The organization of the research presentation is also presented.

Chapter 2 relates the dilemma of design engineers facing the need for implementing reliability and risk studies of systems.

Chapter 3 presents the background information on reliability that is necessary to understand the importance of the research effort. The definition, importance, aspects, measurement, and improvement of reliability is discussed.

Chapter 4 introduces the reliability and risk assessment approach developed, and details the approaches used in the case study of the UT Robot. A general overview of approach is presented first, then a detailed description of the approach is portrayed by method of example with the UT Robot case study. This chapter contains the reliability assessment and improvement information for the UT Robot.

Chapter 5 acquaints the reader with the reliability design tool software developed to compliment the approach generated in the research. This chapter describes the use of the software in performing a reliability analysis, and a description of the programming specifics.

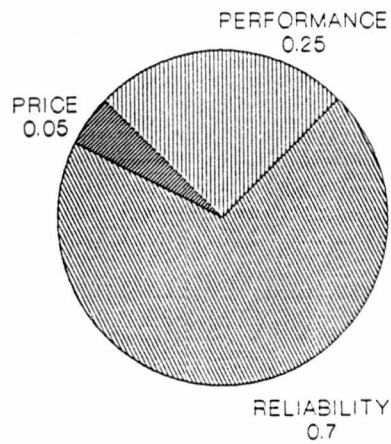
Chapter 6 concludes the discussion of the research effort by summarizing the design tool approach, analysis software, and case study results.

CHAPTER 2

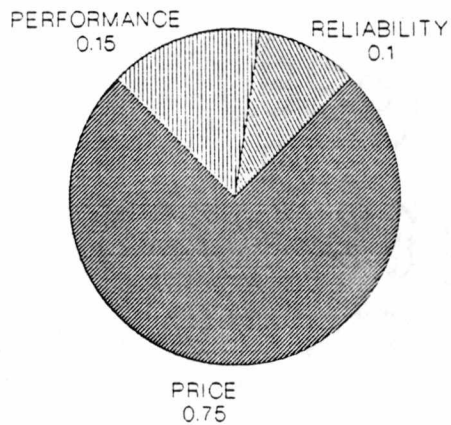
THE RELIABILITY DILEMMA

Around the world, companies have recognized the escalating importance of reliability issues as a part of total quality in meeting product and process specifications, competing in the market place, and providing for public and operator safety. In some situations, as shown in Figure 2-1, reliability and safety issues may dominate other important factors such as performance and price. Correspondingly, corporate reliability expectations have become increasingly demanding, dictating a need for more effective reliability improvement techniques throughout the development, manufacturing, and implementation stages.

Clearly, the "obvious" or "typical" failure modes for systems must be evaluated and eliminated. In addition, many superior products and processes are showing that "important" lower frequency failure events, which interact to affect the reliability of the engineered system, must also be examined and corrected. The process of identifying and correcting this set of "important" potential failure modes, among the many existing "trivial" potential failure modes, is one of the fundamental aspects of an effective reliability analysis program.



(a) SPACE PROGRAM



(b) CONSUMER ELECTRONICS

Figure 2-1. Comparison of Reliability Importance in Two Designs

Source: W. Grant Ireson and Clyde F. Coombs, Jr., Handbook of Reliability Engineering and Management, McGraw-Hill Book Company, NY, 1988, p. 3.3.

Historically, reliability analysis results of engineered systems have shown that the reliability of a system obeys a generalized **Pareto Principle**: a large percentage of the reliability characteristics for a system is determined by a relatively small number of the potential failure modes [Ireson and Coombs, 1988, p. 9.19].

Correcting these "important few" potential failure modes, while not taking specific action against the "trivial many" potential failure modes, makes the most efficient use of time and resources, improving, to some new level, the reliability characteristics of the system. The determination of what qualifies as an "important" potential failure mode needing corrective action is somewhat subjective, depending on corporate attitude, device specifications, consumer needs, competitive benchmarking, failure costs, corrective action costs, and safety issues. Often, a small number of corrective actions will eliminate or reduce a large number of "important" failure modes. Obviously, total elimination of all potential failure modes would be ideal, but can not be economically justified, or physically realizable.

The actual determination of the set of "important" potential failure modes, and the characterization of reliability characteristics for an engineered system, is a specialized, statistically based science still evolving

from its inception in the late 1940's. Reliability analysis has its roots in the analysis of nuclear power generating systems and aerospace development applications, but has grown in scope and analysis techniques to have applications in practically all areas of engineered systems. The application of reliability analysis techniques to engineered systems has been primarily executed by experts from corporate reliability departments, or private consultants, independent of the design or manufacturing engineers responsible for the product or process under consideration. Thus, by the time the reliability analysis is conducted, a substantial amount of design work has been completed, and some commitments to design concepts or manufacturing equipment may have been made. Therefore, significant schedule delays and correction costs may be incurred by having to make notable design or production changes, if they can be changed at all. As shown in Figure 2-2, the later a problem is identified, the cost to correct it will increase drastically.

The level of design evolution required for study by the expert reliability analysts, coupled with the difficulty in making significant changes to a system on a development schedule after a certain level of evolution has been achieved, demonstrates a need to gain insight

Cost Multiplier vs Development Stage

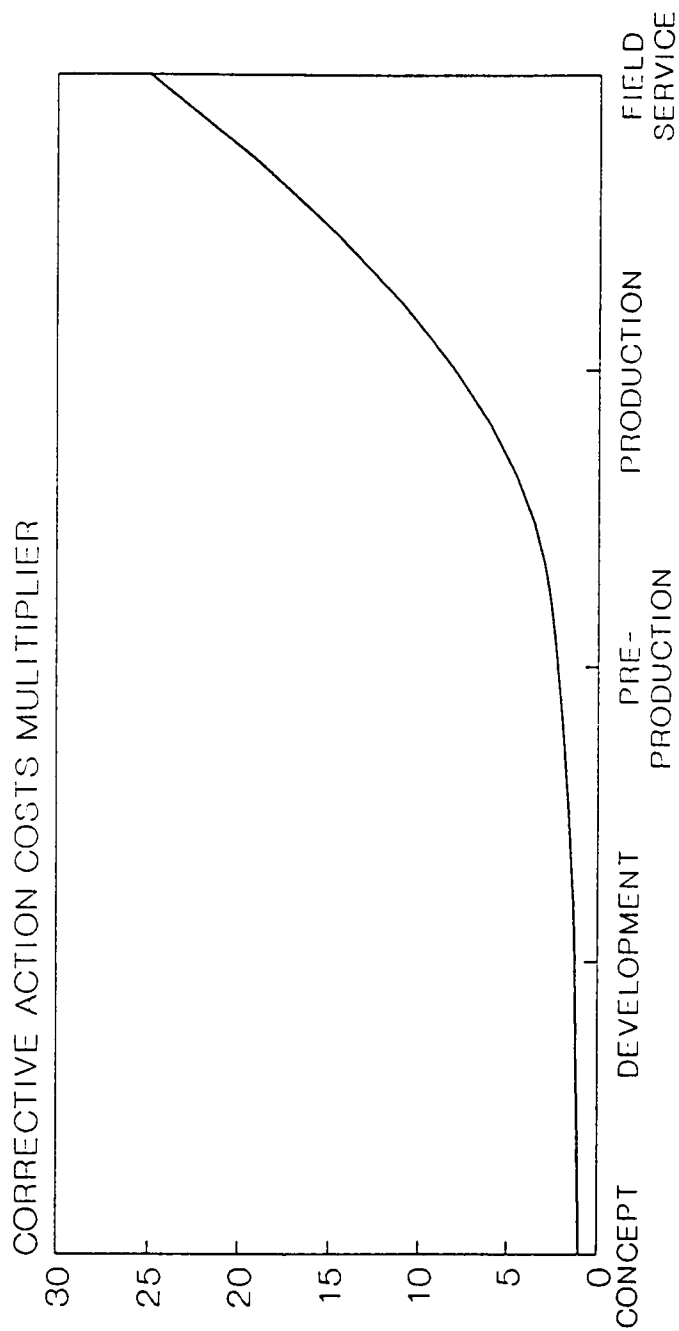


Figure 2-2. Corrective Action Costs During Development Stages

Source: W. Grant Ireson and Clyde F. Coombs, Jr., Handbook of Reliability Engineering and Management, McGraw-Hill Book Company, NY, 1988, p. 11.5.

into the reliability of a design earlier in the design process. Additionally, the analysis should be part of a quick feedback mechanism to the designer, or manufacturing engineer, to implement corrective actions quickly, minimizing time delays and costs while insuring reliability. One of the largest complaints against reliability analysis techniques is the lack of application to systems at times when the full benefits of the results may be realized by making system changes. One particular approach, Failure Modes, Effects, and Criticality Analysis (FMECA), is criticized by MIL-STD-1629A, page iii,:

"Probably the greatest criticism of FMECA has been its limited use in improving designs. The chief causes for this have been untimeliness and isolated performances of FMECA...."

The shortest feedback loop for the reliability analysis information would occur if the reliability analyst were the design engineer, or on the design team. This situation would be a natural choice since a structured reliability analysis is a formal extension of the concepts of developing a successful design that competent design engineers are already familiar. However, the sophistication of the reliability analysis tools used today requires a sound understanding of the many intricacies and limitations of the particular tool being

utilized. This knowledge is only available through special training and actual practice. The development of approaches using designer reliability evaluations early in the design stage has been slow, although some substantial successes for specific applications have been shown [Bellinger and Sims, 1980, p.259, and Walker, 1989].

The goal of this research project is to investigate accepted reliability analysis techniques, to adapt one technique for use by the design engineer to make needed reliability decisions and to characterize the reliability performance of the product, process, or sub-system earlier in the design stage. The technique developed is not meant to be a replacement of the more sophisticated reliability techniques, nor does the research imply that design engineers should, or could, replace "expert" reliability analysts. Both "expert" analysts and more sophisticated analysis tools are valuable to the development of superior products and processes. However, preliminary reliability analysis and modifications by design engineers will produce shorter development schedules, eliminate potential failure modes at optimal times, develop a greater common understanding of reliability concerns, and generate more efficient reliability analysis by the "experts" later in the design and verification process, since many failure

modes have already been eliminated, and the ground work for further study has been lain.

CHAPTER 3

BACKGROUND INFORMATION ON RELIABILITY

This section is meant to provide the reader with an understanding of the basic concepts of reliability associated with the design of devices and systems. It is not a detailed account of all the reliability terms, concepts, methodologies, mathematics, or techniques, since many textbooks and papers are available to fulfill this purpose. Rather, this account is to provide working definitions and concepts for both the experienced and novice reliability analysts and students to understand the technique developed in this research project.

3.1 Description of Reliability

To understand how the design engineer can play a more significant role in assessing and improving the reliability of products and processes, one must have some understanding of what reliability is, and how reliability is characterized. The rigid definition of reliability is "the probability of experiencing no failures to a given time t " [Fussell and Wagner, 1977, 294]. This definition contains three key phrases; "probability," "no failures," and "to a given time t ." The "probability" phrase reflects reliability as a parameter of a system defined in

statistical terms. The "no failures" phrase identifies the system must continue to perform its design intention without interruption. Thus, a **failure** is any event in which the system deviates from its design intention. "To a given time t " describes a time interval. Therefore, reliability is measured as performing the design intention without interruption for a given time interval, characterized by a statistical parameter. Often, this statistical parameter is the Mean Time Between Failures (MTBF), given in units of time, some failure rate, given in failures per unit of time, or could be described with a probability of surviving a given time interval.

An important point is the dependence of reliability on many factors which may cause failures over periods of time. These may include, but are not limited to, design configurations, system components' design strength, environmental conditions, loading conditions, external effects on the system, raw material and vendor part quality, manufacturing quality, quality of installation and maintenance, operator effects, controlling hardware, controlling software, and usage. Clearly, reliability is affected by multi-discipline concerns, reflecting the need for diverse backgrounds in design teams. The difficulty in reliability analysis is determining how all these factors influence the performance of a designed product or process

over time, and determining how to reduce the effects of these parameters.

3.2 Importance of Reliability

Reliability of a product or process has become more than an "added benefit" to the functional aspects of the system. Increasingly, reliability of an engineered system is viewed as one of the major system requirements, often overshadowing cost or some functional concerns. For many devices, the lack of ability to repair failures, or the severe consequences of failures, require the device to be extremely reliable. The repercussions of not providing adequate reliability for a system are experienced through failure costs, losses to competition, liability cases, and safety issues.

The cost consequences of failures may be categorized into **equipment damage costs**, **business interruption costs**, and **repair costs**. **Equipment damage costs** refer to the cost of system components or local equipment damaged by a failure of the system. **Business interruption costs** refer to the costs due to loss of production or function of system. **Repair costs** refer to the costs associated with repairing the failure, not including the equipment cost which is covered in the equipment damage cost. The equipment damage costs depend on the type of failure,

while the business interruption costs and repair costs depend on the type of failure and the time to repair the failure, reflecting a relationship with the maintainability of the system.

In an effort to produce superior products and processes, while reducing liability, competition, safety, and failure cost concerns, the goal of the designer should be to develop the system with adequate reliability for the application. The term adequate is quite general, and reflects the need to consider the application carefully when determining the level of reliability required, avoiding the tendency to over-restrict the design. Furthermore, the engineer is entrusted with a promise to fulfill a fundamental principle of engineering: to preserve the public safety through safe, ethical designs.

3.3 Reliability in Devices and Systems

To achieve superior products or processes, reliability must be incorporated into the system from the design stage, and maintained through the manufacturing, shipping, installation, operation, and maintenance stages. A particular design configuration and parts specification for a product or process inherently determines some level of maximum reliability that is attainable for the product. Whether or not this maximum level of reliability is

realized depends on many "degradation factors" acting to reduce the actual level of reliability performance for the system [Ireson and Coombs, 1988, p. 7.4]. These "degradation factors" refer to the interaction of the manufacturing, shipping, installation, operation, and maintenance techniques with the design of the system. For instance, a manufacturing process that is not in statistical control, or uses poor raw material and vendor parts quality, will never allow the inherent reliability of the best design to be realized. Often, the designer focuses entirely on shaping the design to improve the maximum inherent level of reliability, but ignores the parameters that will not allow the design to achieve its maximum value of reliability. This effect is shown in Figure 3-1. One example is designing redundancy into the system but not recognizing a very precise positioning action in maintenance, or an operator error causing failures even with redundancy designed into the system.

Not only must the designer consider how the design determines the inherent maximum reliability of the system, but also how the design will be affected by the degradation factors that will reduce the actual reliability performance of the product or process. These degradation factors may be separated into a **manufacturing category**, which are influences during manufacturing or

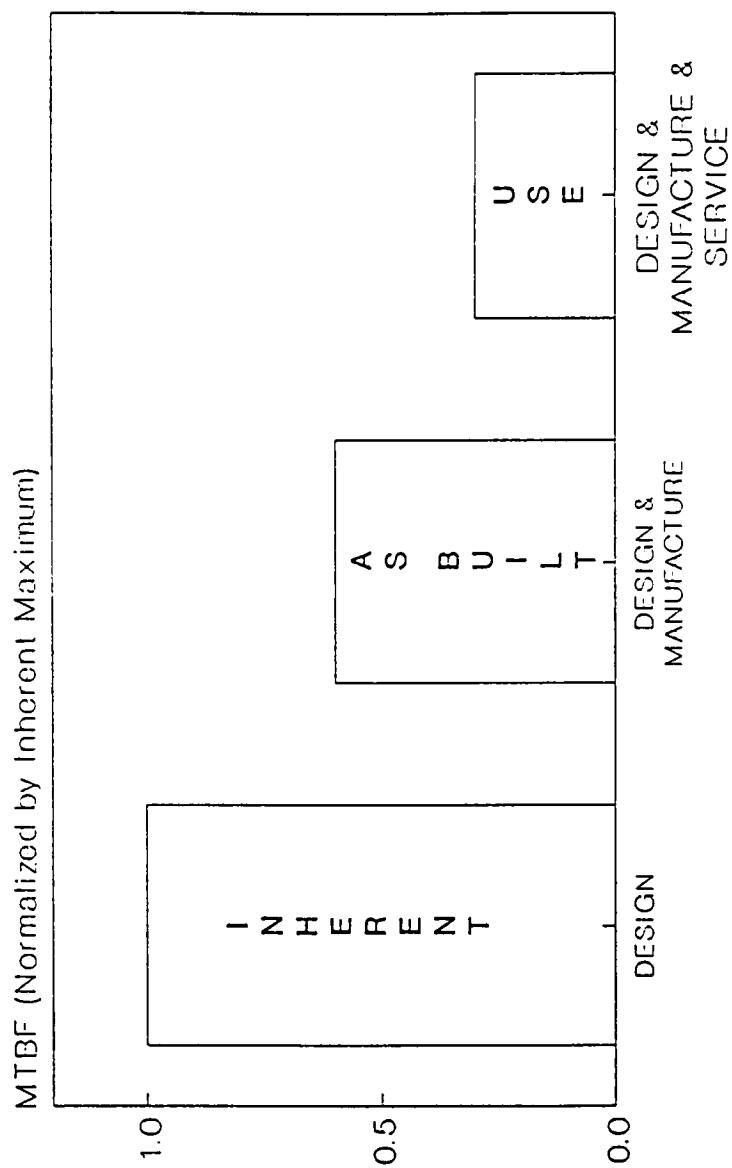


Figure 3-1. Degradation Factors Influence on Reliability

Source: W. Grant Ireson and Clyde F. Coombs, Jr., Handbook of Reliability Engineering and Management, McGraw-Hill Book Company, NY, 1988, p. 7.3.

construction, and an **operation category**, which are influences encountered during installation, use, and maintenance of the system. The relationship between the system's inherent reliability maximum, manufacturing degradation factors, and operation degradation factors is shown in Figure 3-2. The vertical axis determines the system's reliability for values of the manufacturing and operation degradation factors. The superimposed curves represent the manufacturing environment quality curve and the field operation environment quality curve. Figure 3-3a depicts the relationship between manufacturing performance and reliability while Figure 3-3b demonstrates the relationship between the operating environment and reliability. Actual values for the degradation factors would have to be evaluated using some subjective weight rating scheme among the various contributors for each degradation category. Also, reliability measurements would have to be made for each combination of manufacturing and operation category values. The actual determination of a plot, as shown in Figure 3-2, would be subjective, expensive, and time consuming, while providing only minimal benefits. However, a valuable characterization of Figure 3-2 could be given by determining the reliability characteristics for a system under a virtual "worst case" condition, shown as bar B in Figure 3-2, and for a "best

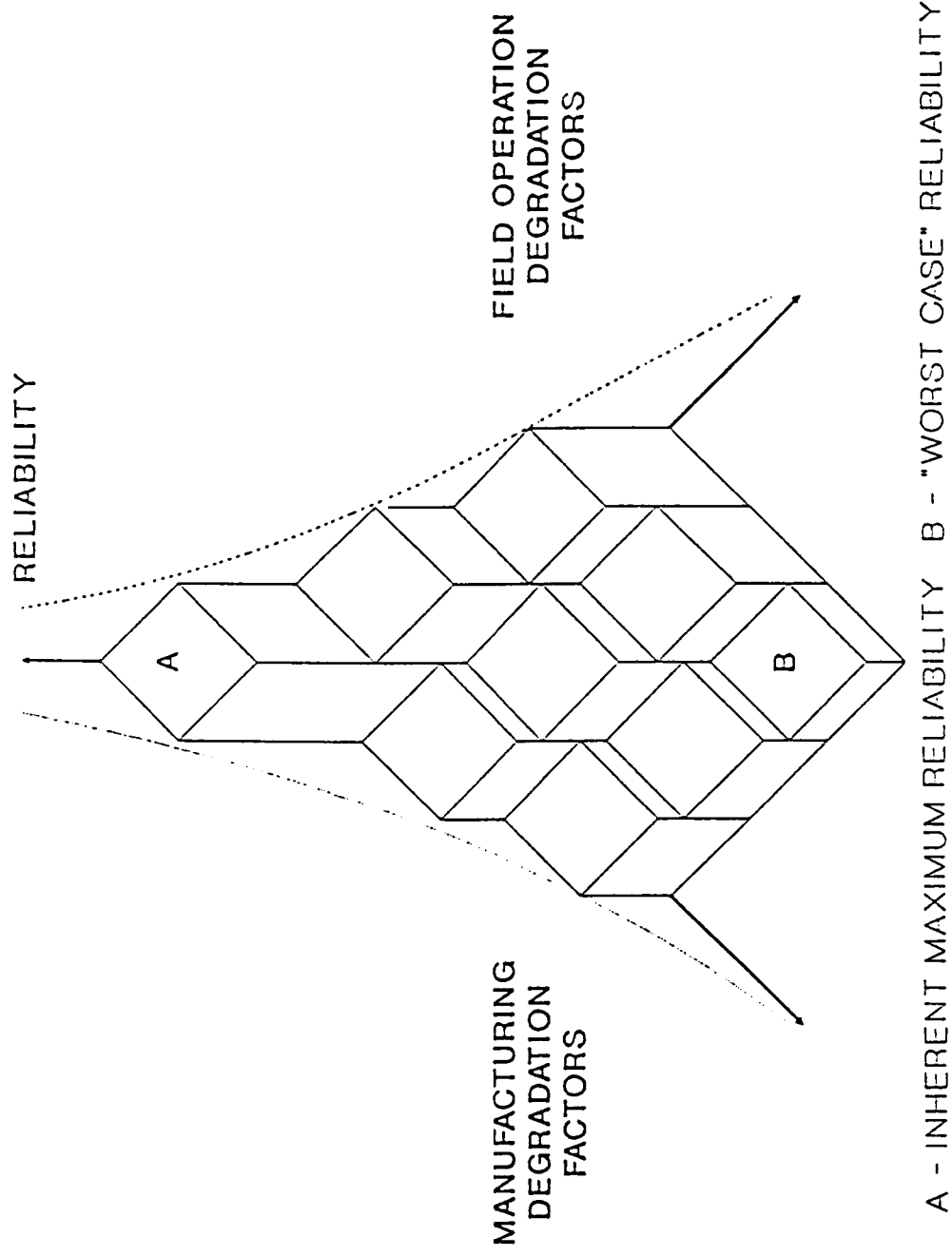
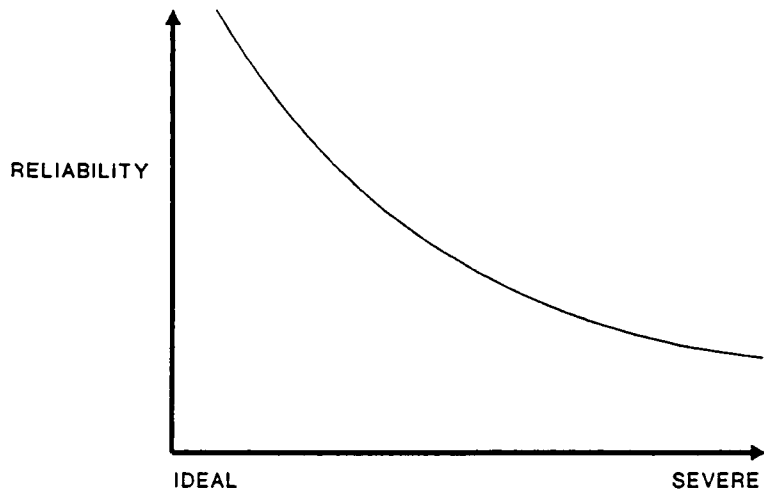
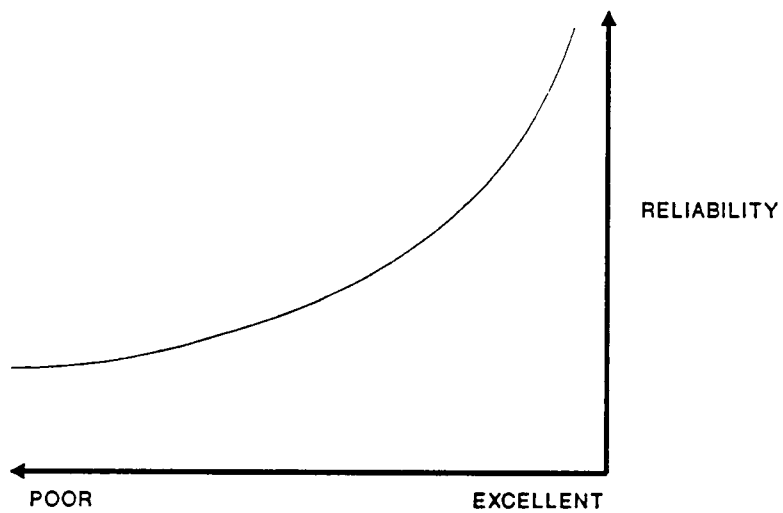


Figure 3-2. Three Dimensional Plot of Reliability Versus Degradation Factors



a) FIELD OPERATION ENVIRONMENT QUALITY



b) MANUFACTURING ENVIRONMENT QUALITY

Figure 3-3. Manufacturing and Operating Environment Quality Effects on Reliability

case" condition, shown as bar A in Figure 3-2. Thus, an approximate bound on the system's reliability performance could be established and compared to required reliability goals in a cost and time effective method.

3.4 Improving Reliability

From the above discussion, there are two basic methods of improving the reliability of an engineered system:

- 1) Modify the design to increase the inherent maximum level of reliability that the system may achieve;
- 2) Modify the design and/or diminish the degradation factors to allow the system to attain its maximum inherent reliability.

The best method for improving the reliability of an engineered system is to utilize a balance of both techniques.

3.4.1 Improving the designed maximum inherent reliability

To improve the maximum inherent reliability of a system, the designer must insure an adequate design margin between expected stress and component strength. An adequate design margin reflects consideration of not only the traditional factor of safety applied to the mean

strength with regard to the mean expected stress, but also considers uncertainty of these values, or their distributions. Figure 3-4 shows an expected stress and component strength depiction that never allows the stress to exceed the component strength, thus eliminating overstress failures due to expected stresses. However, Figure 3-5 shows another depiction, with the same factor of safety, that allows some probability of failure, given by the highlighted area, due to some expected stresses beyond some expected strengths. Although probabilistic methods are available to determine probabilities of failures, control of the parameters affecting the distributions and the mean values for the stresses and strengths could virtually eliminate the failure probabilities. De-rating components is a typical method employed.

Limited life components such as bearings, friction surfaces, or fatiguing members must be carefully controlled, and should be eliminated if possible. If these components have life spans less than the designed life of the system, their failure will significantly affect the reliability of the system, producing an upper bound on the maximum inherent reliability of the system if the limited life component alone causes a system failure.

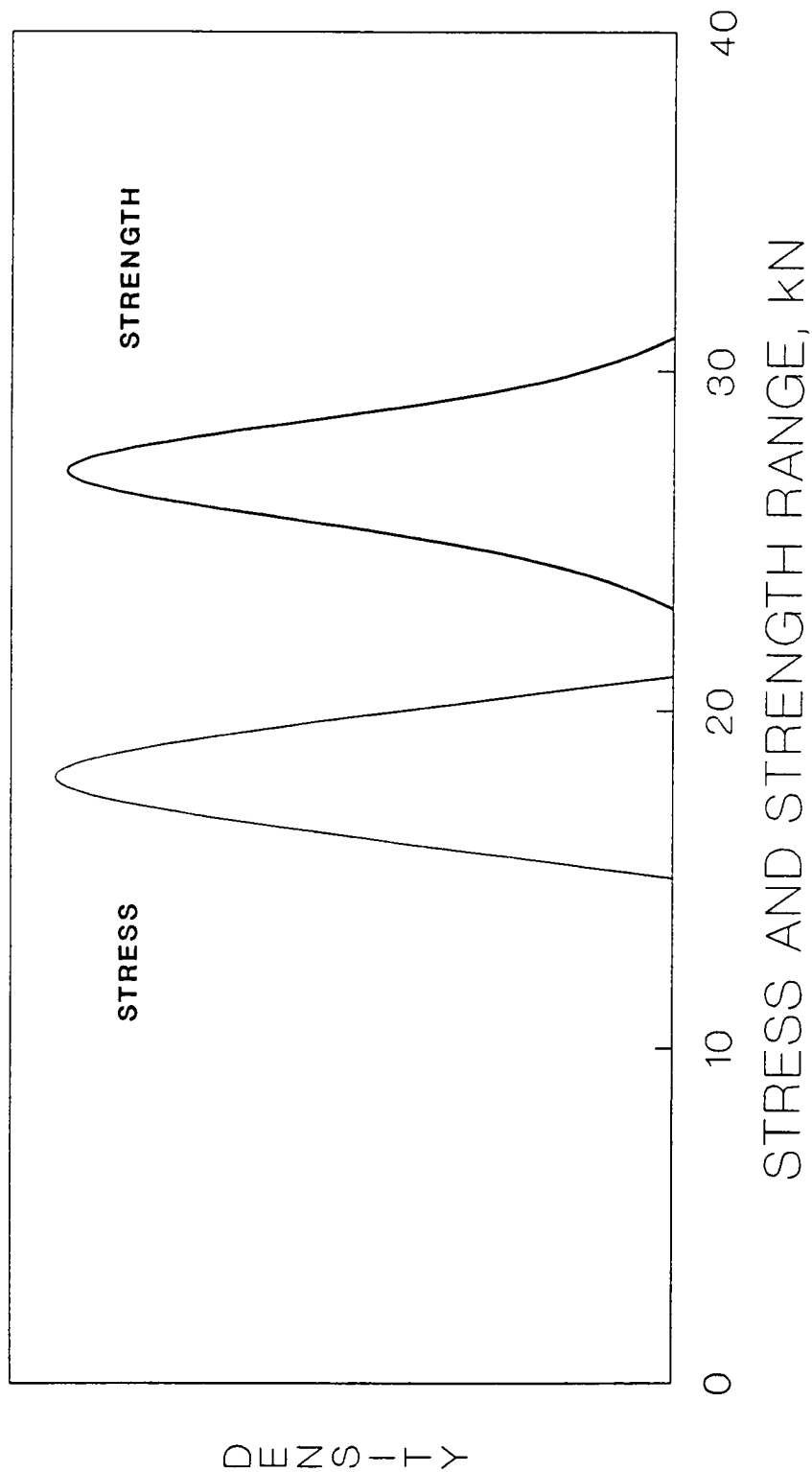


Figure 3-4. Stress and Strength Uncertainty Curves with No Interference
 Source: William H. Miedendorf, Design of Devices and Systems, Marcel Dekker, Inc., NY, 1986, p. 369.

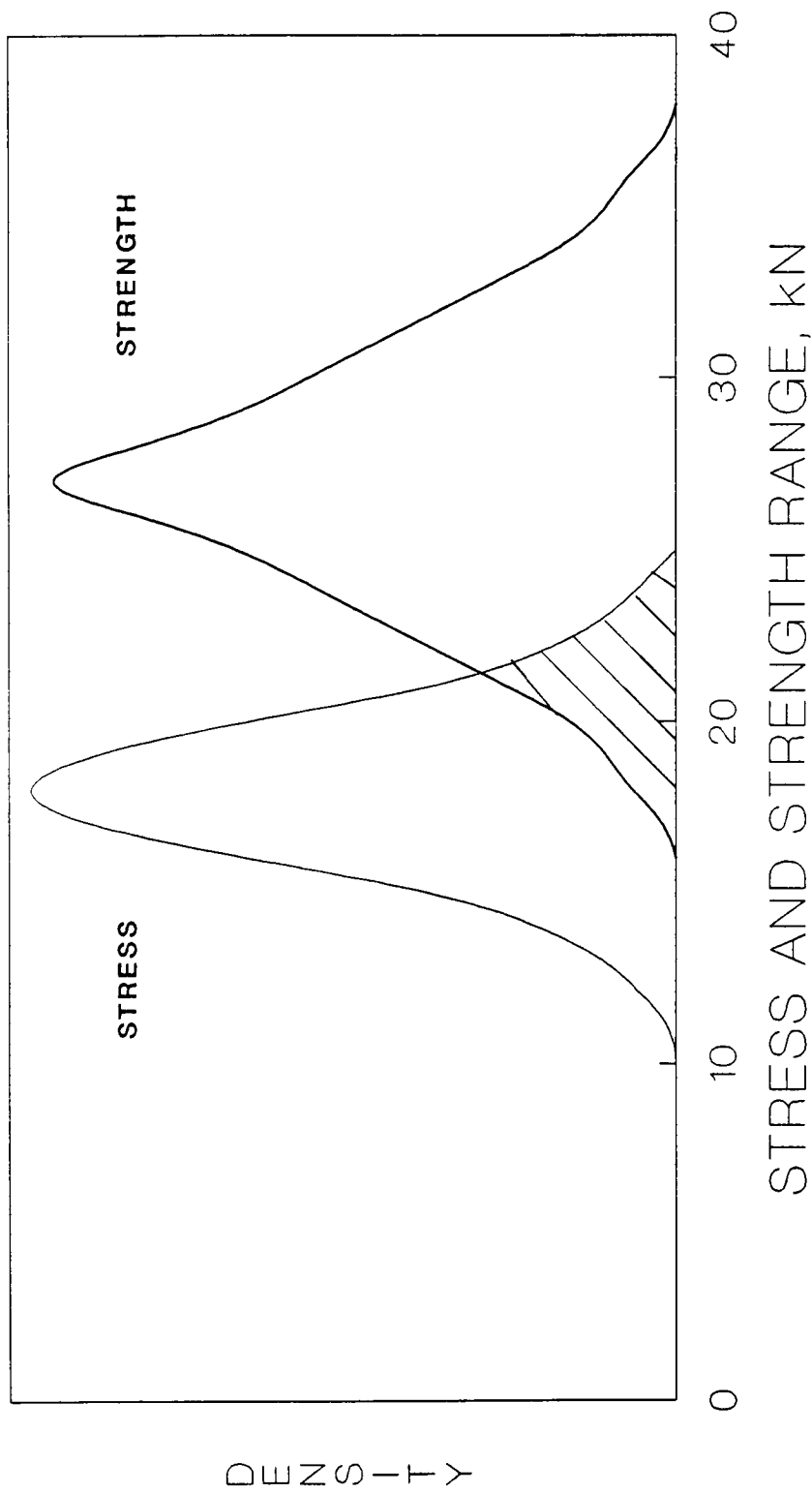


Figure 3-5. Stress and Strength Uncertainty Curves with Interference
 Source: William H. Miedendorf, Design of Devices and Systems, Marcel Dekker, Inc., NY, 1986, p. 369.

The choice of technology, components, and materials used in design will affect the reliability of the system. Utilizing proven, standard, reliable techniques, components, and materials, rather than unproven options, promises a larger maximum inherent reliability for the system. The unproven options should be verified through controlled evaluation before use in any new design.

Design configuration actively contributes to the reliability of a design through series and parallel connections of components and sub-systems. Systems composed of series connections of components result in failures of the system if only one component fails. More components in a series arrangement provide additional sources of failures, and correspondingly decrease the reliability of the system. This fact suggests minimizing the number of parts through component integration of multiple components into single components, assuming the reliability of the single integrated component is not unacceptable. IBM experienced success with this approach during the Proprinter project [Golatha, 1989].

Conversely, parallel connections of components, each serving the same function, require simultaneous failure of all the components in the parallel arrangement, provided surviving components can handle the increased loads due to failed components. A classic example is the use of

redundant pumps in a cooling water system to a reactor. Both pumps must fail together to lose cooling water flow. An electro-mechanical example is the use of a dual prong electrical contact for a switch that only requires a single prong contact [Middendorf, 1986, p. 367]. The prongs are dissimilar by design to have different natural frequencies so, under excitations, one prong will always remain in contact. This is diverse, as opposed to similar, redundancy. Similar redundancy would occur if both prongs were identical, but would not be effective in this situation. Overall, redundancy is a method to increase the reliability of a system composed of components of lesser reliability. Redundancy often contributes to more complex systems and requires more complex reliability analysis tools.

Additionally, the system configuration also dictates sub-system interactions that may affect reliability. Energy and signal transfers between sub-systems, such as radiant and convective heat transfer, or electro-magnetic interference, may degrade system performance over a period of time causing failures. Isolation with controlled interaction between sub-systems will enhance the system's reliability.

Finally, using separation and isolation to protect components from sources of common cause failures will

improve the reliability of a system. Common cause failures are occurrences which cause failure of multiple components due to some single cause. Common cause failures can cause system failures even in the presence of redundancy if all the redundant components have a dependence on a single common cause failure event. As an example, a common cause failure might be the failure of both prongs in the electro-mechanical switch due to some external impact fracturing both prongs. Separation by physical distance or by isolation with a physical barrier between the two prongs could be used to alleviate the dependence of the redundant prongs on the single common cause failure impact event.

3.4.2 Improving the manufacturing degradation factors

In order to take a sufficiently reliable design concept and replicate the design through production without suffering reliability losses, the design must conform to the needs of the manufacturing environment. The design must have predicted and conformed to manufacturing restrictions and tolerances to allow reliable production. These restrictions may include, but are not limited to, single direction assembly, no screws, or no adjustments. The product must have been developed to be manufacturable with available manufacturing

equipment, without suffering reliability degradation. Otherwise, appropriate manufacturing equipment must be selected if the available equipment is not capable.

While the design must conform to manufacturing issues, manufacturing must maintain reliable production conditions. Reliable manufacturing requires reliable manufacturing equipment and operators, defect-free raw materials and parts, and a manufacturing process in statistical control. Reliable manufacturing equipment is achieved through skilled operator preventative maintenance and process improvement, trained maintenance technicians, and reliability analysis of the manufacturing processes. Reliable performance of operators may be enhanced by a wide variety of human factor issues addressing worker motivation, comfort, satisfaction, and training. Furthermore, insuring the quality of incoming materials and parts is a critical issue, since poor quality materials create poor quality devices. Extensive vendor quality assurance programs have been developed, and are producing success stories around the world [Walker, 1989, Wilson and Kennedy, 1989, p. 9, and Bishop, 1989, pp. 9-12]. In addition, maintaining control of the manufacturing process through some type of Statistical Process Control (SPC), or 100% inspection/testing program,

is required to guarantee the manufacturing process is dependably producing reliable products [IBM, 1985].

Finally, the reliability of the product must be preserved after creation through proper handling and packaging. A product must arrive at the customer's site with the same reliability the design and manufacturing processes have produced. The design engineer should consider the environment and stresses imposed during handling, packaging, and shipping, and adequate procedures should be developed to meet any special needs a product may have.

3.4.3 Improving the operation degradation factors

The actual operation of engineered systems introduces many possible degradation factors to reduce the reliability from design expectation levels. Excessive stresses beyond the design values can cause immediate failures or damages, which precipitate future failures. Similarly, excessive environmental conditions or operating conditions can directly cause failures, or weaken components creating future failures. Care must be taken to provide a true indication of actual operating conditions during design, and to isolate the device from severe conditions or excessive loading during operation.

Another issue affecting the experienced reliability of a system is the installation and maintenance effects on the system. A system that is not installed or maintained in accordance with the design intentions will not perform as reliably as the designer anticipated. Accordingly, the designer should act to eliminate, or minimize, complicated installation and maintenance procedures. Specific instructions should be given for any installation or maintenance procedures required, and for any precautions for personal safety or damage to other components. The operator must insure competent personnel to install and maintain the device according to design specifications.

Finally, one of the most important degradation factors reducing the reliability of a system is the system's interaction with potentially unreliable systems, including electrical systems, actuating systems, and human interfaces. Care should be taken to insure the reliability of the overall process or system through reliability analysis of the overall system. Sub-systems should be verified for acceptable reliability performance. The operator is often the "weakest link in the chain" due to a wide variety of factors. This human unreliability can be addressed by many human factors techniques to improve the operator's performance, while the design can

be conceived to simplify human interaction, requiring only necessary operator actions.

3.5 Measuring Reliability

With a basic understanding of reliability and systems, the important issue becomes how to measure the reliability of a system. Three approaches are available to measure reliability: **prediction methods, testing methods, and operation/service feedback methods.** Each method possesses some favorable and unfavorable traits. The best overall approach to measuring the reliability of systems is a balanced strategy combining prediction, testing, and feedback techniques. However, as the focus of this paper, a primary emphasis is placed on reliability prediction by designers during the design stages, resulting in more reliable designs with increased efficiency and effectiveness.

3.5.1 Reliability prediction measurements

Reliability prediction measurement tools provide a means for an analyst to qualitatively and/or quantitatively characterize the reliability of engineered systems before the system is created, or without actually testing an existing system. Prediction tools synthesize reliability information for components and sub-systems to

evaluate the expected overall system reliability performance. Therefore, prediction tools offer the advantage of evaluating reliability during design without physical measurement of a system. This is clearly an optimal benefit during early design stages, allowing failure modes to be identified and eliminated before costly prototypes or first run production models are built or committed to production. In fact, physical testing may not be possible before the design is completed, such as in design of commercial plant systems or nuclear reactors. Common components used in many designs may be individually evaluated thoroughly, and used to increase the accuracy of predictions based on component models. Furthermore, prediction tools yield increased efficiency in evaluating reliability, since reliability models can be changed as modifications are made to the system, while actual devices would have to be physically modified, or re-produced, and re-evaluated through extensive physical testing. Also, a thorough reliability prediction evaluation will yield a broader understanding of the parameters affecting, or not affecting, the reliability of a system than could be discovered through typical testing programs operating under limited time and resource budgets.

Nevertheless, prediction tools are statistically based, and depend on a the level of knowledge of system

components and the production and operating conditions. The results of prediction methods are estimates. Prediction methods depict probable occurrences and the relative importances of factors influencing the reliability of the system, with a "measure of degree of belief." Relative importance of events and relative failure rates for failure modes are generally predicted with sufficient accuracy. However, with ample, applicable component data, many reliability studies do prove to achieve reasonably accurate absolute reliability prediction results [Walker, 1989].

Another difficulty in applying reliability prediction tools, is the complexity and limitations of the available tools. Many of these tools require substantial training and application experience to render accurate results or to make appropriate use of the application results. Reliability analysis requires careful consideration of many system design and operation factors, resulting in more of an engineering art, similar to design, rather than a prescriptive, rigid approach. However, as in design, some basic conceptual approaches provide a guide to completing the task.

Many reliability prediction tools are available in various forms, often adapted to particular uses for a

certain industry or application. These tools provide a variety of qualitative and/or quantitative results with differing levels of analysis complexity. The key is choosing the simplest analysis technique that will accurately provide the desired reliability information. Among these tools are [Goldberg, Haasi, Roberts, Vesely, 1981]:

- 1) **Fault Tree Analysis/Event Tree Analysis** - based on Boolean logic representations of component failure conditions for a particular overall system failure and the effects of the system failure;
- 2) **Failure Modes and Effects Analysis** - based on discovering, describing, and quantifying failure modes for a system by tracing the failure modes of individual system components in a structured table;
- 3) **Hazard Operability Studies** - based on defining process deviation conditions for sub-systems and tracing the deviations to their causes and overall system effects (very similar to Failure Modes and Effects Analysis);
- 4) **Common Mode Failure Analysis** - based on identifying single failure events which cause

failures of multiple components (often included in Fault Tree Analysis);

- 5) **Others** - Reliability Audits, Reliability Block Diagrams, Reliability Checklists, etc.

3.5.2 Reliability testing measurements

The second approach for measuring the reliability of an engineered system is through physical testing. This type of testing is used to verify intended function over specified time intervals. The requirement of testing function over time intervals dictates substantial testing times and costs to verify reliability. Furthermore, failures must be separately analyzed to identify the failure mode, and causes of the failure mode. After modifications are made, extensive re-testing must be undertaken until the reliability levels experienced in testing meet, and/or exceed, those dictated by the design requirements.

The actual data from physical testing may be valuable in decision making, and may provide insights which were not available from prediction methods due to limited components data, or complicated systems. However, physical testing of systems to measure reliability has many difficulties. This approach consumes large percentages of budgeted time and financial resources. To

truly characterize the reliability performance, the testing would have to control numerous parameters, resulting in large numbers of experiments being performed and analyzed. Furthermore, after any needed modifications, much or all of the testing may need to be repeated. Additionally, to perform the physical testing, the design must be well-defined to actually produce a prototype system to test. Furthermore, repeated testing will require production of modified design prototypes. These factors make physical reliability testing an inefficient tool for making reliability based decisions during design stages.

Physical testing is best utilized in conjunction with prediction methods as a tactic to verify the results of the prediction tool, as well as to insure the reliability of the system. The physical testing may identify particular failure mode combinations which are important, but were not identified during a prediction tool application due to deficient data or limitations of the prediction tool.

3.5.3 Operation/service feedback measurements

A final method for measuring the reliability of a device or system is to monitor its field performance. While this will identify any pertinent failure modes, the

failures are already occurring along with their associated failure costs and safety effects. This is clearly an undesirable approach as a sole means of measuring and improving reliability; however, feedback measurements should not be overlooked or discounted as a valuable contributor to improving the reliability of a system. Another benefit is the accumulation of failure data which may be used to improve future reliability predictions. The feedback measurements may be facilitated through warranties, return of failed parts, service report auditing, and field audits of operating units.

CHAPTER 4

THE RELIABILITY DESIGN TOOL

More than ever before, today's engineered systems need reliability analysis and reliability improvement. Unfortunately, only a fraction of the world's engineering community is familiar with available reliability techniques, much less trained in successfully applying these techniques to engineered systems. While reliability issues may be most effectively addressed during design, the limited efficiency of independent reliability evaluations during design, and the designer's inexperience with reliability analysis, are severe obstacles to investigating and improving the reliability of engineered systems during the design stage. With an increasing list of criteria and guidelines being placed on designers, expecting the design engineer to become an expert in reliability analysis is unrealistic. The need for some "common ground" between the well-developed, but somewhat complex reliability analysis techniques, and the needs of the designer for assessing and improving the reliability of designs, is apparent.

The "common ground" developed in this research effort is a simplified reliability analysis methodology formatted for successful use by the design engineer, with

applicability to a wide range of engineered systems. Additionally, the methodology is formed into an automated reliability tool, allowing easier, quicker, more effective application of an accepted reliability methodology for presenting the designer with needed reliability characteristics of a system. Thus, the gap between the realms of reliability engineering and design engineering is spanned by a specifically conceived **reliability design tool** rather than a mere analysis approach.

The **reliability design tool** is based on the prediction approach defined in Failure Modes and Effects Analysis (FMEA). The tool allows great versatility in application, with qualitative and quantitative evaluations and documentations of systems, in order to portray pertinent failure modes and reliability performance for necessary design actions. The tool is automated in a spreadsheet software package, LOTUS 123, in a thoughtfully designed, menu-driven structure. The program guides and manages the reliability analysis of a system, while allowing accumulation and retrieval of qualitative and quantitative reliability information from a knowledge database.

The following sub-sections describe the reliability design tool through a specific application, the case study of the UT Robot, without detailing the specific steps

involved in using the reliability software. These sub-sections are included to demonstrate the need and usefulness of the reliability design tool during an actual design process. Relying on the concepts and issues developed in the specific example, the approach will be extended for implementing the reliability design tool methodology with other engineered systems. Later sections will present the reliability design tool software.

4.1 General FMEA Approach

The basic flow diagram for an FMEA application is presented in Figures 4-1, 4-2, and 4-3. Figure 4-1 depicts the overall FMEA approach. This approach begins by defining the reliability design goals for the system and the necessary information for meeting the design goals to be obtained from the reliability study. Next, the system to be studied is defined with pertinent physical and analytical boundary conditions to focus the reliability study. Then, the system is partitioned into individual sub-systems and components with each component of the system being analyzed individually. For each partitioned component, the potential failure modes are hypothesized, described, and quantified. The accumulation of the potential failure modes of the system's constituent components form the basis of the potential modes of the

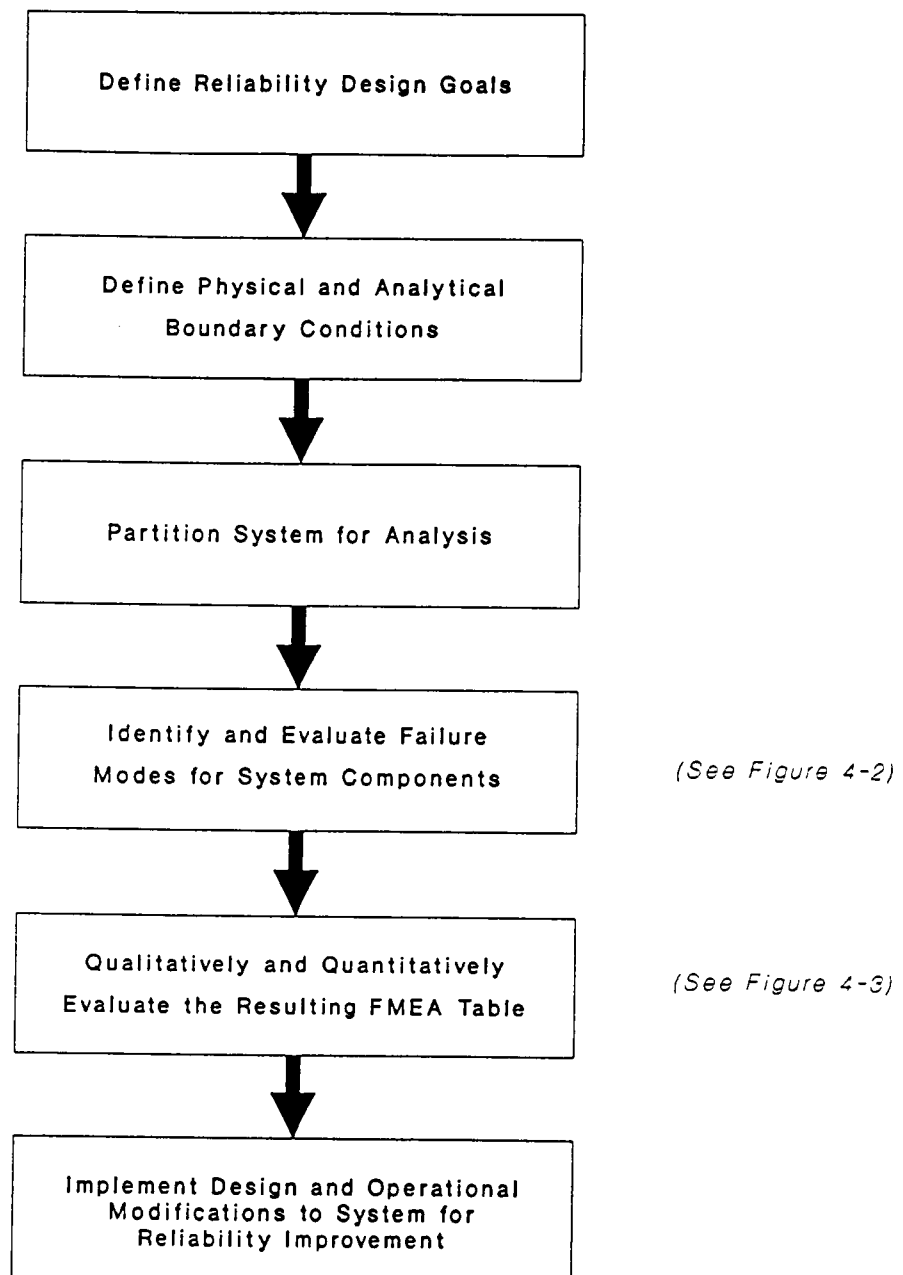


Figure 4-1. General FMEA Method Flow Diagram

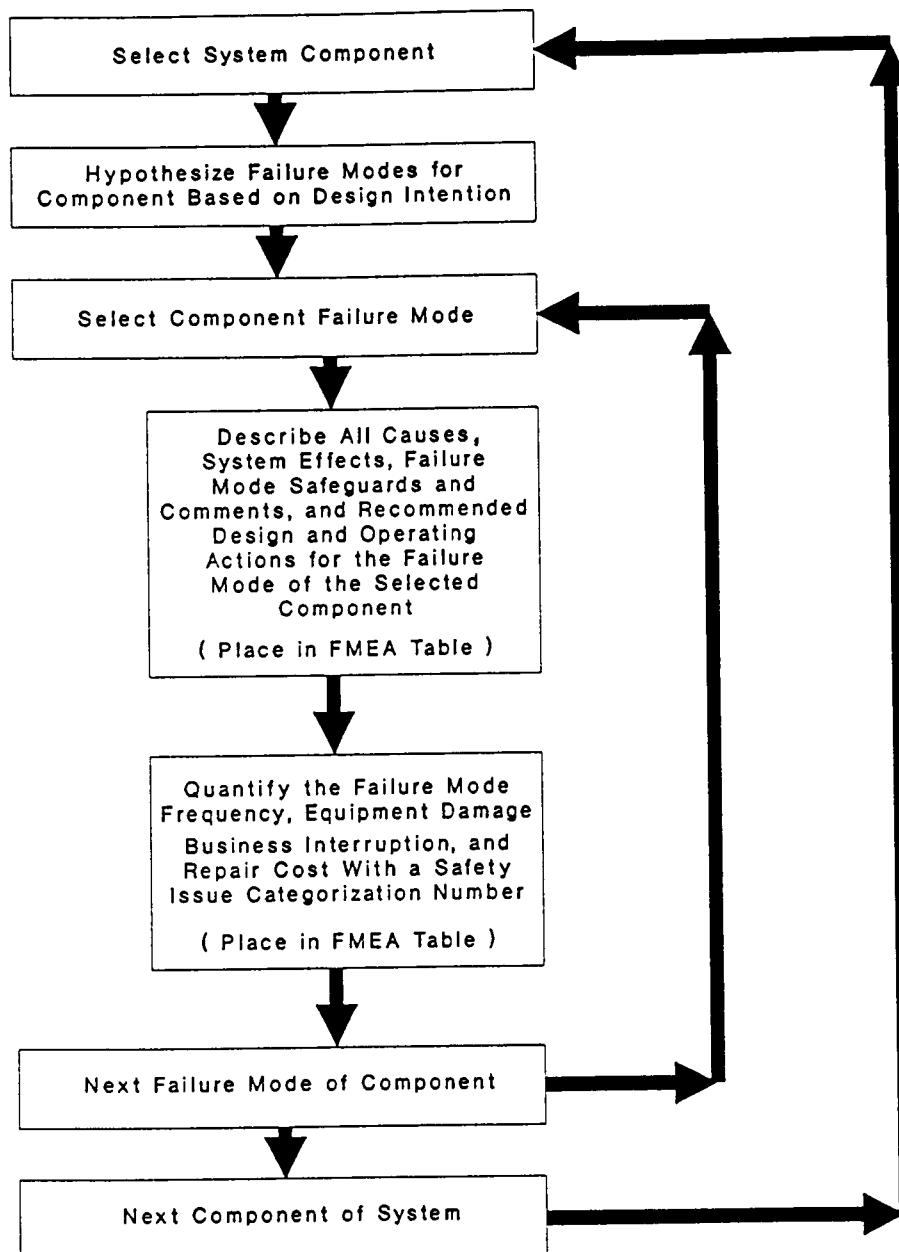


Figure 4-2. Failure Mode Identification, Description, and Quantification Flow Diagram

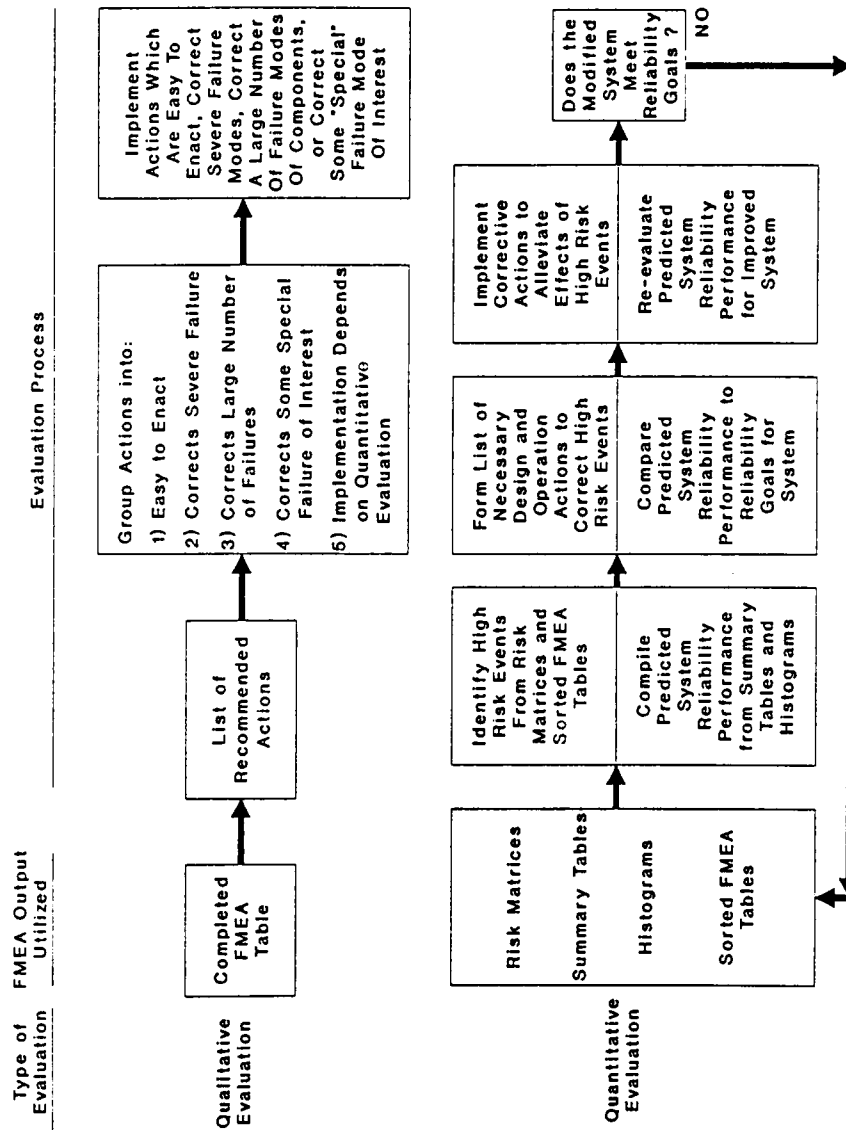


Figure 4-3. Qualitative and Quantitative Failure Mode Evaluation Process Flow Diagram

system. Through qualitative and quantitative evaluations, the accumulated descriptions of the potential failure modes may be evaluated to identify the "important" failure modes which significantly affect the reliability of the system, and to characterize the overall reliability performance of the system. Finally, based on the information gathered from the qualitative and quantitative evaluations, design, manufacturing, and operation modifications are implemented to improve the system's reliability.

Figure 4-2 represents the process for identifying, describing, and quantifying the failure modes of the partitioned system components. A single failure mode of a partitioned system component is selected. For this failure mode, all of the possible causes, system effects, safeguards, comments, and recommended reliability improvement actions are recorded. Then, the expected frequency of failure, equipment damage cost, business interruption cost, repair cost, and safety issue ranking are assigned for the failure mode. This process is repeated until all of the failure modes of all the partitioned system components have been considered.

Figure 4-3 depicts the method for qualitatively evaluating the accumulated failure modes for the system. In qualitative evaluation, the accumulated failure modes

are grouped into categories with failure modes that 1) are easily improved, 2) cause particularly severe effects, 3) possess common causes or improvement action with many other failure modes, or 4) cause some particular failure of interest being termed "important" because of their potential impact on the reliability of the system. Design improvement actions to the failure modes in these categories provide significant system reliability improvement. This process is valuable because it does not rely on the often difficult task of quantitatively describing the failure modes.

Figure 4-3 also portrays the method for quantitatively evaluating the accumulated failure modes of the system. The accumulated failure mode quantifications are organized into risk matrices and summary tables, described in detail later. Two system evaluation procedures are present. First, the most important failure modes may be identified from the risk matrices. These failure modes contribute the most to the unreliability of the system, and provide the most effective and efficient areas to implement reliability improvement actions. Second, the summary tables numerically characterize the overall reliability of the system for comparison to desired goals. The results from the summary tables may be

monitored as improvements are made to the system, until an acceptable level of reliability performance is achieved.

4.2 Description of UT Robot for Case Study

The subject of the example case study is a cartesian co-ordinate industrial robot depicted in Figure 4-4. The robot has four degrees of freedom providing motion in a horizontal plane, the X and Y directions, along a vertical axis, the Z direction, and a rotational motion at the end of the vertical axis. Figure 4-5 depicts the X-Y motion system, Figure 4-6 shows the Z direction motion system, and Figure 4-7 describes the rotational motion system on the Z axis. These motion axes are controlled under electric power with specially written software and a personal computer.

The robot is currently under design at the University of Tennessee as a demonstration of the ideology of the Superior Engineering Design Program, and as a focus of several thesis projects. The robot is aimed at the low-cost, high-volume market for versatile robotic systems to replace complex, high cost robotic systems in a variety of functions. Many types of services could be performed by using different sizes of the robot with specific application end effectors mounted on the Z axis.

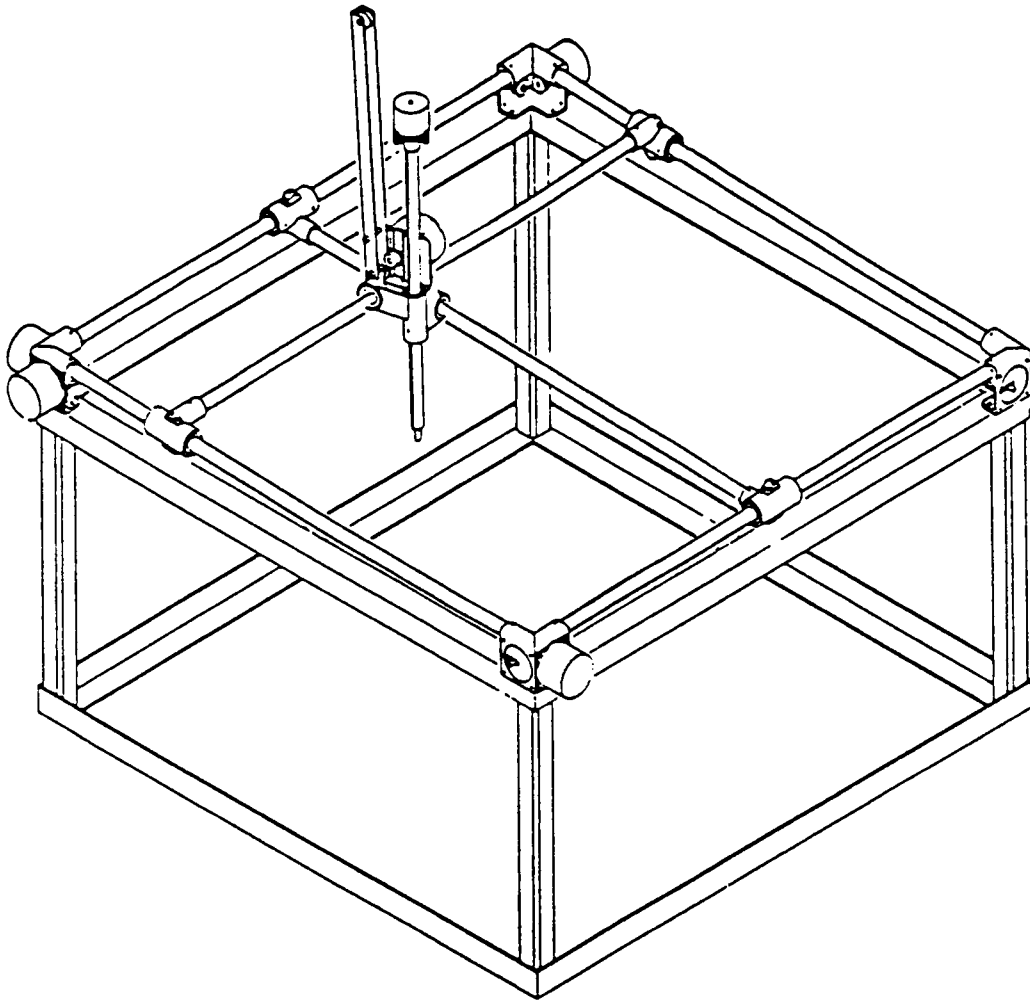


Figure 4-4. UT Robot Schematic Diagram

Source: Lawrence M. Garrett, "Design and Prototyping of a Four Degree of Freedom, Low-Cost, High-Speed, Cartesian-Motion Robot" (unpublished Master's thesis, The University of Tennessee, Knoxville, 1989).

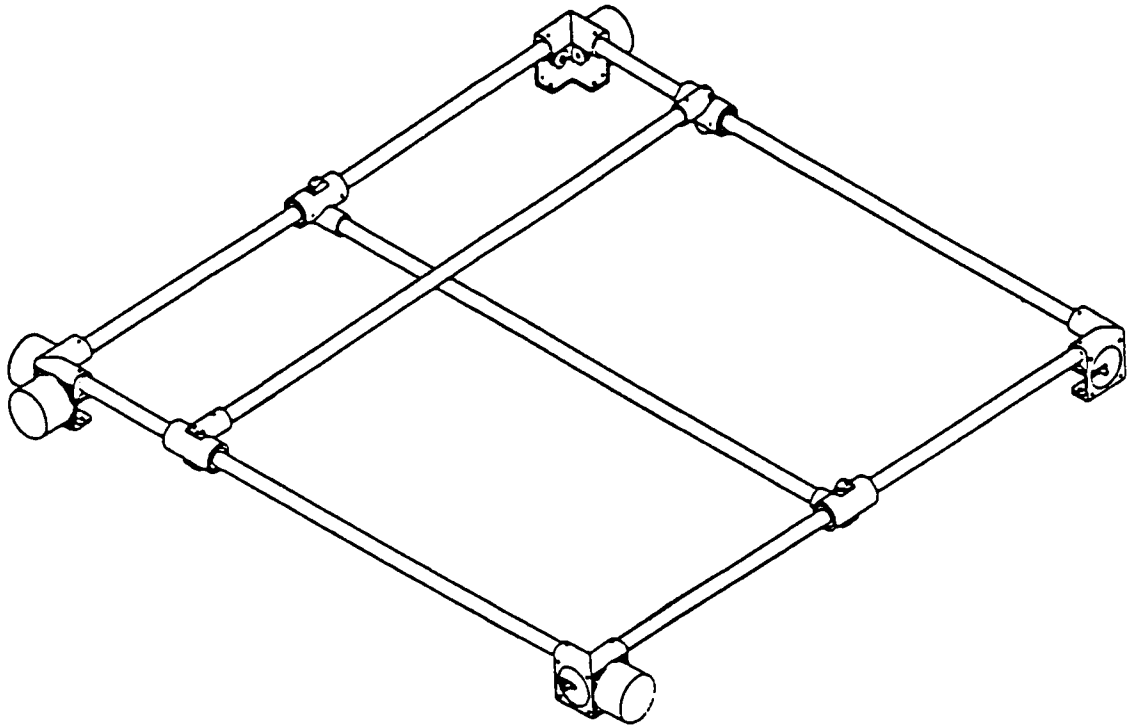


Figure 4-5. UT Robot X-Y Axis Motion System

Source: Lawrence M. Garrett, "Design and Prototyping of a Four Degree of Freedom, Low-Cost, High-Speed, Cartesian-Motion Robot" (unpublished Master's thesis, The University of Tennessee, Knoxville, 1989).

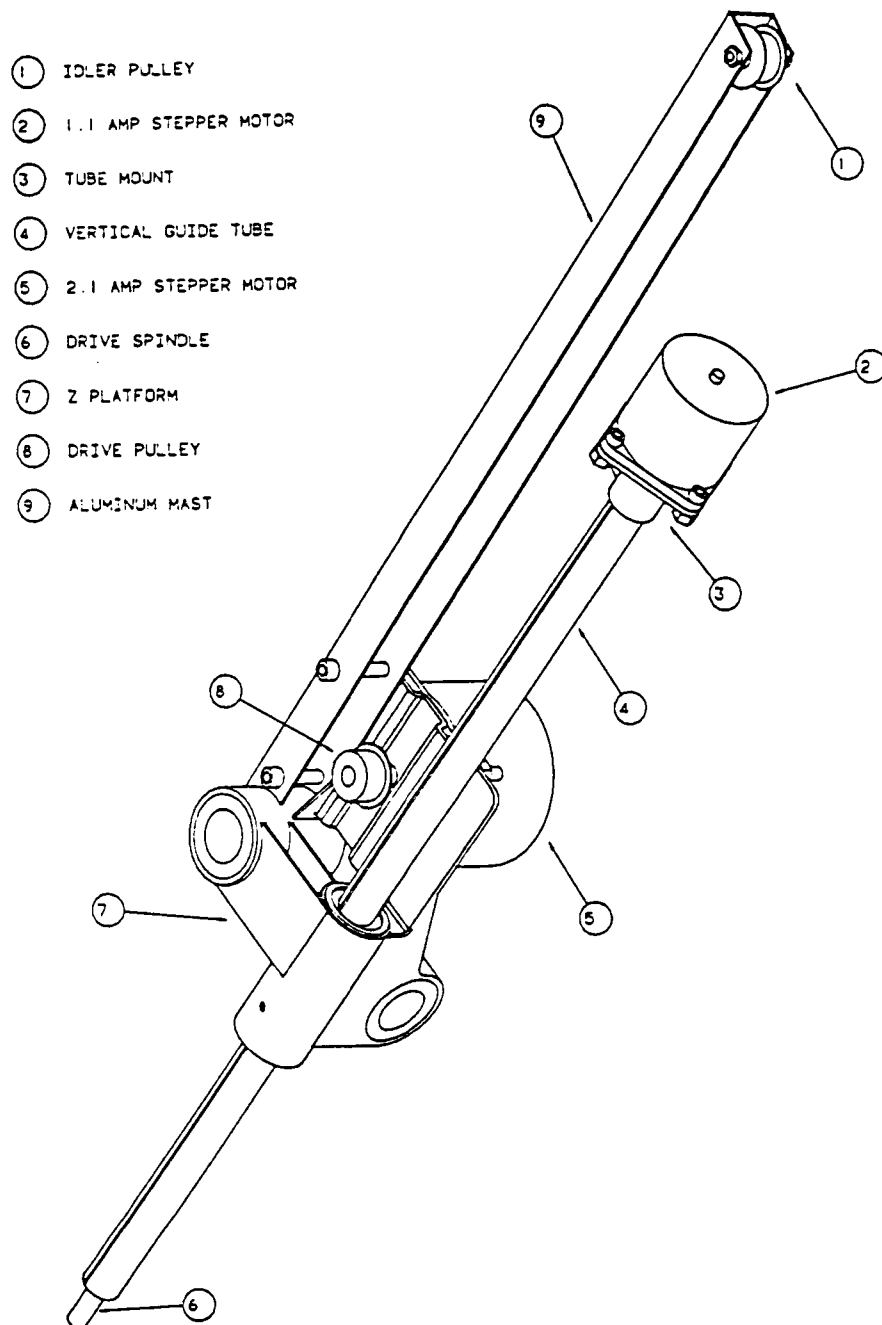


Figure 4-6. UT Robot Z (Vertical) Axis Motion System

Source: Lawrence M. Garrett, "Design and Prototyping of a Four Degree of Freedom, Low-Cost, High-Speed, Cartesian-Motion Robot" (unpublished Master's thesis, The University of Tennessee, Knoxville, 1989).

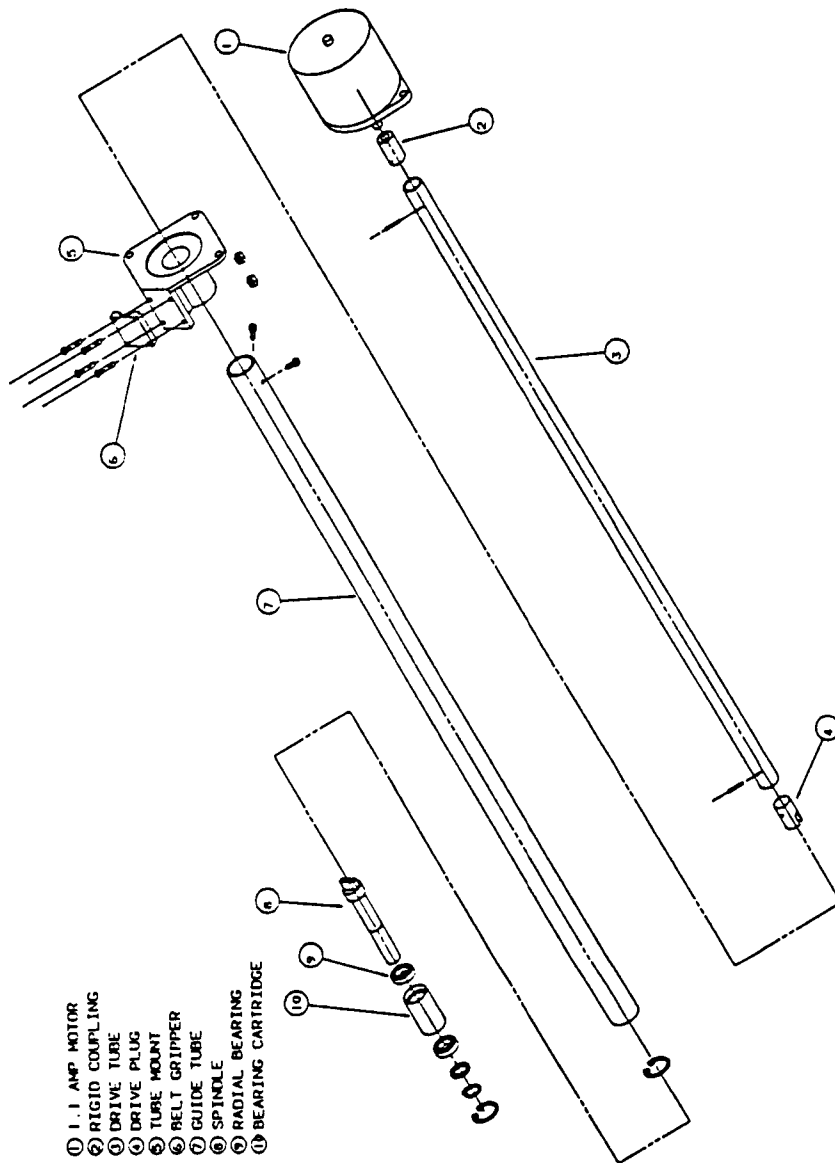


Figure 4-7. UT Robot W (Rotary) Axis Motion System

Source: Lawrence M. Garrett, "Design and Prototyping of a Four Degree of Freedom, Low-Cost, High-Speed, Cartesian-Motion Robot" (unpublished Master's thesis, The University of Tennessee, Knoxville, 1989).

4.3 Reliability Design Goals for Case Study

Since the robot will operate in a variety of conditions and perform an assortment of functions, insuring the reliability of the robotic system is of paramount importance. In some applications, the reliability may not be as important as other design parameters; however, the designer will have no prior knowledge of the specific application. To meet the most severe application requirements, the designer must insure adequate reliability in the generic robotic system for all applications.

The reliability goals for the case study are not defined in numeric terms as some rate of acceptable failures with related failure consequences. Rather, the goal is to identify and improve all influences and elements which genuinely affect the reliability of the robotic system within the constraints of limited time and financial resources. Merely achieving some minimum expected reliability performance is not acceptable in developing a truly **superior** engineered system. Eliminating, or improving, all of the "important few" failure modes is the goal of the study.

In pursuit of this goal, the failure modes of the system will be identified, evaluated, and ranked by importance. As a first examination, an initial group of

the most important failure modes will be considered for prominent design action. Additional groups of less important events could be considered until further improvements produce negligible, or cost ineffective, reliability improvements. Only the presentation of the initial group of important failure modes will be discussed because of space limitations in the text, although the process for considering the subsequent groups of events will be apparent. The failure modes of the generic robotic system will be evaluated under both "severe" and "favorable" operating conditions to characterize the reliability plot shown in Figure 3-2.

4.4 Physical and Analytical Bounds for Case Study

The reliability analysis recognizes some physical and analytical bounds placed on the system. The robotic system is physically limited to include the three motion axes systems, the personal computer hardware, the operating software, the robot support structure, the electric power source, and the operator. No failure events other than deviations of these sub-systems of the robot are considered. The end effector is also included in the study, although failures of the end effector are not considered since the end effector is not actually part of the generic robotic system.

In addition to the physical bounds on the study, some analytical limitations are imposed. This analysis will not consider extraordinary events such as fires, floods, earthquakes, or sabotage. Also, the computer software and hardware, robot support structure, and electrical supply system will not be further subdivided. However, the global performance and effects of these sub-systems will be deliberated.

The evaluation of the system's reliability performance will consider the system's functions, environmental conditions, loading conditions, manufacturing quality, vendor part quality, operating times, and service/installation quality for two applications. The first application will describe a "severe" case in which the manufacturing and operation degradation factors are large. The second application will describe a "favorable" case in which the manufacturing and operation factors are small. These applications will approximate upper and lower bounds for the reliability performance of the system over the range of possible application conditions. Due to the series nature of the robotic system, only single event failures will be considered during the FMEA analysis.

The definition of failure modes is related to the deviations from design function for the components, not

their root cause of failure. The level of detail of analysis for each component is limited to the level which provides useful information to the designer, and for which the designer has control to modify. Excessive levels of detail for the components clutter the analysis and hide important issues, while providing little valuable reliability improvement information.

4.5 Partitioning of UT Robot for Analysis

The robotic system is partitioned into four distinct sub-systems for the reliability analysis, namely the **X-Y axes motion system**, the **Z axis motion system**, the **rotational motion system**, and the **peripheral equipment system**. Each of the four distinct sub-systems is analyzed separately, and the results of the four systems are superimposed to evaluate the overall robotic system. This partitioning is based on the distinctly different design functions of these systems.

For the motion systems, the systems are further divided into constituent components at a macroscopic level. For instance, the stepper motor is considered a component for the reliability analysis rather than subdividing the stepper motor into its members, such as the casing, internal wiring, external wiring, motor bearing, and motor shaft. The further sub-division would add

little pertinent information, and would increase the complexity of the analysis. If a component is found to be an important contributor to the reliability characteristics of the system, and the component's evaluation is not considered thorough enough, the component may be further sub-divided after the initial analysis.

The peripheral equipment system includes the controlling computer hardware and software, the robot support structure, the electrical supply source, the electrical power regulator, and the robotic system operator. These systems are grouped together because they act as controlling or supplementary systems to the mechanical configuration of the robot. They are analyzed as components to the overall robotic system, since the designer has only moderate, or no control, over the design of these systems. However, treating these systems as components, the important failure modes, causes, and effects can be developed, and action may be taken to alleviate the degradation to the robotic system's reliability.

4.6 Identifying and Evaluating Component Failure Modes

For each of the four analytical sub-systems, the failure modes of the constituent components are evaluated.

The steps involved in the reliability analysis for each sub-system are:

- 1) Hypothesize failure modes for each component within the physical and analytical bounds of the system
- 2) For each failure mode of each component:
 - a) Postulate causes for the failure mode
 - b) Postulate local, and global, system and operating effects resulting from the failure mode
 - c) Identify any safeguards or comments associated with the failure mode
 - d) Suggest recommended actions for eliminating or alleviating the failure mode
 - e) Numerically quantify the frequency, cost, and safety concerns associated with the failure mode
- 3) Qualitatively and quantitatively examine the failure mode evaluations to identify the best methods for reaching the desired reliability or safety goals.

When identifying the failure modes for a component, emphasis is primarily concerned with the intended design function of the component. The failure modes identified

for the component may not reflect the actual failure mechanisms, but rather the deviation from the design intention. For example, a structural member may possess a large number of failure mechanisms, such as fatigue, corrosion, overstress fracture, or impacts, but only has two deviations from design intention expressed as 1) failure to provide structural support, and 2) failure to properly maintain the position of the supported equipment. These two broader failure descriptions are easier to quantify, and represent a more efficient approach since the specific failure mechanisms will be included as the causes of the broader failure modes. In this case study, the use of the broader failure descriptions based on deviations from design intentions is implemented. The resulting analysis is more concise, easier to evaluate, and provides the same reliability information. Based on the knowledge of the robotic system's function, and guided by the design checklist depicted in Figure 4-8, the failure mode analyses are completed for the generic robotic system. The resulting FMEA tables for all four analytical sub-systems of the generic robotic system are presented in Appendix A.

aspects which are best dealt with after the behaviour of components has been involved. This section should be complete and would need adjusting for particular applications. As just one illustration, no attempt has been made to deal with equipment involving explosives.

The general categories adopted in this questionnaire are

1. Design concept
2. Environment
3. Operation
4. Material(s) selection
5. Stresing
6. Thermal effects
7. Wear
8. Aging
9. Surface finishes
10. Dimensional factors
11. Manufacture
12. Assembly
13. Prime movers
14. Bearings
15. Seals
16. Roasting parts
17. Pressure vessels
18. Hydraulic, fuel and similar systems
19. Connectors
20. Maintenance
21. Instrumentation
22. Testing
23. Safety considerations.

The rules for completing the questionnaire have been postulated as follows

- (1) All questions must be answered fully. If a question or section does not apply to the device under review the reason for its non-applicability must be set out.
- (2) Indented questions relate directly to a preceding question and may require a number of answers, depending on the number of answers to the original question.
- (3) Depending on the progress of the design, it may not be possible to answer all the questions during the early design stages. However, the earlier in the design process that the questions are completed, the greater will be their value.
- (4) For each design, the design team will formulate additional questions specifically related to the components under review.

1. Design concept

What are the desired functions of the device under review?
Where are these functions specified?

Figure 4-8. Sample Design Checklist

Source: A.D.S. Carter, Mechanical Reliability, Second Edition, John Wiley and Sons, NY, 1986, pp. 269-275.

268	MECHANICAL RELIABILITY	DESIGN FOR RELIABILITY	269
Is this specification comprehensive?	Is any manufacturing process (welding, forming, etc.) likely to destroy the required properties?		
Does the design meet all the desired functions?	What is the required metallurgical state of the finished product?		
In what areas will it perform better than required?	Were any unusual materials used?		
Will complexity or cost be reduced if these areas are eliminated?	If so was adequate information on the relevant properties available from recognized sources?		
Is the design as simple as possible?	What non-destructive tests have been called for to ensure material properties?		
What alternative methods of achieving the desired function were considered before adopting the present design?	Have the material quality control procedures been specified?		
Why were these alternatives not used?			
If it were possible to start again, what changes would be desirable?			
What does this device have in common with existing successful designs? How does it differ?	5. <i>Strutting</i> What methods of stress analysis were adopted? What document presents the stress analysis for the device? What area of stress concentration are present?		
Are any departures from existing designs justified?			
How have scheduler considerations affected the design choices?			
Have all interfaces with other design areas been identified?			
On what basis were safety margins/factors of safety established?			
	6. <i>Thermal effects</i> Identify areas where heat is produced. Identify areas where heat is lost. Prepare an energy balance for the device. Identify any areas carrying large temperature gradients: (a) during steady conditions, (b) during transients. What are the maximum stresses induced by these gradients? For what area has a differential thermal expansion study been performed? What provisions are there for degradation of heat transfer surfaces by fouling, etc.? Has full allowance been made for any creep arising from the operating temperatures?		
	7. <i>Wear</i> Identify any areas subject to wear (sliding, rubbing, rolling, impact surfaces). How might this wear be avoided? How might this wear be reduced? What is the effect of the wear? Can this effect be tolerated? What indications are there in the operation of the device to alert the user to wear taking place?		
	8. <i>Ageing</i> What is the design life of the device? What component controls this design life? Identify any electrical insulation. At what temperature does this normally operate? What is the maximum temperature to which it could be subjected? What class of insulation is this? For which components has a fatigue study been performed? What were the results of this study?		

268	MECHANICAL RELIABILITY	DESIGN FOR RELIABILITY	269
Is this specification comprehensive?	Is any manufacturing process (welding, forming, etc.) likely to destroy the required properties?		
Does the design meet all the desired functions?	What is the required metallurgical state of the finished product?		
In what areas will it perform better than required?	Were any unusual materials used?		
Will complexity or cost be reduced if these areas are eliminated?	If so was adequate information on the relevant properties available from recognized sources?		
Is the design as simple as possible?	What non-destructive tests have been called for to ensure material properties?		
What alternative methods of achieving the desired function were considered before adopting the present design?	Have the material quality control procedures been specified?		
Why were these alternatives not used?			
If it were possible to start again, what changes would be desirable?			
What does this device have in common with existing successful designs? How does it differ?			
Are any departures from existing designs justified?			
How have scheduler considerations affected the design choices?			
Have all interfaces with other design areas been identified?			
On what basis were safety margins/factors of safety established?			
	2. <i>Environment</i> Describe the normal operating load cycle and environments associated with the device: external, internal, etc. To what other environments will the device be subject during shop testing, inspection, shipping, storage, handling, installation, start-up, maintenance? What areas are subject to corrosion in any of the above environments? How is this corrosion controlled? What areas are affected by dust, grit, etc.? How is dust excluded from these areas? What areas are affected by high humidity or condensation of moisture? What is done to protect or prevent this? How is the device lifted? What special tools are required for installation? Who supplies these? What is the effect of freezing during site storage? What is the effect of excessive temperature? Will the device be handled by skilled, semi-skilled or unskilled operators?		
	3. <i>Operation</i> What special starting or stopping procedures are required? What document sets out the operating procedures? Are any special skills required for operation? Has due consideration been given to safety aspects of operation?		
	4. <i>Materials/selection</i> Identify the material(s) used for each part. What three material properties were most important in the selection of this material for this application?		

Figure 4-8 (Continued)

270	MECHANICAL RELIABILITY	DESIGN FOR RELIABILITY	271
For which surfaces has surface fatigue been considered?			
What is the maximum level of nuclear radiation to which the device is subject?			
What non-metallic materials are used in the device?			
What is their life expectancy under the above radiation level?			
Are any ageing phenomena likely to occur if the device is left idle for any period?			
9. Surface finishes			
Identify any surfaces on which: (a) sliding, (b) rubbing, or (c) rolling takes place.			
What finish is specified for these surfaces?			
Identify any plated surfaces.			
Why is this surface plated?			
To what specification is the plating done?			
Identify any painted surfaces.			
Why is this surface painted?			
To what specification is the painting done?			
What requirements are there for cleaning surfaces?			
How are these requirements met?			
Can the appearance be improved by more attention to exterior surfaces?			
What methods are used to prevent galling in screwed joints?			
Identify any hard-surfaced areas.			
Why is this needed?			
What method of hard surfacing is used?			
What procedure controls the application of this hard surfacing?			
10. Dimensional factors			
For what item has a tolerance stack-up study been performed?			
What essential clearances must be maintained?			
How are these clearances maintained?			
What are the effects of thermal expansion?			
What are the effects of deflection due to loading?			
What essential alignment must be maintained?			
How is this alignment maintained?			
What interchangeability provisions are incorporated in the design?			
What standard parts does the device employ?			
Where can 'non-standard' parts be replaced by standard parts?			
11. Manufacturing			
What novel or unique manufacturing methods are required to achieve the design?			
What non-destructive testing techniques are used?			
If welding is used, what welding and weld repair procedures are used?			
What are the largest dimensions requiring machining?			
What heat treatment is involved?			
What special cleanliness controls are required in the process?			
What tolerances will prove most difficult to hold?			
Have quality control procedures been adequately defined?			
12. Assembly			
How is the device supported? Does this allow essential, but only essential, movement?			
What levelness or verticality requirements are there?			
Where are these requirements specified?			
What happens if they are exceeded?			
How are these requirements met?			
What is the direction of rotation of any moving parts?			
Is it possible to reverse this rotation?			
What is the effect of reverse rotation?			
What external connections are required?			
Where are these detailed?			
Is it possible to incorrectly assemble any part?			
Have all nuts, bolts, screws, studs and other connections been adequately locked?			
Have all fluids and their flow direction been identified on all pipelines, valves, etc.?			
Have all moving parts been given adequate clearance?			
What are the maximum overall dimensions for installation?			
What is the smallest opening through which the device must pass for installation?			
What services are required: electrical, air, fluids?			
What are the weights of major components?			
What pull-space access is required?			
Are any special assembly techniques involved?			
13. Prime movers			
Identify any prime movers in the device.			
Where do these get their power?			
How is the drive transmitted to the driven members?			
Are any prime movers bought-in components?			
What evidence exists to substantiate their reliability?			
Are the current environmental conditions the same?			
If new design, how has this reliability been established?			
Are the prime movers new integral designs?			
If so, apply whole questionnaire to unit.			
14. Bearings			
Identify any bearings in the device.			
For each of these:			
What type of bearing is it?			
What alternatives were considered?			
Why were the alternatives not used?			
Identify the direction of loading.			
What are the effects of misalignment?			
How is the bearing lubricated?			

Figure 4-8 (Continued)

4.7 Quantifying the Failure Modes for Components

With the identification and examination of the failure modes completed, the focus turns to quantifying numerically the failure events to characterize the system's reliability performance, and to rank the failure modes by importance. The failure modes will be quantified for the "severe" and "favorable" application conditions mentioned previously. A typical "severe" application condition is a water jet cutting path application in an extremely harsh environment, with low manufacturing, operator, and service performance quality. A typical "favorable" application condition is a "pick and place" function in a clean room environment with high manufacturing, operator, and service performance quality.

The quantification involves assigning a frequency of failure, a consequence cost of failure, and a safety issue category number for each failure mode. The product of the frequency, and the consequence for each failure mode, determines a risk number used to characterize the reliability of the system, and is used to rank the failure modes by importance. The risk number is expressed as a cost per unit time.

4.7.1 Failure mode failure rate assignment

Assigning the failure rates for the failure modes is conducted by using industry standard databases of failure rates, some of which are cited in sub-section 5.1.9. The failure rates included in these data sources are based on actual operating experience in a variety of conditions and applications, not strictly testing conditions. As such, the recorded values reflect an average over many plant and operating conditions, which will not reflect the precise application for which the data is to be used. In this example study, the data is taken to reflect average industrial conditions for the type of component being quantified. A series of multiplicative correction factors, called PI factors, are applied to the standard failure rate obtained from the data books to customize the failure rate to the specific case study examination. The PI factors are a means to include the effects of the expected reliability degradation factors in the numeric reliability analysis. For instance, the effects of the operating environment may be reflected in a PI quantity which will increase, or decrease, the industry standard failure rate for given conditions. The application of the PI factor may be exemplified as follows:

<u>Environmental</u> <u>Condition</u>	<u>PI</u> <u>Factor Value</u>	<u>Standard</u> <u>Failure Rate</u>	<u>Actual</u> <u>Failure Rate</u>
Severe	1.25	1.00E-02	1.25E-02
Average	1.00	1.00E-02	1.00E-02
Favorable	0.75	1.00E-02	0.75E-02

The reliability degradation factors considered in the case study through the use of PI factors are:

- 1) Environmental Conditions
- 2) External Impacts During Operation
- 3) Installation/Maintenance Quality
- 4) Loading Conditions During Operation
- 5) Operating Time
- 6) Component, or Vendor, Quality

Determining the values of the PI quantities may be done with some formal schemes determined through extensive testing, such as that given in MIL-HDBK-217E. However, for many situations, only an estimate of these effects are needed, and engineering judgement based on an understanding of the application, production, and operation conditions will suffice. The exact quantification of the failure rates for component failure modes is very difficult, if not impossible.

For the case studies, the standard failure rates are recorded from the data sources when available. If little or no information is available, the failure rates are estimated in relation to the failure rates of other components for which more details are known. The absolute values of the failure rates may not be completely accurate; however, the relative values are deemed to be as accurately estimated as possible. Again, this

demonstrates the true value of the prediction tool:
determining the most important failure events among the
"trivial many."

4.7.1.1 Severe condition application

The base frequencies for the failure modes of the generic robotic system are estimated from the available failure rate data sources, and from relative failure rate comparisons between failure modes for which some information is known. Some of the failure events group several identical series components together. In this situation, the base failure frequency of an individual component is multiplied by the number of discrete components represented in the failure event. Next, the series of PI factors are selected to reflect the "severe" application conditions of a water jet cutting operation. The actual failure rates used in the reliability analysis are calculated by successively multiplying the base frequency by the estimated PI quantities for each failure mode. The base frequencies, PI factors, and calculated failure rates for each failure event for the severe case are presented in Table 4-1.

The water jet cutting application is especially demanding because of the harsh environment, programmed path motion, fluctuating loading, and potential for

Table 4-1. Failure Mode Frequency Assignments for the Severe Application Case Study

Robot System	Failure Event Number	Base Failure Frequency (Ev./Yr.)	Number of Independent Components in Event	Environmental Impact PI Quantity (xi)	External Maintenance PI Quantity (xi/m)	Load Factor PI Quantity (xi)	% Operating Time PI Quantity (xi)	Component Quality PI Quantity (xiq)	Estimated Event Frequency (Ev./Yr.)
Z AXIS	1.1	7.884E-04	1	1.15	1.10	1.15	0.600	1.10	8.705E-04
Z AXIS	1.2	1.000E-02	1	1.15	1.10	1.15	0.600	1.10	1.104E-02
Z AXIS	2.1	6.132E-02	1	1.15	1.10	1.15	0.600	1.10	6.771E-02
Z AXIS	3.1	1.000E-04	1	1.15	1.10	1.15	0.600	1.10	1.104E-04
Z AXIS	3.2	1.000E-04	1	1.15	1.10	1.15	0.600	1.10	1.104E-04
Z AXIS	3.3	5.000E-02	1	1.15	1.10	1.15	0.600	1.10	5.521E-02
Z AXIS	4.1	5.000E-02	1	1.15	1.10	1.15	0.600	1.10	5.521E-02
Z AXIS	4.2	2.500E-01	1	1.15	1.10	1.15	0.600	1.10	2.760E-01
Z AXIS	4.3	1.000E-02	1	1.15	1.10	1.15	0.600	1.10	1.104E-02
Z AXIS	4.4	2.000E-02	1	1.15	1.10	1.15	0.600	1.10	2.208E-02
Z AXIS	5.1	1.000E-04	1	1.20	1.10	1.15	0.600	1.10	1.152E-04
Z AXIS	5.2	1.000E-01	1	1.20	1.10	1.15	0.600	1.10	1.152E-01
Z AXIS	5.3	5.000E-02	1	1.20	1.10	1.15	0.600	1.10	5.761E-02
Z AXIS	6.1	7.884E-04	1	1.20	1.10	1.15	0.600	1.10	9.874E-04
Z AXIS	6.2	1.000E-03	1	1.20	1.10	1.15	0.600	1.10	1.252E-03
Z AXIS	6.3	1.000E-01	1	1.20	1.10	1.15	0.600	1.10	1.252E-01
Z AXIS	6.4	1.000E-03	1	1.20	1.10	1.15	0.600	1.10	1.252E-03
Z AXIS	7.1	1.000E-02	1	1.25	1.10	1.15	0.600	1.10	1.200E-02
Z AXIS	7.2	2.000E-02	1	1.25	1.10	1.15	0.600	1.10	2.400E-02
Z AXIS	8.1	7.884E-04	1	1.15	1.10	1.15	0.600	1.10	8.705E-04
Z AXIS	8.2	1.000E-04	1	1.15	1.10	1.15	0.600	1.10	1.104E-04
Z AXIS	9.1	4.380E-02	1	1.25	1.10	1.15	0.600	1.10	5.257E-02
Z AXIS	9.2	5.000E-02	1	1.25	1.10	1.15	0.600	1.10	6.001E-02
Z AXIS	10.1	1.000E-02	1	1.25	1.10	1.15	0.600	1.10	1.200E-02
Z AXIS	10.2	1.000E-01	1	1.25	1.10	1.15	0.600	1.10	1.200E-01
Z AXIS	10.3	5.000E-02	1	1.25	1.10	1.15	0.600	1.10	6.001E-02
X-Y AXIS	1.1	7.884E-04	4	1.20	1.10	1.15	0.600	1.10	3.633E-03
X-Y AXIS	1.2	1.000E-03	4	1.20	1.10	1.15	0.600	1.10	4.609E-03
X-Y AXIS	1.3	1.000E-01	4	1.20	1.10	1.15	0.600	1.10	4.609E-01
X-Y AXIS	2.1	7.884E-04	4	1.15	1.10	1.15	0.600	1.10	3.482E-03
X-Y AXIS	2.2	1.000E-02	4	1.15	1.10	1.15	0.600	1.10	4.417E-02
X-Y AXIS	3.1	7.884E-04	4	1.15	1.10	1.15	0.600	1.10	3.785E-03
X-Y AXIS	3.2	1.000E-02	4	1.15	1.10	1.15	0.600	1.10	4.801E-02
X-Y AXIS	4.1	7.884E-04	2	1.25	1.10	1.15	0.600	1.10	2.057E-03
X-Y AXIS	4.2	1.000E-03	2	1.25	1.10	1.15	0.600	1.10	2.609E-03
X-Y AXIS	4.3	1.000E-01	2	1.25	1.10	1.15	0.600	1.10	2.609E-01
X-Y AXIS	5.1	1.000E-02	8	1.25	1.10	1.15	0.600	1.10	9.184E-02
X-Y AXIS	6.1	5.000E-02	4	1.25	1.10	1.15	0.600	1.10	2.400E-01
X-Y AXIS	6.2	2.500E-01	4	1.25	1.10	1.15	0.600	1.10	1.200E+00

Table 4-1 (Continued)

Robot System	Failure Event Number	Base Failure Frequency (Ev./Yr.)	Number of Independent Components in Event	Environmental			External Impact			Installation/Maintenance			Load Factor	% Operating Time			Component Quality PI	Estimated Event Frequency (Ev./Yr.)
				PI	Quantity	(π e)	PI	Quantity	(π i)	PI	Quantity	(π i/m)		PI	Quantity	(π o)		
X-Y AXIS	6.3	1.000E-02	4	1.25	1.15	1.10	1.15	1.10	1.15	1.10	0.600	1.10	1.15	0.600	1.10	0.600	1.10	4.801E-02
X-Y AXIS	6.4	2.000E-02	4	1.25	1.15	1.10	1.15	1.10	1.15	1.10	0.600	1.10	1.15	0.600	1.10	0.600	1.10	9.601E-02
X-Y AXIS	7.1	1.000E-04	8	1.20	1.15	1.10	1.15	1.10	1.15	1.10	0.600	1.10	1.15	0.600	1.10	0.600	1.10	9.217E-04
X-Y AXIS	7.2	1.000E-01	8	1.20	1.15	1.10	1.15	1.10	1.15	1.10	0.600	1.10	1.15	0.600	1.10	0.600	1.10	9.217E-01
X-Y AXIS	7.3	5.000E-02	8	1.20	1.15	1.10	1.15	1.10	1.15	1.10	0.600	1.10	1.15	0.600	1.10	0.600	1.10	4.609E-01
X-Y AXIS	8.1	1.000E-04	8	1.15	1.10	1.10	1.10	1.10	1.10	1.10	0.600	1.10	1.15	0.600	1.10	0.600	1.10	8.449E-04
X-Y AXIS	8.2	1.000E-03	8	1.15	1.10	1.10	1.10	1.10	1.10	1.10	0.600	1.10	1.15	0.600	1.10	0.600	1.10	8.449E-03
X-Y AXIS	9.1	5.000E-02	16	1.25	1.15	1.10	1.15	1.10	1.15	1.10	0.600	1.10	1.15	0.600	1.10	0.600	1.10	9.601E-01
X-Y AXIS	9.2	1.000E-03	16	1.25	1.15	1.10	1.15	1.10	1.15	1.10	0.600	1.10	1.15	0.600	1.10	0.600	1.10	1.920E-02
X-Y AXIS	10.1	1.000E-04	8	1.05	1.15	1.10	1.15	1.10	1.15	1.10	0.600	1.10	1.15	0.600	1.10	0.600	1.10	8.065E-04
X-Y AXIS	10.2	1.000E-01	8	1.05	1.15	1.10	1.15	1.10	1.15	1.10	0.600	1.10	1.15	0.600	1.10	0.600	1.10	8.065E-01
X-Y AXIS	10.3	5.000E-02	8	1.05	1.15	1.10	1.15	1.10	1.15	1.10	0.600	1.10	1.15	0.600	1.10	0.600	1.10	4.033E-01
X-Y AXIS	11.1	5.000E-02	4	1.10	1.15	1.10	1.15	1.10	1.15	1.10	0.600	1.10	1.15	0.600	1.10	0.600	1.10	2.112E-01
X-Y AXIS	11.2	2.500E-01	4	1.10	1.15	1.10	1.15	1.10	1.15	1.10	0.600	1.10	1.15	0.600	1.10	0.600	1.10	1.056E+00
X-Y AXIS	11.3	1.000E-02	4	1.10	1.15	1.10	1.15	1.10	1.15	1.10	0.600	1.10	1.15	0.600	1.10	0.600	1.10	4.225E-02
X-Y AXIS	11.4	2.000E-02	4	1.10	1.15	1.10	1.15	1.10	1.15	1.10	0.600	1.10	1.15	0.600	1.10	0.600	1.10	8.449E-02
X-Y AXIS	12.1	1.000E-02	4	1.25	1.15	1.10	1.15	1.10	1.15	1.10	0.600	1.10	1.15	0.600	1.10	0.600	1.10	4.801E-02
X-Y AXIS	12.2	5.000E-02	4	1.25	1.15	1.10	1.15	1.10	1.15	1.10	0.600	1.10	1.15	0.600	1.10	0.600	1.10	2.400E-01
X-Y AXIS	12.3	6.670E-02	4	1.25	1.15	1.10	1.15	1.10	1.15	1.10	0.600	1.10	1.15	0.600	1.10	0.600	1.10	3.202E-01
X-Y AXIS	13.1	4.380E-02	2	1.25	1.15	1.10	1.15	1.10	1.15	1.10	0.600	1.10	1.15	0.600	1.10	0.600	1.10	1.051E-01
X-Y AXIS	13.2	5.000E-02	2	1.25	1.15	1.10	1.15	1.10	1.15	1.10	0.600	1.10	1.15	0.600	1.10	0.600	1.10	1.200E-01
X-Y AXIS	14.1	7.884E-04	4	1.10	1.15	1.10	1.15	1.10	1.15	1.10	0.600	1.10	1.15	0.600	1.10	0.600	1.10	3.331E-03
X-Y AXIS	14.2	8.000E-04	4	1.10	1.15	1.10	1.15	1.10	1.15	1.10	0.600	1.10	1.15	0.600	1.10	0.600	1.10	3.380E-03
W AXIS	1.1	1.000E-02	1	1.25	1.15	1.10	1.15	1.10	1.15	1.10	0.600	1.10	1.15	0.600	1.10	0.600	1.10	1.200E-02
W AXIS	1.2	1.000E-01	1	1.25	1.15	1.10	1.15	1.10	1.15	1.10	0.600	1.10	1.15	0.600	1.10	0.600	1.10	1.200E-01
W AXIS	1.3	5.000E-02	1	1.25	1.15	1.10	1.15	1.10	1.15	1.10	0.600	1.10	1.15	0.600	1.10	0.600	1.10	6.001E-02
W AXIS	2.1	4.380E-02	1	1.25	1.15	1.10	1.15	1.10	1.15	1.10	0.600	1.10	1.15	0.600	1.10	0.600	1.10	5.257E-02
W AXIS	2.2	5.000E-02	1	1.25	1.15	1.10	1.15	1.10	1.15	1.10	0.600	1.10	1.15	0.600	1.10	0.600	1.10	6.001E-02
W AXIS	3.1	7.884E-04	1	1.05	1.05	1.10	1.05	1.10	1.05	1.10	0.600	1.10	1.15	0.600	1.10	0.600	1.10	7.257E-04
W AXIS	3.2	1.000E-03	1	1.05	1.05	1.10	1.05	1.10	1.05	1.10	0.600	1.10	1.15	0.600	1.10	0.600	1.10	9.205E-04
W AXIS	4.1	1.000E-03	1	1.05	1.05	1.10	1.05	1.10	1.05	1.10	0.600	1.10	1.15	0.600	1.10	0.600	1.10	9.205E-04
W AXIS	5.1	7.884E-04	1	1.05	1.05	1.10	1.05	1.10	1.05	1.10	0.600	1.10	1.15	0.600	1.10	0.600	1.10	7.257E-04
W AXIS	5.2	1.000E-03	1	1.05	1.05	1.10	1.05	1.10	1.05	1.10	0.600	1.10	1.15	0.600	1.10	0.600	1.10	9.205E-04
W AXIS	5.3	1.000E-03	1	1.05	1.05	1.10	1.05	1.10	1.05	1.10	0.600	1.10	1.15	0.600	1.10	0.600	1.10	9.205E-04
W AXIS	6.1	1.000E-03	1	1.05	1.05	1.10	1.05	1.10	1.05	1.10	0.600	1.10	1.15	0.600	1.10	0.600	1.10	9.205E-04
W AXIS	6.2	8.000E-03	1	1.05	1.05	1.10	1.05	1.10	1.05	1.10	0.600	1.10	1.15	0.600	1.10	0.600	1.10	7.364E-03
W AXIS	7.1	8.760E-02	2	1.25	1.10	1.10	1.10	1.10	1.10	1.10	0.600	1.10	1.15	0.600	1.10	0.600	1.10	2.011E-01
W AXIS	7.2	5.000E-03	2	1.25	1.10	1.10	1.10	1.10	1.10	1.10	0.600	1.10	1.15	0.600	1.10	0.600	1.10	1.148E-02
W AXIS	8.1	5.000E-03	1	1.10	1.25	1.10	1.25	1.10	1.25	1.10	0.600	1.10	1.15	0.600	1.10	0.600	1.10	5.740E-03

Table 4-1 (Continued)

Robot System	Failure Event Number	Base Failure Frequency (Ev./Yr.)	Number of Independent Components in Event	Environmental PI Quantity (πe)	External Impact PI Quantity (πi)	Installation/Maintenance PI Quantity ($\pi i/m$)	Load Factor PI Quantity (πl)	% Operating Time PI Quantity (πo)	Component PI Quantity (πq)	Estimated Event Frequency (Ev./Yr.)
W AXIS	9.1	2.000E-03	2	1.25	1.25	1.10	1.15	0.600	1.10	5.218E-03
PERIPHERAL	1.1	4.380E-02	1	1.15	1.15	1.10	1.15	0.600	1.10	4.836E-02
PERIPHERAL	1.2	1.333E-03	1	1.15	1.15	1.10	1.15	0.600	1.10	1.472E-03
PERIPHERAL	2.1	3.000E+00	1	1.10	1.15	1.10	1.15	0.600	1.10	3.168E+00
PERIPHERAL	3.1	2.000E-01	1	1.25	1.15	1.10	1.15	0.600	1.10	2.400E-01
PERIPHERAL	3.2	1.000E-01	1	1.25	1.15	1.10	1.15	0.600	1.10	1.200E-01
PERIPHERAL	4.1	2.000E-01	1	1.00	1.00	1.10	1.15	0.600	1.10	1.670E-01
PERIPHERAL	4.2	1.000E+00	1	1.00	1.00	1.10	1.15	0.600	1.10	8.349E-01
PERIPHERAL	5.1	7.884E-04	1	1.15	1.00	1.10	1.15	0.600	1.10	7.570E-04
PERIPHERAL	5.2	2.628E-03	1	1.15	1.00	1.10	1.15	0.600	1.10	2.523E-03
PERIPHERAL	6.1	2.000E+00	1	1.00	1.00	1.10	1.15	1.00	1.00	2.530E+00
PERIPHERAL	6.2	1.000E+00	1	1.00	1.00	1.10	1.15	1.00	1.00	1.265E+00
PERIPHERAL	6.3	2.000E+00	1	1.00	1.00	1.10	1.15	1.00	1.00	2.530E+00
PERIPHERAL	6.4	1.000E+00	1	1.00	1.00	1.10	1.15	1.00	1.00	1.265E+00
PERIPHERAL	6.5	3.333E-01	1	1.00	1.00	1.10	1.15	1.00	1.00	4.217E-01
PERIPHERAL	6.6	1.000E-01	1	1.00	1.00	1.10	1.15	1.00	1.00	1.265E-01

impacts into the robotic device. Furthermore, to characterize the system under severe degradation factors, the assumption is made that the manufacturing, installation, and maintenance are below average. The cutting operation is not a continuous process, but operates for two eight hour shifts, seven days per week. Under these conditions, the PI quantities for installation/maintenance, load factor, percent operating time, and component quality are globally assigned to all failure modes. The PI quantities for exposure to the environment and external impacts are considered independently for each component's failure modes.

4.7.1.2 Favorable condition application

The favorable application condition is based on the same standard base failure rates for the component failure modes. The degradation factors due to the more favorable conditions are different from those used for the severe application. The calculations for the actual expected failure rates are identical to those for the severe application and the favorable case results are shown in Table 4-2.

The favorable application is chosen to be an intermittent "pick and place" use. The example chosen is moving circuit boards to a diagnostic test apparatus

Table 4-2. Failure Mode Frequency Assignments for the Favorable Application Case Study

Robot System	Failure Event Number	Base Failure Frequency (Ev./Yr.)	Number of Independent Components in Event		Environmental Impact		External Impact		Installation/Maintenance		Load Factor		% Operating Time		Component Quality		Estimated Event Frequency (Ev./Yr.)
			Failure Event	Base Event	PI Quantity	PI Quantity	PI Quantity	PI Quantity	PI Quantity	PI Quantity	PI Quantity	PI Quantity	PI Quantity	PI Quantity	PI Quantity	PI Quantity	
Z AXIS	1.1	7.884E-04	1	1	0.85	0.85	0.85	0.85	0.90	0.90	0.85	0.85	0.33	0.33	0.90	0.90	1.294E-04
Z AXIS	1.2	1.000E-02	1	1	0.85	0.85	0.85	0.85	0.90	0.90	0.85	0.85	0.33	0.33	0.90	0.90	1.642E-03
Z AXIS	2.1	6.132E-02	1	1	0.85	0.85	0.85	0.85	0.90	0.90	0.85	0.85	0.33	0.33	0.90	0.90	1.007E-02
Z AXIS	3.1	1.000E-04	1	1	0.85	0.85	0.85	0.85	0.90	0.90	0.85	0.85	0.33	0.33	0.90	0.90	1.642E-05
Z AXIS	3.2	1.000E-04	1	1	0.85	0.85	0.85	0.85	0.90	0.90	0.85	0.85	0.33	0.33	0.90	0.90	1.642E-05
Z AXIS	3.3	5.000E-02	1	1	0.85	0.85	0.85	0.85	0.90	0.90	0.85	0.85	0.33	0.33	0.90	0.90	8.208E-03
Z AXIS	4.1	5.000E-02	1	1	0.85	0.85	0.85	0.85	0.90	0.90	0.85	0.85	0.33	0.33	0.90	0.90	8.208E-03
Z AXIS	4.2	2.500E-01	1	1	0.85	0.85	0.85	0.85	0.90	0.90	0.85	0.85	0.33	0.33	0.90	0.90	4.104E-02
Z AXIS	4.3	1.000E-02	1	1	0.85	0.85	0.85	0.85	0.90	0.90	0.85	0.85	0.33	0.33	0.90	0.90	1.642E-03
Z AXIS	4.4	2.000E-02	1	1	0.85	0.85	0.85	0.85	0.90	0.90	0.85	0.85	0.33	0.33	0.90	0.90	3.283E-03
Z AXIS	5.1	1.000E-04	1	1	0.80	0.80	0.80	0.85	0.90	0.90	0.85	0.85	0.33	0.33	0.90	0.90	1.545E-05
Z AXIS	5.2	1.000E-01	1	1	0.80	0.80	0.85	0.85	0.90	0.90	0.85	0.85	0.33	0.33	0.90	0.90	1.545E-02
Z AXIS	5.3	5.000E-02	1	1	0.80	0.80	0.85	0.85	0.90	0.90	0.85	0.85	0.33	0.33	0.90	0.90	7.725E-03
Z AXIS	6.1	7.884E-04	1	1	0.80	0.80	0.75	0.75	0.90	0.90	0.85	0.85	0.33	0.33	0.90	0.90	1.075E-04
Z AXIS	6.2	1.000E-03	1	1	0.80	0.80	0.75	0.75	0.90	0.90	0.85	0.85	0.33	0.33	0.90	0.90	1.363E-04
Z AXIS	6.3	1.000E-01	1	1	0.80	0.80	0.75	0.75	0.90	0.90	0.85	0.85	0.33	0.33	0.90	0.90	1.363E-02
Z AXIS	6.4	1.000E-03	1	1	0.80	0.80	0.75	0.75	0.90	0.90	0.85	0.85	0.33	0.33	0.90	0.90	1.363E-04
Z AXIS	7.1	1.000E-02	1	1	0.75	0.75	0.85	0.85	0.90	0.90	0.85	0.85	0.33	0.33	0.90	0.90	1.448E-03
Z AXIS	7.2	2.000E-02	1	1	0.75	0.75	0.85	0.85	0.90	0.90	0.85	0.85	0.33	0.33	0.90	0.90	2.897E-03
Z AXIS	8.1	7.884E-04	1	1	0.85	0.85	0.85	0.85	0.90	0.90	0.85	0.85	0.33	0.33	0.90	0.90	1.294E-04
Z AXIS	8.2	1.000E-04	1	1	0.85	0.85	0.85	0.85	0.90	0.90	0.85	0.85	0.33	0.33	0.90	0.90	1.642E-05
Z AXIS	9.1	4.380E-02	1	1	0.75	0.75	0.85	0.85	0.90	0.90	0.85	0.85	0.33	0.33	0.90	0.90	6.344E-03
Z AXIS	9.2	5.000E-02	1	1	0.75	0.75	0.85	0.85	0.90	0.90	0.85	0.85	0.33	0.33	0.90	0.90	7.242E-03
Z AXIS	10.1	1.000E-02	1	1	0.75	0.75	0.85	0.85	0.90	0.90	0.85	0.85	0.33	0.33	0.90	0.90	1.448E-03
Z AXIS	10.2	1.000E-01	1	1	0.75	0.75	0.85	0.85	0.90	0.90	0.85	0.85	0.33	0.33	0.90	0.90	1.448E-02
Z AXIS	10.3	5.000E-02	1	1	0.75	0.75	0.85	0.85	0.90	0.90	0.85	0.85	0.33	0.33	0.90	0.90	7.242E-03
X-Y AXIS	1.1	7.884E-04	4	4	0.80	0.80	0.85	0.85	0.90	0.90	0.85	0.85	0.33	0.33	0.90	0.90	4.872E-04
X-Y AXIS	1.2	1.000E-03	4	4	0.80	0.80	0.85	0.85	0.90	0.90	0.85	0.85	0.33	0.33	0.90	0.90	6.180E-02
X-Y AXIS	1.3	1.000E-01	4	4	0.80	0.80	0.85	0.85	0.90	0.90	0.85	0.85	0.33	0.33	0.90	0.90	5.177E-04
X-Y AXIS	2.1	7.884E-04	4	4	0.85	0.85	0.85	0.85	0.90	0.90	0.85	0.85	0.33	0.33	0.90	0.90	6.566E-03
X-Y AXIS	2.2	1.000E-02	4	4	0.85	0.85	0.85	0.85	0.90	0.90	0.85	0.85	0.33	0.33	0.90	0.90	4.568E-04
X-Y AXIS	3.1	7.884E-04	4	4	0.85	0.85	0.75	0.75	0.90	0.90	0.85	0.85	0.33	0.33	0.90	0.90	5.794E-03
X-Y AXIS	3.2	1.000E-02	4	4	0.85	0.85	0.75	0.75	0.90	0.90	0.85	0.85	0.33	0.33	0.90	0.90	2.015E-04
X-Y AXIS	4.1	7.884E-04	2	2	0.75	0.75	0.75	0.75	0.90	0.90	0.85	0.85	0.33	0.33	0.90	0.90	2.556E-04
X-Y AXIS	4.2	1.000E-03	2	2	0.75	0.75	0.75	0.75	0.90	0.90	0.85	0.85	0.33	0.33	0.90	0.90	2.556E-02
X-Y AXIS	4.3	1.000E-01	2	2	0.75	0.75	0.75	0.75	0.90	0.90	0.85	0.85	0.33	0.33	0.90	0.90	1.227E-02
X-Y AXIS	5.1	1.000E-02	8	8	0.75	0.75	0.90	0.90	0.90	0.90	0.85	0.85	0.33	0.33	0.90	0.90	2.897E-02
X-Y AXIS	6.1	5.000E-02	4	4	0.75	0.75	0.85	0.85	0.90	0.90	0.85	0.85	0.33	0.33	0.90	0.90	1.448E-01
X-Y AXIS	6.2	2.500E-01	4	4	0.75	0.75	0.85	0.85	0.90	0.90	0.85	0.85	0.33	0.33	0.90	0.90	1.448E-01

Table 4-2 (Continued)

Robot System	Failure Event Number	Base Failure Frequency (Ev./Yr.)	Number of Independent Components in Event	Environmental PI Quantity (we)	External Impact PI Quantity (xi)	Installation Maintenance PI Quantity (xi/m)	Load Factor PI Quantity (xi)	% Operating Time PI Quantity (xo)	Component Quality PI Quantity (xq)	Estimated Event Frequency (Ev./Yr.)
X-Y AXIS	6.3	1.000E-02	4	0.75	0.85	0.90	0.85	0.33	0.90	5.794E-03
X-Y AXIS	6.4	2.000E-02	4	0.75	0.85	0.90	0.85	0.33	0.90	1.159E-02
X-Y AXIS	7.1	1.000E-04	8	0.80	0.85	0.90	0.85	0.33	0.90	1.236E-04
X-Y AXIS	7.2	1.000E-01	8	0.80	0.85	0.90	0.85	0.33	0.90	1.236E-01
X-Y AXIS	7.3	5.000E-02	8	0.80	0.85	0.90	0.85	0.33	0.90	6.180E-02
X-Y AXIS	8.1	1.000E-04	8	0.85	0.90	0.90	0.85	0.33	0.90	1.390E-04
X-Y AXIS	8.2	1.000E-03	8	0.85	0.90	0.90	0.85	0.33	0.90	1.390E-03
X-Y AXIS	9.1	5.000E-02	16	0.75	0.85	0.90	0.85	0.33	0.90	1.159E-01
X-Y AXIS	9.2	1.000E-03	16	0.75	0.85	0.90	0.85	0.33	0.90	2.317E-03
X-Y AXIS	10.1	1.000E-04	8	0.95	0.85	0.90	0.85	0.33	0.90	1.468E-04
X-Y AXIS	10.2	1.000E-01	8	0.95	0.85	0.90	0.85	0.33	0.90	1.468E-01
X-Y AXIS	10.3	5.000E-02	8	0.95	0.85	0.90	0.85	0.33	0.90	7.339E-02
X-Y AXIS	11.1	5.000E-02	4	0.90	0.85	0.90	0.85	0.33	0.90	3.476E-02
X-Y AXIS	11.2	2.500E-01	4	0.90	0.85	0.90	0.85	0.33	0.90	1.738E-01
X-Y AXIS	11.3	1.000E-02	4	0.90	0.85	0.90	0.85	0.33	0.90	6.952E-03
X-Y AXIS	11.4	2.000E-02	4	0.90	0.85	0.90	0.85	0.33	0.90	1.390E-02
X-Y AXIS	12.1	1.000E-02	4	0.75	0.85	0.90	0.85	0.33	0.90	5.794E-03
X-Y AXIS	12.2	5.000E-02	4	0.75	0.85	0.90	0.85	0.33	0.90	2.897E-02
X-Y AXIS	12.3	6.670E-02	4	0.75	0.85	0.90	0.85	0.33	0.90	3.864E-02
X-Y AXIS	13.1	4.380E-02	2	0.75	0.85	0.90	0.85	0.33	0.90	1.269E-02
X-Y AXIS	13.2	5.000E-02	2	0.75	0.85	0.90	0.85	0.33	0.90	1.448E-02
X-Y AXIS	14.1	7.884E-04	4	0.90	0.85	0.90	0.85	0.33	0.90	5.481E-04
X-Y AXIS	14.2	8.000E-04	4	0.90	0.85	0.90	0.85	0.33	0.90	5.562E-04
W AXIS	1.1	1.000E-02	1	0.75	0.85	0.90	0.85	0.33	0.90	1.448E-03
W AXIS	1.2	1.000E-01	1	0.75	0.85	0.90	0.85	0.33	0.90	1.448E-02
W AXIS	1.3	5.000E-02	1	0.75	0.85	0.90	0.85	0.33	0.90	7.242E-03
W AXIS	2.1	4.380E-02	1	0.75	0.85	0.90	0.85	0.33	0.90	6.344E-03
W AXIS	2.2	5.000E-02	1	0.75	0.85	0.90	0.85	0.33	0.90	7.242E-03
W AXIS	3.1	7.884E-04	1	0.95	0.95	0.90	0.85	0.33	0.90	1.617E-04
W AXIS	3.2	1.000E-03	1	0.95	0.95	0.90	0.85	0.33	0.90	2.051E-04
W AXIS	4.1	1.000E-03	1	0.95	0.95	0.90	0.85	0.33	0.90	2.051E-04
W AXIS	5.1	7.884E-04	1	0.95	0.95	0.90	0.85	0.33	0.90	1.617E-04
W AXIS	5.2	1.000E-03	1	0.95	0.95	0.90	0.85	0.33	0.90	2.051E-04
W AXIS	5.3	1.000E-03	1	0.95	0.95	0.90	0.85	0.33	0.90	2.051E-04
W AXIS	6.1	1.000E-03	1	0.95	0.95	0.90	0.85	0.33	0.90	1.640E-03
W AXIS	6.2	8.000E-03	1	0.95	0.95	0.90	0.85	0.33	0.90	2.687E-02
W AXIS	7.1	8.760E-02	2	0.75	0.90	0.90	0.85	0.33	0.90	1.534E-03
W AXIS	7.2	5.000E-03	2	0.75	0.90	0.90	0.85	0.33	0.90	7.668E-04
W AXIS	8.1	5.000E-03	1	0.90	0.75	0.90	0.85	0.33	0.90	

Table 4-2 (Continued)

Robot System	Failure Event Number	Base Failure Frequency (Ev./Yr.)	Number of Independent Components in Event		Environmental		External Impact		Installation/Maintenance		Load Factor		% Operating Time		Component Quality	Estimated Event Frequency (Ev./Yr.)
			Pi	Quantity	Pi	Quantity	Pi	Quantity	Pi	Quantity	Pi	Quantity	Pi	Quantity		
W AXIS	9.1	2.000E-03	2	0.75	0.85	0.75	0.90	0.85	0.33	0.90	0.90	0.33	0.90	0.90	5.112E-04	5.112E-04
PERIPHERAL	1.1	4.380E-02	1	0.85	0.85	0.85	0.90	0.85	0.33	0.90	0.85	0.33	0.90	0.90	7.190E-03	7.190E-03
PERIPHERAL	1.2	1.333E-03	1	0.85	0.85	0.85	0.90	0.85	0.33	0.90	0.85	0.33	0.90	0.90	2.189E-04	2.189E-04
PERIPHERAL	2.1	3.000E+00	1	0.90	0.85	0.85	0.90	0.85	0.33	0.90	0.85	0.33	0.90	0.90	5.214E-01	5.214E-01
PERIPHERAL	3.1	2.000E-01	1	0.75	0.85	0.85	0.90	0.85	0.33	0.90	0.85	0.33	0.90	0.90	2.897E-02	2.897E-02
PERIPHERAL	3.2	1.000E-01	1	0.75	0.85	0.85	0.90	0.85	0.33	0.90	0.85	0.33	0.90	0.90	1.448E-02	1.448E-02
PERIPHERAL	4.1	2.000E-01	1	1.00	1.00	1.00	0.90	0.85	0.33	0.90	0.85	0.33	0.90	0.90	4.544E-02	4.544E-02
PERIPHERAL	4.2	1.000E+00	1	1.00	1.00	1.00	0.90	0.85	0.33	0.90	0.85	0.33	0.90	0.90	2.272E-01	2.272E-01
PERIPHERAL	5.1	7.884E-04	1	0.85	0.85	1.00	0.90	0.85	0.33	0.90	0.85	0.33	0.90	0.90	1.523E-04	1.523E-04
PERIPHERAL	5.2	2.628E-03	1	1.00	1.00	1.00	0.90	0.85	0.33	0.90	0.85	0.33	0.90	0.90	5.075E-04	5.075E-04
PERIPHERAL	6.1	2.000E+00	1	1.00	1.00	1.00	0.90	0.85	1.00	1.00	0.85	1.00	1.00	1.00	1.530E+00	1.530E+00
PERIPHERAL	6.2	1.000E+00	1	1.00	1.00	1.00	0.90	0.85	1.00	1.00	0.85	1.00	1.00	1.00	7.650E-01	7.650E-01
PERIPHERAL	6.3	2.000E+00	1	1.00	1.00	1.00	0.90	0.85	1.00	1.00	0.85	1.00	1.00	1.00	1.530E+00	1.530E+00
PERIPHERAL	6.4	1.000E+00	1	1.00	1.00	1.00	0.90	0.85	1.00	1.00	0.85	1.00	1.00	1.00	7.650E-01	7.650E-01
PERIPHERAL	6.5	3.333E-01	1	1.00	1.00	1.00	0.90	0.85	1.00	1.00	0.85	1.00	1.00	1.00	2.550E-01	2.550E-01
PERIPHERAL	6.6	1.000E-01	1	1.00	1.00	1.00	0.90	0.85	1.00	1.00	0.85	1.00	1.00	1.00	7.650E-02	7.650E-02

during manufacturing. This example is characterized by light loading, a clean and dry environment, and limited interaction with other equipment. Robot manufacturing, installation, and maintenance are assumed above average. Again, the PI quantities for installation/maintenance, load factor, percent operating time, and component quality are globally assigned to all failure modes. The PI quantities for exposure to the environment and external impacts are considered independently for each component's failure modes.

4.7.2 Failure mode consequence assignment

After evaluating the failure rates for the potential failure modes, the consequences of the failure modes must be numerically assessed. As discussed, quantifying the financial costs of a failure mode requires calculation of the complete costs due to equipment damage, costs due to business interruption, and costs due to repair of the system. Additionally, safety issues must be addressed through a rating category scheme. The evaluation of the failure costs is highly application dependent, and requires an estimate of the time to repair and re-calibrate the system for operation.

For the equipment damage costs, the previously determined system effects of each failure mode are

studied. The costs of all damaged equipment, including other local equipment not specifically part of the robotic system, are summed to determine the total equipment damage cost of each failure event.

The business interruption costs are determined by summing the value of lost production due to downtime and other costs associated with lost production, such as idle workers, market share loss to competitors, and inability to fulfill contracts or orders. These costs depend on the application and the time to re-initiate full operation after a failure event. The time to re-start operation after a failure is composed of the times to obtain replacement parts, correct and repair damage after a failure event, and re-calibrate the system. This cost is calculated by some hourly downtime cost multiplied by the downtime. Added to this amount is any additional costs described above.

The repair time is merely the cost of performing the repair activities on the system after a failure event. This cost is calculated by multiplying the man-hours spent on repair and re-calibration by the hourly repair rate.

The safety issues are more subjective than the costs. A scale from 1 to 5 represents levels of safety concerns as follows:

1	-	Very Low Safety Concerns
2	-	Low Safety Concerns

- 3 - Moderate Safety Concerns
- 4 - High Safety Concerns
- 5 - Very High Safety Concerns

Each event is assigned a category level representing all of the system safety effects of the failure mode.

For the robotic system, a common theme appears in the system effects for all of the failure modes. In each of the system effect descriptions, the ultimate system effect is a positioning error. This is expected since the robotic system is primarily designed as a positioning device, and the failure modes are defined as deviations from design intention of components. The major distinguishing feature among the consequences of the failure modes is the degree of the positioning error, and the damage due to the error. The amount of system damage due to the failure mode is generally dependent upon the degree of positioning error, with larger positioning errors causing more extensive damage. For both of the case study applications, the consequences for a very large position error and a small position error are calculated. Then, the estimated percentage of time a large system error exists, compared to the percentage of time a small system error exists, is used as a weighting factor to calculate the estimated consequences of each failure mode.

The evaluation of each failure event is calculated in a spreadsheet template, which allows the inputs described

above to be entered to determine and record the consequence quantification. Figure 4-9 depicts the failure event quantification table for the severe application case study, while Figure 4-10 shows the table for the favorable application case study. The calculations used to calculate the costs due to large and small position error are described in Appendix B. The quantification table includes the equipment damage cost and repair time for the end effector, the equipment in the workspace of the robot, and the equipment in the vicinity of the robotic system. The shipping time for components not at the operation site, and the re-calibration time to reset the robot are included. Hourly cost rates for the repair time and the process downtime are utilized to calculate the business interruption and repair costs.

4.7.2.1 Severe condition application

For the water jet cutting application, the list of system components with the respective component cost, repair time, and probable inventory status is presented in Table 4-3. The end effector is expensive and subject to damage even under small positioning error events. The analysis hypothesizes a high volume production environment of moderately valued items for the cutting tool application. One hour is assumed necessary to re-

System: PERIPHERY	Item:	6.6		
Initiating Event Parts Cost:		0	EQD	\$614.38
End Effector Cost:	\$2,000.00		BIC	\$1,882.35
Equipment in Workspace Cost:	\$300.00		REP	\$159.63
Equipment Near Workspace Cost:	\$35,000.00		SAFETY	5
Percentage Large Position Error:		0.50		
Replacement Shipping Time:		0		
Initiating Event Repair Time:		0		
End Effector Repair Time:		12		
Equip. in Workspace Repair Time:		12		
Equip. Near Worksp. Repair Time:		8		
Recalibration/Reset Time:		1		
Business Interruption Cost/Hr:	\$350.00			
Repair Labor Cost/Hr:		30		
Safety Category:		5		
Value of Parts Moved/Worked:	\$20.00			

Figure 4-9. Failure Mode Consequence Evaluation Spreadsheet for the Severe Application Case Study

System: PERIPHERY	Item:	6.6		
Initiating Event Parts Cost:	\$0.00	EQD	\$116.25	
End Effector Cost:	\$250.00	BIC	\$121.50	
Equipment in Workspace Cost:	\$500.00	REP	\$69.93	
Equipment Near Workspace Cost:	\$0.00	SAFETY	5	
Percentage Large Position Error:	0.50			
Replacement Shipping Time:	0			
Initiating Event Repair Time:	0			
End Effector Repair Time:	4			
Equip. in Workspace Repair Time:	4			
Equip. Near Worksp. Repair Time:	0			
Recalibration/Reset Time:	1			
Number of Good Units Scraped:	1			
Repair Labor Cost/Hr:	30			
Safety Category:	5			
Value of Parts Moved/Worked:	\$150.00			

Figure 4-10. Failure Mode Consequence Evaluation Spreadsheet for the Favorable Application Case Study

Table 4-3. Component Cost, Repair Time, and Inventory Status for the Severe Application Case Study

System Component	Component Cost (\$)	Acquisition Time (Hours)	Repair Time (Hours)
Z Support Mast	50	8	1.5
Needle Bearing	10	0	1
Timing Belt	10	0	1
Timing Belt Pulley	10	0	1
Guide Tube	35	8	2
Guide Tube with Groove	45	8	2.5
Linear Ball Bushings	20	0	3
Z Support Platform	100	8	4
Stepper Motor Driver	100	8	1
Stepper Motor - 2.1 Amp	100	8	1
Stepper Motor - 1.1 Amp	100	8	2.5
Corner Bracket	75	8	2
Slider Housing	75	8	2.5
Motor Mounting Plates	50	8	1.5
Rigid Drive Plug	10	1	1.5
Rotary Drive Tube	30	8	1.5
Rotary Drive Plug	10	1	1.5
Rotary Spindle	25	8	1.5
Radial Bearing	10	0	2
Bearing Cartridge	15	8	1.5
Electric Power Supply	250	4	1.5
Computer Hardware (avg.)	350	4	0.5
Robot Support Structure (avg.)	50	4	1.5
End Effector (Water Jet Cutter)	2000	8	4
Workspace Equipment	300	5	3
Vicinity Equipment	35000	8	4

Source: Interview of UT Robot Designer Michael E. Kennedy, University of Tennessee, October 1989.

calibrate the robotic system after repair of the initiating failure is completed. Other substantially expensive equipment and human operators are also working in the same vicinity. Table 4-4 documents the results of the potential failure modes' consequence evaluations for the water jet cutter application. In Table 4-4, the Equipment Damage, Business Interruption, and Repair Costs for each failure event are presented. Also, the Safety Issue Category ranking is listed for each failure event for the FMEA table.

4.7.2.2 Favorable Condition application

For the "Pick and Place" electronic testing application, the list of system components with the respective component cost, repair time, and probable inventory status is presented in Table 4-5. This end effector is substantially less expensive, but is still subject to damage, even from small positioning errors. While the pick and place application does not require the path accuracy of the cutting operation, this application involves more expensive parts in lower volumes. The testing of the electronic equipment is very rapid and can be completed much more quickly than the electronic parts can be manufactured. The testing operation is intermittent, which allows downtimes of several hours, to

Table 4-4. Failure Mode Consequence Assignments for the Severe Application Case Study

Robot System	Failure Event Number	Equipment	Business	Repair Cost (\$)	Safety Category
		Damage Cost (\$)	Interruption Cost (\$)		
Z AXIS	1.1	715.75	5668.30	244.14	4
Z AXIS	1.2	680.48	5576.11	236.24	3
Z AXIS	2.1	358.28	1863.59	158.02	3
Z AXIS	3.1	587.56	2462.83	209.39	3
Z AXIS	3.2	323.00	1771.40	150.12	2
Z AXIS	3.3	411.19	2001.88	169.88	3
Z AXIS	4.1	675.75	2693.30	229.14	4
Z AXIS	4.2	587.56	2462.83	209.39	4
Z AXIS	4.3	323.00	1771.40	150.12	3
Z AXIS	4.4	675.75	2693.30	229.14	4
Z AXIS	5.1	675.75	2693.30	229.14	4
Z AXIS	5.2	675.75	2693.30	229.14	4
Z AXIS	5.3	665.75	2693.30	229.14	4
Z AXIS	6.1	710.75	6018.30	274.14	5
Z AXIS	6.2	358.00	5096.40	195.12	2
Z AXIS	6.3	534.38	5557.35	234.63	3
Z AXIS	6.4	569.65	5649.54	242.53	3
Z AXIS	7.1	597.56	3162.83	269.39	4
Z AXIS	7.2	524.65	2149.54	182.53	3
Z AXIS	8.1	765.75	6543.30	319.14	5
Z AXIS	8.2	413.00	5621.40	240.12	3
Z AXIS	9.1	765.75	5493.30	229.14	4
Z AXIS	9.2	595.20	2508.92	213.34	4
Z AXIS	10.1	765.75	5493.30	229.14	4
Z AXIS	10.2	595.20	2508.92	213.34	3
Z AXIS	10.3	448.28	4663.59	158.02	3
X-Y AXIS	1.1	700.75	5843.30	259.14	4
X-Y AXIS	1.2	489.10	5290.16	211.73	3
X-Y AXIS	1.3	524.38	5382.35	219.63	3
X-Y AXIS	2.1	740.75	5843.30	259.14	4
X-Y AXIS	2.2	476.19	5151.88	199.88	3
X-Y AXIS	3.1	740.75	6018.30	274.14	4
X-Y AXIS	3.2	564.38	5557.35	234.63	3
X-Y AXIS	4.1	700.75	5843.30	259.14	4
X-Y AXIS	4.2	489.10	5290.16	211.73	3
X-Y AXIS	4.3	524.38	5382.35	219.63	3
X-Y AXIS	5.1	597.56	2987.83	254.39	3
X-Y AXIS	6.1	640.48	2601.11	221.24	4
X-Y AXIS	6.2	630.48	2601.11	221.24	4
X-Y AXIS	6.3	358.28	1863.59	158.02	3
X-Y AXIS	6.4	640.48	2601.11	221.24	4
X-Y AXIS	7.1	640.48	2601.11	221.24	4
X-Y AXIS	7.2	665.75	2693.30	229.14	4

Table 4-4 (Continued)

Robot System	Equipment		Business		Safety Category
	Failure Event Number	Damage Cost (\$)	Interruption Cost (\$)	Repair Cost (\$)	
X-Y AXIS	7.3	630.48	2601.11	221.24	4
X-Y AXIS	8.1	680.75	3043.30	259.14	4
X-Y AXIS	8.2	469.10	2490.16	211.73	3
X-Y AXIS	9.1	587.56	2812.83	239.39	4
X-Y AXIS	9.2	340.64	2167.50	184.07	3
X-Y AXIS	10.1	640.48	2601.11	221.24	4
X-Y AXIS	10.2	665.75	2693.30	229.14	4
X-Y AXIS	10.3	630.48	2601.11	221.24	4
X-Y AXIS	11.1	675.75	2693.30	229.14	4
X-Y AXIS	11.2	630.48	2601.11	221.24	4
X-Y AXIS	11.3	323.00	1771.40	150.12	3
X-Y AXIS	11.4	675.75	2693.30	229.14	4
X-Y AXIS	12.1	765.75	5493.30	229.14	4
X-Y AXIS	12.2	595.20	5308.92	213.34	4
X-Y AXIS	12.3	448.28	4663.59	158.02	3
X-Y AXIS	13.1	765.75	5493.30	229.14	4
X-Y AXIS	13.2	695.20	5308.92	213.34	4
X-Y AXIS	14.1	715.75	5668.30	244.14	4
X-Y AXIS	14.2	680.48	5576.11	236.24	4
W AXIS	1.1	765.75	5493.30	229.14	4
W AXIS	1.2	595.20	2508.92	213.34	4
W AXIS	1.3	589.38	5032.35	189.63	3
W AXIS	2.1	765.75	5493.30	229.14	4
W AXIS	2.2	595.20	2508.92	213.34	4
W AXIS	3.1	675.75	2868.30	244.14	4
W AXIS	3.2	587.56	2637.83	224.39	3
W AXIS	4.1	695.75	5668.30	244.14	4
W AXIS	5.1	675.75	2868.30	244.14	4
W AXIS	5.2	323.00	1946.40	165.12	3
W AXIS	5.3	640.48	2776.11	236.24	4
W AXIS	6.1	690.75	5668.30	244.14	4
W AXIS	6.2	338.00	4746.40	165.12	3
W AXIS	7.1	534.65	2674.54	227.53	4
W AXIS	7.2	323.00	2121.40	180.12	2
W AXIS	8.1	328.00	4746.40	165.12	2
W AXIS	9.1	666.75	2693.30	229.14	5
PERIPHERAL	1.1	915.75	4268.30	244.14	4
PERIPHERAL	1.2	774.65	3899.54	212.53	3
PERIPHERAL	2.1	665.75	2868.30	244.14	4
PERIPHERAL	3.1	1015.75	4268.30	244.14	4
PERIPHERAL	3.2	839.38	3807.35	204.63	3
PERIPHERAL	4.1	489.38	2932.35	249.63	4
PERIPHERAL	4.2	489.38	2932.35	249.63	4

Table 4-4 (Continued)

Robot System	Failure Event Number	Equipment	Business	Repair Cost (\$)	Safety Category
		Damage Cost (\$)	Interruption Cost (\$)		
PERIPHERAL	5.1	715.75	4093.30	229.14	4
PERIPHERAL	5.2	398.28	3263.59	158.02	4
PERIPHERAL	6.1	665.75	2343.30	199.14	4
PERIPHERAL	6.2	454.10	1790.16	151.73	3
PERIPHERAL	6.3	665.75	2343.30	199.14	4
PERIPHERAL	6.4	612.84	2205.02	187.29	5
PERIPHERAL	6.5	665.75	2343.30	199.14	5
PERIPHERAL	6.6	489.38	1882.35	159.63	5

Table 4-5. Component Cost, Repair Time, and Inventory Status for the Favorable Application Case Study

System Component	Component Cost (\$)	Acquisition Time (Hours)	Repair Time (Hours)
Z Support Mast	50	8	1.5
Needle Bearing	10	0	1
Timing Belt	10	0	1
Timing Belt Pulley	10	0	1
Guide Tube	35	8	2
Guide Tube with Groove	45	8	2.5
Linear Ball Bushings	20	0	3
Z Support Platform	100	8	4
Stepper Motor Driver	100	8	1
Stepper Motor - 2.1 Amp	100	8	1
Stepper Motor - 1.1 Amp	100	8	2.5
Corner Bracket	75	8	2
Slider Housing	75	8	2.5
Motor Mounting Plates	50	8	1.5
Rigid Drive Plug	10	1	1.5
Rotary Drive Tube	30	8	1.5
Rotary Drive Plug	10	1	1.5
Rotary Spindle	25	8	1.5
Radial Bearing	10	0	2
Bearing Cartridge	15	8	1.5
Electric Power Supply	250	4	1.5
Computer Hardware (avg.)	350	4	0.5
Robot Support Structure (avg.)	50	4	1.5
End Effector (Gripper)	250	0	4
Workspace Equipment	500	2	2
Vicinity Equipment	0	0	0

Source: Interview of UT Robot Designer Michael E. Kennedy, University of Tennessee, October 1989.

a full day, without causing significant downtime losses. The actual testing equipment is included in the robot operating space, which introduces an opportunity for impacts during failure events. Table 4-6 documents the results of the potential failure modes' consequence evaluations for the electronic testing application.

4.8 Qualitative Evaluation of UT Robot Failure Modes

One of the best benefits of FMEA analysis techniques is the wealth of information available from qualitative evaluation of a system. Since quantitative evaluations can be difficult, the simplicity of qualitative evaluations are very attractive to inexperienced analysts, such as designers.

The most obvious results from the FMEA analysis are the recommended actions developed for the failure modes. The FMEA table presents an unsorted list of recommended actions for the failure modes based entirely on qualitative engineering evaluation. Table 4-7 displays the generated recommendations, in the order that they were formulated during the FMEA analysis. From a qualitative point of view, choosing which recommendations deserve the most attention is difficult. However, qualitative evaluations may provide insight into which failure events should be addressed. Many recommendations are somewhat

Table 4-6. Failure Mode Consequence Assignments for the Favorable Application Case Study

Robot System	Failure Event Number	Equipment	Business	Repair Cost (\$)	Safety Category
		Damage Cost (\$)	Interruption Cost (\$)		
Z AXIS	1.1	219.00	163.00	115.62	2
Z AXIS	1.2	208.45	154.70	127.48	1
Z AXIS	2.1	124.05	88.30	87.38	1
Z AXIS	3.1	152.63	142.25	107.78	1
Z AXIS	3.2	63.50	80.00	84.24	1
Z AXIS	3.3	99.88	100.75	92.09	1
Z AXIS	4.1	179.00	163.00	115.62	2
Z AXIS	4.2	152.63	142.25	107.78	2
Z AXIS	4.3	73.50	80.00	84.24	1
Z AXIS	4.4	179.00	163.00	115.62	2
Z AXIS	5.1	179.00	163.00	115.62	2
Z AXIS	5.2	169.00	163.00	115.62	2
Z AXIS	5.3	179.00	163.00	115.62	2
Z AXIS	6.1	214.00	163.00	160.62	2
Z AXIS	6.2	108.50	80.00	129.24	1
Z AXIS	6.3	161.25	121.50	144.93	1
Z AXIS	6.4	171.80	129.80	148.07	1
Z AXIS	7.1	162.63	142.25	167.78	2
Z AXIS	7.2	146.80	129.80	163.07	1
Z AXIS	8.1	269.00	163.00	205.62	3
Z AXIS	8.2	163.50	80.00	174.24	1
Z AXIS	9.1	269.00	163.00	115.62	2
Z AXIS	9.2	147.90	146.40	109.34	2
Z AXIS	10.1	269.00	163.00	115.62	2
Z AXIS	10.2	147.90	146.40	109.34	1
Z AXIS	10.3	174.05	88.30	87.38	1
X-Y AXIS	1.1	204.00	163.00	145.62	2
X-Y AXIS	1.2	140.70	113.20	126.79	1
X-Y AXIS	1.3	151.25	121.50	129.93	1
X-Y AXIS	2.1	244.00	163.00	145.62	2
X-Y AXIS	2.2	164.88	100.75	122.09	1
X-Y AXIS	3.1	244.00	163.00	160.62	2
X-Y AXIS	3.2	191.25	121.50	144.93	1
X-Y AXIS	4.1	204.00	163.00	145.62	2
X-Y AXIS	4.2	140.70	113.20	126.79	1
X-Y AXIS	4.3	151.25	121.50	129.93	1
X-Y AXIS	5.1	162.63	142.25	167.78	1
X-Y AXIS	6.1	168.45	154.70	112.48	2
X-Y AXIS	6.2	158.45	154.70	112.48	2
X-Y AXIS	6.3	84.05	88.30	87.38	1
X-Y AXIS	6.4	168.45	154.70	112.48	2
X-Y AXIS	7.1	168.45	154.70	112.48	2
X-Y AXIS	7.2	169.00	163.00	115.62	2

Table 4-6 (Continued)

Robot System	Failure Event Number	Equipment	Business	Repair Cost (\$)	Safety Category
		Damage Cost (\$)	Interruption Cost (\$)		
X-Y AXIS	7.3	158.45	154.70	112.48	2
X-Y AXIS	8.1	184.00	163.00	130.62	2
X-Y AXIS	8.2	120.70	113.20	111.79	1
X-Y AXIS	9.1	152.63	142.25	122.78	2
X-Y AXIS	9.2	78.78	84.15	100.81	1
X-Y AXIS	10.1	168.45	154.70	112.48	2
X-Y AXIS	10.2	179.00	163.00	115.62	2
X-Y AXIS	10.3	168.45	154.70	112.48	2
X-Y AXIS	11.1	179.00	163.00	115.62	2
X-Y AXIS	11.2	168.45	154.70	112.48	2
X-Y AXIS	11.3	73.50	80.00	84.24	1
X-Y AXIS	11.4	179.00	163.00	115.62	2
X-Y AXIS	12.1	269.00	163.00	115.62	2
X-Y AXIS	12.2	247.90	146.40	109.34	2
X-Y AXIS	12.3	174.05	88.30	87.38	1
X-Y AXIS	13.1	269.00	163.00	115.62	2
X-Y AXIS	13.2	147.90	146.40	109.34	2
X-Y AXIS	14.1	219.00	163.00	130.62	2
X-Y AXIS	14.2	208.45	154.70	127.48	2
W AXIS	1.1	259.00	163.00	115.62	2
W AXIS	1.2	147.90	146.40	109.34	2
W AXIS	1.3	206.25	121.50	99.93	1
W AXIS	2.1	269.00	163.00	115.62	2
W AXIS	2.2	247.90	146.40	109.34	2
W AXIS	3.1	179.00	163.00	130.62	2
W AXIS	3.2	152.63	142.25	122.78	1
W AXIS	4.1	199.00	163.00	130.62	2
W AXIS	5.1	179.00	163.00	130.62	2
W AXIS	5.2	73.50	80.00	99.24	1
W AXIS	5.3	168.45	154.70	127.48	2
W AXIS	6.1	194.00	163.00	130.62	2
W AXIS	6.2	88.50	80.00	99.24	1
W AXIS	7.1	136.80	129.80	133.07	2
W AXIS	7.2	73.50	80.00	114.24	1
W AXIS	8.1	78.50	80.00	99.24	1
W AXIS	9.1	64.50	80.00	84.24	3
PERIPHERAL	1.1	419.00	163.00	130.62	2
PERIPHERAL	1.2	376.80	129.80	118.07	1
PERIPHERAL	2.1	169.00	163.00	85.62	2
PERIPHERAL	3.1	519.00	163.00	115.62	2
PERIPHERAL	3.2	466.25	121.50	99.93	1
PERIPHERAL	4.1	116.25	121.50	114.93	2
PERIPHERAL	4.2	116.25	121.50	114.93	2

Table 4-6 (Continued)

Robot System	Failure Event Number	Equipment	Business	Repair Cost (\$)	Safety Category
		Damage Cost (\$)	Interruption Cost (\$)		
PERIPHERAL	5.1	244.00	163.00	130.62	2
PERIPHERAL	5.2	149.05	88.30	102.38	2
PERIPHERAL	6.1	169.00	163.00	85.62	3
PERIPHERAL	6.2	105.70	113.20	66.79	2
PERIPHERAL	6.3	169.00	163.00	85.62	3
PERIPHERAL	6.4	153.18	150.55	80.91	3
PERIPHERAL	6.5	169.00	163.00	85.62	4
PERIPHERAL	6.6	116.25	121.50	69.93	5

Table 4-7. Recommended Design Actions from FMEA Tables for Case Study

Recommendation	Description
Recommendation 1	Insure proper installation and maintenance procedures are developed and followed for each component. When available, these should be the manufacturer's specifications. Full procedures, lists of equipment which must be shutdown, safety checks, list of tools, lubricants, and chemicals needed should be included. Special emphasis should be given to action which may cause further damage or damage to other equipment. See FMEA table Comments for specific details for each component and failure mode.
Recommendation 2	Insure proper design for each component is created, verified, and utilized. See FMEA table Comments for specific details for each component and failure mode.
Recommendation 3	Develop means of restricting sources of external impacts to robot. This may involve programming to verify position of both robot and feeding equipment, not allowing equipment to enter robot operating space, and/or placing a protective barrier around robot to protect from stray impact sources.
Recommendation 4	Provide for operator position verification system. This calls for remote, normally open switches, which must be held manually by operator to insure the operator is in a safe position while robot is in operation.

Table 4-7 (Continued)

Recommendation	Description
Recommendation 5	Provide isolating barrier to protect other equipment and personnel from robot. This calls for barriers for protecting local equipment and personnel from contact with robot application streams, particles, or objects during a fault event.
Recommendation 6	Provide belt guards to protect belts and pulleys from environment, and to protect components near belts from contact with broken or loose belts.
Recommendation 7	Provide a fail-safe brake for Z axis guide tube to prevent falling of Z arm during a fault event, and to reduce holding torque required of Z axis drive motor. This could be a device such as normally engaged solenoid type mechanism, which disengages on "high" command from controller. This allows locking of the Z arm during loss of power or during periods in which the Z arm remains at a constant position.
Recommendation 8	Provide a robot position verification system to provide periodic position checks for the robot to insure accuracy. This is recommended to reduce the consequences of positioning inaccuracy fault events, by identifying the fault event quickly before major damage can be afflicted. To avoid having to utilize traditional "closed loop" techniques, consider using a photocell and hole in pulley scheme, combined with periodically programmed photocell readings to identify go/no go position checks. The frequency of position checks is dictated by the potential hazards of position inaccuracies.

Table 4-7 (Continued)

Recommendation	Description
Recommendation 9	Consider shielding or sealing areas in which liquids may accumulate causing corrosion damage. This is especially dangerous inside of the Z guide tube with the components constituting the rotational drive system.
Recommendation 10	Provide bellows on the guide tubes to protect the guide tube surfaces, and to protect the linear ball bushings. This will protect the surfaces from corrosives, particles, and impact damage.
Recommendation 11	Design bearings for no re-lubrication with sealed bearings. Also, use large radius spacers on timing pulley shafts to shelter bearings from excessive contact with operating environment. The large number of these bearings in the design dictates extreme care in insuring the quality and operating conditions for these components.
Recommendation 12	Provide current regulating mechanism in supply circuit to stepper motor driver. Excessive current to stepper motors can cause stepper motor damage or instabilities in operation.
Recommendation 13	Isolate wiring and connectors from environmental effects, protect from impacts by protected positioning, and isolate from stray electric or magnetic fields.

Table 4-7 (Continued)

Recommendation	Description
Recommendation 14	Take steps to improve reliability of power source to system, or consider using a secondary power source for critical applications. Making efforts to insure reliable delivery of ac-power to system by protecting power lines, and properly balancing electrical power distribution circuits. For critical applications, a secondary power source may be justified to prevent downtime costs or consequences.
Recommendation 15	Provide robot with ability to transmit or receive error signals between robot and other linked equipment, generating shutdown condition for all linked equipment. This is to prevent an error in one system in a series of systems from causing additional failures in other systems, such as parts being supplied in wrong positions, causing damages to the robot.
Recommendation 16	Consider using a separate power source for error signal generation so that loss of power at the robot is identified as an error to other linked equipment.
Recommendation 17	Require re-calibration of robot with manual initiation after error or loss of power event. This will prevent additional failures from loss of calibration during maintenance or due to re-starting after a power loss.

Table 4-7 (Continued)

Recommendation	Description
Recommendation 18	Provide rubber stops at ends of guide tubes to cushion any impacts at the limits of motion on each axis. This will act to reduce the consequences of errors which cause incorrect positioning, or errors which try to force the robot beyond the operating space.
Recommendation 19	Provide configuration setting menu or feature to simplify hardware to software interfacing. This will allow simplified and more reliable installation of software to hardware. This menu may also allow settings acceleration ramping and other operation settings.
Recommendation 20	Institute a slow speed test and verification cycle for programmed paths before automatic operation can be engaged. This will insure no human errors in programming paths have been introduced into an automatic cycle which could be very destructive.
Recommendation 21	Require all path and position moving programs to begin and end in some key home position. This will allow repeated operation of a programmed path. The operator should consider that the last programmed point should be the key home position. Programming practices which merely "add" the key home position as the last point in the program need to consider that the path to the key home position from the last programmed point may be obstructed during operation.

Table 4-7 (Continued)

Recommendation	Description
Recommendation 22	Consider automating the load calibration procedure to prevent errors in selecting the proper acceleration ramping. This could be achieved iteratively by loading the robot and successively increasing the acceleration ramping until an error is detected from the position sensing device or an adequate ramping is achieved.
Recommendation 23	Consider automating the process of locating the key home position in the robot operating space. This may be achieved by using the robot position verification system with an appropriate algorithm, and might possibly need an additional sensor.
Recommendation 24	Provide a master switch for emergency manual operator shutdown of robot, end effector, and linked equipment. This is to provide an explicit safety response feature which can completely shutdown the system in an appropriate manner, releasing all stored energy in a controlled process.
Recommendation 25	Consider limiting the number of automatic cycles which may be executed automatically without manual verification of operator. This will require that some level of operator supervision be maintained to continue operation. Before operation is re-initiated, some minor inspection of robot may be utilized.

Table 4-7 (Continued)

Recommendation	Description
Recommendation 26	Provide thorough operator training in use of robot and linked equipment, as well as in the process being carried out by the robot system. The operator needs to understand the operation of the robot, and possess a mastery of the process for which the robot is used, in order to detect deviations and errors before they occur.
Recommendation 27	Provide single source control of robot dictated from main control panel. This will allow only one source of control for the robot at any one time. If multiple sources of control can be used, such as teach pendants, only one can control the robot.
Recommendation 28	Allow automatic operation initiation only from the main control panel, not from the teach pendants or remotes. This will prevent hazardous initiation of program from teach pendants, which might be used near or in robot operation space.
Recommendation 29	Provide at least a two step user procedure to initiate operation. This should require at least two actions, preferably utilizing two different switches or buttons. This recommendation is aimed at preventing accidental initiation of robot system.

Table 4-7 (Continued)

Recommendation	Description
Recommendation 30	Establish part quality control structure under 100% inspection or Statistical Process Control (SPC) to insure quality of manufactured or vendor parts. The key parameters for each component are identified in the FMEA study as the key factors affecting the occurrence of the failure modes. Inspection or monitoring of these parameters, especially for the more important failure modes, may be used to insure the quality of robot system components.

simple to enact, require minor changes, or require small resource consumption. Some suggested actions will eliminate, or alleviate, failure events which are agreed to be unacceptable. Also, some recommendations affect a large number of components, which increases the importance of those recommendations. Recommendations which are simple to enact, or eliminate particularly severe failure occurrences, are easily justified through qualitative evaluation. Other recommendations may require more effort to enact, or may not be cost effective to implement. Clearly, some form of quantitative evaluation is needed to make decisions concerning these recommendations. In some instances, all the recommendations may be able to be implemented. Table 4-8 categorizes the recommended actions from the FMEA table by qualitative evaluation.

While qualitative analysis is very restrictive, many benefits may be realized through its use. The analysis may determine whether significant hazards and reliability issues exist for the system, as well as identifying how many contributors to the hazard or unreliability exist. Furthermore, key improvement ideas may be developed and deliberated for implementation. Qualitative considerations of the FMEA table provide a material understanding of the failure modes of the system, and should be undertaken before any quantitative evaluations

Table 4-8. Qualitative Evaluation Groupings for Case Study

Qualitative Evaluation Grouping	Rec. Number
Recommendations Which Are Convenient to Implement	1 9 12 13 17 18 19 20 21 27 28 29
Recommendations Which Eliminate Particularly Severe Failure Conditions	2 3 4 5 7 8 11 15 24 26 30
Recommendations Which Need Quantitative Evaluation for Implementation Decisions	6 10 14 16 22 23 25

are ventured. The qualitative evaluation of the UT robot has shown that many failure modes contribute to a true potential for reliability problems in the robotic system. The qualitative analysis also identifies several pertinent corrective actions to improve the reliability.

4.9 Quantitative Evaluation of UT Robot Failure Modes

To supplement the qualitative reliability evaluations, a quantitative reliability evaluation for each robotic system application is performed. The quantitative evaluations are based on the risk of each failure mode calculated from the frequency and consequence estimations discussed earlier. Additionally, the frequency and consequence numbers for each failure mode are categorized by some scale. The basis and procedure for the categorization is given in Appendix B. A matrix of coinciding frequency and consequence categories is generated for each type of financial cost and safety for each application. The matrices for the combined effects of all four analytical sub-systems in the water jet cutting application are shown in Figure 4-11, while the matrices for the electronic testing application are shown in Figure 4-12. The numbers in the matrix cells are the number of failure events which fall in the indicated frequency and cost, or safety, range. The categories are

COMPOSITE SYSTEM FOR THE UT ROBOT
EQUIPMENT DAMAGE COST MATRIX

		COST CATEGORY									
		1	2	3	4	5	6	7	8		
E V E N T S P E R Y E A R	> 13	1	1	1	1	1	1	1	1	1	10
	1.259E+01	1	1	1	1	1	1	1	1	1	9
	3.548E+00	1	1	1	1	1	1	1	1	1	8
	1.000E+00	1	1	1	1	1	1	1	1	1	7
	2.818E-01	1	1	1	1	3	6	1	1	1	6
	7.943E-02	1	1	1	1	5	14	1	1	1	5
	2.239E-02	1	1	1	1	7	10	1	1	1	4
	6.310E-03	1	1	1	1	5	5	1	1	1	3
	1.778E-03	1	1	1	1	4	7	1	1	1	2
	5.012E-04	1	1	1	1	2	15	1	1	1	1
		0	4	13	45	158	562	1995	7079	> 7079	
DOLLARS PER EVENT											

COMPOSITE SYSTEM FOR THE UT ROBOT
BUSINESS INTERRUPTION COST MATRIX

		COST CATEGORY									
		1	2	3	4	5	6	7	8		
E V E N T S P E R Y E A R	> 13	1	1	1	1	1	1	1	1	1	10
	1.259E+01	1	1	1	1	1	1	1	1	1	9
	3.548E+00	1	1	1	1	1	1	1	1	1	8
	1.000E+00	1	1	1	1	1	1	1	1	1	7
	2.818E-01	1	1	1	1	1	1	9	1	1	6
	7.943E-02	1	1	1	1	1	1	18	1	1	5
	2.239E-02	1	1	1	1	1	3	14	1	1	4
	6.310E-03	1	1	1	1	1	1	9	1	1	3
	1.778E-03	1	1	1	1	1	1	11	1	1	2
	5.012E-04	1	1	1	1	1	1	16	1	1	1
		0	4	13	45	158	562	1995	7079	> 7079	
DOLLARS PER EVENT											

Figure 4-11. Financial Risk Matrices for the Severe Application Case Study

COMPOSITE SYSTEM FOR THE UT ROBOT
REPAIR COST MATRIX

		COST CATEGORY									
		1	2	3	4	5	6	7	8		
> 13		1	1	1	1	1	1	1	1	10	
1.259E+01		1	1	1	1	1	1	1	1	9	F
E	3.548E+00	1	1	1	1	1	1	1	1	8	R
V	1.000E+00	1	1	1	1	1	1	1	1	7	E
E	2.818E-01	1	1	1	1	1	1	1	1	6	Q
N	7.943E-02	1	1	1	1	1	1	1	1	5	E
T	2.239E-02	1	1	1	1	1	1	1	1	4	N
S	6.310E-03	1	1	1	1	1	1	1	1	3	C
P	1.778E-03	1	1	1	1	1	1	1	1	2	Y
E	5.012E-04	1	1	1	1	1	1	1	1	1	
R											
		0	4	13	45	158	562	1995	7079	> 7079	
DOLLARS PER EVENT											

COMPOSITE SYSTEM FOR THE UT ROBOT
TOTAL COST MATRIX

		COST CATEGORY									
		1	2	3	4	5	6	7	8		
> 13		1	1	1	1	1	1	1	1	10	
1.259E+01		1	1	1	1	1	1	1	1	9	F
E	3.548E+00	1	1	1	1	1	1	1	1	8	R
V	1.000E+00	1	1	1	1	1	1	1	1	7	E
E	2.818E-01	1	1	1	1	1	1	1	1	6	Q
N	7.943E-02	1	1	1	1	1	1	1	1	5	E
T	2.239E-02	1	1	1	1	1	1	1	1	4	N
S	6.310E-03	1	1	1	1	1	1	1	1	3	C
P	1.778E-03	1	1	1	1	1	1	1	1	2	Y
E	5.012E-04	1	1	1	1	1	1	1	1	1	
R											
		0	4	13	45	158	562	1995	7079	> 7079	
DOLLARS PER EVENT											

Figure 4-11 (Continued)

COMPOSITE SYSTEM FOR THE UT ROBOT
SAFETY MATRIX

		SAFETY CATEGORY						
		1	2	3	4	5		
> 13		-----	-----	-----	-----	-----		
								10
1.259E+01		-----	-----	-----	-----	-----		F
E								9
V		-----	-----	-----	-----	-----		R
E	3.548E+00	-----	-----	-----	-----	-----		E
					1	5		8
N		-----	-----	-----	-----	-----		Q
T	1.000E+00	-----	-----	-----	-----	-----		E
					2	6		7
S		-----	-----	-----	-----	-----		N
					5	13		6
P		-----	-----	-----	-----	-----		C
					9	8		5
E		-----	-----	-----	-----	-----		A
R	2.239E-02	-----	-----	-----	-----	-----		T
				1		5		4
Y		-----	-----	-----	-----	-----		E
				1		2		3
E		-----	-----	-----	-----	-----		G
A	1.778E-03	-----	-----	-----	-----	-----		O
				1		4		10
R		-----	-----	-----	-----	-----		2
				1		10		2
5.012E-04		-----	-----	-----	-----	-----		Y
				1		2		1
		-----	-----	-----	-----	-----		
		VERY	LOW	MODERATE	HIGH	VERY		
		LOW				HIGH		
		SAFETY CATEGORY						

Figure 4-11 (Continued)

COMPOSITE SYSTEM FOR THE UT ROBOT
EQUIPMENT DAMAGE COST MATRIX

		COST CATEGORY									
		1	2	3	4	5	6	7	8		
E V E N T S P E R Y E A R	> 13	1	1	1	1	1	1	1	1	10	F
	1.259E+01	1	1	1	1	1	1	1	1	9	R
	3.548E+00	1	1	1	1	2	1	1	1	8	E
	1.000E+00	1	1	1	2	1	1	1	1	7	Q
	2.818E-01	1	1	1	3	1	1	1	1	6	E
	7.943E-02	1	1	1	7	1	1	1	1	5	N
	2.239E-02	1	1	1	7	1	1	1	1	4	C
	6.310E-03	1	1	1	3	1	1	1	1	3	A
	1.778E-03	1	1	1	8	1	1	1	1	2	T
	5.012E-04	1	1	1	6	1	1	1	1	1	E
		0	4	13	45	158	562	1995	7079	> 7079	G
DOLLARS PER EVENT											D

COMPOSITE SYSTEM FOR THE UT ROBOT
BUSINESS INTERRUPTION COST MATRIX

		COST CATEGORY									
		1	2	3	4	5	6	7	8		
E V E N T S P E R Y E A R	> 13	1	1	1	1	1	1	1	1	10	F
	1.259E+01	1	1	1	1	1	1	1	1	9	R
	3.548E+00	1	1	1	1	2	1	1	1	8	E
	1.000E+00	1	1	1	2	1	1	1	1	7	Q
	2.818E-01	1	1	1	5	1	1	1	1	6	E
	7.943E-02	1	1	1	11	1	1	1	1	5	N
	2.239E-02	1	1	1	13	1	1	1	1	4	C
	6.310E-03	1	1	1	4	1	1	1	1	3	A
	1.778E-03	1	1	1	12	1	1	1	1	2	T
	5.012E-04	1	1	1	12	1	1	1	1	1	E
		0	4	13	45	158	562	1995	7079	> 7079	G
DOLLARS PER EVENT											D

Figure 4-12. Financial Risk Matrices for the Favorable Application Case Study

COMPOSITE SYSTEM FOR THE UT ROBOT
REPAIR COST MATRIX

		COST CATEGORY									
		1	2	3	4	5	6	7	8		
> 13											10
1.259E+01											
E											9
V	3.548E+00										
E					2						8
N	1.000E+00										
T					3						7
S	2.818E-01										
					8						6
P	7.943E-02										
E					12						5
R	2.239E-02										
					21						4
Y	6.310E-03										
E					6		1				3
A	1.778E-03										
R					14		2				2
	5.012E-04										
					21		4				1
		0	4	13	45	158	562	1995	7079	> 7079	
DOLLARS PER EVENT											

COMPOSITE SYSTEM FOR THE UT ROBOT
TOTAL COST MATRIX

		COST CATEGORY									
		1	2	3	4	5	6	7	8		
> 13											10
1.259E+01											
E											9
V	3.548E+00					2					
E											8
N	1.000E+00										
T						3					7
S	2.818E-01										
						7		1			6
P	7.943E-02										
E						11		1			5
R	2.239E-02										
						20		1			4
Y	6.310E-03										
E						7					3
A	1.778E-03										
R						16					2
	5.012E-04										
						22		3			1
		0	4	13	45	158	562	1995	7079	> 7079	
DOLLARS PER EVENT											

Figure 4-12 (Continued)

COMPOSITE SYSTEM FOR THE UT ROBOT
SAFETY MATRIX

		SAFETY CATEGORY						
		1	2	3	4	5		
> 13		-----						
								10
1.259E+01		-----						
E V E N T S P E R Y E A R	3.548E+00							9
	1.000E+00				2			8
	2.818E-01			2		1		7
	7.943E-02		1		6			6
	2.239E-02		3		8			5
	6.310E-03		8		13			4
	1.778E-03		4		3			3
	5.012E-04		8		7		1	2
			9		15		1	1

		VERY LOW	LOW	MODERATE	HIGH	VERY HIGH		
		SAFETY CATEGORY						

Figure 4-12 (Continued)

established such that the failure events in the cells on any diagonal from upper left to lower right of the matrix have approximately the same risk. The value of the constant risk lines, from the upper left of the matrix to the lower right, increase in magnitude as the lines near the upper right corner of the risk matrix. Thus, when the failure events of an FMEA analysis have been entered in a risk matrix, the highest risk events are found on the constant risk line nearest the upper right corner of the risk matrix. The next lower constant risk line would determine the group of events with the next highest risk. This method is used to determine which failure events are the most important with respect to risk.

Each failure event has some risk index number generated from the frequency and consequence categories. The method for calculating the risk index numbers is given in Appendix B. The FMEA may be sorted to list the failure events by their risk indices, placing the highest risk events at the beginning of the table. Thus, the actual failure events and descriptions which correspond to the numbers in the risk matrices may be determined.

Another method of presenting the numeric reliability information resulting from the FMEA analysis is through summary tables as shown in Figure 4-13 for the water jet cutter application, and Figure 4-14 for the electronic

COMPOSITE SYSTEM FOR THE UT ROBOT
EQUIPMENT DAMAGE COST SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMULATIVE FREQUENCY	RISK
0 TO 4	1				
4 TO 13	2				
13 TO 45	3				
45 TO 158	4				
158 TO 562	5	29	4.178467	4.1784673	1988.958
562 TO 1995	6	65	18.55355	22.7320248	12165.89
1995 TO 7079	7			22.7320248	
ABOVE 7079	8			22.7320248	

COMPOSITE SYSTEM FOR THE UT ROBOT
BUSINESS INTERRUPTION COST SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMULATIVE FREQUENCY	RISK
0 TO 4	1				
4 TO 13	2				
13 TO 45	3				
45 TO 158	4				
158 TO 562	5				
562 TO 1995	6	8	1.561540	1.5615409	2814.709
1995 TO 7079	7	86	21.17048	22.7320248	60821.45
ABOVE 7079	8			22.7320248	

COMPOSITE SYSTEM FOR THE UT ROBOT
REPAIR COST SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMULATIVE FREQUENCY	RISK
0 TO 4	1				
4 TO 13	2				
13 TO 45	3				
45 TO 158	4	9	1.816853	1.8168534	278.7204
158 TO 562	5	85	20.91517	22.7320248	4588.118
562 TO 1995	6			22.7320248	
1995 TO 7079	7			22.7320248	
ABOVE 7079	8			22.7320248	

Figure 4-13. Failure Mode Category Summary Tables
for the Severe Application Case Study

COMPOSITE SYSTEM FOR THE UT ROBOT
TOTAL COST SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMMULATIVE FREQUENCY	RISK
0 TO 4	1				
4 TO 13	2				
13 TO 45	3				
45 TO 158	4				
158 TO 562	5				
562 TO 1995	6				
1995 TO 7079	7	93	22.73115	22.7311543	82651.21
ABOVE 7079	8	1	0.000870	22.7320248	6.640339

COMPOSITE SYSTEM FOR THE UT ROBOT
SAFETY SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMMULATIVE FREQUENCY
VERY LOW	1			
LOW	2	4	0.018582	0.0185824
MODERATE	3	30	3.282516	3.3010992
HIGH	4	54	17.61064	20.9117489
VERY HIGH	5	6	1.820275	22.7320248

Figure 4-13 (Continued)

COMPOSITE SYSTEM FOR THE UT ROBOT
EQUIPMENT DAMAGE COST SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMMULATIVE FREQUENCY	RISK
0 TO 4	1				
4 TO 13	2				
13 TO 45	3				
45 TO 158	4	36	2.453274	2.45327444	324.2826
158 TO 562	5	58	4.786284	7.23955871	872.5758
562 TO 1995	6			7.23955871	
1995 TO 7079	7			7.23955871	
ABOVE 7079	8			7.23955871	

COMPOSITE SYSTEM FOR THE UT ROBOT
BUSINESS INTERRUPTION COST SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMMULATIVE FREQUENCY	RISK
0 TO 4	1				
4 TO 13	2				
13 TO 45	3				
45 TO 158	4	59	3.006870	3.00687076	400.4043
158 TO 562	5	35	4.232687	7.23955871	689.9281
562 TO 1995	6			7.23955871	
1995 TO 7079	7			7.23955871	
ABOVE 7079	8			7.23955871	

COMPOSITE SYSTEM FOR THE UT ROBOT
REPAIR COST SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMMULATIVE FREQUENCY	RISK
0 TO 4	1				
4 TO 13	2				
13 TO 45	3				
45 TO 158	4	87	7.233276	7.23327659	649.8822
158 TO 562	5	7	0.006282	7.23955871	1.041331
562 TO 1995	6			7.23955871	
1995 TO 7079	7			7.23955871	
ABOVE 7079	8			7.23955871	

Figure 4-14. Failure Mode Category Summary Tables
for the Favorable Application Case Study

COMPOSITE SYSTEM FOR THE UT ROBOT
TOTAL COST SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMULATIVE FREQUENCY	RISK
0 TO 4	1				
4 TO 13	2				
13 TO 45	3				
45 TO 158	4				
158 TO 562	5	88	7.057793	7.05779361	2809.829
562 TO 1995	6	6	0.181765	7.23955871	128.2853
1995 TO 7079	7			7.23955871	
ABOVE 7079	8			7.23955871	

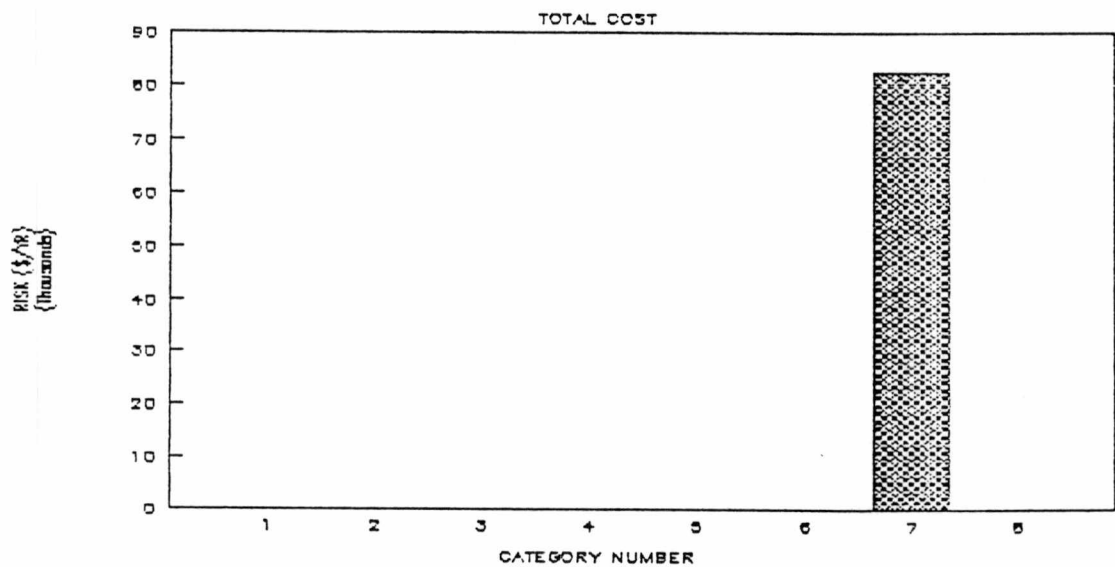
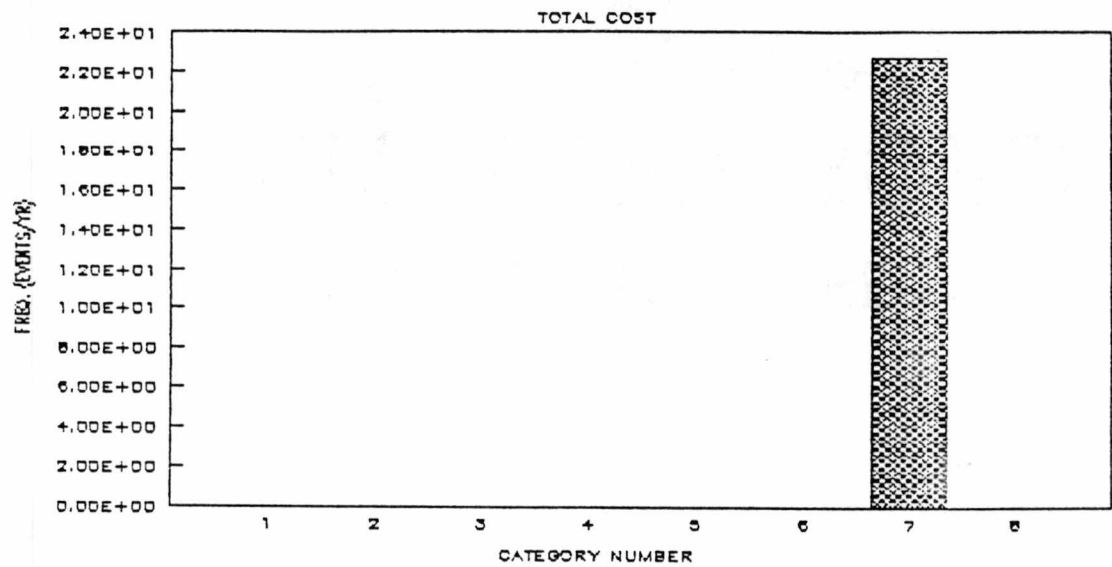
COMPOSITE SYSTEM FOR THE UT ROBOT
SAFETY SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMULATIVE FREQUENCY
VERY LOW	1	33	0.373658	0.37365836
LOW	2	54	2.708759	3.08241811
MODERATE	3	5	3.825640	6.90805871
HIGH	4	1	0.255	7.16305871
VERY HIGH	5	1	0.0765	7.23955871

Figure 4-14 (Continued)

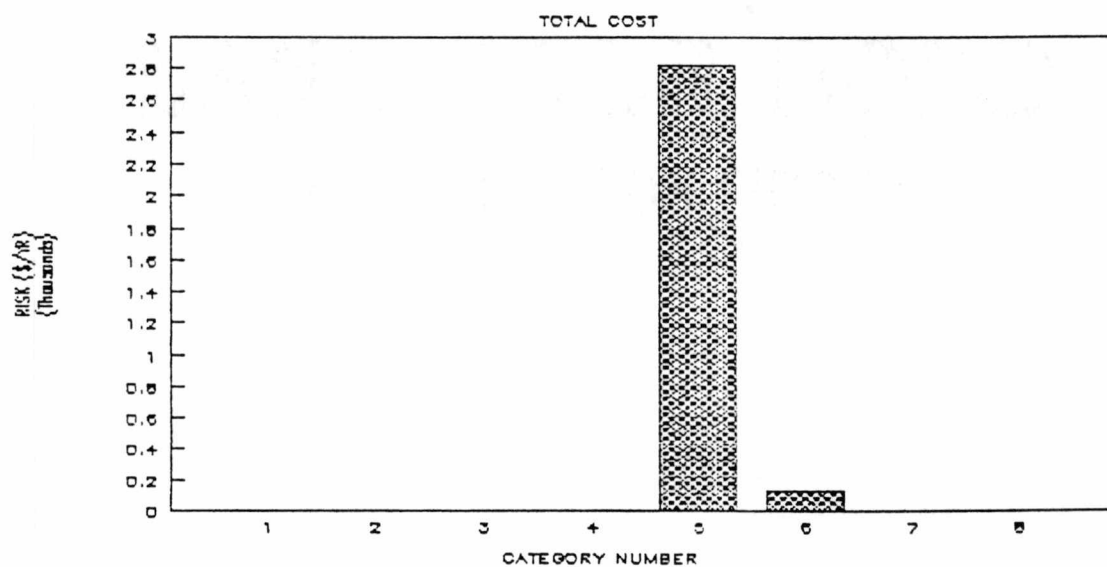
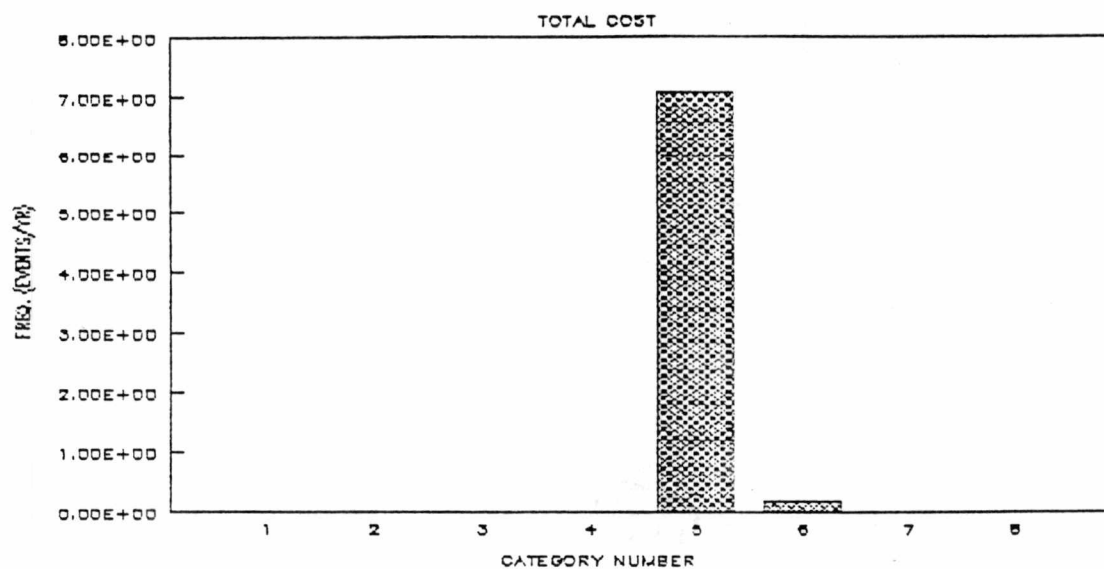
testing application. This format depicts the expected reliability performance of the robotic system. The data is presented by cost category. The tables describe the frequency of failure for each cost category, the cumulative frequency of failure for all cost categories, and the risk for each cost category. The tables also include the number of failure events in each cost category. This information is used to characterize the reliability of the overall system in numeric terms in relation to reliability goals. The distributions of the failure frequencies and risks for the cost categories are also presented graphically in the frequency histogram and the financial risk histograms in Figure 4-15, for the water jet cutter application. The same type of information is presented for the electronic testing application in Figure 4-16. Histograms for the safety risks are given for both the water jet cutting application and the electronic testing application, Figure 4-17 and Figure 4-18 respectively.

Complete representations of the risk matrices and summary tables for each analytical sub-system in each case study application are contained in Appendix C. Due to space limitations in the text, only the first group of important failure events for the robotic system will be discussed. However, the procedure can easily be re-



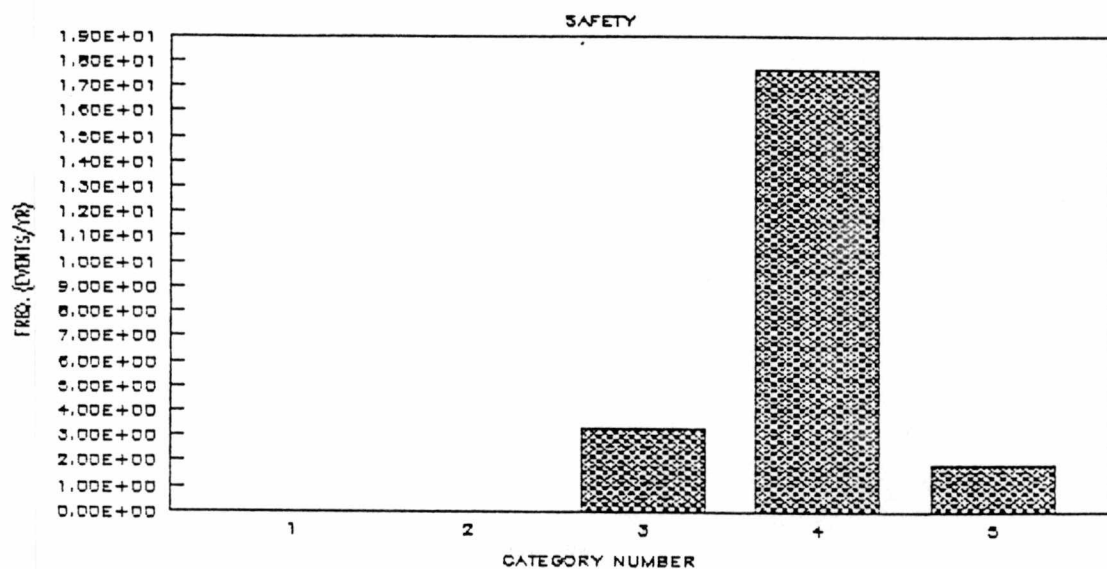
TOTAL COST HISTOGRAMS FOR COMPOSITE SYSTEM FOR THE UT ROBOT

Figure 4-15. Total Cost Frequency and Risk Histograms for the Severe Application Case Study



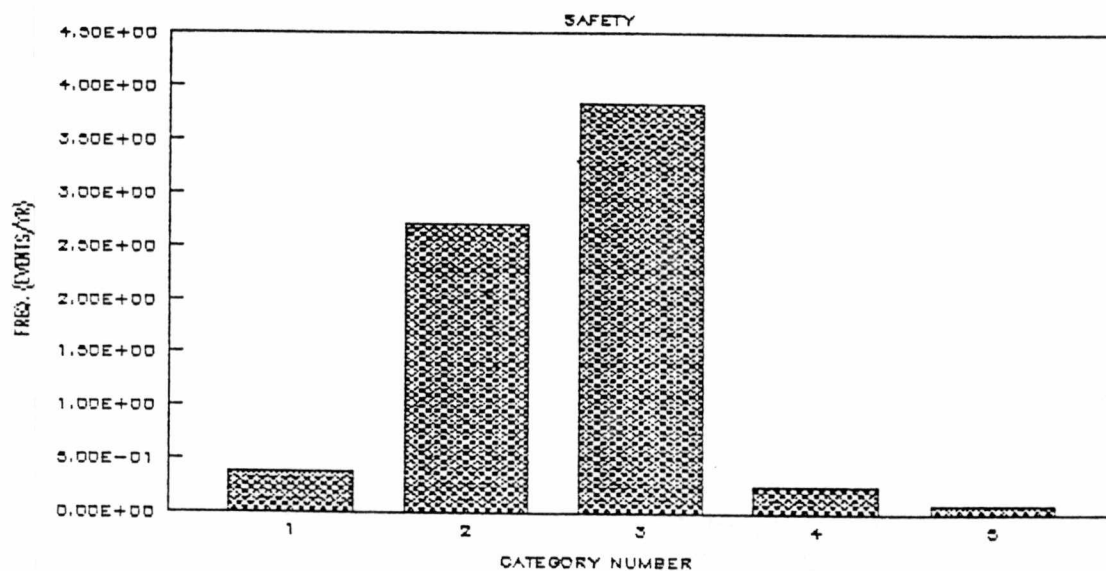
TOTAL COST HISTOGRAMS FOR COMPOSITE SYSTEM FOR THE UT ROBOT

Figure 4-16. Total Cost Frequency and Risk Histograms for the Favorable Application Case Study



SAFETY HISTOGRAM FOR COMPOSITE SYSTEM FOR THE UT ROBOT

Figure 4-17. Safety Frequency Histogram for the Severe Application Case Study



SAFETY HISTOGRAM FOR COMPOSITE SYSTEM FOR THE UT ROBOT

Figure 4-18. Safety Frequency Histogram for the Favorable Application Case Study

applied for the next, less important, grouping of events after the initial group has been treated.

4.9.1 Severe condition application

A complete listing of the identified failure events for the robotic system, sorted by financial risk and safety importances, are included in Appendix D. The initial group of the most important events considered for the financial risk will consider the sixteen events on the first two constant risk lines shown in the total cost risk matrix. The actual events which constitute the sixteen events in the risk matrix are found by sorting the FMEA tables based on total cost risk. These sixteen events are listed in Table 4-9, identifying which failure events, with their respective recommended actions, are included in each risk index category.

The same process is repeated for safety risks instead of financial risks. The top fifteen events which comprise the first three constant safety risk lines in the safety matrix are presented with their respective recommended actions in Table 4-10.

The summary tables presented in Figure 4-13 indicate the overall reliability performance of the robotic system in the water cutter application. During operation, the system is expected to experience between 22 and 23

Table 4-9. High Financial Risk Events for the Severe Application Case Study

Risk Index	Item	Sub-System	Component	Failure Mode	Recommended Actions
15.7	2.1	Peripheral	Electric Power Source	Fails to Provide Adequate Power	1, 2, 14, 15, 16, 17
	6.1	Peripheral	Operator	Teaches or Inputs Incorrect Path	18, 20, 21
	6.2	Peripheral	Operator	Fails to Properly Calibrate Operation for Acceleration Ramping of Loads	15, 17, 18, 22
	6.3	Peripheral	Operator	Fails to Begin Robot Operation from Key Home Position	1, 2, 17, 18, 20, 23
	6.4	Peripheral	Operator	Fails to Shut Down System When Error Exists	1, 2, 4, 24, 25, 26

Table 4-9 (Continued)

Risk Index	Item	Sub-System	Component	Failure Mode	Recommended Actions
14.7	6.2	X-Y Axis	Inside Workspace Timing Belt	Loss of Meshing with Timing Belt Pulley; Belt Held Accountable	1, 2, 3, 4, 5, 6
	11.2	X-Y Axis	Outside Workspace Timing Belt	Loss of Meshing with Timing Belt Pulley; Belt Held Accountable	1, 2, 3, 4, 5, 6
14.7	4.2	Peripheral	Computer Software	Sends Wrong or Incorrectly Timed Signal	1, 2, 8, 15, 17
	6.5	Peripheral	Operator	Initiates Operation at Incorrect Time	27, 28, 29, 24
	1.3	X-Y Axis	Stationary Guide Tubes	Fails to Provide Smooth, Uniform Guide Surface	1, 2, 3, 4, 5, 10

Table 4-9 (Continued)

Risk Index	Item	Sub-System	Component	Failure Mode	Recommended Actions
	7.2	X-Y Axis	Inside Workspace Timing Belt	Loss of Shaft to Pulley Coupling	1, 2, 3, 4, 5, 6, 8
	7.3	X-Y Axis	Inside Workspace Timing Belt	Loss of Pulley to Belt Meshing; Pulley Held Accountable	1, 2, 3, 4, 5, 6
	9.1	X-Y Axis	Pulley Shaft Bearings	Fails to Provide Free Rotary Motion	1, 2, 3, 4, 5, 8, 11
	10.2	X-Y Axis	Outside Workspace Timing Belt Pulley	Loss of Shaft to Pulley Coupling	1, 2, 3, 4, 5, 6, 8
	10.3	X-Y Axis	Outside Workspace Timing Belt Pulley	Loss of Pulley to Belt Meshing; Pulley Held Accountable	1, 2, 3, 4, 5, 6

Table 4-9 (Continued)

Risk Index	Item	Sub-System	Component	Failure Mode	Recommended Actions
	12.3	X-Y Axis	2.1 Amp Stepper Motor	Inaccurate Positioning	1, 2, 3, 4, 5, 8

Table 4-10. High Safety Risk Events for the Severe Application Case Study

Risk Index	Item	Sub-System	Component	Failure Mode	Recommended Actions
13.5	6.4	Peripheral	Operator	Fails to Shut Down System When Error Exists	1, 2, 4, 24, 25, 26
12.5	6.5	Peripheral	Operator	Initiates Operation at Incorrect Time	27, 28, 29, 24
12.4	2.1	Peripheral	Electric Power Source	Fails to Provide Adequate Power	1, 2, 14, 15, 16, 17
	6.1	Peripheral	Operator	Teaches or Inputs Incorrect Path	18, 20, 21
	6.3	Peripheral	Operator	Fails to Begin Robot Operation from Key Home Position	1, 2, 17, 18, 20, 23

Table 4-10 (Continued)

Risk Index	Item	Sub-System	Component	Failure Mode	Recommended Actions
	6.2	X-Y Axis	Inside the Workspace Timing Belt	Loss of Meshing with Timing Belt Pulley; Belt Held Accountable	1, 2, 3, 4, 5, 6
	11.2	X-Y Axis	Outside the Workspace Timing Belt	Loss of Meshing with Timing Belt Pulley; Belt Held Accountable	1, 2, 3, 4, 5, 6
11.5	6.6	Peripheral	Operator	Contact with Robot During Normal Operation	4, 5, 13
11.4	4.2	Peripheral	Computer Software	Sends Wrong or Incorrectly Timed Signal	1, 2, 8, 15, 17
	7.2	X-Y Axis	Inside the Workspace Timing Belt	Loss of Shaft to Pulley Coupling	1, 2, 3, 4, 5, 6, 8

Table 4-10 (Continued)

Risk Index	Item	Sub-System	Component	Failure Mode	Recommended Actions
	7.3	X-Y Axis	Inside the Workspace Timing Belt	Loss of Pulley to Belt Meshing; Pulley Held Accountable	1, 2, 3, 4, 5, 6
	9.1	X-Y Axis	Pulley Shaft Bearings	Fails to Provide Free Rotary Motion	1, 2, 3, 4, 5, 8, 11
	10.2	X-Y Axis	Outside the Workspace Timing Belt Pulley	Loss of Shaft to Pulley Coupling	1, 2, 3, 4, 5, 6, 8
	10.3	X-Y Axis	Outside the Workspace Timing Belt Pulley	Loss of Pulley to Belt Meshing; Pulley Held Accountable	1, 2, 3, 4, 5, 6
	12.3	X-Y Axis	2.1 Amp Stepper Motor	Inaccurate Positioning	1, 2, 3, 4, 5, 8

failures per year, with an expected annual cost of approximately \$82,657 based on the 94 failure events considered. This translates to a Mean Time Between Failures (MTBF) of 0.044 years, or 16.06 days. The system is expected to experience 1.82 events per year that will produce Very High safety issues, and 17.61 events per year that will produce High safety issues. Clearly, the expected reliability performance of the system is not acceptable for a superior product or process. The expected failure rate is extremely high, and the expected cost per year is extraordinary. In fact, the expected cost due to failures during a single year far exceeds the cost of the complete robotic system. The key factor in this case study is the business interruption costs due to failures. By reducing the number of expected failures through the recommended actions, these costs may be considerably reduced. Furthermore, reducing the downtime associated with any remaining failures by minimizing recalibration times, storing needed replacement parts on site, and maintaining a skilled service facility, will reduce the effects of the failures.

To improve the system's reliability performance, the high risk events identified, Table 4-9, are important to correct. This small group of failure events contribute 84% of the overall system's failure rate, and 78% of the

financial risk. Eliminating, or improving, these failure events will have the largest effect on the system's reliability performance. The key analytical sub-system for this case study is the peripheral equipment. These components are typically not given sufficient consideration during design. Design considerations for the operator, power supply, and controlling software/hardware are critical areas which demand more attention. The FMEA table describes the critical parameters and recommendations for these failure events.

After the peripheral equipment sub-system, the X-Y axis sub-system is the next area for needed improvements. The key potential failure modes identified are the timing belt to timing belt pulley meshing, timing belt pulley loosening on a shaft, pulley shaft bearing lubrication failures, guide tube surface damage, and stepper motor placement inaccuracies. These failure events, key parameters, and recommended actions are described in the FMEA table. Curiously, the Z axis and rotational drive systems do not have any failures ranked in the initial group of high risk events, but do have the same components which are listed as high risk contributors to the X-Y axis sub-system. This seemingly contradictory result is readily explained. Although the Z axis and rotational sub-systems have the same components with the same failure

modes, the individual component failure rates for the X-Y axis sub-system are compounded by the large quantity of the components in a series arrangement. For instance, loosening of a timing belt pulley has the same frequency for the Z axis as it does in the X-Y axis system, but there are 16 timing belt pulleys in the X-Y axis system and only 2 in the Z axis sub-system. However, if the designer corrects the difficulties with the timing belt pulleys for the X-Y axis because they are high risk events, the Z axis timing belt pulleys will almost certainly be corrected also. Correcting a few of the high risk events will often correct, or improve, many of the other events not being considered at that time.

After addressing and re-evaluating the high risk events under consideration, the overall reliability performance of the system may be appraised again. If the reliability of the system is unacceptable, a new list of high risk events may be generated and addressed. Assuming the designer is not making design changes which are adversely affecting the system's reliability, the predicted reliability should quickly improve toward some limiting condition. Improvements beyond this state may require extensive re-design, or even a completely different design concept.

4.9.2 Favorable condition application

The complete listing of failure events, sorted by financial and safety risks, for this example are given in Appendix IV. The initial group of high financial risk failure events will consider the fourteen events on the first three constant risk lines from the total cost risk matrix. As before, the actual event descriptions are found by sorting the FMEA table by risk importances. The high risk failure modes, with their recommended actions, are presented in Table 4-11. The descriptions and recommended actions of the thirteen failure events on the first four constant safety risk lines are presented in Table 4-12.

The summary tables in Figure 4-14 depict the overall reliability performance of the robotic system in the electronic testing application. The system is expected to experience between 7 and 8 failures per year, with an expected annual cost due to failures of \$2,938. The system has an expected MTBF of 0.138 years, or 50.5 days. The system is expected to experience one event every 13 years which results in Very High safety issues, and one event every 4 years which results in High safety issues.

The performance of the system in this application is far superior to the performance of the robotic system in the water cutter application. Nevertheless, the system

Table 4-11. High Financial Risk Events for the Favorable Application Case Study

Risk Index	Item	Sub-System	Component	Failure Mode	Recommended Actions
13.5	6.1	Peripheral	Operator	Teaches or Inputs Incorrect Path	18, 20, 21
	6.3	Peripheral	Operator	Fails to Begin Robot Operation from Key Home Position	1, 2, 17, 18, 20, 23
12.6	3.2	Peripheral	Computer Hardware	Causes Spurious Control or Motion	1, 2, 8, 15, 17, 18
12.5	2.1	Peripheral	Electric Power Source	Fails to Provide Adequate Power	1, 2, 14, 15, 16, 17
	6.2	Peripheral	Operator	Fails to Properly Calibrate Operation for Acceleration Ramping of Loads	15, 17, 18, 22

Table 4-11 (Continued)

Risk Index	Item	Sub-System	Component	Failure Mode	Recommended Actions
11.6	6.4	Peripheral	Operator	Fails to Shut Down System When Error Exists	1, 2, 4, 24, 25, 26
	3.1	Peripheral	Computer Hardware	Fails Off, Not Allowing Robot Control or Operation	1, 2, 8, 15, 17
	4.2	Peripheral	Computer Software	Sends Wrong or Incorrectly Timed Signal	1, 2, 8, 15, 17
11.5	6.5	Peripheral	Operator	Initiates Operation at Incorrect Time	27, 28, 29, 24
	6.2	X-Y Axis	Inside the Workspace Timing Belt	Loss of Meshing with Timing Belt Pulley; Belt Held Accountable	1, 2, 3, 4, 5, 6

Table 4-11 (Continued)

Risk Index	Item	Sub-System	Component	Failure Mode	Recommended Actions
	11.2	X-Y Axis	Outside the Workspace Timing Belt	Loss of Meshing with Timing Belt Pulley; Belt Held Accountable	1, 2, 3, 4, 5, 6
	7.2	X-Y Axis	Inside the Workspace Timing Belt	Loss of Shaft to Pulley Coupling	1, 2, 3, 4, 5, 6, 8
	9.1	X-Y Axis	Pulley Shaft Bearings	Fails to Provide Free Rotary Motion	1, 2, 3, 4, 5, 8, 11
	10.2	X-Y Axis	Outside the Workspace Timing Belt Pulley	Loss of Shaft to Pulley Coupling	1, 2, 3, 4, 5, 6, 8

Table 4-12. High Safety Risk Events for the Favorable Application Case Study

Risk Index	Item	Sub-System	Component	Failure Mode	Recommended Actions
11.3	6.1	Peripheral	Operator	Teaches or Inputs Incorrect Path	18, 20, 21
	6.3	Peripheral	Operator	Fails to Begin Robot Operation from Key Home Position	1, 2, 17, 18, 20, 23
10.5	6.6	Peripheral	Operator	Contact With Robot During Normal Robot Operation	4, 5, 13
10.4	6.5	Peripheral	Operator	Initiates Operation at Incorrect Time	27, 28, 29, 24
10.3	6.4	Peripheral	Operator	Fails to Shut Down System When Error Exists	1, 2, 4, 24, 25, 26

Table 4-12 (Continued)

Risk Index	Item	Sub-System	Component	Failure Mode	Recommended Actions
9.2	2.1	Peripheral	Electric Power Source	Fails to Provide Adequate Power	1, 2, 14, 15, 16, 17
	6.2	Peripheral	Operator	Fails to Properly Calibrate Operation for Acceleration Ramping of Loads	15, 17, 18, 22
8.2	4.2	Peripheral	Computer Software	Sends Wrong or Incorrectly Timed Signal	1, 2, 8, 15, 17
	6.2	X-Y Axis	Inside Workspace Timing Belt	Loss of Meshing with Timing Belt Pulley; Belt Held Accountable	1, 2, 3, 4, 5, 6

Table 4-12 (Continued)

Risk Index	Item	Sub-System	Component	Failure Mode	Recommended Actions
	11.2	X-Y Axis	Outside Workspace Timing Belt	Loss of Meshing with Timing Belt Pulley; Belt Held Accountable	1, 2, 3, 4, 5, 6
	7.2	X-Y Axis	Inside Workspace Timing Belt	Loss of Shaft to Pulley Coupling	1, 2, 3, 4, 5, 6, 8
	9.1	X-Y Axis	Pulley Shaft Bearings	Fails to Provide Free Rotary Motion	1, 2, 3, 4, 5, 8, 11
	10.2	X-Y Axis	Outside Workspace Timing Belt Pulley	Loss of Shaft to Pulley Coupling	1, 2, 3, 4, 5, 6, 8

still has a high failure rate and an annual cost due to failures which are a notable percentage of the cost of the robotic system. Even the preferable performance of the system in this application requires improvement.

Therefore, the place to begin improving the system is with the group of high risk events identified in Table 4-11. These events comprise 88% of the overall system failure rate, and 86% of the financial risk. Eliminating, or improving, these events through their recommended actions will produce the best system reliability performance gains. As with the severe case application, the peripheral equipment sub-system dominates the other sub-systems in regard to the reliability performance. Also, the large number of components in series arrangements in the X-Y axis sub-system make the X-Y sub-system an important area of consideration.

4.10 Improving the Robotic System

The qualitative and quantitative analysis described for the FMEA table identifies the pertinent corrective actions for the robotic system. Implementation of design actions discovered from the most important failure events, and other corrective actions found by examining the subsequent, decreasingly important groups of failure events, indicates to the designer how to improve the

reliability of the system. This section depicts the actions which should be taken by the designer, based on the results of the FMEA analysis, and estimates the reliability performance of the improved robotic system in severe and favorable applications.

Table 4-13 describes the specific actions which should be taken by the designer to improve the reliability of the robotic system. These actions are established by finding the most important events for the robotic system, improving the failure events through a decreased frequency of occurrence or decreased consequence, and re-evaluation of the robotic system to find the next group of important failure events. This process is repeated until a satisfactory level of reliability performance is reached, or until reliability improvement actions have little effect on the reliability of the system. In this second case, the maximum inherent reliability of the configuration and boundary conditions is being approached. Additional reliability improvement will require modifying the overall system concept, extending the boundary conditions to analyze deficient systems not already studied in detail, improving the global reliability factors which affect the system, such as environment or operation, or implementing very exhaustive reliability improvement actions for components beyond normal methods.

Table 4-13. Necessary Development Actions Against Identified High Risk Events

No.	Necessary Development Action Description
1	Improve the reliability of the power supply source to the robotic system through dedicating electric circuits for robot components, maintaining electric power supply lines, and working with local power distributor to insure reliable supply of power. This will reduce the failure frequency of loss of power events.
2	Design a robot position verification system to control robot position errors. This system should quickly detect small position errors and appropriately discontinue operation when an error exists. Additionally, the system should provide a means to locate a "key" home position as a point of reference in the robot's operating space. The author suggests a photo-cell with a "hole in disk" scheme on each motion axis. This method will allow a three dimensional node mesh of position comparisons points for determining whether the robot position matches the computer counter expected position. The robot position verification system will allow only very small position errors to exist, thus drastically reducing the consequences of failure events.
3	Design a Z axis locking mechanism to restrain the Z axis arm. This device should restrain the Z axis arm when the Z arm is not being commanded to move. The locking device will provide a safety benefit by restraining the Z arm in any loss of power event, or if any position error in the Z direction occurs. This will eliminate the falling of the Z arm during any failure of the Z axis components. Furthermore, the locking mechanism will reduce the holding torque required of the Z axis motor, since the motor will not have to hold the Z arm during motions which do not require changes in the Z direction. The author suggests some type of solenoid device which is "locked" when not energized. The device should lock on a position error signal. The locking mechanism will reduce the consequences of any failures of the Z axis motion system components.

Table 4-13 (Continued)

No.	Necessary Development Action Description
4	Implement software features which will minimize operator errors causing system failures. These features should include: a) a slow speed programmed path test before allowing automatic operation, b) a requirement to force all programmed paths to begin and end at the "key" home position under user direction, c) an ability to transmit a robotic system error and to shutdown all inter-related systems upon error signal from robotic system, d) a feature to require re-calibration of robot with manual initiation after error or loss of power event, e) an automatic process for locating the "key" home position, f) a limiting number of cycles which may be performed without manual verification of successful operation, g) a single source control panel for robot at any instance in time, h) allowing automatic operation initiation only from main control panel, not from teach pendants or remotes, i) requiring a two step procedure to initiate operation, possibly a verification question or two different switches or buttons, j) a shutdown key to safely terminate operation of robotic system and linked equipment,

Table 4-13 (Continued)

No.	Necessary Development Action Description
	k) a configuration menu to simplify the computer hardware to software interface, l) a programmed "limit switch" which will not allow the robot to try to move beyond the operating limits of the system.
	These features are given to reduce the frequency of failures, and to reduce the consequences of failures once they occur.
5	Institute an extensive software evaluation testing program to eliminate defects in the software. Any defects in the software used in an industrial environment will cause re-occurring failures when discovered, with potentially hazardous results. Simplify the program at every possible juncture, including only needed motion, safety, and control features.
6	Design for protecting the meshing of the timing belt and the timing belt pulleys by: a) protecting the belts and pulleys with belt guards to isolate from environmental contaminant liquids and particles, and to protect other local equipment from loose or broken belts b) using a belt tensioning device which will not loosen during operation, and which is easily adjusted to the proper tension c) insuring the alignment of the pulleys with spacers on the shafts d) insuring the quality of the pulley teeth.

Table 4-13 (Continued)

No.	Necessary Development Action Description
7	Design the timing belt pulleys to maintain position on the pulley shaft under reversing loads. This dictates eliminating the currently used set screws on round shafts, and using a more reliable fastening method.
8	Modify the guide tube design to withstand expected environmental conditions by: a) changing to Thompson Shafting b) using bellows on the guide tubes to protect from nicks, scratches, and surface corrosion.
9	Design pulley shaft bearings to operate for extended service without maintenance. This requires using: a) pre-lubricated sealed bearings b) bearing life design based on L_1, not L_{10}, for number of operating cycles calculated from maximum operating time of device.
10	Design to avoid unstable regions of stepper motor operation by half-, or multi-, stepping techniques in unstable regions.
11	Construct a retaining structure around robotic system to isolate the robotic system from sources of external impacts from the environment, and to protect local equipment and operators from hazardous streams, particles, or objects from within the robotic system during a fault event.
12	Design a master switch for emergency manual operator shutdown of robotic system, end effector, and other linked equipment. This switch should be independent of the controlling software, and placed in accessible locations. The switches should be labelled and colored red. More than one switch may be necessary in some applications.

Table 4-13 (Continued)

No.	Necessary Development Action Description
13	Establish a part quality control structure under 100% inspection or Statistical Process Control (SPC) to insure the quality of manufactured or vendor parts. Quality control of the key operating factors defined in the FMEA table for each hardware component is ideal. However, emphasis should initially be placed on controlling the quality characteristics of the items identified as high risk components, namely the guide tubes, timing belts, timing belt pulleys, and pulley shaft bearings.
14	Design the structural and support components of the robotic system with automatic alignment features to insure reliable adjustment of the robotic system. This could entail using deep, controlled diameter holes for tubes, locating surfaces on components, alignment holes, and locating pins. The corner brackets, and the robot base structure, are the key components which need alignment consideration, since their placement dictates the accuracy of the X-Y axis motion system.

By executing the design actions in Table 4-13, the robotic system is expected to demonstrate radical reliability performance improvement as shown in Figure 4-19 and Figure 4-20. For the severe application conditions, the annual failure rate is expected to decrease from approximately 23 failures per year with a failure cost \$82,657 per year, to 6.26 failures per year with a failure cost of \$9,430 per year. The severe application is still expected to have significant degradation factors due to the environment, poor maintenance quality, and operating times. These degradation factors are the characteristics of the severe application, and are not assumed to be corrected, because improvements would no longer depict the severe application. Additional reliability improvements could be gained by limiting the severity of the application, but this would reduce the generality of this study.

For the favorable application case study, the annual failure rate is expected to decrease from approximately 8 failures per year with a failure cost \$2,938 per year, to 1.53 failures per year with a failure cost of \$258.50 per year. One failure per year is expected due to loss of electric power to the robotic system. This is a major contributor to the unreliability of the system, but is beyond the control of the robotic system designer.

Generic Robot Reliability Performance Current and Improved System Predictions Financial Risk Comparison

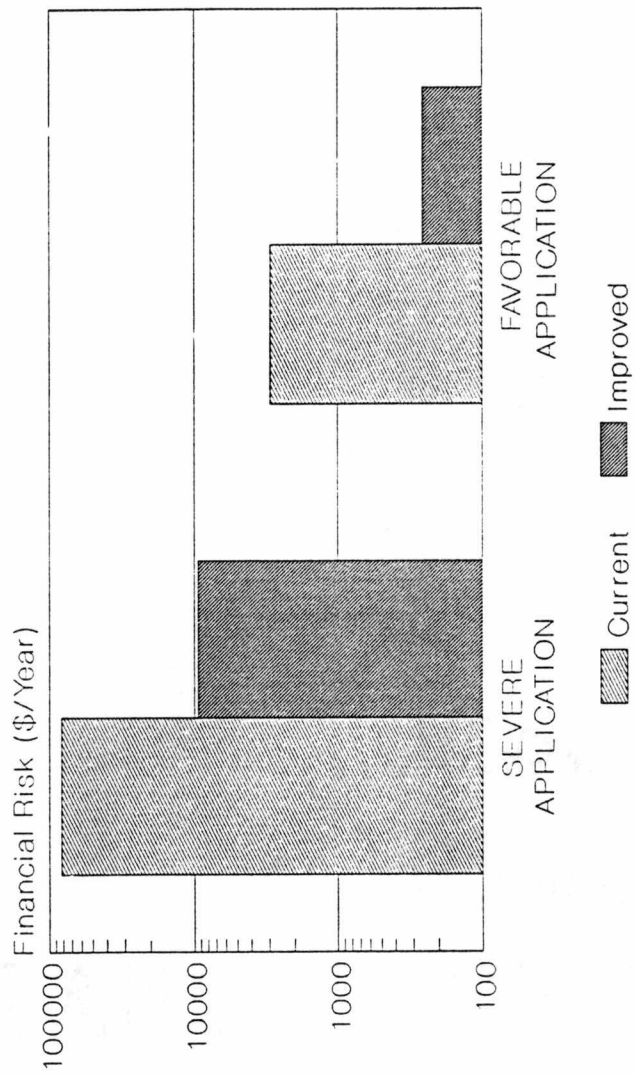


Figure 4-19. Improved Financial Risk After Design Actions Against High Risk Events

Generic Robot Reliability Performance Current and Improved System Predictions Failure Rate Comparison

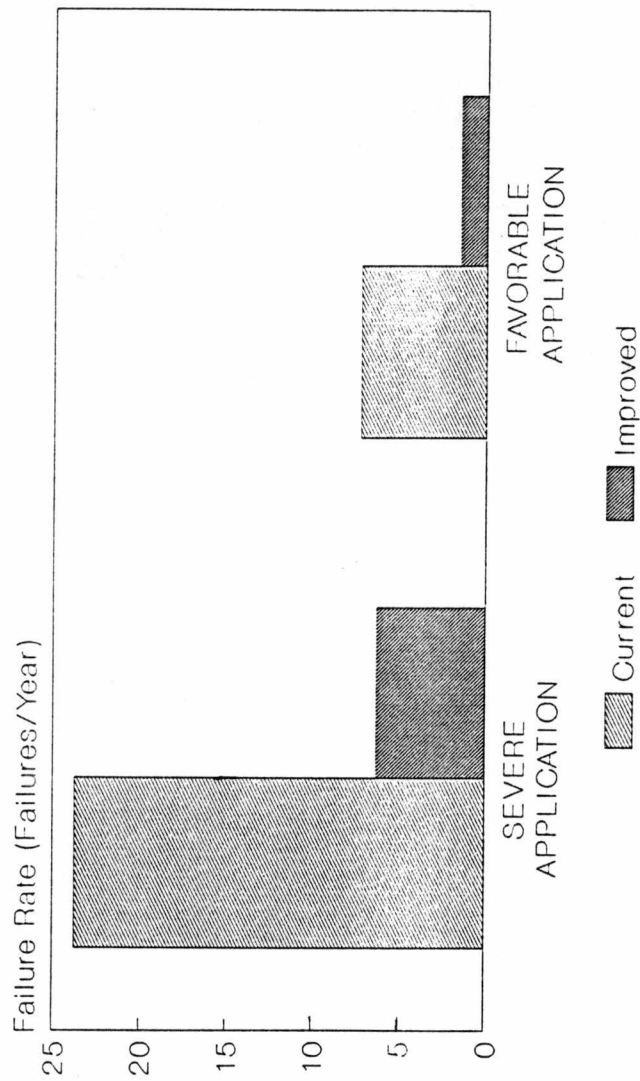


Figure 4-20. Improved Failure Rate After Design Actions Against High Risk Events

The improved robotic system is expected to exhibit a significantly enhanced reliability performance over a range of operating conditions and applications. However, one should not place too much emphasis on the absolute results of the quantitative reliability evaluations. Characteristic of most quantitative reliability predictions, the absolute results may be somewhat inaccurate [Arendt, Lorenzo, and Lusby, 1989, pp. 27-28]. Absolute quantitative reliability analysis results that are within the actually observed performance order of magnitude are considered good. Nevertheless, the enormous improvements to the reliability performance of the system by implementing the actions in Table 4-13 are verified by the more accurate relative comparisons of the quantitative results. The comparatively low cost for making these described development changes is clearly justified by the projected improvement in reliability performance.

4.11 Evaluation of Case Study Results

The case studies presented have developed and evaluated the failure modes of the generic robotic system. Many recommendations have been developed. Qualitative and quantitative evaluations have shown which failure modes and recommended actions should be addressed first.

Additionally, the information has been detailed, allowing further evaluations to identify and correct the next groups of high risk events after the first group of modifications to the design, manufacturing process, and/or operating procedures have been made. The overall expected reliability performance of the system has been quantified for both applications. The two chosen case study applications form approximate upper and lower bounds on the reliability performance of the generic robotic system. The FMEA analysis also documents the design and the designer's efforts to insure the reliability of the system.

The question arises, "How well does the reliability design tool predict the failure characteristics of the generic robotic system?" The only method to truly answer the question is through extensive testing of the robotic system in the application. However, operating experience has been compiled over the last one and a half years, and can be used to critique the performance of the reliability design tool. Table 4-14 indicates the failures which have actually been experienced on the prototype robotic system, along with an indication of whether the failure has occurred once, or has occurred multiple times. Table 4-14 also indicates if the failure is identified in the FMEA generated by the reliability design tool, and if the

Table 4-14. Evaluation of Actually Experienced Failures

Actual Failure	Occurrences	Predicted	Predicted High Risk
Software Interaction Difficulties with Other Software	Single	Yes	Yes
Computer Hardware/ Software Out of Memory Failure	Single	Yes	Yes
Errors in a "Verified" Program	Single	Yes	Yes
Insufficient Power Supply Device	Single	Yes	No
Electric Power Lost to System	Single	Yes	Yes
Stepper Driver Wiring Error	Single	Yes	No
Program Not Initiated From Key Home Position	Multiple	Yes	Yes
Power Not On to All System Components	Multiple	Yes	Yes
Unintentional Program Initiation	Multiple	Yes	Yes
Programmed Beyond Physical Bounds of System	Single	Yes	Yes
Bearing Lubrication Failure Due To Lack of Lubrication	Single	Yes	Yes
Guide Shaft Corrosion	Single	Yes	Yes
Timing Belt Fraying	Single	Yes	Yes
Set Screw Loosening	Single	Yes	Yes

Table 4-14 (Continued)

Actual Failure	Occurrences	Predicted	Predicted High Risk
Belt Fasteners Loosening	Multiple	Yes	Yes
Improper Installation -- Skewed Axes	Single	Yes	No
Vibrating Motor Inaccuracy At Resonance	Multiple	Yes	Yes

failure is considered a high risk event from the evaluation of the predicted failure modes.

Certainly, from Table 4-14, the use of the reliability design tool has predicted all of the failures which have occurred. All but three of the failures which have been experienced are ranked among the most important failure events. The system has experienced over 20 failures during the past year and a half. The reliability design tool indicates between 7 and 23 failure should be expected. While some failures may have been precipitated due to the developmental use of the robot, the conditions and usage times are superior to average industrial environments and applications. Furthermore, the robot has been individually produced and assembled, a significant difference compared to high volume production manufacturing operations for the robot. Thus, the robotic system, as currently designed, would likely experience additional failures if it were committed to manufacturing and industrial application. With this in mind, the industrial application predictions for the robotic system seem to be supported. Design verification testing and operational feedback methods may be used to further evaluate the results of the prediction study as they become available. Nevertheless, the reliability design tool has been shown to be a valuable aid to the designer

for estimating and improving the reliability of the robotic system.

4.12 Extending the FMEA Procedure to Other Systems

Applying FMEA to other engineered systems is not complicated, although some additional issues must be considered. These additional considerations are primarily involved in the formulation of the FMEA application. Setting the reliability design goals, defining the boundary conditions, partitioning the system, and identifying failure modes are the key areas in which different analyses may vary. The process of evaluating the failure modes of a properly formulated FMEA remains virtually unchanged. The initial steps of the FMEA can determine the success of the FMEA application in fulfilling the needs of the designer.

4.12.1 Setting reliability design goals

Reliability design goals may be expressed in various forms, such as quantitative reliability requirement levels, design configuration comparisons, or qualitative aims to simply identify and eliminate as many failure modes as possible. The goals should be well-defined, and should be adequate for the application. The goals may be based on customer requirements, competitive benchmarking,

product improvement goals, company standards, or industrial standards.

The term "adequate" is an important concept in performing FMEA, or any other reliability analysis. Adequacy is not a negative term, but reflects the meeting of certain needs. If the level of information which constitutes adequacy is properly specified, attempts to transcend adequacy reduce the efficiency and effectiveness of the FMEA approach by consuming time and financial resources without need. Thus, adequate goals and requirements are strict, but not overly obstructive or limiting.

4.12.2 Setting physical and analytical boundary conditions

Before beginning the FMEA investigation, the physical boundary conditions of the system must be defined. The various sub-system and components to be considered in the analysis must be specified. Clearly, the dedicated parts of an engineered system must be included in the physical boundaries. Additionally, the actuating or power systems, measuring and controlling systems, other functionally integrated systems, and human operators may be included in the physical boundaries, depending on the needs of the analysis. If the constituent parts of the

overall system are very reliable, the effects of the interrelated sub-systems may dominate the reliability characteristics of the overall system, making the analysis of the interrelated sub-systems very important. However, including too many peripheral sub-systems may only confuse the reliability analysis of the engineered system, and may become ineffective and inefficient in the process. Beginning the analysis with a narrow focus and expanding the scope as needed is suggested.

In addition to defining the physical bounds, certain analytical bounds must be established to determine how the system will be analyzed. These analytical bounds include defining failure events which will not be explored, identifying the environmental and operational conditions, specifying the initial state of system operation under analysis, and any other conditions which could affect the identification and evaluation of the potential failure modes. The analytical bounds of the analysis are critical to portraying the desired reliability characteristics of a system. A particular analysis may only be interested in a specific failure, and potential failure modes which do not cause this system failure may not be evaluated. Furthermore, a system which serves multiple functions through multiple operating states may exhibit different reliability characteristics in one state than in another. For

instance, a chemical system may demonstrate better reliability during continual operation than in some type of system cleaning operation, or during start-up.

In many instances, considering the set of individual failure modes of the system's components as the complete set of failure modes for the system is acceptable. This is true for series systems such the robot examined in this case study. However, the case arises when the combination of two or more component failure modes at the same time results in a distinctly different failure mode for the system. This different failure mode, while occurring less frequently due to the need for co-existing failures, generally causes much more severe effects. The combination of component failure modes needed to cause this different failure is called a **cut set**. The length of the cut-set is determined by the number of component failures needed to cause the different failure mode. For a series systems, all of the failure modes are one event cut sets. For systems with some parallel aspects, longer cut sets will need to be considered. Determining the length of the cut sets to be considered is another analytical bound placed on the system. A tradeoff exists between the length of the cut sets examined and the complexity of the analysis. Longer cuts drastically increase the complexity of the analysis, and at some point

add no important information to the reliability analysis. Even considering only two event cut sets, the task can be quite difficult. If more than a few higher order cut sets are anticipated to be important contributors, the identification of the failure modes of the system should be conducted with Fault Tree Analysis (FTA), an approach specifically designed to treat these inter-relationships. This concept is explored in the section on the Limitations of the FMEA Approach.

4.12.3 Partitioning the system and level of analysis

The procedure used to discretize the system into individual sub-systems or components determines the level of analysis of the system. In general, the higher the degree of analysis, the more complex and difficult the analysis becomes to perform. Many times, the increased complexity of a higher degree of analysis yields little additional information to the system designer, as described in the case study. Thus, determining the correct level of detail for the analysis is another critical factor in the successful application of the FMEA design tool.

During conceptual design, the system is not well defined, necessitating a low level of detail. In fact, only the major sub-systems may be considered.

Nevertheless, this type of analysis can still present much information concerning critical areas which need to be addressed as the design continues, and may allow one to concentrate the further FMEA analysis on important, or deficient, sub-systems, rather than trying to perform detailed analysis on all the sub-systems. This approach allows more efficient use of resources, and provides for a continually evolving analysis, which supplies reliability information to the designer at all stages through the design.

Again, the procedure is in search of an adequate level of analysis, not extraordinary levels of detail. Actually, performing FMEA at too fine a level of detail creates several difficulties. First, the volume of information being recorded becomes too large to be effectively managed and interpreted. Second, the availability of failure information for very fine levels of analysis is limited. One may be able to develop failure information and data for a pump, but specific information and data for failures of the pump's windings, connections, rotors, and casings is not likely available, nor pertinent to a large system. Third, the information gained from a very fine level of analysis may not present the designer with any options which can be modified. A designer can seldom improve the reliability of a class of

devices which must be bought from vendors, other than to insure the inherent maximum reliability of the vendor's parts are achieved.

4.12.4 Identifying and describing failure modes

For systems in which only one event cut sets are examined, the failure mode identification and description process is exactly as described in the robot case study. When higher order cut sets are considered, the process is slightly different. First, the individual system component failure modes are identified and described as in the case study example. Then, combinations of system components are considered for simultaneous failures. The simultaneous failures are developed like the individual component failures. Only simultaneous failures which are seen to have a significant effect on the system need to be recorded, thus minimizing analysis efforts. Again, the failures are based on deviations from design intentions.

4.12.5 Evaluating the FMEA Table

Once the FMEA Table has been properly generated, the analysis proceeds as in the robot case study. The evaluation measures the overall reliability performance of the system, and identifies the largest contributors to unreliability and failure costs. One should try to avoid

being guided by only the overall risk, or the expected failure rate. The distribution of the expected failure rate and the risk over the cost categories is also important. As discussed in the case study presentation, the quantitative results should focus on relative comparisons unless the input data is deemed very accurate.

4.12.6 Improving the reliability of the system

The background information on reliability previously presented in the text describes several methods for improving the reliability of an engineered system. As part of the FMEA approach, many recommendations will be generated based on those methods. The designer must recognize, and the FMEA should highlight the fact, that a wide variety of parameters effect the reliability of the system. Design improvement actions must provide a balanced improvement of the inherent maximum reliability of the design configuration, the manufacturing degradation factors, and the field operation degradation factors.

4.12.7 Limitations of the FMEA approach

In general, reliability analysis through FMEA techniques provides pertinent and useful information to the design engineer during design better than any of the

other reliability approaches. However, FMEA techniques do possess some limiting factors.

First, the FMEA approach is time consuming and labor intensive. However, the FMEA approach provides a detailed examination and understanding of the system. Additionally, the approach may be enhanced with software to drastically reduce the time and repetition involved in FMEA studies.

Another difficulty in using FMEA is the limited quantitative evaluations which may be utilized. Fault Tree Analysis is a better approach for implementing comprehensive quantitative reliability evaluations, but with a loss of design improvement information and a focus on only one system deviation. Thus, the complexity and intricacy of comprehensive quantitative reliability evaluations suggests this area is best left to experienced analysts.

The greatest deficiency of FMEA is the inability to comprehensively identify and evaluate multiple event cut sets. For a series systems, FMEA does fulfill the reliability design tool goals. As a demonstration, the FTA in Figure 4-21 and the FMEA in Figure 4-22 represent a series system with two components and three failure modes. The FTA identifies and develops a single important failure event, TOP EVENT 1, based on component failure

COMPONENT DESCRIPTION	FAILURE MODE DESCRIPTION	FAILURE MODE CAUSES	SYSTEM EFFECTS	FREQUENCY	RECOMMENDED ACTIONS
COMPONENT NUMBER 1	FAILURE MODE NUMBER 1 (A)	LIST OF IDENTIFIED CAUSES FOR THIS FAILURE MODE	TOP EVENT 1 OTHER SYSTEM EFFECTS OF THIS FAILURE MODE	1.0 E-02 /YR	LIST OF RECOMMENDED ACTIONS AGAINST THIS FAILURE MODE
COMPONENT NUMBER 1	FAILURE MODE NUMBER 2 (B)	LIST OF IDENTIFIED CAUSES FOR THIS FAILURE MODE	TOP EVENT 1 OTHER SYSTEM EFFECTS OF THIS FAILURE MODE	1.0 E-04 /YR	LIST OF RECOMMENDED ACTIONS AGAINST THIS FAILURE MODE
COMPONENT NUMBER 2	FAILURE MODE NUMBER 1 (C)	LIST OF IDENTIFIED CAUSES FOR THIS FAILURE MODE	TOP EVENT 1 OTHER SYSTEM EFFECTS OF THIS FAILURE MODE	1.0 E-01 /YR	LIST OF RECOMMENDED ACTIONS AGAINST THIS FAILURE MODE

FAILURE MODE FREQUENCY IMPORTANCE RANKING: C
A
B

Figure 4-22. One Event Cut Set FMEA

information. The FTA reveals an expected system failure rate of $1.101\text{E-}01/\text{yr}$, and identifies the events in order of importance as C, A, B. The FMEA identifies the potential failures with their causes and system effects for each component. TOP EVENT 1 is identified, along with other system effects, for each failure mode. The FMEA also calculates the system failure rate as $1.101\text{E-}01/\text{yr}$, and generates the same importance ranking of failure modes. Yet, FMEA reveals more useful information to the designer by developing the causes, and additional system effects, of the individual failures, which were not developed in the FTA. Furthermore, comments concerning each failure mode, and the important recommendations for eliminating, or attenuating, the failure event have been made for use by the designer. For the series system, FMEA is more effective for design use than FTA.

Conversely, a parallel system is developed with FTA in Figure 4-23 and FMEA in Figure 4-24. The FTA yields a TOP EVENT 2 failure rate of $2.77\text{E-}9/\text{yr}$, significantly less than the individual component failure rates. The FMEA, considering only single failures of components, identifies some system effects, but fails to identify TOP EVENT 2. However, if one considers an additional failure mode in the FMEA as the simultaneous occurrence of the previous two failure modes, TOP EVENT 2 is discovered, and the FMEA

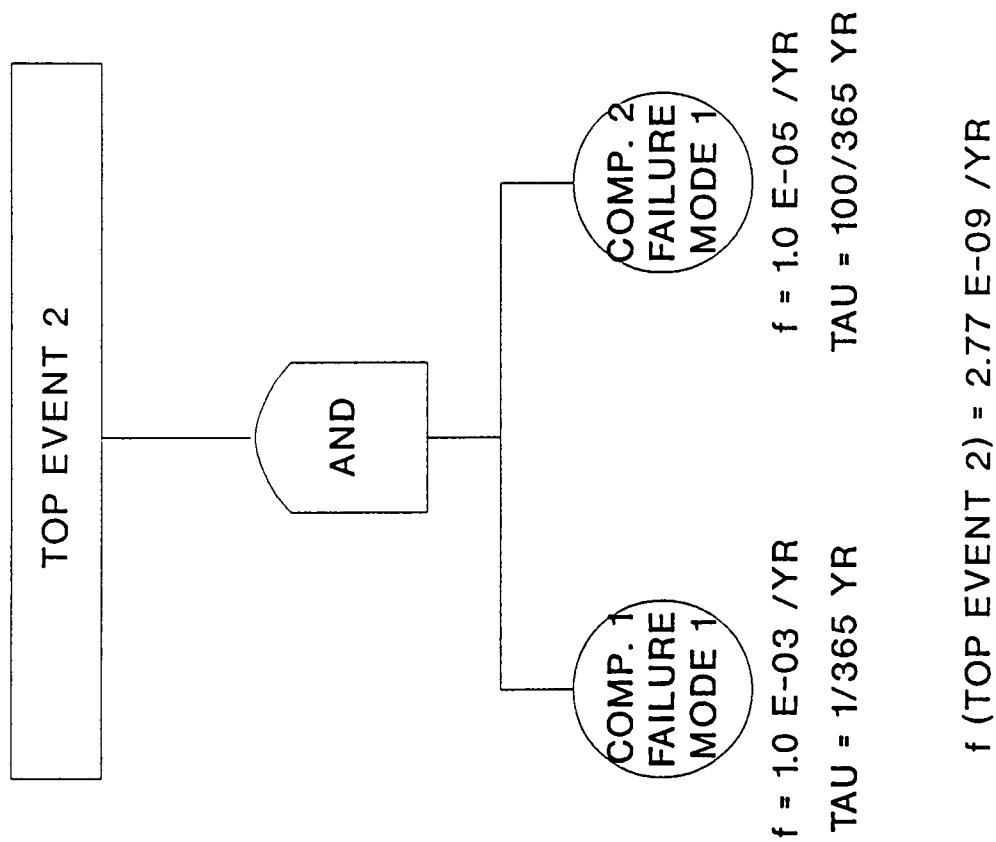


Figure 4-23. Two Event Cut Set Fault Tree Analysis

COMPONENT DESCRIPTION	FAILURE MODE DESCRIPTION	FAILURE MODE CAUSES	SYSTEM EFFECTS	FREQUENCY	RECOMMENDED ACTIONS
COMPONENT NUMBER 1	FAILURE MODE NUMBER 1	LIST OF IDENTIFIED CAUSES FOR THIS FAILURE MODE	LIST OF SYSTEM EFFECTS FOR THIS FAILURE MODE	1.0 E-03 /YR	LIST OF RECOMMENDED ACTIONS AGAINST THIS FAILURE MODE
COMPONENT NUMBER 2	FAILURE MODE NUMBER 1	LIST OF IDENTIFIED CAUSES FOR THIS FAILURE MODE	LIST OF SYSTEM EFFECTS FOR THIS FAILURE MODE	1.0 E-05 /YR	LIST OF RECOMMENDED ACTIONS AGAINST THIS FAILURE MODE
COMPONENT NUMBER 1 AND COMPONENT NUMBER 2	COMBINED FAILURE OF BOTH COMPONENTS AT THE SAME TIME	LIST OF IDENTIFIED CAUSES FOR THIS FAILURE MODE	TOP EVENT 2 OTHER SYSTEM EFFECTS OF THIS FAILURE MODE	2.77 E-09 /YR	LIST OF RECOMMENDED ACTIONS AGAINST THIS FAILURE MODE

Figure 4-24. Two Event Cut Set FMEA

is equivalent to the FTA. Unless TOP EVENT 2 is particularly unacceptable, or the effects of the single failures are non-critical, the low frequency of TOP EVENT 2 makes the event somewhat unimportant compared to the individual component failures. Considering the relative costs and safety issues of the failure events could determine if TOP EVENT 2 is truly important.

As shown in the above example, for a system with some parallel configuration, reliability analysis requires consideration of multiple component failure events, cut sets, which cause an overall system failure. The previous example identified a two event cut set for TOP EVENT 2. For systems with more components, all the possible combinations of component failures would have to be considered to systematically identify failures not discovered by the single event failure analysis. Furthermore, three event cut sets would also have to be identified in the same manner. This process would be repeated for four, five, six, . . . event cut sets. Clearly, this approach is not achievable in practice. In fact, just considering one and two event cut sets for a system of 20 components requires 20 single component failure evaluations and 190 evaluations of dual component failures. This unwieldy amount of analysis is the most severe restriction of FMEA.

However, by understanding the system and recognizing potential sources of multiple event cut sets, such as redundancy, the work may be significantly reduced. Only combinations which will precipitate significant system failures need to be analyzed in the FMEA table. Additionally, as shown in the example, the failure frequency of multiple event cut sets quickly decreases with increasing numbers of components in the cut set, provided the individual events do not have high failure frequencies or extended repair times. Therefore, the single event cut sets typically dominate the reliability characteristics followed by successively longer cut sets. By considering the single event failures and the identifiable two event cut sets, the reliability characteristics and the important contributors for many systems may be modelled.

A final weakness of FMEA is the lack of assurance that all of the potential failure modes have been identified. While this is a practical dilemma, several features are instilled to minimize this effect. First, the design engineering team has a greater knowledge of the potential failure modes of system components than any group associated with the project. Second, the design team collectively reviewing the FMEA should be able to identify most potential failure modes which might have

been missed by a single designer, or analyst. Third, the incorporation of a database of failure information, which should be continually updated and reviewed, provides another check to improve completeness and accuracy in the study. Fourth, information from previously analyzed related systems, or operating experience, can be used as a reference. Finally, using independent "experts" with experience in failure identification or reliability analysis could be used to assure the quality of the study.

4.12.8 Types of system which may be analyzed

Almost any engineered system which is primarily a series system can be analyzed with this FMEA approach. Both small and large engineered devices, manufacturing or process equipment and systems, and laboratory experimental systems may be considered. This approach provides a large degree of flexibility in application, while providing pertinent design insights into reliability at optimal times.

CHAPTER 5

THE RELIABILITY DESIGN TOOL SOFTWARE

The FMEA technique is labor and time intensive. The FMEA tables can become large and difficult to manage, even on a word processing system. Analysis of the FMEA table requires mathematical considerations and information management skills. Both qualitative and quantitative reliability information must be manipulated into a useful format conducive to decision making by the designer. Furthermore, previously recorded reliability characteristics and failure mode identifications are often repeated in future studies with similar components requiring duplicate analysis.

Manual management of an FMEA methodology as a design tool is cumbersome, inefficient, and ineffective. Using an information systems program to manage the reliability design tool is a necessity in developing a tool that a designer can truly utilize. By placing a reliability design tool on an engineering design workstation, the true benefits of designer reliability analysis may be realized [Walker, 1989]. The goal is to allow the designer to focus on the engineering analysis of the system rather than managing volumes of information.

5.1 Description of Use During an FMEA

The FMEA software is designed to draw information from the engineering design team, a Component Failure Mode Description Library, and a Component Failure Mode Failure Rate Library. From these sources, the software manages an FMEA study of a system, described in Section 4, and generates formatted output needed to make reliability improvement decisions. The output of the software is formatted FMEA Tables, Failure Event Risk Matrices, Failure Event Category Summary Tables, Frequency and Risk Histograms, and sorted lists of failure events based on frequency or risk importance. The interaction of the input sources and formatted outputs with the FMEA software is represented in Figure 5-1.

5.1.1 Creating the FMEA Table

As described in Section 4, an FMEA is completed by examining the failure modes of each component individually. Thus, the FMEA Table is completed one failure mode at a time. Similarly, the FMEA software uses input screens, as shown in Figure 5-2, to receive the failure descriptions of each failure mode. The designer may manually enter failure mode descriptions, utilize the Component Failure Mode Description Library, or use a combination of both.

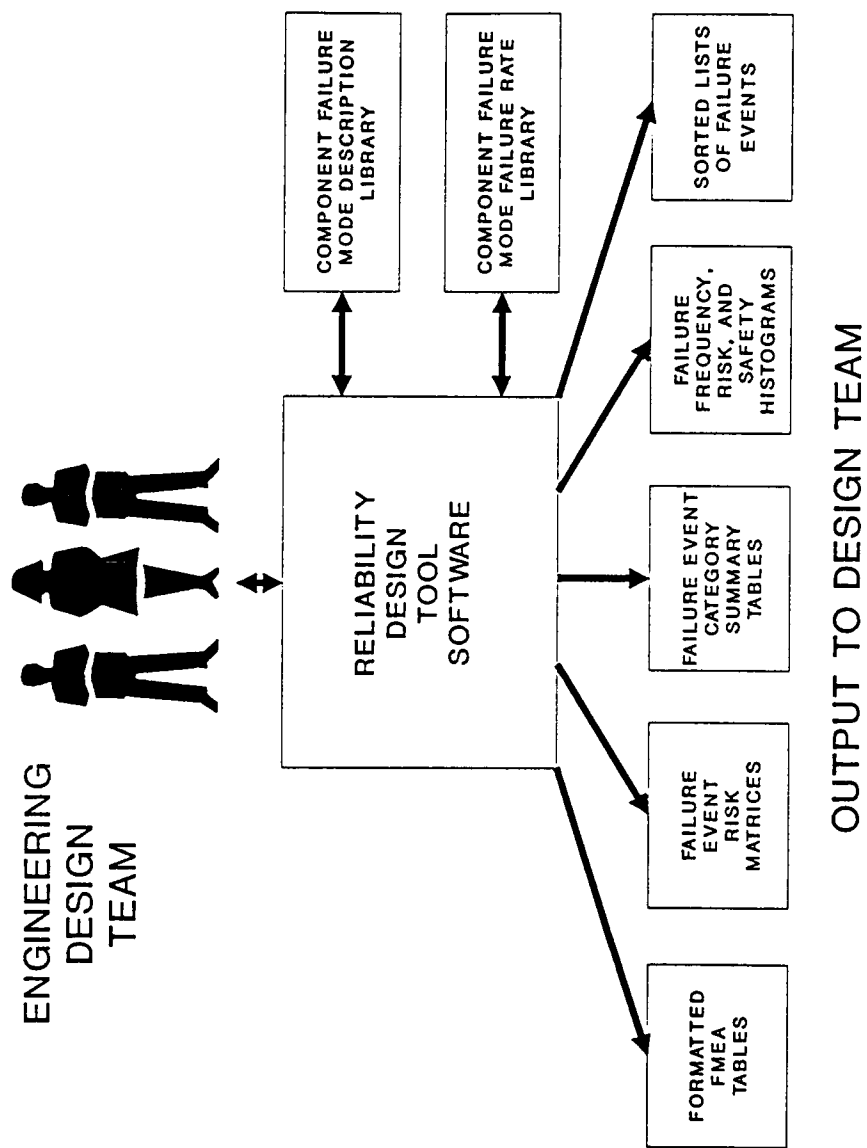


Figure 5-1. FMEA Software Input Sources and Outputs

FAILURE MODE INPUT TABLE	
COMPONENT :	
FAILURE MODE :	
CAUSES 1:	
2:	
3:	
4:	
5:	
6:	
7:	
8:	
SYSTEM 1:	
EFFECTS 2:	
3:	
4:	
5:	
6:	
7:	
8:	
COMMENTS 1:	
2:	
3:	
4:	
5:	
RECOMMENDED 1:	
ACTIONS 2:	
3:	
4:	
5:	
6:	
7:	
8:	

INPUT TABLE FOR THE FREQUENCY AND EFFECT QUANTIFICATION	
FOR FAILURE MODE OF COMPONENT	
FREQUENCY (EVENTS/YR) :	
EQUIPMENT DAMAGE (\$/EVENT) :	
BUSINESS INTERRUPTION (\$/EVENT):	
REPAIR COST CATEGORY (\$/EVENT) :	
SAFETY CATEGORY (1,2,3,4,5) :	
	<FINISHED>

Figure 5-2. FMEA Software Input Tables

When manually entering a failure mode description, the designer is presented a blank input screen for text descriptions of the failure mode. The designer completes the failure mode input screen by identifying the failure mode, causes, system effects, comments and safeguards, and recommended design actions. The software provides menu-driven editing features for entering, editing, or deleting the information displayed in the input screen. Also, a text storage feature is supplied to allow the designer to store long text strings which must be repeated often in the analysis. To avoid re-typing, stored text strings may be recalled into any location in the input screen while evaluating subsequent failure modes. When all the text information for the first input screen has been entered, the FMEA software places all of the information in the appropriate columns of the FMEA Table.

Rather than entering the information manually, the designer may retrieve text descriptions of failure modes for components which have Component Failure Mode Description Library files. After selecting the component library file from a library menu, the first stored failure mode input screen is displayed with all of the completed causes, system effects, comments and safeguards, and recommended design actions. The designer may then modify the entries to fit the particular application. Again, the

same menu-driven entering, editing, deleting, and text storage/retrieval capabilities are available for modifying the entries. When all the information for the failure mode input screen is complete, the FMEA software places all of the information in the appropriate columns of the FMEA Table.

After the text description of the failure mode is completed, a second input screen is displayed for entering the numeric quantification of the failure mode. The designer may elect to enter the numeric data later, or may enter the failure rate, equipment damage cost, business interruption cost, repair cost, and safety category for the failure mode being analyzed. If the numeric information is entered, each numeric entry is placed in the FMEA Table along with the calculated total cost and financial risk of the failure mode.

5.1.2 Modifying the FMEA Table

After the FMEA Table is created, the need will arise to modify the entries in the table when discovering additional failure modes, modifying the text or numeric descriptions, or deleting failure mode records. Menu-driven features are included to facilitate these needs.

A failure mode insertion option is available to add failure modes for any component already include in the

FMEA Table. The designer merely selects the position in the FMEA Table for the new failure mode. Then, blank text and numeric input tables are presented to describe the additional failure mode. The descriptions are entered the as previously described.

An option to modify any existing failure mode record is also incorporated into the software. The designer selects the entry by entering the item number of the failure mode record in the FMEA Table, or by placing the cursor on the item number of the failure mode record in the FMEA Table. Once selected, the text and numeric descriptions for the failure mode are read back into the appropriate input screens. Then, the previously described entering, editing, deleting, and text storage/retrieval features may be used to modify the descriptions for the failure mode. After the modification to the failure mode descriptions are completed, the information is replaced into the FMEA Table in the appropriate columns.

The ability to delete a failure mode record is also included in the software. To delete a failure mode record, the item number of the record is selected by typing the item number, or highlighting the item number with the cursor. After a verification of intention step, the failure mode is deleted from the FMEA Table, and the other records are moved to fill the voided space.

5.1.3 Numerically analyzing the FMEA Table

After the failure modes have been numerically described, the designer will wish to generate the numerical summary information for quantitative evaluation of the FMEA Table. An option has been included to perform the analysis. The numerical approach used for the analysis is presented in Appendix B. When selected, this option:

- 1) groups each failure mode numeric descriptor into a cost or frequency category, counts the number of events in each cost-frequency category pair for display in the Failure Event Risk Matrices,
- 2) sums the frequency and risk of each cost category for display in the Failure Event Category Summary Tables,
- 3) generates the histograms based on the values in the Failure Event Category Summary Tables,
- 4) and determines the sorting indices used to sort the FMEA Table records by importance.

This option does not display the results. Viewing and printing the numerical summary information is achieved in the View options. The frequency and cost category assignments are based on the currently selected category divisions.

5.1.4 Viewing options

During operation, the designer continually sees the text input screen with the menus at the top of the screen. Other areas of the worksheet are presented for viewing only when an option has been selected which requires the designers to view these areas. A viewing option has been included to allow the user to see the current FMEA Table or the Numeric Summary Information.

After selecting the view option, the designer would select the table option to view the FMEA Table. The screen will then display the title, header block, and the first few lines of the FMEA Table. The rest of the table may be viewed by scrolling through the subsequent lines of the FMEA Table. The title and header block will remain at the top of the screen.

After selecting the view option, the designer will select the numeric summary option to view the Numerical Summary Information. This option also contains the options to print the Numeric Summary Information. An option is available to combine the numeric summary information from another FMEA file if desired. Then, a series of menus are displayed to allow the designer to view the matrices, summary tables, histograms. Also, a print option to generate the formatted numeric output is available.

5.1.5 Sorting the FMEA Table

The failure event records in the FMEA Table may be sorted by importance based on frequency of occurrence, financial risks, or safety risk. This option is provided to identify which events deserve the most attention during reliability improvement actions. The numeric analysis option generates a set of sorting indices, described in Appendix II, which allow all of the events in the FMEA Table to be easily re-arranged in order of importance. The indices also allow the table to be returned to its original order. While sorted, the FMEA Table may be viewed or printed.

5.1.6 Printing the FMEA Table

The printing option is presented to allow the designer to print the FMEA Table in a formatted output for further study or documentation. The designer may specify the entire table, or any range, for printing. The printing routine spaces the entries so that no failure mode records are interrupted by page breaks, unless the record is too long to fit on one page.

5.1.7 Additional modification features

The software allows the designer the ability to make several other modifications to the FMEA Table through menu

options. A renumbering feature is included to correct the item numbers for the failure mode records after failure modes have been added or deleted. The title of the FMEA Table can be changed. The available memory of the computer may be monitored to identify when an FMEA should be completed in a separate table. The category range tables, shown in Figure 5-3, may be modified to span the appropriate range of frequencies and costs for the FMEA application. As the program is initiated, the default directories for the duration of that program execution may be established. Finally, the designer may define up to 36 Component Failure Mode Description Library files to be displayed as menu options when selecting the library file options. These changes are made in the tables shown in Figure 5-4. The number of library files which may exist in the library file subdirectory is limited only by computer disk space. However, only 36 of these files will be displayed in the menu options at any time. Changing the files that will be available is a simple procedure guided by the software.

5.1.8 Component Failure Mode Description Library

The Component Failure Mode Description Library has been previously mentioned. Basically, the library is composed of files which describe the failure modes for

COST SCALE FACTOR	LOWEST COST IN CATEGORY	CATEGORY
2.00	\$0.00	1
	\$0.32	2
BASE	\$3.16	3
10.00	\$31.62	4
	\$316.23	5
	\$3,162.28	6
	\$31,622.78	7
	\$316,227.77	8

a) COST CATEGORY DEFINITION TABLE

FREQ. SCALE FACTOR	LOWEST FREQUENCY IN CATEGORY	CATEGORY
2.00	0.000	1
	3.162e-09	2
BASE	3.162e-08	3
10.00	3.162e-07	4
	3.162e-06	5
	3.162e-05	6
	3.162e-04	7
	3.162e-03	8
	3.162e-02	9
	3.162e-01	10

b) FREQUENCY CATEGORY DEFINITION TABLE

Figure 5-3. FMEA Software Cost and Frequency Category Range Tables

GROUP ASSIGNMENTS	DESCRIPTION	STATUS
SUBGROUP A:	BEARINGS, BELTS, PULLEYS	ACTIVE
SUBGROUP B:	ELECTRIC MOTORS	ACTIVE
SUBGROUP C:	GUIDES AND SUPPORTS	ACTIVE
SUBGROUP D:	CONTROLLERS	ACTIVE
SUBGROUP E:	SUBGROUP E	INACTIVE
SUBGROUP F:	SUBGROUP F	INACTIVE

SUBGROUP A:	DESCRIPTION	FILENAME
CHOICE A:	LINEAR BALL BUSHING	LNBLBSH
CHOICE B:	TIMING BELT	TIMBELT
CHOICE C:	TIMING BELT PULLEY	TIMPULL
CHOICE D:	CHOICE D	INACTIVE
CHOICE E:	CHOICE E	INACTIVE
CHOICE F:	CHOICE F	INACTIVE

SUBGROUP B:	DESCRIPTION	FILENAME
CHOICE A:	STEPPER MOTOR	STEPMTR
CHOICE B:	CHOICE B	INACTIVE
CHOICE C:	CHOICE C	INACTIVE
CHOICE D:	CHOICE D	INACTIVE
CHOICE E:	CHOICE E	INACTIVE
CHOICE F:	CHOICE F	INACTIVE

SUBGROUP C:	DESCRIPTION	FILENAME
CHOICE A:	GUIDE SHAFTS	GUIDSHFT
CHOICE B:	SUPPORT STRUCTURE	SUPPSTRC
CHOICE C:	CHOICE C	INACTIVE
CHOICE D:	CHOICE D	INACTIVE
CHOICE E:	CHOICE E	INACTIVE
CHOICE F:	CHOICE F	INACTIVE

Figure 5-4. FMEA Software Library Menu Definition Tables

SUBGROUP D:	DESCRIPTION	FILENAME
CHOICE A:	STEPPER MOTOR DRIVER	STPMTCNT
CHOICE B:	CHOICE B	INACTIVE
CHOICE C:	CHOICE C	INACTIVE
CHOICE D:	CHOICE D	INACTIVE
CHOICE E:	CHOICE E	INACTIVE
CHOICE F:	CHOICE F	INACTIVE

SUBGROUP E:	DESCRIPTION	FILENAME
CHOICE A:	CHOICE A	INACTIVE
CHOICE B:	CHOICE B	INACTIVE
CHOICE C:	CHOICE C	INACTIVE
CHOICE D:	CHOICE D	INACTIVE
CHOICE E:	CHOICE E	INACTIVE
CHOICE F:	CHOICE F	INACTIVE

SUBGROUP F:	DESCRIPTION	FILENAME
CHOICE A:	CHOICE A	INACTIVE
CHOICE B:	CHOICE B	INACTIVE
CHOICE C:	CHOICE C	INACTIVE
CHOICE D:	CHOICE D	INACTIVE
CHOICE E:	CHOICE E	INACTIVE
CHOICE F:	CHOICE F	INACTIVE

Figure 5-4 (Continued)

commonly encountered components. These files contain the failure mode text descriptions, as presented in Figure 5-2. The descriptions address the typical failure modes, causes, system effects, comments and safeguards, and recommended design actions for a component. A wealth of reliability improvement information may be gained from well prepared library files.

The software contains the ability to create and modify component library files. The same input screen is used for creating the library files as for creating the FMEA Table. However, after the input screen is completed for each failure mode during library file creation, the information in the input table is stored in the component library file rather than placed in the FMEA Table. The same entering and editing features are available for completing the failure mode analysis in the input table. A list of the currently identified failure modes for the component is maintained in the component library file.

The software also allows the Component Failure Mode Description Library file to be modified. Additional failure modes may be added by the procedure described, existing failure modes may be modified using the previously described editing features, and a failure mode may be deleted from the component library file.

5.1.9 Component Failure Mode Failure Rate Library

As a supplement to the software, physical library data books, and some computerized databases, are available to provide failure rates for component failure modes. These are available from a variety of sources including government agencies, professional societies, plant specific data, and independent evaluators. Some of the more prominent sources are:

- 1) Non-Electronic Parts Reliability Data from the Reliability Analysis Center [Rome Air Development Center, 1981];
- 2) IEEE Guide to the Collection and Presentations of Electrical, Electronic, and Sensing Component Reliability Data for Nuclear Power Generating Stations [Institute of Electrical and Electronic Engineers, 1987];
- 3) SRS Databank [National Centre of Systems Reliability, 1981];
- 4) Nuclear Plant Reliability Data Systems (NPRDS A02 and A03) [Institute of Nuclear Power Operations, 1983];
- 5) Guidelines for Process Equipment Reliability Data with Data Tables [American Institute of Chemical Engineers, 1989];
- 6) Offshore Reliability Data [OREDA, 1984];

- 7) Gendata [Systems Reliability Service, 1986];
- 8) Military Handbook 217-E for Reliability
Prediction of Electronic Equipment [Department
of Defense, 1982].

These data sources are used to quantify the failure events recorded in the FMEA Table. The data is entered through the numeric failure mode description input screen, shown in Figure 5-2.

5.2 Description of Software Programming

This sub-section describes the programming code written for the reliability design tool software. The operating computer system hardware and software requirements are presented. Then, the reasoning for choosing the programming medium is discussed. Next, the specific programming code format is described, including the multiple file format, the menu configuration, the general algorithms for the code routines, and the definitions of the named ranges in the worksheets. The complete reliability design tool software is included "In Pocket" on two floppy disks. The first disk, Plate 5-1, contains the program files for the software, while the second disk, Plate 5-2, stores the Component Failure Mode Description Library files. Finally, an assessment of the software programming is given.

5.2.1 Software operation requirements and specifications

Certain computer requirements must be met for operation of the reliability design tool software. The computer must be an IBM, or 100% compatible, PC, XT, AT, or PS/2 model. A minimum of 640 kilobytes of memory should be available on the computer. Additional extended memory can be accessed by LOTUS, and is suggested to increase storage capacity in the FMEA worksheet. A hard disk for file storage is required. One megabyte of hard disk space is sufficient, although storing several large FMEA worksheets will quickly exceed the one megabyte allotment. Additionally, the computer must have at least one disk drive. This disk drive may be a low or high density drive, but the large size of the FMEA files may require compressed copying techniques with a low density drive. A wide carriage printer, using 11 inch by 14 inch paper, is necessary for printing the FMEA Table. The printer used during creation of this software was the IBM Proprinter II.

In addition to the computer hardware configuration, the computer system must have LOTUS 123, version 2.2, already installed. LOTUS should be installed with no add-ins automatically attached, the undo feature turned off, and the screen display set for 25 lines of the worksheet

to be exhibited. Any version of DOS compatible with LOTUS 123 version 2.2 is acceptable.

The software files are installed in subdirectories under the LOTUS subdirectory on the hard disk. These files are accessed by a batch file. A suggested directory configuration is presented. The batch file, found in Plate 5-1, should be copied in the computer's batch file subdirectory. The program files, contained in Plate 5-1, should be copied into a subdirectory, called FMEA, under the LOTUS subdirectory. The library files, contained in Plate 5-2, should be copied into a subdirectory, called LIB, under the FMEA subdirectory.

5.2.2 The programming language

The software package is written in LOTUS 123, version 2.2. Several benefits are realized by using LOTUS. First, LOTUS is quickly becoming a universal engineering tool throughout the country. LOTUS is relatively inexpensive, and has found favor in both large and small firms. The availability and familiarity of LOTUS to potential users is a strong benefit, although the user need not be proficient in LOTUS to use the FMEA program.

Second, LOTUS provides a very comprehensive macro language, which provides most of the common flow controls of programming languages such as BASIC. In addition to the

program flow features, the macro language provides the ability to develop a layered menu structure with explanation windows for the menu commands. The menu features provide great speed, utility, and ease of use. These features, combined with the ability to control the screen, use indicator windows to identify operating stages, and issue user prompts, make the macro language very useful as a programming tool.

Third, the intrinsic features of LOTUS provide a solid means of accomplishing much of the manipulation necessary for the input information. The text manipulation is allowed from the natural ability of the spreadsheet to portray tabular information, internal justification routines, and input table capability, along with the move, copy, row insert, row delete, and erase features. Additionally, the numeric manipulation capabilities are very attractive for formatting numerics, algebraic functions, and sorting importance. Fourth, the graphing capabilities available with LOTUS inside a single package allow graphs to be automatically generated and presented to the user. This speeds the decision making process, and simplifies the overall FMEA program procedure.

Fifth, the formatted printing of information through LOTUS and ALWAYS yields high quality printed output.

Several different fonts, line options, headers, and footers, combined with macro routines for determining the amount of information on a single page, result in an attractive and easy to understand output of the FMEA table and numeric information.

However, LOTUS does present some drawbacks to the overall goals of the program. Using LOTUS limits the speed which the program can be executed. Additionally, the LOTUS macro commands must be interpreted and then executed each time they are encountered, rather than just executed as in a compiled program. This takes substantially more time to accomplish than a compiled program. Also, the sheer volume of information being input into the failure mode records, and the overall size of the FMEA table, cause memory and speed problems. A substantial amount of time, approximately 25 seconds for the largest entries, is needed to format and place large entries in the FMEA table. As the FMEA table grows, the available memory is reduced relatively quickly because of the memory used by LOTUS, the memory used to contain the program information, and the memory used to hold the FMEA table information.

The limitations of LOTUS are minimized by understanding the speed limitations versus the tremendous features available, and by using multiple files to store

the program code and large FMEA analysis projects. Currently, the overall benefits from using LOTUS as the program medium far outweigh the liabilities. Additionally, the current research and software is to prove the value and applicability of the developed technique as an engineering design tool. Future updates of the software could be created in an advanced programming language, such as C. This type of effort would be primarily a computer science project, which is beyond the scope of this research effort.

5.2.3 Multiple file format

To reduce the problems associated with the limited memory available on personal computers, the software features are divided into five distinct files. These files contain the menu structure, coded routines, input/output ranges, and other necessary information to accomplish specific features of the software. By dividing the coded features and operating information of the software between files, much more memory is reserved for the FMEA study. The five files are:

- 1) the default directory file, FMEACNFG.WK1, responsible for setting the default directories during an FMEA study;

- 2) the main software code file, ZETA8.WK1, responsible for executing most of the FMEA features, storing the FMEA Table, and controlling interactions with the three additional files;
- 3) the numerical summary information file, MATRICES.WK1, responsible for controlling the display and printing of the numerical summary information for a file and for superimposing the results of multiple FMEA Tables;
- 4) the FMEA Table printing file, FMTPRT.WK1, responsible for formatting and printing the FMEA Table;
- 5) and the Component Failure Mode Description Library management file, LIBCRT.WK1, responsible for creating and editing the files for the library.

These files are included in Plate 5-1 which is "In Pocket." A physical depiction of the information contained in each file is presented in Appendix E.

The FMEA batch file, also included in Plate 5-1, displays a title screen, and then copies the default directory file into the LOTUS subdirectory as AUTO123.WK1. The default directory file is now an automatically

retrieved file upon initiation of the 123 program. Next, the batch file initiates the 123 program.

After the 123 program retrieves the default directory file, the file begins an automatically executing macro, commencing the first stage in the FMEA software application. The designer is presented with the needed default directories, and their current locations, for the remaining operation of the software. The designer may modify these directories as necessary. After modifications are complete, the designer selects the finished option to begin the next stage of the FMEA software application. The default directories are modified, the default directory file is saved, and the main software code file is retrieved. Retrieval of the main code file purges the default directory file from memory.

After the main software code file is retrieved, a macro in the file automatically activates the main menu responsible for accessing the FMEA application features described previously. This file contains most of the menus and routines which guide the FMEA application. The software execution utilizes only one code in the main software code file until a feature is requested through the menu structure which is coded in another file.

Selecting the option to view the numerical summary information requires accessing another file. The main software code file in which the FMEA Table is being created is temporarily stored on the hard disk in XXXXXXXX.WK1 at the current state of completion. The numerical summary information file is retrieved, and the main software code file is purged from active memory. Upon retrieval, the numerical summary information file begins an automatically-executing macro, which reads the numerical analysis data from file XXXXXXXX.WK1. Then, the macro asks the user if information should be combined from any other FMEA Table files, which were previously saved in other files. If other results are to be combined, the macro adds these results from the appropriate files to those retrieved from XXXXXXXX.WK1. Afterward, the macro activates the menu control structure for viewing and printing the numerical summary information which has been retrieved. When completed with numerical summary information viewing and printing, the finished option is selected. The temporary XXXXXXXX.WK1 file is retrieved, purging the numerical summary information file from the active memory. Execution of the menu control macro in the XXXXXXXX.WK1 file is resumed from where it was exited. The control is now in the main software code file for this analysis.

Choosing the printing option for the FMEA Table requires code from a separate file. Within the main software code file, the print option is selected, and the range of the FMEA Table to print is designated. This range is extracted from the main software code file into a separate file named XXXXXPRT.WK1. The main software code file is temporarily saved on the disk in XXXXXXXX.WK1, and the FMEA Table print file is retrieved. The main software code file is purged from the active memory. Upon retrieval, the FMEA Table print file begins an automatically-executing macro which imports the range to be printed, XXXXXPRT.WK1, formats the FMEA Table range, and prints the FMEA Table range. After printing, the FMEA Table print file retrieves the XXXXXXXX.WK1 file, and purges the FMEA Table print file from active memory. Execution of the menu control macro in the XXXXXXXX.WK1 file is resumed from where it was exited. The control is now in the main software code file for this analysis.

Selecting the option for the Component Failure Mode Description Library also requires a transfer to another supplementary code file. When selected, the main software code file is saved to the disk in XXXXXXXX.WK1. The library creation and modification file is retrieved, and the main software code is purged from active memory. An automatically-executing macro activates the menu control

structure in this file. The menu options allow creation or editing of Component Failure Mode Description Files.

For creating the data files, the Failure Mode Descriptions are completed using the menu structured features. This file, with the input Failure Mode Descriptions, is saved to the disk under a name reflecting the component type. Thus, the component data file includes the original code of the library code file and the input Failure Mode Descriptions. After the data file is created and saved to the disk, the designer may create other component data files, edit previously existing component data files, or exit back to the main software code file. When exiting to the main software code file, the XXXXXXXX.WK1 file is retrieved, and the library code file is purged from active memory. Execution of the menu control macro in the XXXXXXXX.WK1 file is resumed from where it was exited. The control is now in the main software code file for this analysis.

Since the code for editing a Component Failure Mode Description Library File is actually contained within the file, modifying an existing library file is simple. The menu structure merely retrieves the Component Failure Mode Description Library File to be modified. The automatic execution macro activates the menu structure, and the editing is immediately available through the menus. The

file is modified and saved to the disk. When exiting to the main software code file, the XXXXXXXX.WK1 file is retrieved, and the library code file is purged from active memory. Execution of the menu control macro in the XXXXXXXX.WK1 file is resumed from where it was exited. The control is now in the main software code file for this analysis.

After all of the FMEA features have been utilized as desired, the main software code file with all the input FMEA information is saved to the disk under a unique filename for the study. A new analysis may be undertaken by retrieving the template main software code file, ZETA8.WK1. When exiting the reliability design tool software, the macro terminates the 123 program. The AUTO123.WK1 file is copied as the new default directory file, FMEACNFG.WK1, and the AUTO123.WK1 file is deleted. Afterward, LOTUS may be used without invoking the FMEA software.

5.2.4 Programming structure

As mentioned, the programming is controlled through a menu structure for accessing the various features and options of the FMEA software. The menu structure is conceived to minimize keystrokes and the level of user knowledge about the software. The menu structure also

provides a safe, reliable interface between the software user, and the software routines responsible for executing the features of the program. A complete listing of the reliability design tool software menus is presented in Appendix F.

For each menu option selected, a series of program routines are executed as appropriate for the menu choice. These routines provide the basis for the programming of the FMEA approach. Each routine is accessed as a subroutine, with a call and return format, or as a branch command, like a GOTO line number statement. All the routines for the FMEA software are contained in code areas of the spreadsheet files in Plate 5-1. Each routine serves a specific purpose. The purpose and general algorithm for each significant routine in the FMEA software is included in Appendix G.

Each programmed routine, branch location, variable, information storage location, or significant position location in each spreadsheet file is assigned a range name. The range names are used to identify the location of code lines, stored information, or special cursor positions during program execution. A complete listing of the range names in each file, with a brief description for each range name, is given in Appendix H. By understanding the significance of each range encountered in a routine,

coupled with the general algorithm of the routine, an experienced LOTUS macro user should be able to understand the individual routine codes.

CHAPTER 6

CONCLUSION

The area of reliability engineering portrays the interrelationships between design, manufacturing, and service better than any other analysis area. Many types of reliability analysis techniques are available, with varying levels of difficulty and usefulness. However, utilization of these techniques at optimal times during the design process has been overlooked. Therefore, the analysis techniques have been underemployed by merely analyzing systems, rather than utilizing the full benefits of reliability studies to improve products and processes during design.

This research has demonstrated a tool to evaluate the reliability of systems throughout the development stages by the design engineers. Also, the benefit of considering not only the inherent reliability in the design configuration, but also the effects of manufacturing and field operation environments on the inherent reliability have been explored.

The reliability design tool approach presented, based on FMEA, meets the requirements of reliability prediction goals for many systems. The approach identifies the important potential failure modes of systems,

characterizes the reliability performance of systems, and presents specific reliability improvement actions for improving reliability.

The reliability design tool software makes efficient and effective use of the FMEA approach. The software guides and facilitates the FMEA study, and manages a Component Failure Mode Description Library for commonly encountered components. The FMEA software compliments the FMEA approach, by allowing the designer to perform valuable reliability analysis studies while focusing on the study, rather than information management skills.

Through application of the developed approach and software, substantial reliability improvement opportunities have been discovered for the UT Robot. The case study of the UT Robot presented the predicted "best" and "worst" case reliability performance characteristics of the system. Additionally, the case study presented the improved reliability characteristics of the UT Robot based on a minimal number of corrective design actions. These corrective design actions were formulated through the FMEA approach, and represent the most effective actions for improving the reliability of the UT Robot.

The resulting reliability approach and software have been shown to be valuable assets during design, when initiated with reasonable expectations. The approach is

not completely prescribed, or restrictive. Some engineering art and judgement are required. By building from the approach described, the design engineer will be able to improve and characterize the reliability of a system early in design. Using this approach, as a part of a solid product development methodology, will aid the designer in achieving truly superior products and processes.

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APPENDICES

APPENDIX A

CASE STUDY FMEA TABLES

Z AXIS MOTION SUB-SYSTEM FMEA TABLES FOR CASE STUDY

Z AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION		FAILURE MODE CAUSE & EFFECT ANALYSIS			FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION		
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST (\$/YR)	FAILURE MODE COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
1.1.1	SUPPORT MAST	FAILS TO PROVIDE SUPPORT DUE TO FRACTURED MAST	FASTENER, MAST, OR IDLER PULLEY SHAFT FAILURE DUE TO FATIGUE, WATER OR CHEMICAL CORROSION, OR OVERSTRESS DUE TO IMPACT LOADING OF SYSTEM OR PARTS IN WORKSPACE, EXTERNAL IMPACTS ON MAST ASSEMBLY OR ON Z AXIS	LOSS OF Z AXIS DRIVE AND HOLDING TORQUE ALLOWING Z AXIS TO FALL POTENTIAL DAMAGE TO THE END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	8.70E-04	\$715.75	\$5,668.30	\$244.14	4	\$6,628.19	END EFFECTOR TYPE AND FUNCTION MAY CAUSE VIBRATIONS OR SPORADIC FORCES ON Z ARM	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS AND BELT MISALIGNMENT ARE MOST IMPORTANT FAILURE PARAMETERS FOR INSTALL./MAINT. AND DESIGN ALUMINUM FOR MAST HAS NO DEFINED ENDURANCE LIMIT AGAINST FATIGUE
1.1.2	SUPPORT MAST	FAILS TO MAINTAIN ACCURATE POSITIONING OF IDLER PULLEY CENTER	DEFORMATION OF MAST, FASTENERS, OR IDLER PULLEY SHAFT DUE TO CORROSION, WEAR, OR IMPACT LOADS ON THE Z AXIS DEFORINATION DUE TO EXTERNAL IMPACTS TO MAST ASSEMBLY OR TO Z AXIS INSTALL./MAINT. ERROR IN ALIGNING LOADS CAUSING MAST DEFLECTIONS EXCESSIVE VIBRATION OF MAST CAUSING MOTION OF IDLER PULLEY CENTER	PREMATURE BELT WEAR LEADING TO BELT FAILURE OR MISALIGNMENT LEADING TO BELT JUMPING FROM PULLEY IF BELT FAILS, LOSS OF Z AXIS DRIVE AND HOLDING TORQUE ALLOWING Z AXIS TO FALL POTENTIAL DAMAGE TO THE END EFFECTOR, EQUIPMENT AND PARTS IN THE WORKSPACE, AND/OR DAMAGE OR INJURY TO PERSONNEL IN VICINITY	1.104E-02	\$680.48	\$5,576.11	\$236.24	3	\$6,492.83	END EFFECTOR TYPE AND FUNCTION MAY CAUSE VIBRATIONS OR SPORADIC FORCES IN THE Z ARM MISALIGNED BELTS AND LOOSE FASTENERS ARE THE KEY FACTORS IMPACT LOADS MAY CAUSE SMALL LOCAL YIELDING	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS RECS. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL

2 AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION		FAILURE MODE CAUSE & EFFECT ANALYSIS			FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION			
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST (\$/EVENT)	TOTAL COST RISK (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
2.1	NEEDLE BEARING	FAILS TO PROVIDE FREE ROTARY MOTION	IMPROPER FIT IN PULLEY OR WITH SHAFT LUBRICANT CORROSION OR CONTAMINATION FROM CHEMICALS, WATER OR MOISTURE, OR SOLID PARTICLES BEARING SURFACE DAMAGE FROM IMPACT OR EXCEEDED OVERLOADS	LOSS OR REDUCED POWER TRANSMISSION CAPABILITY CAUSES LOSS OF POSITION CONTROL. POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	6.77E-02	\$258.28	\$1,863.59	\$158.02	3	\$2,379.89	\$161.14	LUBRICANT FAILURES ARE THE MOST LIKELY, ALTHOUGH THIS BEARING DOES CARRY A SUBSTANTIAL LOAD FOR ITS SIZE	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS RECS. 4 AND 5 FOR PROVIDING OPERATION POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 8 FOR USING A ROBOT POSITION VERIFICATION SYSTEM TO MAINTAIN ACCURACY
3.1	INLER PULLEY	FAILS TO TRANSMIT POWER OR MOTION -- PULLEY FAILURE	IMPACTS ON PULLEY OR PULLEY TEETH FROM FOREIGN OBJECTS CORROSIVES IN CONTACT WITH PULLEY FROM PROCESS CHEMICALS, MAINTENANCE CHEMICALS OR SOLVENTS, OR HIGH HUMIDITY FATIGUE FAILURE DUE TO ALTERNATING STRESSES RESULTING FROM PULLEY MISALIGNMENT BENDING LOADS	LOSS OR REDUCED POWER TRANSMISSION CAPABILITY CAUSES LOSS OF POSITION CONTROL. POTENTIAL DAMAGE TO THE END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	1.10E-04	\$567.56	\$2,462.63	\$209.39	3	\$3,259.78	\$0.36	THE CAUSES FOR THIS EVENT MAY ALSO CAUSE PULLEY SHAFT OR BEARING FAILURES OR DAMAGE PULLEY MATERIAL SELECTION, CORROSION RESISTANCE, SURFACE AND TEETH CONDITIONS, FATIGUE STRENGTH WITH STRESS CONCENTRATION, AND BELT ALIGNMENT ARE CRITICAL PARAMETERS	REC. 6 FOR ISOLATING BELT AND PULLEYS FROM ENVIRONMENT AND PROTECTING COMPONENTS FROM BROKEN OR LOOSE BELTS RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 8 FOR USING A ROBOT POSITION VERIFICATION SYSTEM TO MAINTAIN ACCURACY

2 AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION			FAILURE MODE CAUSE & EFFECT ANALYSIS				FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION	
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST (\$/EVENT)	TOTAL COST RISK (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
3.2	INLER PULLEY	FAILS TO TRANSMIT POWER OR MOTION -- LOSS OF BEARING TO PULLEY COUPLING	LOOSENING DUE TO QUICKLY OR HIGH REVERSING LOADS OR THERMAL EXPANSION OF INTERFERENCE FITS	RESULTS IN EXCESSIVE FRICTION AND HEATING, DEGRADED POWER TRANSMISSION, AND VIBRATION	1.10E-04	\$323.00	\$1,771.40	\$150.12	2	\$2,244.52	\$0.25	MAINTAINING PULLEY INNER DIAMETER, INNER SURFACE QUALITY, AND SIMILAR THERMAL EXPANSION CHARACTERISTICS ARE KEY FACTORS	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN
3.3	INLER PULLEY	FAILS TO TRANSMIT POWER OR MOTION -- LOSS OF PULLEY TO BELT MESHING WITH PULLEY HELD ACCOUNTABLE	PULLEY TEETH BLOCKED OR CLOGGED WITH CONTAMINANT PARTICLES, CHIPS, OR SHAVINGS PULLEY TEETH DAMAGED FROM IMPACTS WITH FOREIGN OBJECTS OR WEAR MISALIGNMENT CAUSING BELT TO TEND TO RIDE ON PULLEY FLANGES OR JUMP FROM PULLEY	LOSS OF 2 AXIS DRIVE AND HOLDING TORQUE ALLOWING 2 AXIS TO FALL POTENTIAL DAMAGE TO THE END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY POTENTIAL DAMAGE TO OTHER COMPONENTS NEAR THE PULLEY FROM CONTACT WITH LOOSE BELT	5.521E-02	\$411.19	\$2,001.88	\$149.88	3	\$2,582.95	\$142.60	TIGHTEN BELT ALIGNMENT, PULLEY TEETH SURFACE CONDITIONS, AND OBSTRUCTIONS OF PULLEY TEETH MESHING WITH BELT ARE THE KEY OPERATING PARAMETERS	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS OR CONTACT REC. 4 FOR PROVIDING OPERATOR POSITION VERIFICATION REC. 5 FOR ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 6 FOR ISOLATING BELT AND PULLEYS FROM ENVIRONMENT AND PROTECTING OTHER COMPONENTS FROM BROKEN OR FREE BELTS REC. 7 FOR PROVIDING FAILSAFE BRAKE DURING OPERATION AND STANDBY

2 AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION		FAILURE MODE CAUSE & EFFECT ANALYSIS		FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION				
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST (\$/EVENT)	TOTAL COST RISK (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	FAILURE MODE RECOMMENDED ACTIONS FOR FAILURE MODE
4.1	TYPING BELT	FAILS TO TRANSMIT POWER OR MOTION -- BROKEN BELT	EXCESSIVE TENSION IN BELT DUE TO OVERTENSIONED ADJUSTMENT, RELATIVE MOTION BETWEEN PULLEY CENTERS, OR EXTERNAL IMPACTS BELT FATIGUE DUE TO ALTERNATING STRESSES IN BELT PASSING AROUND PULLEYS FRICTIONAL WEAR OF BELT DUE TO DEFECTIVE PULLEY TEETH, LOW TENSION, EXTERNAL SOURCES OF CONTACT, OR BELT-PULLEY FLANGE FRICTION DUE TO MISALIGNMENT CORROSIVES IN CONTACT WITH BELT FROM PROCESS CHEMICALS, MAINTENANCE CHEMICALS OR SOLVENTS, LUBRICANTS, OR HIGH HUMIDITY CONTAMINANT PARTICLES, CHIPS, OR SHAVINGS LODGING IN BELT CAUSING STRESS RISERS OVERHEATING OF FELT DUE TO HIGH AMBIENT TEMPERATURES, FRICTIONAL HEATING, OR EXTERNAL HEAT SOURCES	LOSS OF 2 AXIS DRIVE AND HOLDING TORQUE ALLOWING 2 AXIS TO FALL POTENTIAL DAMAGE TO THE END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY POTENTIAL DAMAGE TO OTHER COMPONENTS NEAR THE PULLEY FROM CONTACT WITH BROKEN BELT	5.52E-02	\$675.75	\$2,495.30	\$229.14	4	\$3,398.19	\$198.66	BELT LIFE IS A STRONG FUNCTION OF BELT TENSION, FATIGUE EFFECTS, CORROSION AND EMBEDDED PARTICLES, TEMPERATURE, AND BELT OF EXTERNAL IMPACT OR SURFACE CONDITIONS. THESE SHOULD BE ADDRESSED IN DESIGN AND INSTALL./MAINT.	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACT OR CONTACT REC. 4 FOR PROVIDING OPERATOR POSITION VERIFICATION REC. 5 FOR ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 6 FOR ISOLATING BELT AND PULLEYS FROM ENVIRONMENT AND PROTECTING OTHER COMPONENTS FROM BROKEN OR FREE BELT REC. 7 FOR PROVIDING FAILSAFE BRAKE FOR SUPPORTING 2 AXIS DURING OPERATION OR STANDBY

Z AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION		FAILURE MODE CAUSE & EFFECT ANALYSIS		FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION			
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST RISK (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
A.2	TIMING BELT	FAILS TO TRANSMIT POWER OR MOTION -- LOSS OF MESHING WITH PULLEY AND BELT HELD ACCOUNTABLE	UNDERTENSION IN BELT DUE TO STRETCHING, MISADJUSTMENT, MOVEMENT BETWEEN PULLEY CENTERS, OR BELT FASTENER/TENSIONING DEVICE LOOSENING DAMAGED OR DEFECTIVE BELT TEETH FROM INSTALL./MAINT., MANUFACTURING, DEFECTIVE OR DAMAGED PULLEY TEETH, EXCESSIVE FRICTION, OR CORROSIVES/CONTAMINANTS	LOSS OF Z AXIS DRIVE AND HOLDING TORQUE ALLOWING Z AXIS TO FALL POTENTIAL DAMAGE TO THE END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY POTENTIAL DAMAGE TO OTHER COMPONENTS NEAR THE BELT FROM CONTACT WITH BROKEN OR FREE BELT	2.760E-01	\$587.56	\$2,462.63	\$209.39	A	\$3,259.78	BELT TENSION, CORROSION OR CONTAMINANT, BELT ALIGNMENT, AND BELT TEETH CONDITIONS ARE THE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN DAMAGE TO OTHER EQUIPMENT SHOULD BE CONSIDERED IF BELT IMPACT FORCES COULD CAUSE SOME EQUIPMENT AND PERSONNEL DAMAGE/INACCURACY; SENSING AND CONTROL EQUIPMENT ARE COMMON EXAMPLES	REC. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS OR CONTACT REC. 4 FOR PROVIDING OPERATOR POSITION VERIFICATION REC. 5 FOR ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 6 FOR ISOLATING BELTS AND PULLEYS FROM ENVIRONMENT AND PROTECTING COMPONENTS FROM BROKEN OR FREE BELT REC. 7 FOR PROVIDING FAULTSAFE BRAKE DURING OPERATION AND STANDBY

2 AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION			FAILURE MODE CAUSE & EFFECT ANALYSIS		FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION			
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST RISK (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE	
A.3	TYPING BELT	LOSS OF POSITION ACCURACY	OVERSTRESSES FROM OVERTENSIONING OF IMPACT LOADING RESULTING IN LOCAL YIELDING AND ELONGATION FRICTIONAL WEAR OF BELT DUE TO DEFECTIVE PULLEY TEETH, LOW TENSION, EXTERNAL SOURCES OF CONTACT, OR BELT-PULLEY FLANGE FRICTION FROM MISALIGNMENT UNDERTENSIONING RESULTING IN INACCURATE MESHING (BUT NOT SEPARATION) BETWEEN BELT AND PULLEY INCOMPATIBLE THERMAL EXPANSION BETWEEN PULLEY TEETH AND BELT TEETH YIELDING BACKLASH IN MOVEMENT IN HIGH ACCURACY REQUIREMENT CONDITIONS CORROSION OR CONTAMINANTS MESHED IN BELT WHICH DEGRADE BELT TEETH OR INTERFERE WITH MESHING	LOST OR REDUCED POWER TRANSMISSION CAPABILITY CAUSES LOSS OF POSITION CONTROL. POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	1.104E-02	\$323.00	\$1,771.40	\$150.12	3	\$2,244.52	\$24.78	THE INACCURACY INCURRED BY THIS FAILURE WILL NOT BE CUMULATIVE UNLESS GROSS ERRORS EXIST BELT TENSION, BELT ALIGNMENT, AND PULLEY OR BELT TEETH CONDITIONS FROM WEAR, CORROSION OR TYPEBED PARTICLES, OR THERMAL EXPANSIONS ARE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 6 FOR ISOLATING BELT AND PULLEYS FROM ENVIRONMENT AND PROTECTING OTHER COMPONENTS FROM BROKEN OR FREE BELT REC. 8 FOR USING A ROBOT POSITION VERIFICATION SYSTEM TO MAINTAIN ACCURACY

2 AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION		FAILURE MODE CAUSE & EFFECT ANALYSIS		FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION				
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST (\$/EVENT)	TOTAL COST RISK (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
4.4	TIRING BELT	FAILS TO TRANSMIT POWER -- BELT PARTNER FAILS	FATIGUE FAILURE DUE TO ALTERNATING TENSILE STRESSES IN BELT OVERSTRESS IN PARTNER DUE TO OVERTENSION IN BELT OR IMPACT LOADING AT OPERATING TEMPERATURES AND ENVIRONMENTS CORROSIVES IN CONTACT WITH PARTNER FROM PROCESS CHEMICALS, MAINTENANCE CHEMICALS OR SOLVENTS, AND HUMIDITY	LOSS OF 2 AXIS DRIVE AND HOLDING TORQUE ALLOWING 2 AXES TO FALL POTENTIAL DAMAGE TO THE END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY POTENTIAL DAMAGE TO OTHER COMPONENTS NEAR THE BELT FROM CONTACT WITH FREE BELT	2.20E-02	9175.75	42,493.30	4229.14	4	45,598.19	979.45	PARTNER FATIGUE, CORROSION, AND IMPACT DAMAGE ARE THE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN	REC. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTIVE SOURCES OF EXTERNAL IMPACTS OR CONTACT RECS. 4 AND 5 FOR PROVIDING OPERATOR VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 6 FOR ISOLATING BELT AND PULLEYS FROM ENVIRONMENT AND PROTECTING OTHER COMPONENTS FROM FREE BELT REC. 7 FOR PROVIDING FAILSAFE BRAKE DURING OPERATION AND STANDBY

2 AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION		FAILURE MODE CAUSE & EFFECT ANALYSIS			FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION		
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST RISK (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
2.1	DRIVE PULLEY	FAILS TO TRANSMIT POWER OR MOTION -- PULLEY FAILURE	IMPACTS ON PULLEY OR PULLEY TEETH FROM FOREIGN OBJECTS CORROSIVES IN CONTACT WITH PULLEY FROM PROCESS CHEMICALS, MAINTENANCE CHEMICALS OR SOLVENTS, OR HIGH HUMIDITY FATIGUE FAILURE DUE TO ALTERNATING STRESSES RESULTING FROM PULLEY MISALIGNMENT BENDING LOADS	LOSS OF 2 AXIS DRIVE AND HOLDING TORQUE ALLOWING 2 AXIS TO FALL POTENTIAL DAMAGE TO THE END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY POTENTIAL DAMAGE TO OTHER COMPONENTS NEAR THE PULLEY FROM CONTACT WITH BROKEN PULLEY OR LOOSE BELT	1.152E-04	\$675.75	\$2,493.30	\$229.14	4	\$3,398.19	THE CAUSES FOR THIS EVENT MAY ALSO CAUSE PULLEY SHAFT OR BEARING FAILURES OR DAMAGE IMPACTS, CORROSION, OBSTRUCTIONS ON TEETH, AND FATIGUE ARE THE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN REC. 6 FOR ISOLATING BELTS AND PULLEYS FROM ENVIRONMENT AND PROTECTING OTHER COMPONENTS FROM BROKEN OR FREE BELT REC. 7 FOR PROVIDING FAIRSAFE BRAKE DURING OPERATION AND STANDBY	REC. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS REC. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 6 FOR ISOLATING BELTS AND PULLEYS FROM ENVIRONMENT AND PROTECTING OTHER COMPONENTS FROM BROKEN OR FREE BELT REC. 7 FOR PROVIDING FAIRSAFE BRAKE DURING OPERATION AND STANDBY

Z AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION		FAILURE MODE CAUSE & EFFECT ANALYSIS			FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION			
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST (\$/EVENT)	TOTAL COST RISK (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
5.2	DRIVE PULLEY	FAILS TO TRANSMIT POWER OR MOTION -- LOSS OF SHAFT TO PULLEY COUPLING	FAILURE OF COUPLING DEVICE MECHANISM DUE TO FATIGUE, EXCESSIVE LOADS, WEAR, OR CORROSION	EARLY STAGES -- RESULTS IN ACCURACY PROBLEMS, DEGRADED POWER TRANSMISSION, AND VIBRATION	1.152E-01	\$675.75	\$2,493.30	\$229.14	4	\$3,598.19	\$414.51	SET SCREWS ARE HIGHLY UNRELIABLE, ESPECIALLY IN REVERSING LOAD APPLICATIONS	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN
			LOOSENING OF COUPLING DEVICE DUE TO REVERSING LOADS, WEAR OF COUPLING DEVICE, OR THERMAL EXPANSION OF INTERFERENCE FITS	LOSS OF Z AXIS DRIVE AND HOLDING TORQUE ALLOWING Z AXIS TO FALL								HOLDING PRESSURE, WEAR, CORROSION, FATIGUE, AND THERMAL EXPANSIONS ARE THE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN	REC. 3 FOR RESTRICTIVE SOURCES OF EXTERNAL IMPACTS
				POTENTIAL DAMAGE TO THE END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY									REC. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL
													REC. 6 FOR ISOLATING BELT AND PULLEYS FROM ENVIRONMENT AND PROTECTING OTHER COMPONENTS FROM BROKEN OR FREE BELT
													REC. 7 FOR PROVIDING FAILSAFE BRAKE DURING OPERATION AND STANDBY
													REC. 8 FOR USING A ROBOT POSITION VERIFICATION SYSTEM TO MAINTAIN ACCURACY

Z AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION		FAILURE MODE CAUSE & EFFECT ANALYSIS			FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION		
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST RISK (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
5.3	DRIVE PULLEY	FAILS TO TRANSMIT POWER OR MOTION -- LOSS OF PULLEY TO BELT MESHING WITH PULLEY HELD ACCOUNTABLE	PULLEY TEETH RUCCED OR CLOSED WITH CONTAMINANT PARTICLES, CHIPS, OR SHAVINGS PULLEY TEETH DAMAGED FROM IMPACTS WITH FOREIGN OBJECTS OR WEAR MISALIGNMENT CAUSING BELT TO TEND TO RIDE ON PULLEY FLANGES OR JUMP FROM PULLEY	LOSS OF Z AXIS DRIVE AND HOLDING TORQUE ALLOWING Z AXIS TO FALL POTENTIAL DAMAGE TO THE END EFFECTOR, EQUIPMENT AND PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY POTENTIAL DAMAGE TO OTHER COMPONENTS NEAR THE PULLEY FROM CONTACT WITH FREE BELT	5.76E-02	6465.75	42,493.30	829.14	4	43,588.19	PULLEY TEETH CONDITIONS FROM WEAR, CORROSION, OR BLOCKAGE ALONG WITH MISALIGNMENTS ARE THE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS RECS. 4 AND 5 FOR PROVIDING OPERATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 6 FOR ISOLATING BELTS AND PULLEYS FROM ENVIRONMENT AND PROTECTING OTHER COMPONENTS FROM BROKEN OR FREE BELT REC. 7 FOR PROVIDING FAILSAFE BRAKE DURING OPERATION AND STANDBY

Z AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION			FAILURE MODE CAUSE & EFFECT ANALYSIS		FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION		
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST RISK (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
5.1	GUIDE TUBE	FAILS TO PROVIDE SUPPORT BECAUSE OF FRACTURE	COMBINED LOADING OF BENDING, TORSIONAL, SHEAR, AND AXIAL STRESS CAUSING YIELDING AND EVENTUALLY FRACTURE. SOURCES OF LOADS ARE OPERATING LOADS, MISALIGNMENTS, THERMAL EXPANSIONS, VIBRATIONS, AND EXTERNAL LOADS	LOSS OF Z AXIS DRIVE AND HOLD CAPABILITY ALLOWING Z AXIS TO FALL POTENTIAL DAMAGE TO THE END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, ANY/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	5.67E-04	\$710.75	\$6,018.30	\$274.14	5	\$7,003.19	IMPACTS, BENDING LOADS, FATIGUE EFFECTS, AND CORROSION ARE THE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS RECS. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 6 FOR PROVIDING FAILSAFE BRAKE DURING OPERATION AND STANDBY REC. 10 FOR USING BELLOW ON THE GUIDE TUBE TO PROTECT SURFACE AND LINEAR BALL RUSHING
6.2	GUIDE TUBE	ALLOWS EXCESSIVE RADIAL MOTION	DRIVEN AT RESONANT FREQUENCY EXCESSIVE CLEARANCE OR TOLERANCE BUILD-UP AT BALL RUSHING DIFFERENTIAL THERMAL EXPANSION WITH BEARING OUT OF SPEC. TUBING USED	INACCURATE POSITION CONTROL PRODUCING DEFECTIVE PARTS CAUSES INCREASED WEAR ON GUIDE TUBE, BEARING WEAR AND IMPACTS, AND ADDITIONAL BELT FORCES	1.22E-03	\$358.00	\$5,096.40	\$195.12	2	\$5,649.52	IMPROPER INSTALL./MAINT., THERMAL EXPANSION EFFECTS, AND TOLERANCE BUILD-UPS ARE THE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN	REC. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 7 FOR PROVIDING FAILSAFE BRAKE DURING OPERATION AND STANDBY

Z AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION			FAILURE MODE CAUSE & EFFECT ANALYSIS		FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION						FAILURE MODE EVALUATION	
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST RISK (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
6.3	GUIDE TUBE	FAILS TO PROVIDE SMOOTH, UNIFORM GUIDE SURFACE	SURFACE DEFORMATION TO GUIDE TUBE DURING INSTALL./MAINT. OR DUE TO YIELDING FROM OPERATION IMPACTS OR LOADS SURFACE DAMAGE DUE TO INSTALL./MAINT. CHIPPING OR KNICKS, OR DUE TO DAMAGE DUE TO IMPACTS DURING OPERATION	LOST OR DEGRADED POWER TRANSMISSION CAPABILITY CAUSES LOSS OF POSITION CONTROL ACCURACY. POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	1.22E-01	\$594.38	\$5,557.35	\$234.63	3	\$6,326.36	ANY IMPACTS, SCRATCHING, CHIPPING, OR WEAR OF GUIDE TUBE SURFACE ALONG WITH MAINTAINING STRAIGHTNESS OF TUBE ARE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN SURFACE DAMAGE TO GUIDE TUBE ALSO ALLOWS BALL BUSHING DAMAGE	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS RECS. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 8 FOR USING A ROBOT POSITION VERIFICATION SYSTEM TO MAINTAIN ACCURACY REC. 10 FOR USING BELLGOWS ON GUIDE TUBE TO PROTECT SURFACE AND LINEAR BALL BUSHING

2 AXIS ROTATION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION			FAILURE MODE CAUSE & EFFECT ANALYSIS			FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION	
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST RISK (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
6.4	GUIDE TUBE	GUIDE TUBE BROOVE FAILS TO MAINTAIN ROTARY COUPLING	BROOVE DAMAGED BY IMPACTS DURING INSTALL./MAINT. OR OPERATION, EXCESSIVE WEAR FROM HIGH RADIAL LOADS, OR CORROSION BROOVE DIMENSIONS CHANGE EXCESSIVELY DURING TEMPERATURE CHANGES DEFECTIVE BROOVE INITIALLY ON TUBE	LOSS OF ROTARY POSITION CONTROL OF 2 AXIS PRODUCING DEFECTIVE PARTS POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	1.252E-03	\$569.45	\$5,449.54	\$242.53	3	\$6,441.72	98.09 THE BROOVE FIT WITH THE BALLS IN THE LINEAR BALL BUSHING IS THE KEY OPERATING PARAMETER. IT SHOULD BE INSURED IN INSTALL./MAINT. AND DESIGN REC. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS AND CONTACT REC. 8 FOR USING A ROBOT POSITION VERIFICATION SYSTEM TO MAINTAIN ACCURACY REC. 10 FOR USING BELLOWS ON THE GUIDE TUBE TO PROTECT THE SURFACE AND LINEAR BALL BUSHING	

Z AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION		FAILURE MODE CAUSE & EFFECT ANALYSIS			FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION				
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST (\$/EVENT)	TOTAL COST RISK (\$/YR)	FAILURE MODE COMMENTS	FAILURE MODE	RECOMMENDED ACTIONS FOR FAILURE MODE
7.1	THOMPSON LINEAR BALL BUSHING	FAILS TO ALLOW FREE LINEAR MOTION	LUBRICATION FAILURE DUE TO INCORRECT OR INSUFFICIENT LUBRICATION; CORROSION OR CONTAMINATION; HIGH TEMPERATURE EFFECTS; OR MIGRATION	LOST OR REDUCED POWER TRANSMISSION CAPABILITY CAUSES POSITION CONTROL INACCURACY. POTENTIAL DAMAGES TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	1.200E-02	\$597.56	\$3,162.63	\$269.39	4	\$4,029.78	\$48.36	BEARING ORIENTATION MUST BE MAINTAINED SUCH THAT LOAD IS APPLIED HALF WAY BETWEEN ADJACENT BALL TRACKS	REC. 10 FOR USING BELLWORM GUIDE TUBE TO PROTECT SURFACE AND LINEAR BALL	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN
			INSUFFICIENT INTERNAL CLEARANCE DUE TO INCORRECT FITS CAUSING BINDING OR DEFLECTIONS; OR THERMAL EXPANSION	MAY CAUSE OVERLOAD DAMAGE TO DRIVE MECHANISM OR DRIVE TRAIN								BEARING USE IS A SCIENCE WITHIN ITSELF -- CONSULT MANUFACTURER SPECIFICATIONS FOR DETAILS OR SOURCES SUCH AS SKF SERVICE GUIDE BOOKLET	REC. 11 FOR USING NO MAINTENANCE BEARINGS OR, IF NECESSARY, PROVIDING EASY RE-LUBRICATION	
			DAMAGE TO RACES FROM MISALIGNMENT OR OVERLOAD; IMPACT LOADING, WEAR FROM EXCESSIVE FRICTION; OR DEFECTIVE HOUSINGS	POTENTIAL GUIDE SHAFT DAMAGE								LUBRICATION, APPLIED LOADS, DESIGN LIFE, AND MOUNTING FITS ARE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN		
			USAGE IN EXCESS OF DESIGNED AND EXPECTED LIFE											
			EXCESSIVE TIGHTNESS OF ADJUSTABLE RACE USED FOR TORQUE CONTROL											

2 AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION			FAILURE MODE CAUSE & EFFECT ANALYSIS		FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION		
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST RISK (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
7-2	THOMPSON LINEAR BALL BUSHING	FAILS TO MAINTAIN ROTATIONAL COUPLING WITH SHAFT	SET SCREW AND RESTRAINING NUT LOOSENS DURING OPERATION SET SCREW ADJUSTMENT NOT TORQUED HIGH ENOUGH ALLOWING BALLS TO LEAVE SHAFT GROOVE	LOSS OF ROTARY POSITION CONTROL OF Z AXIS PRODUCING DEFECTIVE PARTS POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	2.400E-02	\$524.65	\$2,149.54	\$182.53	3	\$2,854.72	ALIGNING BEARING WITH SHAFT GROOVE AND ESTABLISHING PROPER TORQUE FOR SET SCREW ARE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS REC. 7 FOR PROVIDING FAILSAFE BRAKE DURING OPERATION AND STANDBY
8-1	Z SUPPORT PLATFORM	FAILS TO PROVIDE STRUCTURAL SUPPORT AND ACCURACY OF PLACEMENT	PLATFORM ALTERNATING STRESS FATIGUE, CORROSION, OR OVERSTRESS DUE TO IMPACT LOADING OF SYSTEM EXTERNAL IMPACTS ON PLATFORM DEFORMATION IN SHAPE DUE TO LOADS OR CORROSION	LOSS OF Z AXIS DRIVE AND HOLDING TORQUE ALLOWING Z AXIS TO FALL POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	8.702E-04	\$745.75	\$6,543.30	\$319.14	5	\$7,628.19	IMPACTS, FATIGUE, AND CORROSION ARE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS RECS. 4 AND 5 FOR PROVIDING OPERATION POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL
8-2	Z SUPPORT PLATFORM	FAILS TO RESTRAIN BEARINGS	EXCESSIVE THERMAL DIFFERENTIAL EXPANSION OUT OF ROUND BEARING HOUSINGS INCORRECTLY MOUNTED BEARINGS	INACCURATE POSITION PLACEMENT RESULTING IN DEFECTIVE PARTS	1.104E-04	\$413.00	\$5,421.40	\$240.12	3	\$6,274.52	THERMAL EXPANSION, MANUFACTURING, AND INSTALL./MAINT. ARE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 7 FOR PROVIDING FAILSAFE BRAKE DURING OPERATION AND STANDBY

2 AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION		FAILURE MODE CAUSE & EFFECT ANALYSIS		FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION				
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST (\$/EVENT)	TOTAL COST RISK (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
9.1	STEPPER MOTOR DRIVER/CONTROLLER FAILS OFF -- CONTROLLER FAILURE		INSTALLATION OR MAINTENANCE ERROR FROM CROSSING WIRING, SHIFTING CONNECTORS, OR SOLDERING RESISTORS, OR REVERSING THE INPUT AND OUTPUT	LOSS OF COMMAND TO DRIVE SYSTEM RESULTING IN LOSS OF DRIVE POWER OR MOTION TO SYSTEM	5.257E-02	\$765.75	\$5,453.30	\$229.14	4	\$6,488.19	\$341.08	PROPER INSTALL./MAINT., PROTECTING CONNECTIONS AND WIRES FROM CORROSION, IMPACTS, HIGH TEMPERATURES, AND MOTION ARE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN THE INSTALL./MAINT. AND DESIGN	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS RECS. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND FOR ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 7 FOR PROVIDING FAILSAFE BRAKE DURING OPERATION AND STANDBY REC. 8 FOR USING A ROBOT POSITION VERIFICATION SYSTEM TO MAINTAIN ACCURACY REC. 12 FOR USING CURRENT REGULATION DEVICE TO PREVENT MOTOR OR MOTOR DRIVER OVERLOADS REC. 13 FOR ISOLATING WIRING, CONNECTORS, AND MOTOR DRIVER UNIT FROM ENVIRONMENT CONDITIONS, IMPACTS, AND STRAY ELECTRICAL OR MAGNETIC FIELDS

2 AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION		FAILURE MODE CAUSE & EFFECT ANALYSIS			FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION			
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST (\$/EVENT)	TOTAL COST RISK (\$/YR)	FAILURE MODE COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
9.2	STEPPER MOTOR DRIVER	ISSUES INCORRECT COMMAND TO MOTOR	INSTALLATION OR MAINTENANCE ERROR WHICH REVERSES DIRECTION OF MOTOR OR CONNECTS WRONG MOTOR TO CONTROLLER	INACCURATE POSITION CONTROL. POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	6.00E-02	\$595.20	\$2,506.92	\$213.34	4	\$2,317.46	\$199.08	INSTALL./MAINT. ARE THE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED BY INSTALL./MAINT. PROCEDURES	REC. 1 FOR INSTALL./MAINT. RECS. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL
			INSUFFICIENT SETTLING TIME BEFORE REVERSING DIRECTIONS OF MOTOR									RECOGNIZE LIMITATIONS IMPOSED ON SYSTEM BY DRIVER SPECS. SUCH AS SETTLING TIMES AND RESPONSE TIMES	REC. 13 FOR ISOLATING WIRING, CONNECTORS, AND MOTOR DRIVER FROM ENVIRONMENTAL CONDITIONS, IMPACTS, AND STRAY ELECTRIC OR MAGNETIC FIELDS
10.1	12.1 AMP STEPPER MOTOR	FAILS TO PROVIDE COMMANDED TORQUE OR MOTION -- PRIMARY MOTOR FAILURE	MOTOR BEARING FAILURE DUE TO EXCESSIVE LOADS, LUBRICATION MIGRATION OR CONTAMINATION, OR WEAR INTERNAL WINDING FAILURE FROM OVERHEATING, EXCESSIVE CURRENT OR SURGES, MECH. SHOCKS OR VIBRATIONS, OR WINDING CORROSION DEFECTIVE STEPPER MOTOR FROM MANUFACTURER	LOSS OF 2 AXIS DRIVE AND HOLDING TORQUE ALLOWING 2 AXIS TO FALL POTENTIAL DAMAGE TO THE END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	1.200E-02	\$765.75	\$5,493.30	\$229.14	4	\$6,488.19	\$77.86	BEARING LIFE, CORROSIVES AND CONTAMINATE, OVERHEATING, AND EXCESSIVE CURRENT ARE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN RECS. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 7 FOR PROVIDING FAILSAFE BRAKE DURING OPERATION AND STANDBY REC. 6 FOR USING A ROBOT POSITION VERIFICATION SYSTEM TO MAINTAIN ACCURACY REC. 12 FOR REGULATING CURRENT IN CIRCUIT

Z AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION		FAILURE MODE CAUSE & EFFECT ANALYSIS			FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION				FAILURE MODE EVALUATION			
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST RISK (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	FAILURE MODE RECOMMENDED ACTIONS FOR FAILURE MODE
10.2	2.1 AMP STEPPER MOTOR	FAILS TO PROVIDE COMMAND TORQUE OR MOTION — SECONDARY MOTOR FAILURE	REQUIRED TORQUE BEYOND FULL-IN TORQUE FOR STARTING OR FULL-OUT TORQUE FOR CURRENT SPEED REQUIRED TORQUE TO MAINTAIN ZERO MOTION BEYOND MAXIMUM HOLDING TORQUE LOSS OF FORWARD POWER FROM MOTOR DRIVER DUE TO IMPACTS AND CORROSION OF CONNECTORS RESTRICTED DRIVE TRAIN DUE TO FOREIGN OBJECT INTERFERENCE OR DRIVE TRAIN FAILURES INSTALLATION AND MAINTENANCE ERRORS IN WIRING MOTOR	LOSS OF DRIVE POWER OR MOTION OR HOLDING TORQUE TO SYSTEM POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY WIRING ERRORS MAY CAUSE NO MOTION BUT ALSO MAY CAUSE REVERSED MOTION	1.200E-01	\$595.20	\$2,508.92	\$213.34	3	\$3,317.46	TORQUE AND SPEED LIMITATIONS SHOULD BE OBSERVED WITH ACCELERATION RAMPING EXCESSIVE LOADS AND CORROSIVES OR CONTAMINANTS ARE KEY AND FOR ISOLATING OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN REC. 4 AND 5 FOR PROVIDING OPERATION VERIFICATION AND FOR ISOLATING EQUIPMENT AND PERSONNEL REC. 7 FOR PROVIDING FAILSAFE BRAKE DURING OPERATION AND STANDBY REC. 8 FOR USING A ROBOT POSITION VERIFICATION SYSTEM TO MAINTAIN ACCURACY	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN RECS. 4 AND 5 FOR PROVIDING OPERATION VERIFICATION AND FOR ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 7 FOR PROVIDING FAILSAFE BRAKE DURING OPERATION AND STANDBY REC. 8 FOR USING A ROBOT POSITION VERIFICATION SYSTEM TO MAINTAIN ACCURACY
10.3	2.1 AMP STEPPER MOTOR	INACCURATE POSITIONING	EXCESSIVE ACCELERATION AND/OR DECELERATION RESONANCE VIBRATION OF STEPPER MOTOR MOTOR OR STATOR DAMAGE OR DEFECT IMPACTS OF HIGH LOADS IN OPERATING REGIONS WHICH CAUSE LOSS OF STEPS	INACCURATE POSITION CONTROL. POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	4.001E-02	\$448.28	\$4,463.59	\$158.02	3	\$5,219.89	THESE SOURCES OF INACCURACY ARE CUMULATIVE STEPPER MOTORS HAVE RESONANT FREQUENCIES WHICH PRODUCE VIBRATION AND LOSS OF STEPPING MOTION RAMPING OF ACCELERATION AND DECELERATION IS USED TO AVOID MISSING STEPS. THE RAPPS ARE DEPENDENT ON MASS AND FRICTION IN SYSTEM	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS RECS. 4 AND 5 FOR PROVIDING OPERATION VERIFICATION AND FOR ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 8 FOR USING A ROBOT POSITION VERIFICATION SYSTEM TO MAINTAIN ACCURACY
										\$316.25		

X-Y AXIS MOTION SUB-SYSTEM FMEA TABLES FOR CASE STUDY

1-Y AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION		FAILURE MODE CAUSE & EFFECT ANALYSIS			FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION		
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST RISK (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
1.1	STATIONARY GUIDE TUBES (QTY. 4)	FAILS TO PROVIDE SUPPORT DUE TO FRACTURE OF GUIDE TUBES	COMBINED LOADING OF BENDING, TORSIONAL, SHEAR, AND AXIAL STRESS CAUSING YIELDING AND EVENTUALLY FRACTURE. SOURCES OF LOADS ARE OPERATING LOADS, MISALIGNMENTS, THERMAL EXPANSIONS, VIBRATIONS, AND EXTERNAL LOADS	LOSS OF DRIVE GUIDANCE AND SUPPORT TO TRANSLATING TUBES AND SLIDER UNITS POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OF INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	3.433E-03	\$706.75	\$5,845.30	\$259.14	4	\$6,803.19	A FULL SPECIFICATION OF SHFT MATERIAL, MATERIAL PROCESSING, FINISHING, IN ADDITION TO PROPER TOLERANCES AND STRENGTHING IS REQUIRED	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN
			FATIGUE FAILURE OF SHFT DUE TO ALTERNATING TENSILE LOADING								LIMIT STRESS CONCENTRATION FACTORS TO MAINTAIN FATIGUE STRENGTH	REC. 10 FOR USING BELLINGS ON GUIDE TUBE TO PROTECT SURFACE
			WEAR FACTORS CONTRIBUTING TO STRESS CONCENTRATION FACTORS OR DECREASED STRENGTHS OF THE MATERIAL								THE EFFECTS OF COMBINED LOADING, FATIGUE, STRESS CONCENTRATIONS, SURFACE WEAR AND DAMAGE, CORROSION, AND ALIGNMENT ALONG DESIRED PATH ARE THE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN	REC. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL
			CORROSION OF MATERIAL LEADING TO FRACTURES									REC. 8 FOR USING A ROBOT POSITION VERIFICATION SYSTEM TO MAINTAIN ACCURACY
			EXTERNAL IMPACT LOADS INTO GUIDE SHFT									
			MATERIAL DEFECTS FROM MANUFACTURING PROCESS OF VOIDS IN MATERIAL, SURFACE SCRATCHES OR DAMAGE DURING MACHINING, IMPROPER HEAT TREAT, OR UNEXPECTED INTERNAL STRESSES CREATED									

3-Y AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION		FAILURE MODE CAUSE & EFFECT ANALYSIS			FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION				FAILURE MODE EVALUATION				
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST (\$/EVENT)	TOTAL COST RISK (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
1.1.2	STATIONARY GUIDE TUBES (QTY. 4)	FAILS TO PROVIDE DESIRED GUIDE PATH ACCURATELY	INSTALL./MAINT. ERRORS SUCH AS MOUNTING IN A STRESSED CONFIGURATION OR SHAPE DAMAGE TO GUIDE TUBE MANUFACTURING DEFECTS SUCH AS TAPERS OR DRIFTS IN CUTTING TUBE DEFORMATIONS DUE TO EXTERNAL IMPACTS OR COMBINED STRESS LOADING	CAUSES INACCURATE PLACEMENT. POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY MAY CAUSE BINDING OF TRANSLATING GUIDE TUBE	4.60E-03	1485.10	45,290.16	4211.73	3	45,990.99	\$27.61	HIGH QUALITY PARTS AND VERIFIED INSTALL./MAINT. IN ADDITION TO EXTERNAL IMPACTS ARE THE KEY OPERATING PARAMETERS	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS RECS. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 6 FOR USING A ROBOT POSITION VERIFICATION SYSTEM TO MAINTAIN ACCURACY
1.3	STATIONARY GUIDE TUBES (QTY. 4)	FAILS TO PROVIDE SMOOTH, UNIFORM GUIDE SURFACE	SURFACE DAMAGE DUE TO INSTALL./MAINT. CHIPPING OR KNICKS SURFACE DAMAGE DUE TO EXTERNAL IMPACTS OR FRICTIONAL WEAR SURFACE DAMAGE DUE TO CORROSIVES OR ABRASIVES CONTACTING THE GUIDE TUBE FROM PROCESS OR MAINTENANCE CHEMICALS AND ABRASIVES OR HUMIDITY INCORRECT SURFACE HARDNESS OR PLATING FOR CONDITIONS	LOST OR DEGRADED POWER TRANSMISSION CAPABILITIES CAUSING PLACEMENT INACCURACY WILL LIKELY CAUSE DESTRUCTION OF LINEAR BALL RUSHING IN SLIDER MOVING POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	4.60E-01	1524.38	45,382.25	4219.63	3	46,126.36	\$2,623.64	ANY IMPACTS, SCRATCHING, CHIPPING, OR WEAR OF GUIDE TUBE WARE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. SURFACE DAMAGE TO GUIDE TUBE MAY ALSO ALLOW DAMAGE TO GUIDED OBJECT	RECS. 1 AND 2 FOR INSTALL./MAINT. REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS REC. 10 FOR USING PROTECTIVE COVER FOR GUIDE SHAFT TO PROTECT SURFACE RECS. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL

1-Y AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION		FAILURE MODE CAUSE & EFFECT ANALYSIS		FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION			
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST RISK (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
2.1	CORNER BRACKET SUPPORTS (QTY. 4)	FAILS TO PROVIDE STRUCTURAL SUPPORT	COMBINED NORMAL, SHEAR, BENDING, AND TORSIONAL STRESSES IN EXCESS OF MATERIAL STRENGTH FATIGUE FAILURE DUE TO ALTERNATING STRESSES FROM VIBRATIONS AND LOAD APPLICATIONS CORROSION DUE TO PROCESS OR MAINTENANCE CHEMICALS OR LUBRICANTS OR DUE TO HUMIDITY EXTERNAL IMPACTS FROM WITHIN OR OUTSIDE THE ROBOT WORKSPACE DEFECTIVE MATERIAL, CASTING, OR MACHINING OPERATIONS WHICH REDUCE THE STRENGTH OF THE PART INSTALL./MAINT. ERRORS WHICH MOUNT THE CORNER BRACKET UNDER A LARGE PRE-LOAD	EXCESS POSITIONING ERRORS AND LOSS OF SUPPORT FOR STATIONARY GUIDE TUBES, SLIDERS, AND 2 PLATFORM POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	3.462E-03	\$740.75	\$5,843.30	\$259.14	4	\$6,843.19	EFFECTS OF COMBINED STRESSES, CORROSION RESISTANCE, FATIGUE STRENGTH WITH STRESS CONCENTRATIONS, MATERIAL QUALITY, AND UNSTRESSED MOUNTING ARE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN RECS. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ERROR FROM OTHER EQUIPMENT AND PERSONNEL REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS REC. 6 FOR USING A ROBOT POSITION VERIFICATION SYSTEM TO MAINTAIN ACCURACY

1-Y AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION		FAILURE MODE CAUSE & EFFECT ANALYSIS		FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION			
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
2.2	CORNER BRACKET SUPPORTS (QTY. 4)	FAILS TO MAINTAIN PLACEMENT ACCURACY STATIONARY GUIDE TUBES AND PULLEY DRIVE SHAFT BEARINGS	IMPROPER FITS WHICH ALLOW FRICTIONAL WEAR OF CORNER BRACKET SEATS CORNER BRACKET SEATS FROM MANUFACTURING PROCESS LOCAL YIELDING, CRACKING, OR DEFORMATION AROUND CORNER BRACKET SEATS FROM HIGH STRESS OR CORROSIVE CONDITIONS LARGE SCALE DEFORMATION OF CORNER BRACKET FROM STRESS CONDITIONS OR EXTERNAL IMPACTS ON CORNER BRACKET OR ON SUPPORTED COMPONENTS	ALLOWS INACCURATE POSITIONING OF SLIDERS OR IMPROPER TENSIONING AND ALIGNMENT OF TITING BELTS POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	4.417E-02	\$476.19	\$5,151.88	\$199.88	3	\$5,827.95	IMPACT LOADS, LOCAL STRESS CONDITIONS, AND INITIAL QUALITY FROM MANUFACTURE AND INSTALL./MAINT. ARE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN IF THE STATIONARY GUIDE TUBES ARE MOUNTED WITH CLEARANCE FITS, THIS COULD BE AN IMPORTANT EVENT	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS RECS. 4 AND 5 FOR PROVIDING OPERATION POSITION VERIFICATION FROM OTHER EQUIPMENT AND PERSONNEL REC. 6 FOR USING A ROBOT POSITION VERIFICATION SYSTEM TO MAINTAIN ACCURACY

1-Y AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION		FAILURE MODE CAUSE & EFFECT ANALYSIS		FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION				FAILURE MODE EVALUATION				
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST RISK (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	FAILURE MODE RECOMMENDED ACTIONS FOR FAILURE MODE
3.1	SLIDER HOUSINGS (C7, 4)	FAILS TO PROVIDE STRUCTURAL SUPPORT	COMBINED LOADING DUE TO NORMAL, SHEAR, BENDING, AND TORSIONAL STRESSES ALTERNATING STRESSES LEADING TO FATIGUE FAILURE WITH STRESS CONCENTRATIONS CORROSION DUE TO PROCESS OR MAINTENANCE CHEMICALS OR LUBRICANTS OR DUE TO HUMIDITY EXTERNAL IMPACTS TO THE SLIDER HOUSING FROM OUTSIDE OR INSIDE OF THE ROBOT WORKSPACE FRICTIONAL WEAR AT SEATS FOR TRANSLATING GUIDE TUBES DUE TO CLEARANCE FITS CAUSE STRESS RISERS	LOSS OF SUPPORT TO THE TRANSLATING GUIDE ROD AND/OR LOSS OF POSITION DRIVE POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	3.7E-03	\$740.75	\$6,018.30	\$274.14	4	\$7,033.19	THE EFFECTS OF COMBINED LOADING, CORROSION RESISTANCE, FATIGUE, IMPACTS, AND FRICTIONAL WEAR ARE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL/MAINT. AND DESIGN	RECS. 1 AND 2 FOR INSTALL/MAINT. AND DESIGN REC. 3 FOR RESTRICTING THE SOURCES OF EXTERNAL IMPACTS RECS. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 8 FOR USING A ROBOT POSITION VERIFICATION SYSTEM TO MAINTAIN ACCURACY

1-Y AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION			FAILURE MODE CAUSE & EFFECT ANALYSIS		FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION			
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST (\$/EVENT)	TOTAL COST RISK (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
3-2	SLIDER HOUSINGS (87% 4)	FAILS TO MAINTAIN PLACEMENT ACCURACY OF LINEAR BALL BUSHINGS AND TRANSLATING GUIDE TUBES	LOCAL DEFORMATION DUE TO COMBINED STRESSES FROM NORMAL, SHEAR, BENDING, AND TORSIONAL STRESSES EXCESSIVE THERMAL DEFORMATIONS BETWEEN SLIDER HOUSING AND LINEAR BALL BUSHINGS AND TRANSLATING GUIDE TUBES DEFORMATIONS DUE TO EXTERNAL IMPACTS ON SLIDER HOUSINGS FOR OUTSIDE OR INSIDE OF ROBOT WORKSPACE CASTING, MANUFACTURING, OR INSTALL./MAINT. ERRORS	CAUSES INACCURATE POSITIONING OR DECREASED POWER TRANSMISSION CAPABILITIES POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	4.801E-02	\$544.38	\$5,557.35	\$234.43	3	\$6,356.36	\$305.17	THE EFFECTS OF COMBINED STRESSES, THERMAL DEFORMATIONS, EXTERNAL IMPACTS, AND PART QUALITY ARE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS RECS. 4 AND 5 FOR PROVIDING OPERATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 8 FOR USING A ROBOT POSITION VERIFICATION SYSTEM TO MAINTAIN ACCURACY

1-Y AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION			FAILURE MODE CAUSE & EFFECT ANALYSIS		FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION		
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSE	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST RISK (\$/YR)	FAILURE MODE COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
4.1	TRANSLATING GUIDE TUBES (QTY. 2)	FAILS TO PROVIDE STRUCTURAL SUPPORT DUE TO FRACTURE OF TUBE	COMBINED LOADING OF BENDING, TORSIONAL, SHEAR, AND AXIAL STRESS CAUSING YIELDING AND EVENTUALLY FRACTURE. SOURCES OF LOADS ARE OPERATING LOADS, MISALIGNMENTS, THERMAL EXPANSIONS, AND EXTERNAL LOADS	LOSS OF DRIVE GUIDANCE AND SUPPORT TO TRANSLATING ROD AND SLIDER HOUSING	2.057E-03	\$700.75	\$5,843.30	\$259.14	4	\$6,803.19	LIMIT STRESS CONCENTRATION FACTORS, ESPECIALLY AT HOLDING SURFACE WITH SLIDER	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN
				POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY							THE EFFECTS OF COMBINED STRESS LOADING, FATIGUE, STRESS CONCENTRATIONS, SURFACE WEAR AND DAMAGE, CORROSION, AND ALIGNMENT ARE THE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN	REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS
			FATIGUE FAILURE OF SHIRT DUE TO ALTERNATING TENSILE LOADING									RECS. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL
			WEAR FACTORS CONTRIBUTING TO STRESS CONCENTRATION FACTORS OR DECREASED STRENGTHS OF THE MATERIAL									REC. 8 FOR USING A ROBOT POSITION VERIFICATION SYSTEM TO MAINTAIN ACCURACY
			CORROSION OF MATERIAL LEADING TO FRACTURES									REC. 10 FOR USING BELLGWS ON GUIDE TUBES TO PROTECT SURFACE AND LINEAR BALL BUSHING
			EXTERNAL IMPACT LOADS INTO GUIDE SHAFT									
			MATERIAL DEFECTS FROM MANUFACTURING PROCESS OF HOLES IN MATERIAL, SURFACE SCRATCHES OR DAMAGE DURING MACHINING, IMPROPER HEAT TREATMENT, OR UNEXPECTED INTERNAL STRESSES CREATED									

1-Y AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION		FAILURE MODE CAUSE & EFFECT ANALYSIS			FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION			
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST (\$/EVENT)	TOTAL COST RISK (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	FAILURE MODE EVALUATION
4.2	TRANSLATING GUIDE TUBES (QTY. 2)	FAILS TO PROVIDE DESIRED GUIDE PATH ACCURATELY	INSTALL./MAINT. ERRORS SUCH AS MOUNTING IN A STRESSED DEFORMATION OR SHAPE DAMAGE TO GUIDE TUBE MANUFACTURING DEFECTS SUCH AS TAPERS OR DRAFTS IN CUTTING TUBE DEFORMATIONS DUE TO EXTERNAL IMPACTS OR COMBINED STRESS LOADING	CAUSES INACCURATE PLACEMENT. POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	2.609E-03	\$489.10	\$5,290.16	\$211.73	3	\$5,990.99	\$15.63	HIGH QUALITY PARTS AND VERIFIED INSTALL./MAINT. IN ADDITION TO EXTERNAL IMPACTS ARE THE KEY OPERATING PARAMETERS	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS RECS. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 8 FOR USING A ROBOT POSITION VERIFICATION SYSTEM TO MAINTAIN ACCURACY
4.3	TRANSLATING GUIDE TUBES (QTY. 2)	FAILS TO PROVIDE SMOOTH, UNIFORM GUIDE SURFACE	SURFACE DAMAGE DUE TO INSTALL./MAINT. CHIPPING OR KNOCKS SURFACE DAMAGE DUE TO EXTERNAL IMPACTS OR FRICTIONAL WEAR SURFACE DAMAGE DUE TO CORROSIVES OR ABRASIVES CONTACTING THE GUIDE TUBE FROM PROCESS OR MAINTENANCE CHEMICALS AND ABRASIVES OR HUMIDITY INCORRECT SURFACE HARDNESS OR PLATING FOR CONDITIONS	LOST OR DEGRADED POWER TRANSMISSION CAPABILITIES CAUSING PLACEMENT INACCURACY WILL LIKELY CAUSE DESTRUCTION OF LINEAR BALL BEARING IN SLIDER HOUSING POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	2.609E-01	\$524.28	\$5,382.35	\$219.63	3	\$6,126.36	\$1,598.37	ANY IMPACTS, SCRATCHING, CHIPPING, OR WEAR OF GUIDE TUBE ARE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. SURFACE DAMAGE TO GUIDE TUBE MAY ALSO ALLOW DAMAGE TO GUIDED OBJECT	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS RECS. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 10 FOR USING BELLGOWS ON GUIDE TUBES TO PROTECT SURFACE AND LINEAR BALL BEARING

1-Y AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION		FAILURE MODE CAUSE & EFFECT ANALYSIS		FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION			
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST RISK (\$/YR)	FAILURE MODE COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
5.1	THOMPSON LINEAR BALL BUSHINGS (QTY. 8)	FAILS TO ALLOW FREE LINEAR MOTION	LUBRICATION FAILURE DUE TO INCORRECT OR INSUFFICIENT LUBRICATION; CORROSION OR CONTAMINATION; HIGH TEMPERATURE EFFECTS; OR MISALIGNMENT	LOSS OF DRIVE POWER OR MOTION TO SYSTEM POTENTIAL GUIDE SHAFT DAMAGE MAY CAUSE OVERLOAD DAMAGE TO DRIVE MECHANISM OR DRIVE TRAIN POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	9.18E-02	\$597.56	\$2,967.63	\$254.39	3	43,639.78	BEARING ORIENTATION MUST BE MAINTAINED SUCH THAT LOAD IS APPLIED HALF WAY BETWEEN ADJACENT BALL TRACKS BEARING USE IS A SCIENCE WITHIN ITSELF -- CONSULT MANUFACTURER SPECIFICATIONS FOR DETAILS OR SOURCES SUCH AS SKF SERVICE GUIDE BOOKLET BEARING LUBRICATION, LOAD RATING, AND BELLOWS ON GUIDE MOUNTING ARE THE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN RECS. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION FROM OTHER EQUIPMENT AND PERSONNEL REC. 6 FOR USING A ROBOT POSITION VERIFICATION SYSTEM TO MAINTAIN ACCURACY REC. 10 FOR USING BELLOWS ON GUIDE TUBES TO PROTECT SURFACE AND LINEAR BALL BUSHING

1-Y AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION			FAILURE MODE CAUSE & EFFECT ANALYSIS		FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION		
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST RISK (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
6.1	INSIDE WORKSPACE TITLING BELT (CTY. 4)	FAILS TO TRANSMIT POWER OR MOTION -- BROKEN BELT	EXCESSIVE TENSION IN BELT DUE TO OVERTENSIONING, ADJUSTMENT, RELATIVE MOTION BETWEEN PULLEY CENTERS, OR EXTERNAL IMPACTS	LOSS OF BELT POWER OR MOTION TO SYSTEM POTENTIAL DAMAGE TO OTHER COMPONENTS NEAR THE BELT FROM CONTACT WITH BROKEN BELT	2.400E-01	\$640.48	\$2,400.11	\$221.24	4	\$3,442.63	IMPACTS, FRICTIONAL WEAR, INSTALL./MAINT., AND TEMPERATURES ARE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL/MAINT. AND DESIGN	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN
			BELT FATIGUE DUE TO ALTERNATING STRESSES IN BELT PASSING AROUND PULLEY'S	LOSS OF BELT SUPPORT MAY CAUSE UNDESIRABLE FREE MOTION OF DRIVEN COMPONENT'S								REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS
			FRICTIONAL WEAR OF BELT DUE TO DEFECTIVE PULLEY TEETH, OR TENSION, EXTERNAL SOURCES OF CONTACT, OR BELT-PULLEY FLANGE FRICTION DUE TO MISALIGNMENT	POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY							DAMAGE TO OTHER EQUIPMENT SHOULD BE CONSIDERED IF BELT IMPACT FORCES COULD CAUSE SOME DAMAGE/INACCURACY; SENSING AND CONTROL DEVICES ARE COMMON EXAMPLES	RECS. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL
			BELT CORROSION FROM PROCESS CHEMICALS, MAINTENANCE CHEMICALS OR SOLVENTS, LUBRICANTS, OR HIGH HUMIDITY									REC. 6 FOR USING A ROBOT POSITION VERIFICATION SYSTEM TO MAINTAIN ACCURACY
			CONTAMINANT PARTICLES, CHIPS, OR SWARMS LODGING IN BELT CAUSING STRESS RISERS									RECS. 4 FOR USING BELT GUARDS TO PROTECT BELTS AND PULLEYS FROM ENVIRONMENT AND PROTECT COMPONENTS NEAR BELT FROM CONTACT WITH BROKEN OR LOOSE BELTS
			OVERHEATING OF BELT DUE TO HIGH AMBIENT TEMPERATURES, FRICTIONAL HEATING, OR EXTERNAL HEAT SOURCES									
			DEFECTIVE BELT DUE TO INCORRECT THICKNESS, POOR MATERIAL PROPERTIES, OR SURFACE DAMAGE									

I-Y AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION			FAILURE MODE CAUSE & EFFECT ANALYSIS			FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION	
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST RISK (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
6.2	INSIDE WORKSPACE TIGHTENING BELT (CITY, 4)	FAILS TO TRANSMIT POWER OR MOTION -- LOSS OF RESKING WITH PULLEY AND BELT HELD ACCOUNTABLE	UNDERTENSION IN BELT DUE TO STRETCHING, MISADJUSTMENT, MOVEMENT BETWEEN PULLEY CENTERS, OR BELT FASTENER/TENSIONING DEVICE LOOSENING DAMAGED OR DEFECTIVE BELT TEETH FROM INSTALL./MAINT., MANUFACTURING, DEFECTIVE OR DAMAGED PULLEY TEETH, EXCESSIVE FRICTION, OR CORROSIVES/CONTAMINANTS	LOSS OF BELT POWER OR MOTION TO SYSTEM POTENTIAL DAMAGE TO OTHER COMPONENTS NEAR THE BELT FROM CONTACT WITH BROKEN BELT LOSS OF BELT SUPPORT MAY CAUSE UNDESIRABLE FREE MOTION OF DRIVEN COMPONENTS POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	1.200E+00	\$630.48	\$2,401.11	\$221.24	4	\$3,552.63	BELT TENSION, CORROSION OR CONTAMINATION, ALIGNMENT, AND BELT TEETH CONDITIONS ARE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT AND DESIGN DAMAGE TO OTHER EQUIPMENT SHOULD BE CONSIDERED IF BELT IMPACT FORCES COULD CAUSE SOME DAMAGE/INACCURACY; SENSING AND CONTROL EQUIPMENT ARE COMMON EXAMPLES DESIGN FOR ALIGNMENT AND TENSIONING	RECS. 1 AND 2 FOR INSTALL/MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS RECS. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 6 FOR USING BELT GUARDS TO PROTECT BELTS AND PULLEYS FROM ENVIRONMENT AND PROTECT COMPONENTS NEAR BELT FROM CONTACT WITH BROKEN OR LOOSE BELTS

3-Y AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION		FAILURE MODE CAUSE & EFFECT ANALYSIS		FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION				
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE	
A-3	INLINE WORKSPACE TYPING BELT (QTY. 4) ACCURACY	LOSS OF POSITION	OVERSTRESS FROM OVERTENSION OR IMPACT LOADING RESULTING IN LOCAL YIELDING AND ELONGATION FRICTIONAL WEAR OF BELT AND/OR DAMAGE OR INJURY DUE TO DEFECTIVE PULLEY TEETH, LOW TENSION, EXTERNAL SOURCES OF CONTACT, OR BELT-PULLEY FLANGE FRICTION FROM MISALIGNMENT UNDER TENSIONING RESULTING IN INACCURATE MESHING (BUT NOT SEPARATION) BETWEEN BELT AND PULLEY INCOMPATIBLE THERMAL EXPANSION BETWEEN PULLEY TEETH AND BELT TEETH YIELDING BACKLASH IN MOVEMENT IN HIGH ACCURACY REQUIREMENT CONDITIONS CORROSION OR CONTAMINANTS ON OR IMBEDDED IN BELT WHICH DEGRADE BELT TEETH OR INTERFERE WITH MESHING	LOSS OF ACCURACY OF BELT DRIVE TO SYSTEM POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	4.801E-02	\$358.28	\$1,843.59	\$158.02	3	\$2,379.89	\$174.26	THE INACCURACY INCURRED BY THIS FAILURE WILL NOT BE CUMULATIVE UNLESS GROSS ERRORS EXIST BELT TENSION, ALIGNMENT, AND TEETH CONDITIONS FROM WEAR, CORROSION OR IMBEDDED PARTICLES, OR THERMAL EXPANSIONS ARE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL/MAINT. AND DESIGN DESIGN FOR ALIGNMENT AND TENSIONING	RECS. 1 AND 2 FOR INSTALL/MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS RECS. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 8 FOR USING A ROBOT POSITION VERIFICATION SYSTEM TO MAINTAIN ACCURACY REC. 6 FOR ISOLATING BELT AND PULLEYS FROM ENVIRONMENT AND PROTECTING OTHER COMPONENTS FROM BROKEN OR FREE BELT

2-Y AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION			FAILURE MODE CAUSE & EFFECT ANALYSIS			FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION	
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST RISK (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
6.4	INSIDE WORKSPACE TYPING BELT (QTY. 4)	FAILS TO TRANSMIT POWER -- BELT FASTENER FAILS	FATIGUE FAILURE DUE TO ALTERNATING TENSILE STRESSES IN BELT OVERSTRESS IN FASTENER DUE TO OVERTENSION IN BELT OR IMPACT LOADING AT OPERATING TEMPERATURES AND ENVIRONMENTS CORROSIVES IN CONTACT WITH FASTENER FROM PROCESS CHEMICALS, MAINTENANCE CHEMICALS OR SOLVENTS, AND HUMIDITY DEFECTIVE TURNBUCKLE FROM MANUFACTURE	LOSS OF BELT POWER OR MOTION TO SYSTEM POTENTIAL DAMAGE TO OTHER COMPONENTS NEAR THE BELT FROM CONTACT WITH LOOSE BELT LOSS OF BELT SUPPORT MAY CAUSE UNDESIRABLE FREE MOTION OF DRIVEN COMPONENTS POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, HAND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	9.401E-02	\$640.48	\$2,401.11	\$221.24	4	\$3,442.63	FASTENER FATIGUE, CORROSION, AND IMPACT DAMAGE ARE THE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN	REC. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS RECS. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 6 FOR ISOLATING BELT AND PULLEYS FROM ENVIRONMENT AND PROTECTING OTHER COMPONENTS FROM BROKEN OR FREE BELT
7.1	INSIDE WORKSPACE TYPING BELT PULLEY (QTY. 8)	FAILS TO TRANSMIT POWER OR MOTION -- PULLEY FAILURE	IMPACTS ON PULLEY OR PULLEY TEETH FROM FOREIGN OBJECTS CORROSIVES IN CONTACT WITH PULLEY FROM PROCESS CHEMICALS, MAINTENANCE CHEMICALS OR SOLVENTS, OR HIGH HUMIDITY FATIGUE FAILURE DUE TO ALTERNATING STRESSES RESULTING FROM PULLEY MISALIGNMENT BENDING LOADS	LOSS OF DRIVE POWER OR MOTION TO SYSTEM POTENTIAL DAMAGE TO OTHER COMPONENTS NEAR THE PULLEY FROM CONTACT WITH BROKEN PULLEY OR LOOSE BELT LOSS OF BELT SUPPORT MAY CAUSE UNDESIRABLE FREE MOTION OF DRIVEN COMPONENTS POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, HAND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	5.217E-04	\$640.48	\$2,401.11	\$221.24	4	\$3,442.63	THE CAUSES FOR THIS EVENT MAY ALSO CAUSE PULLEY SHAFT OR BEARING FAILURES OR DAMAGE IMPACTS, CORROSION, OBSTRUCTIONS ON TEETH, AND FATIGUE ARE THE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS RECS. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 6 FOR ISOLATING BELTS AND PULLEYS FROM ENVIRONMENT AND PROTECTING OTHER COMPONENTS FROM BROKEN OR FREE BELT

1-Y AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION		FAILURE MODE CAUSE & EFFECT ANALYSIS		FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION			
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
7.2	INSIDE WORKSPACE TIMING BELT PULLEY (QTY. 6)	FAILS TO TRANSMIT POWER OR MOTION -- LOSS OF SHAFT TO PULLEY COUPLING	FAILURE OF COUPLING DEVICE MECHANISM DUE TO FATIGUE, EXCESSIVE LOADS, WEAR, OR CORROSION LOOSENING OF COUPLING DEVICE DUE TO REVERSING LOADS, WEAR OF COUPLING DEVICE, OR THERMAL EXPANSION OF INTERFERENCE FITS	EARLY STAGES -- RESULTS IN ACCURACY PROBLEMS, DEGRADED POWER TRANSMISSION, AND VIBRATION LOSS OF DRIVE POWER OR MOTION TO SYSTEM LOSS OF SUPPORT ALLOWING FREE MOTION OF DRIVEN COMPONENTS POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	9.217E-01	\$665.75	\$2,493.30	\$229.14	4	\$3,398.19	SET SCREWS ARE HIGHLY UNRELIABLE, ESPECIALLY IN REVERSING LOAD APPLICATIONS HOLDING PRESSURE, WEAR, CORROSION, FATIGUE, AND THERMAL EXPANSIONS ARE THE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS RECS. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 6 FOR USING A ROBOT POSITION VERIFICATION SYSTEM TO MAINTAIN ACCURACY REC. 8 FOR ISOLATING BELT AND PULLEYS FROM ENVIRONMENT AND PROTECTING OTHER COMPONENTS FROM BROKEN OR FREE BELT	

1-Y AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT

ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSE & EFFECT ANALYSIS			FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION				FAILURE MODE EVALUATION		
			FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
7.3	INSIDE WORKSPACE TIGHTENING BELT PULLEY (QTY. 8)	FAILS TO TRANSMIT POWER OR MOTION -- LOSS OF PULLEY TO BELT MESHING WITH PULLEY HELD ACCOUNTABLE	PULLEY TEETH BLOCKED OR CLOGGED WITH CONTAMINANT PARTICLES, CHIPS, OR SHAVINGS PULLEY TEETH DAMAGED FROM IMPACTS WITH FOREIGN OBJECTS OR WEAR MISALIGNMENT CAUSING BELT TO TEND TO RIDE ON PULLEY FLANGES OR JUMP FROM PULLEY	LOSS OF DRIVE POWER OR MOTION TO SYSTEM POTENTIAL DAMAGE TO OTHER COMPONENTS NEAR THE PULLEY FROM CONTACT WITH LOOSE BELT LOSS OF BELT SUPPORT ALLOWING FREE MOTION OF DRIVEN COMPONENTS POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, HAND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	4,609E-01	\$630.48	\$2,601.11	\$221.24	4	\$3,452.69	PULLEY TEETH CONDITIONS FROM WEAR, CORROSION, OR BLOCKAGE ALONG WITH MISALIGNMENTS ARE THE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS RECS. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 6 FOR ISOLATING BELT AND PULLEYS FROM ENVIRONMENT AND PROTECTING OTHER COMPONENTS FROM BROKEN OR FREE BELT

3-T AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION			FAILURE MODE CAUSE & EFFECT ANALYSIS			FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION				FAILURE MODE EVALUATION	
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST (\$/EVENT)	TOTAL COST RISK (\$/YR)
8.1	TIMING BELT PULLEY SHAFTS (QTY. 8)	FAILS TO PROVIDE STRUCTURAL SUPPORT	COMBINED NORMAL, SHEAR, BENDING, AND TORSIONAL STRESSES EXTERNAL IMPACTS FROM OUTSIDE OR INSIDE OF WORKSPACE ON PULLEY SHAFT, PULLEY, OR THROUGH DRIVE TRAIN CORROSION DUE TO PROCESS OR MAINTENANCE CHEMICALS OR HUMIDITY FATIGUE FAILURE DUE TO ALTERNATING STRESSES DUE TO LOADING AND MISALIGNMENT'S. STRESS CONCENTRATIONS SUCH AS SCREW OR KEY HOLES WILL AMPLIFY STRESSES WEAR OR EXTERNAL CONTACT CAUSING SURFACE DAMAGE AND STRESS RISERS	FAILS TO TRANSMIT POWER CAUSING LOSS OF DRIVE POWER TO SYSTEM MAY ALLOW BROKEN OR FREED PARTS TO CONTACT OTHER COMPONENTS POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	8.449E-04	\$680.75	\$3,043.30	\$259.14	4	\$3,983.19	\$3.37
										SHAFT MATERIAL FATIGUE AND CORROSION RESISTANCE ALONE WITH STRENGTH AND COMBINED LOADS AND EXTERNAL IMPACTS ARE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS RECS. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 6 FOR USING BELT GUARDS TO PROTECT BELTS AND PULLEYS FROM ENVIRONMENT AND PROTECT OTHER COMPONENTS FROM BROKEN OR LOOSE COMPONENTS	

1-Y AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION		FAILURE MODE CAUSE & EFFECT ANALYSIS			FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION				FAILURE MODE EVALUATION				
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST (\$/EVENT)	TOTAL COST RISK (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	FAILURE MODE RECOMMENDED ACTIONS FOR FAILURE MODE
B.2	TIMING BELT PULLEY SHAFTS (QTY. 8)	FAILS TO MAINTAIN PLACEMENT ACCURACY OF TIMING BELT PULLEYS	LOCAL DEFORMATION DUE TO NORMAL OR MISALIGNMENT CAUSED BY LOADING FROM NORMAL, SHEAR, BENDING, AND TORSIONAL STRESSES OF ENTIRE SHAFT OR AT LOCATING POSITION FOR PULLEY	CAUSES REDUCED OR LOSS OF DRIVE POWER TO SYSTEM MAY CAUSE INACCURATE POSITIONING OF SLIDER OR CAUSE BELT JUMPING FROM PULLEY POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, HAND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	8.44E-03	\$469.10	\$2,490.16	\$211.73	3	\$3,170.99	\$26.79	IMPACTS, ALIGNMENT, FATIGUE, AND CORROSION ARE THE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS RECS. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 6 FOR USING A ROBOT POSITION VERIFICATION SYSTEM TO MAINTAIN ACCURACY REC. 6 FOR USING BELT GUARDS TO PROTECT BELTS AND PULLEYS FROM ENVIRONMENT AND PROTECT OTHER COMPONENTS FROM BROKEN OR LOOSE COMPONENTS

1-Y AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION		FAILURE MODE CAUSE & EFFECT ANALYSIS			FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION		
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST RISK (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
9.1	TIMING BELT PULLEY SHAFT BEARINGS (B7Y, 16)	FAILS TO PROVIDE FREE ROTARY MOTION	LUBRICATION FAILURE DUE TO CONTAMINANTS OR CORROSIVES, OVERHEATING, AND INADEQUATE OR INSUFFICIENT LUBRICANT MISALIGNED, CRACK, OR LARGE SHOCK AND IMPACT LOADING IMPROPER MOUNTING CAUSING BALL OR RACE DAMAGE VIBRATIONS WHILE NOT ROTATING CAUSING LUBRICATION MIGRATION AND BALL/RACE DAMAGE OPERATING LIFE IN EXCESS OF DESIGN LIFE FOR BEARING	LOSS OR DEGRADED POWER TRANSMISSION CAPABILITIES TO SYSTEM POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	9.401E-01	\$587.56	\$2,812.63	\$239.39	4	\$3,439.78	INSTALL /MAINT., OR DESIGN FOR NO MAINTENANCE OF THE BEARING IN ADDITION TO ALIGNMENT AND LIFE CONSIDERATIONS ARE THE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN BEARING USE IS A SCIENCE WITHIN ITSELF -- CONSULT MANUFACTURER SPECS. FOR DETAILS OR SOURCES SUCH AS SKF SERVICE BU'DE BOOKLET TO MAINTAIN ACCURACY DESIGN FOR NO MAINTENANCE OF BEARING IF POSSIBLE OR DESIGN FOR EASY MAINTENANCE	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS RECS. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 8 FOR USING A ROBOT POSITION VERIFICATION SYSTEM TO MAINTAIN ACCURACY REC. 11 FOR USING LARGE RADIUS SPACERS ON SHAFT BETWEEN PULLEY AND BEARING TO PROTECT BEARING FROM CORROSIVE AND CONTAMINANTS, OR USE SEALED BEARINGS

3-Y AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION			FAILURE MODE CAUSE & EFFECT ANALYSIS		FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION		
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
9.2	TIMING BELT PULLEY SHAFT BEARINGS (QTY. 16)	FAILS TO PROVIDE POSITION AND SUPPORT	INSTALL./MAINT. ERRORS IN PULLEYING SHAFT IN BEARING OR BEARING IN HOUSING EXCESSIVE THERMAL EXPANSIONS DEGRADING FIT QUALITY EXTERNAL IMPACTS IN EXCESS OF FIT HOLDING PRESSURES	ALLOWS IMPROPER POSITIONING OF COMPONENTS LOCATED ON SHAFT LEADS TO BELT AND PULLEY MISALIGNMENTS AND POOR POWER TRANSMISSION	1.920E-02	\$340.64	\$2,167.50	\$184.07	3	\$2,692.21	INSTALL./MAINT., THERMAL EXPANSION, AND IMPACT LOADS ARE THE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN USING SPACERS ON THE SHAFT BETWEEN PULLEY AND BEARING TO PROTECT BEARING FROM CORROSION AND CONTAMINANTS, OR USE SEALED BEARINGS	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR LIMITING IMPACT LOADS REC. 11 FOR USING LARGE RADIIUS SPACERS ON SHAFT BETWEEN PULLEY AND BEARING TO PROTECT BEARING FROM CORROSION AND CONTAMINANTS, OR USE SEALED BEARINGS
10.1	OUTSIDE WORKSPACE TIMING BELT PULLEY (QTY. 8)	FAILS TO TRANSMIT POWER OR MOTION -- PULLEY FAILURE	IMPACTS ON PULLEY OR PULLEY TEETH FROM FOREIGN OBJECTS CORROSIVES IN CONTACT WITH PULLEY FROM PROCESS CHEMICALS, MAINTENANCE CHEMICALS OR SOLVENTS, OR HIGH HUMIDITY FATIGUE FAILURE DUE TO ALTERNATING STRESSES RESULTING FROM PULLEY MISALIGNMENT BENDING LOADS	LOSS OF DRIVE POWER OR MOTION TO SYSTEM POTENTIAL DAMAGE TO OTHER COMPONENTS NEAR THE PULLEY FROM CONTACT WITH BROKEN PULLEY OR LOOSE BELT LOSS OF BELT SUPPORT MAY CAUSE UNDESIRABLE FREE MOTION OF DRIVEN COMPONENTS POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	8.045E-04	\$640.48	\$2,601.11	\$221.24	4	\$3,462.83	THE CAUSES FOR THIS EVENT MAY ALSO CAUSE PULLEY SHAFT OR BEARING FAILURES OR DAMAGE IMPACTS, CORROSION, OBSTRUCTIONS ON TEETH, AND FATIGUE ARE THE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS RECS. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 6 FOR ISOLATING BELTS AND PULLEYS FROM ENVIRONMENT AND PROTECTING OTHER COMPONENTS FROM BROKEN OR FREE BELT

1-Y AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION		FAILURE MODE CAUSE & EFFECT ANALYSIS		FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION				
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST (\$/EVENT)	TOTAL COST RISK (\$/YR)	FAILURE MODE COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
10.2	OUTSIDE WORKSPACE TIMING BELT PULLEY (OTT, 8)	FAILS TO TRANSMIT POWER OR MOTION -- LOSS OF SHAFT TO PULLEY COUPLING	FAILURE OF COUPLING DEVICE MECHANISM DUE TO FATIGUE, EXCESSIVE LOADS, WEAR, OR CORROSION LOOSENING OF COUPLING DEVICE DUE TO REVERSING LOADS, WEAR OF COUPLING DEVICE, OR THERMAL EXPANSION OF INTERFERENCE FITS	EARLY STAGES -- RESULTS IN ACCURACY PROBLEMS, DEGRADED POWER TRANSMISSION, AND VIBRATION LOSS OF DRIVE POWER OR MOTION TO SYSTEM LOSS OF SUPPORT ALLOWING FREE MOTION OF DRIVEN COMPONENTS POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	0.005E-01	\$465.75	\$2,473.30	\$229.14	4	\$3,586.19	\$2,873.88	SET SCREWS ARE HIGHLY UNRELIABLE, ESPECIALLY IN REVERSING LOAD APPLICATIONS HOLDING PRESSURE, WEAR, CORROSION, FATIGUE, AND THERMAL EXPANSIONS ARE THE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN REC. 8 FOR USING A ROBOT POSITION VERIFICATION SYSTEM TO MAINTAIN ACCURACY REC. 6 FOR ISOLATING BELT AND PULLEYS FROM ENVIRONMENT AND PROTECTING OTHER COMPONENTS FROM BROKEN OR FREE BELT	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS RECS. 4 AND 5 FOR PROVIDING OPERATION POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 8 FOR USING A ROBOT POSITION VERIFICATION SYSTEM TO MAINTAIN ACCURACY REC. 6 FOR ISOLATING BELT AND PULLEYS FROM ENVIRONMENT AND PROTECTING OTHER COMPONENTS FROM BROKEN OR FREE BELT

I-Y AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION		FAILURE MODE CAUSE & EFFECT ANALYSIS			FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION				
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST (\$/EVENT)	TOTAL COST RISK (\$/YR)	FAILURE MODE COMMENTS	FAILURE MODE	RECOMMENDED ACTIONS FOR FAILURE MODE
10.3	OUTSIDE WORKSPACE TIGHTEN BELT PULLEY (OPT. 8)	FAILS TO TRANSMIT POWER OR MOTION -- LOSS OF PULLEY TO BELT MESHING WITH PULLEY HELD ACCOUNTABLE	PULLEY TEETH BLOCKED OR CLOGGED WITH CONTAMINANT PARTICLES, CHIPS, OR SHAVINGS PULLEY TEETH DAMAGED FROM IMPACTS WITH FOREIGN OBJECTS OR WEAR MISALIGNMENT CAUSING BELT TO TEND TO RIDE ON PULLEY FLANGES OR JUMP FROM PULLEY	LOSS OF DRIVE POWER OR MOTION TO SYSTEM POTENTIAL DAMAGE TO OTHER COMPONENTS NEAR THE PULLEY FROM CONTACT WITH LOOSE BELT LOSS OF BELT SUPPORT ALLOWING FREE MOTION OF DRIVEN COMPONENTS POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	4.033E-01	4630.48	42,401.11	\$221.24	4	43,452.83	\$1,392.53	PULLEY TEETH CONDITIONS FROM WEAR, CORROSION, OR BLOCKAGE ALONG WITH MISALIGNMENTS ARE THE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN		RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS RECS. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 6 FOR ISOLATING BELT AND PULLEYS FROM ENVIRONMENT AND PROTECTING OTHER COMPONENTS FROM BROKEN OR FREE BELT

1-Y AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION			FAILURE MODE CAUSE & EFFECT ANALYSIS		FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION		
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST RISK (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
11.1	OUTSIDE WORKSPACE TYPING BELT (QTY. 4)	FAILS TO TRANSMIT POWER OR MOTION -- BROKEN BELT	EXCESSIVE TENSION IN BELT DUE TO OVERTENSIONED ADJUSTMENT, RELATIVE MOTION BETWEEN PULLEY CENTERS, OR EXTERNAL IMPACTS BELT FATIGUE DUE TO ALTERNATING STRESSES IN BELT PASSING AROUND PULLEYS FRICTIONAL WEAR OF BELT DUE TO DEFECTIVE PULLEY TEETH, LOW TENSION, EXTERNAL SOURCES OF CONTACT, OR BELT-PULLEY FLANGE FRICTION DUE TO MISALIGNMENT BELT CORROSION FROM PROCESS CHEMICALS, MAINTENANCE CHEMICALS OR SOLVENTS, LUBRICANTS, OR HIGH HUMIDITY CONTAMINANT PARTICLES, CHIPS, OR SHAVINGS LOGGING IN BELT CAUSING STRESS RISERS OVERHEATING OF BELT DUE TO HIGH AMBIENT TEMPERATURES, FRICTIONAL HEATING, OR EXTERNAL HEAT SOURCES DEFECTIVE BELT DUE TO INCORRECT THICKNESS, POOR MATERIAL PROPERTIES, OR SURFACE DAMAGE	LOSS OF BELT POWER OR MOTION TO SYSTEM POTENTIAL DAMAGE TO OTHER COMPONENTS NEAR THE BELT FROM CONTACT WITH BROKEN BELT LOSS OF BELT SUPPORT MAY CAUSE UNDESIRABLE FREE MOTION OF DRIVEN COMPONENTS POTENTIAL DAMAGE TO EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	2.112E-01	\$675.75	\$2,493.30	\$229.14	4	\$3,598.19	IMPACTS, CORROSION AND CONTAMINANTS, FRICTIONAL WEAR, INSTALL./MAINT., AND TEMPERATURES ARE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN DAMAGE TO OTHER EQUIPMENT SHOULD BE CONSIDERED IF BELT IMPACT FORCES COULD CAUSE SOME DAMAGE/INCOMPATIBILITY SENSING AND CONTROL DEVICES ARE COMMON EXAMPLES CONSIDER METHODS TO GUARDS TO PROTECT BELTS AND PULLEYS FROM ENVIRONMENT AND TENSIONING PROTECT OTHER COMPONENTS FROM BROKEN OR LOOSE BELTS	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS RECS. 4 AND 5 FOR PROVIDING OPERATION POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 8 FOR USING A ROBOT POSITION VERIFICATION SYSTEM TO MAINTAIN ACCURACY REC. 6 FOR USING BELT GUARDS TO PROTECT BELTS AND PULLEYS FROM ENVIRONMENT AND TENSIONING PROTECT OTHER COMPONENTS FROM BROKEN OR LOOSE BELTS

1-Y AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION		FAILURE MODE CAUSE & EFFECT ANALYSIS			FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION				FAILURE MODE EVALUATION			
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST RISK (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
11.2	OUTSIDE WORKSPACE TIMING BELT (QTY. 4)	FAILS TO TRANSMIT POWER OR MOTION -- LOSS OF MESHING WITH PULLEY AND BELT HELD ACCOUNTABLE	UNDERTENSION IN BELT DUE TO STRETCHING, MISADJUSTMENT, MOVEMENT BETWEEN PULLEY CENTERS, OR BELT FASTENER/TENSIONING DEVICE LOOSENING DAMAGED OR DEFECTIVE BELT TEETH FROM INSTALLATION/MAINTENANCE DEFECTIVE OR DAMAGED PULLEY TEETH, EXCESSIVE FRICTION, OR CORROSIVES/CONTAMINANTS	LOSS OF BELT POWER OR MOTION TO SYSTEM POTENTIAL DAMAGE TO OTHER COMPONENTS NEAR THE BELT FROM CONTACT WITH BROKEN BELT LOSS OF BELT SUPPORT MAY CAUSE UNDESIRABLE FREE MOTION OF DRIVEN COMPONENTS POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	1.05E+00	\$630.48	\$2,401.11	\$221.24	4	\$3,446.19	BELT TENSION, CORROSION AND CONTAMINANTS, ALIGNMENT, AND BELT TEETH CONDITIONS ARE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN DAMAGE TO OTHER EQUIPMENT SHOULD BE CONSIDERED IF BELT IMPACT FORCES COULD CAUSE SOME DAMAGE/INACCURACY; SENSING AND CONTROL EQUIPMENT ARE COMMON EXAMPLES DESIGN FOR ALIGNMENT AND TENSIONING	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS RECS. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 6 FOR USING BELT GUARDS TO PROTECT BELTS AND PULLEYS FROM ENVIRONMENT AND PROTECT OTHER COMPONENTS FROM BROKEN OR LOOSE BELTS

X-Y AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION			FAILURE MODE CAUSE & EFFECT ANALYSIS		FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION			
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST (\$/YR)	TOTAL COST RISK (\$/YR)	FAILURE MODE COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
11.3	OUTSIDE WORKSPACE TITING BELT (QTY. 4)	LOSS OF POSITION ACCURACY	OVERSTRESS FROM OVERTENSION OR IMPACT LOADING RESULTING IN LOCAL YIELDING AND ELONGATION FRICTIONAL WEAR OF BELT DUE TO DEFECTIVE PULLEY TEETH, LOW TENSION, EXTERNAL SOURCES OF CONTACT, OR BELT-PULLEY FLANGE FRICTION FROM MISALIGNMENT UNDERTENSIONING RESULTING IN INACCURATE MESHING (BUT NOT SEPARATION) BETWEEN BELT AND PULLEY INCOMPATIBLE THERMAL EXPANSION BETWEEN PULLEY TEETH AND BELT PULLEY YIELDING BACKLASH IN MOVEMENT IN HIGH ACCURACY REQUIREMENT CONDITIONS CORROSION OR CONTAMINANTS ON OR IMBEDDED IN BELT WHICH DEGRADE BELT TEETH OR INTERFERE WITH MESHING	LOSS OF ACCURACY OF BELT DRIVE TO SYSTEM POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	4.225E-02	\$323.00	\$1,771.40	\$150.12	3	\$2,244.52	\$94.83	THE INACCURACY INCURRED BY THIS FAILURE WILL NOT BE CUMULATIVE UNLESS GROSS ERRORS EXIST BELT TENSION, ALIGNMENT, AND TEETH CONDITIONS OR IMBEDDED PARTICLES, OR THERMAL EXPANSION ARE THE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN DESIGN FOR ALIGNMENT AND TENSIONING	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS RECS. 4 AND 5 FOR PROVIDING OPERATION POSITION VERIFICATION FROM OTHER EQUIPMENT AND PERSONNEL REC. 8 FOR USING A ROBOT POSITION VERIFICATION SYSTEM TO MAINTAIN ACCURACY REC. 6 FOR ISOLATING BELT AND PULLEYS FROM ENVIRONMENT AND PROTECTING OTHER COMPONENTS FROM BROKEN OR FREE BELT

2-Y AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION			FAILURE MODE CAUSE & EFFECT ANALYSIS		FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION		
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
11.4	OUTSIDE WORKSPACE TYPING BELT (QTY. 4)	FAILS TO TRANSMIT POWER -- BELT FASTENER FAILS	FATIGUE FAILURE DUE TO ALTERNATING TENSILE STRESSES IN BELT OVERSTRESS IN FASTENER DUE TO OVERSTRESS IN BELT OR IMPACT LOADING AT OPERATING TEMPERATURES AND ENVIRONMENTS CORROSIVES IN CONTACT WITH FASTENER FROM PROCESS CHEMICALS, MAINTENANCE CHEMICALS OR SOLVENTS, AND HUMIDITY DEFECTIVE TURNBUCKLE FROM MANUFACTURE	LOSS OF BELT POWER OR MOTION TO SYSTEM POTENTIAL DAMAGE TO OTHER COMPONENTS NEAR THE BELT FROM CONTACT WITH LOOSE BELT LOSS OF BELT SUPPORT MAY CAUSE UNDESIRABLE FREE MOTION OF DRIVEN COMPONENTS POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	8.449E-02	\$675.75	\$2,493.30	\$229.14	4	\$3,598.19	FASTENER FATIGUE, CORROSION, AND IMPACT DAMAGE ARE THE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS RECS. 4 AND 5 FOR PROVIDING OPERATION POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 6 FOR USING A ROBOT POSITION VERIFICATION SYSTEM TO MAINTAIN ACCURACY REC. 6 FOR ISOLATING BELT AND PULLEYS FROM ENVIRONMENT AND PROTECTING OTHER COMPONENTS FROM BROKEN OR FREE BELT

1-Y AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION			FAILURE MODE CAUSE & EFFECT ANALYSIS			FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION		
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST (\$/EVENT)	TOTAL RISK (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
12.1	2.1 AMP STEPPER MOTORS (Qty. 4)	FAILS TO PROVIDE COMMAND TORQUE OR MOTION -- PRIMARY MOTOR FAILURE	MOTOR BEARING FAILURE DUE TO EXCESSIVE LOADS, LUBRICATION MISRATION OR CONTAMINATION, OR WEAR INTERNAL WINDING FAILURE FROM OVERHEATING, EXCESSIVE CURRENT OR SURGES, MECH. SHOCKS OR VIBRATIONS, OR WINDING CORROSION DEFECTIVE STEPPER MOTOR FROM MANUFACTURER	LOSS OF DRIVE POWER OR MOTION TO SYSTEM POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	4.801E-02	\$765.75	\$5,493.30	\$229.14	4	\$6,488.19	\$311.50	BEARING LIFE, CORROSIVES AND CONTAMINANTS, OVERHEATING, AND EXCESSIVE CURRENT ARE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN RECS. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL
12.2	2.1 AMP STEPPER MOTORS (Qty. 4)	FAILS TO PROVIDE COMMAND TORQUE OR MOTION -- SECONDARY MOTOR FAILURE	REQUIRED TORQUE BEYOND PULL-IN TORQUE FOR STARTING OR PULL-OUT TORQUE FOR CURRENT SPEED REQUIRED TORQUE TO MAINTAIN ZERO MOTION BEYOND MAXIMUM HOLDING TORQUE LOSS OF COMMAND POWER FROM MOTOR DRIVES DUE TO IMPACTS AND CORROSION OF CONNECTORS RESTRICTED DRIVE TRAIN DUE TO FOREIGN OBJECT INTERFERENCE OR DRIVE TRAIN FAILURES INSTALLATION AND MAINTENANCE ERRORS IN WIRING MOTOR	LOSS OF DRIVE POWER OR MOTION OR HOLDING TORQUE TO SYSTEM POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY WIRING ERRORS MAY CAUSE NO ACTION BUT ALSO MAY CAUSE REVERSED MOTION	2.400E-01	\$595.20	\$5,306.92	\$213.34	4	\$6,117.46	\$1,468.19	TORQUE AND SPEED LIMITATIONS SHOULD BE OBSERVED WITH ACCELERATING RAMPING EXCESSIVE LOADS AND CORROSIVES OR CONTAMINANTS ARE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN RECS. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 8 FOR USING A ROBOT POSITION VERIFICATION SYSTEM TO MAINTAIN ACCURACY

X-Y AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION			FAILURE MODE CAUSE & EFFECT ANALYSIS			FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION	
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (E/VENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST RISK (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
12.3	2.1 AMP STEPPER MOTORS (QTY. 4)	INACCURATE POSITIONING	EXCESSIVE ACCELERATION AND/OR DECELERATION RESONANCE VIBRATION OF STEPPER MOTOR ROTOR OR STATOR DAMAGE OR DEFECT IMPACTS OF HIGH LOADS IN OPERATING REGIONS WHICH CAUSE LOSS OF STEPS	LOSS OF ACCURATE POSITIONING OF DRIVEN SYSTEM POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	3.202E-01	\$448.28	\$4,663.59	\$158.02	3	\$5,269.89	THESE SOURCES OF INACCURACY ARE CUMULATIVE STEPPER MOTORS HAVE RESONANT FREQUENCIES WHICH PRODUCE VIBRATION AND LOSS OF STEPPING MOTION RAMPING OF ACCELERATION AND DECELERATION IS USED TO AVOID MISSING STEPS. THE RAMPS ARE DEPENDENT ON MASS AND FRICTION IN SYSTEM	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS RECS. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 8 FOR USING A ROBOT POSITION VERIFICATION SYSTEM TO MAINTAIN ACCURACY

1-4 AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION		FAILURE MODE CAUSE & EFFECT ANALYSIS			FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION		
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST RISK (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	FAILURE MODE RECOMMENDED ACTIONS FOR FAILURE MODE
13.1	STEPPER MOTOR DRIVER (QTY. 2)	CONTROLLER FAILS OFF -- CONTROLLER FAILURE	INSTALLATION OR MAINTENANCE ERROR FROM CROSSING WIRES, SHIFTING CONNECTORS, OR REVERSING THE INPUT AND OUTPUT	LOSS OF COMMAND TO DRIVE SYSTEM RESULTING IN LOSS OF DRIVE POWER OR MOTION TO SYSTEM	1.051E-01	\$765.75	\$5,493.30	\$229.14	4	\$6,488.19	PROPER INSTALL./MAINT., PROTECTING CONNECTORS AND WIRES FROM CORROSION, IMPACTS, HIGH TEMPERATURES, AND EXCESSIVE MOTION ARE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN
			INTERNAL CIRCUIT FAILURE DUE TO CIRCUIT FATIGUE, EXTERNAL IMPACTS, CORROSION, OR VIBRATIONS (INCLUDING PHOTO-TRANSFORMER)	POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY								REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS
			OPERATION ERROR FROM OVERPOWER CONNECTIONS OR SURGES									RECS. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL
			OVERHEATING OF CONTROLLER FROM ELECTRIC CURRENT HEATING OR EXTERNAL SOURCES									REC. 6 FOR USING A ROBOT POSITION VERIFICATION SYSTEM TO MAINTAIN ACCURACY
												REC. 12 FOR REGULATING CURRENT IN CIRCUIT
												REC. 13 FOR ISOLATING WIRES, CONNECTOR, AND MOTOR DRIVER FROM ENVIRONMENT, IMPACTS, AND STATIC ELECTRIC OR MAGNETIC FIELDS

3-Y AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION			FAILURE MODE CAUSE & EFFECT ANALYSIS			FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION		
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST (\$/EVENT)	TOTAL COST RISK (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
13.2	STEPPER MOTOR DRIVER (QTY. 2)	ISSUES INCORRECT COMMAND TO MOTOR	INSTALLATION OR MAINTENANCE ERROR WHICH REVERSES DIRECTION OF MOTOR OR CONNECTS WRONG MOTOR TO CONTROLLER INSUFFICIENT SETTLING TIME BEFORE REVERSING DIRECTIONS OF MOTOR SPURIOUS SIGNAL CAUSED BY STRAY ELECTRIC OR MAGNETIC FIELD	CAUSES INACCURACY IN MOTOR POSITIONING POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	1.200E-01	\$695.20	\$5,308.92	\$212.34	4	\$6,217.46	\$746.10	INSTALL./MAINT. ARE THE KEY OPERATING PARAMETERS	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN RECS. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 13 FOR ISOLATING WIRING, CONNECTION, AND MOTOR DRIVER FROM ENVIRONMENT, IMPACTS, AND STRAY ELECTRIC OR MAGNETIC FIELDS
14.1	STEPPER MOTOR MOUNTING PLATES (QTY. 4)	FAILS TO PROVIDE STRUCTURAL SUPPORT	COMBINED STRESS LOADING CAUSING YIELDING AND EVENTUALLY FRACTURE FATIGUE FAILURE DUE TO ALTERNATING STRESSES CORROSION OF PLATE MATERIAL EXTERNAL IMPACT LOADS INTO PLATE MATERIAL DEFECTS FROM MANUFACTURING PROCESS FAILURE OF MOTOR PLATE MOUNTING BOLTS	LOSS OF DRIVE POWER TO SYSTEM AND LOSS OF SUPPORT TO MOTOR POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	3.331E-03	\$715.75	\$5,448.30	\$244.14	4	\$6,628.19	\$22.08	THE EFFECTS OF COMBINED LOADS, CORROSION, IMPACTS, BELT MISALIGNMENTS, AND FATIGUE ARE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS RECS. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 8 FOR USING A ROBOT POSITION VERIFICATION SYSTEM TO MAINTAIN ACCURACY

X-Y AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION		FAILURE MODE CAUSE & EFFECT ANALYSIS		FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION			
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST RISK (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
14.2	STEPPER MOTOR MOUNTING PLATES (QTY. 4)	FAILS TO MAINTAIN PLACEMENT ACCURACY OF STEPPER MOTOR	LOOSENING OF MOTOR PLATE MOUNTING BOLTS DEFORMATION OF MOUNTING PLATE DUE TO COMBINED STRESS LOADING, THERMAL EXPANSION, OR IMPACT LOADS	ALLOWING RELATIVE MOTION BETWEEN OUTSIDE THE WORKSPACE PULLEY CENTERS AFFECTING BELT TENSION AND ALIGNMENT CAUSES REDUCED OR LOST POWER TRANSMISSION OR PLACEMENT INACCURACIES POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	3.380E-03	1680.48	45,576.11	4236.24	4	46,492.83	IMPACT LOADS, COMBINED STRESS LOADING, THERMAL EXPANSION, AND PART QUALITY ARE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS RECS. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 8 FOR USING A ROBOT POSITION VERIFICATION SYSTEM TO MAINTAIN ACCURACY

ROTATIONAL MOTION SUB-SYSTEM FMEA TABLES FOR CASE STUDY

ROTATIONAL MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION			FAILURE MODE CAUSE & EFFECT ANALYSIS		FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION		
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST RISK (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
1.1.1	1.1 AMP STEPPER MOTOR	FAILS TO PROVIDE COMMANDED TORQUE OR MOTION -- PRIMARY MOTOR FAILURE	MOTOR BEARING FAILURE DUE TO EXCESSIVE LOADS, LUBRICATION VIBRATION OR CONTAMINATION, OR WEAR INTERNAL WINDING FAILURE FROM OVERHEATING, EXCESSIVE CURRENT OR SURGES, MECH. SHOCKS OR VIBRATIONS, OR WINDING CORROSION DEFECTIVE STEPPER MOTOR FROM MANUFACTURER	LOSS OF DRIVE POWER OR MOTION TO SYSTEM POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	1.200E-02	\$765.75	\$5,493.30	\$225.14	4	\$6,488.19	BEARING LIFE, CORROSIVES AND CONTAMINANTS, OVERHEATING, AND EXCESSIVE CURRENT ARE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 8 FOR USING A ROBOT POSITION VERIFICATION SYSTEM TO MAINTAIN ACCURACY REC. 12 FOR REGULATING CURRENT IN CIRCUIT
1.1.2	1.1 AMP STEPPER MOTOR	FAILS TO PROVIDE COMMANDED TORQUE OR MOTION -- SECONDARY MOTOR FAILURE	REQUIRED TORQUE BEYOND FULL-IN TORQUE FOR STARTING OR PULL-OUT TORQUE FOR CURRENT SPEED REQUIRED TORQUE TO MAINTAIN ZERO MOTION BEYOND MAXIMUM HOLDING TORQUE LOSS OF COMMAND POWER FROM MOTOR DRIVER DUE TO IMPACTS AND CORROSION OF CONNECTORS RESTRICTED DRIVE TRAIN DUE TO FOREIGN OBJECT INTERFERENCE OR DRIVE TRAIN FAILURES INSTALLATION AND MAINTENANCE ERRORS IN DRIVING MOTOR	LOSS OF DRIVE POWER OR MOTION OR HOLDING TORQUE TO SYSTEM POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY WIRING ERRORS MAY CAUSE NO MOTION BUT ALSO MAY CAUSE REVERSED MOTION	1.200E-01	\$555.20	\$2,508.92	\$215.34	4	\$3,317.46	TORQUE AND SPEED LIMITATIONS SHOULD BE OBSERVED WITH ACCELERATING RAMPING EXCESSIVE LOADS, AND CORROSIVES OR CONTAMINANTS ARE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 8 FOR USING A ROBOT POSITION VERIFICATION SYSTEM TO MAINTAIN ACCURACY

ROTATIONAL MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION		FAILURE MODE CAUSE & EFFECT ANALYSIS		FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION			
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST RISK (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
1.3	1.1 AMP STEPPER MOTOR	INACCURATE POSITIONING	EXCESSIVE ACCELERATION AND/OR DECELERATION RESONANCE VIBRATION OF STEPPER MOTOR ACTOR OR STATOR DAMAGE OR DEFECT IMPACTS OF HIGH LOADS IN OPERATING REGIONS WHICH CAUSE LOSS OF STEPS	INACCURATE POSITIONING CONTROL. POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	6.00E-02	\$589.38	\$5,032.35	\$189.63	3	\$5,811.36	THESE SOURCES OF INACCURACY ARE CUMULATIVE STEPPER MOTORS HAVE RESONANT FREQUENCIES WHICH PRODUCE VIBRATION AND LOSS OF STEPPING MOTION SCRAPING OF ACCELERATION AND DECELERATION IS USED TO AVOID MISSING STEPS. THE RAMPS ARE DEPENDENT ON MASS AND FRICTION IN SYSTEM	REC. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS REC. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 8 FOR USING A ROBOT POSITION VERIFICATION SYSTEM TO MAINTAIN ACCURACY

ROTATIONAL MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION		FAILURE MODE CAUSE & EFFECT ANALYSIS			FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION				FAILURE MODE EVALUATION			
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
2.1	STEPPER MOTOR DRIVER	CONTROLLER FAILS OFF --- CONTROLLER FAILURE	INSTALLATION OR MAINTENANCE ERROR FROM CROSSING WIRES, SHIFTING CONNECTORS, OR DRIPPING RESISTORS, OR REVERSING THE INPUT AND OUTPUT	LOSS OF COMMAND TO DRIVE SYSTEM RESULTING IN LOSS OF DRIVE POWER OR MOTION TO SYSTEM	5.257E-02	\$765.75	\$5,493.30	\$229.14	4	\$6,488.19	PROPER INSTALL./MAINT. PROTECTING CONNECTORS AND WIRES FROM CORROSION, IMPACTS, HIGH TEMPERATURES, AND MOTION ARE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN
			INTERNAL CIRCUIT FAILURE DUE TO CIRCUIT FATIGUE, EXTERNAL IMPACTS, CORROSION, OR VIBRATIONS (INCLUDING PHOTO-TRANSFORMER)	POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY								REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS
			OPERATION ERROR FROM OVERPOWER CONNECTIONS OR SURGES									REC. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL
			OVERHEATING OF CONTROLLER FROM ELECTRIC CURRENT HEATING OR EXTERNAL SOURCES									REC. 8 FOR USING A ROBOT POSITION VERIFICATION SYSTEM TO MAINTAIN ACCURACY
												REC. 12 FOR USING CURRENT REGULATION DEVICE
												REC. 13 FOR ISOLATING WIRING, CONNECTORS, AND MOTOR DRIVER UNIT FROM ENVIRONMENT, IMPACTS, AND STRAY ELECTRICAL OR MAGNETIC FIELDS

ROTATIONAL MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION			FAILURE MODE CAUSE & EFFECT ANALYSIS			FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION		
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST (\$/EVENT)	TOTAL COST RISK (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	FAILURE MODE RECOMMENDED ACTIONS FOR FAILURE MODE
2.2	STEPPER MOTOR DRIVER ISSUES INCORRECT COMMAND TO MOTOR		INSTALLATION OR MAINTENANCE ERROR WHICH REVERSES DIRECTION OF MOTOR OR CONNECTS WIRING MOTOR TO CONTROLLER INSUFFICIENT SETTLING TIME BEFORE REVERSING DIRECTIONS OF MOTOR	CAUSES INACCURACY IN MOTOR POSITIONING POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	6.001E-02	\$555.20	\$2,508.92	\$213.34	4	\$3,317.46	\$199.08	INSTALL./MAINT. ARE THE KEY OPERATING PARAMETERS. RECOGNIZE LIMITATIONS IMPOSED ON SYSTEM BY PROVIDING OPERATOR POSITION VERIFICATION DRIVER SPECS. SUCH AS SETTLING TIMES AND RESPONSE TIMES FROM OTHER EQUIPMENT AND PERSONNEL	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION DRIVER SPECS. SUCH AS SETTLING TIMES AND RESPONSE TIMES FROM OTHER EQUIPMENT AND PERSONNEL REC. 12 FOR USING CURRENT REGULATION DEVICE REC. 13 FOR ISOLATING WIRING, CONNECTORS, AND MOTOR DRIVER UNIT FROM ENVIRONMENT, IMPACTS, AND STRAY ELECTRICAL OR MAGNETIC FIELDS
3.1	RIGID DRIVE PLUS FAILS TO TRANSMIT POWER DUE TO FRACTURE		COMBINED STRESS LOADING CAUSING YIELDING AND FRACTURE. SOURCES OF LOADS ARE OPERATING LOADS, MISALIGNMENTS, THERMAL DEFORMATIONS, VIBRATIONS, AND EXTERNAL IMPACTS FATIGUE DUE TO ALTERNATING TENSILE STRESSES IN REVERSING LOADS CORROSION FROM PROCESS OR MAINTENANCE CHEMICALS OR HUMIDITY MATERIAL DEFECTS FROM MANUFACTURING PROCESS	LOSS OR REDUCED DRIVE POWER TO SYSTEM POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	7.227E-04	\$675.75	\$2,868.30	\$244.14	4	\$3,788.19	\$2.75	THE EFFECTS OF COMBINED STRESS LOADS, CORROSION, AND IMPACT LOADS ARE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN THIS COMPONENT IN PROTECTED IN MAIN 2 ROUTINE TUBE	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS REC. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 9 FOR SEALING OR SHIELDING AREAS WHERE LIQUIDS OR PARTICLES MAY ACCUMULATE

ROTATIONAL MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION		FAILURE MODE CAUSE & EFFECT ANALYSIS			FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION		
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
3.2	RIGID DRIVE PLUG	FAILS TO TRANSMIT POWER DUE TO LOSS OF COUPLING WITH DRIVE TUBE OR MOTOR SHAFT	LOOSENING OF FASTENING SCREWS UNDER REVERSING LOADS FAILURE OF FASTENING SCREWS UNDER COMBINED STRESS, FATIGUE, CORROSION, OR IMPACT LOADS EXCESSIVE DIFFERENTIAL THERMAL EXPANSIONS	LOSS OF DRIVE POWER TO SYSTEM POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	9.205E-04	\$587.56	\$2,637.83	\$224.39	3	\$3,449.78	SET SCREWS ARE HIGHLY UNRELIABLE, ESPECIALLY IN REVERSING LOAD APPLICATIONS IMPACT LOADS, FASTENER STRENGTH, OR HOLDING PRESSURE ARE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS REC. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL
4.1	ROTARY DRIVE TUBE	FAILS TO TRANSMIT POWER DUE TO FRACTURE OR SEVERE DEFORMATION	COMBINED STRESS LOADS CAUSING YIELDING AND FRACTURE. SOURCES OF LOADS ARE OPERATING LOADS, MISALIGNMENTS, VIBRATIONS, AND EXTERNAL IMPACTS FATIGUE FAILURE DUE TO ALTERNATING STRESSES FROM REVERSING LOADS CORROSION FROM PROCESS OR MAINTENANCE CHEMICALS OR HUMIDITY MATERIAL DEFECTS FROM MANUFACTURING PROCESS	LOSS OF DRIVE POWER TO SYSTEM POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	9.205E-04	\$695.75	\$5,648.30	\$244.14	4	\$6,608.19	COMBINED LOADS, CORROSION, AND IMPACT LOADS ARE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN THIS COMPONENT IS PROTECTED INSIDE THE MAIN Z GUIDE TUBE	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS REC. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 9 FOR SEALING, OR SHIELDING, AREAS IN WHICH LIQUIDS OR PARTICLES MAY ACCUMULATE

ROTATIONAL MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION			FAILURE MODE CAUSE & EFFECT ANALYSIS			FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION	
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
5.1	ROTARY DRIVE PLUG	FAILS TO TRANSMIT POWER DUE TO FRACTURE	COMBINED STRESS LOADS CAUSING YIELDING AND FRACTURE. SOURCES OF LOADS ARE OPERATING LOADS, MISALIGNMENTS, VIBRATIONS, AND EXTERNAL IMPACTS	LOSS OF REDUCE POWER TRANSMISSION TO SYSTEM POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	7.257E-04	\$675.75	\$2,868.30	\$244.14	4	\$3,788.19	COMBINED LOADS, IMPACTS, AND CORROSION ARE THE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS
			FATIGUE FROM ALTERNATING STRESSES DUE TO REVERSING LOADS CORROSION FROM PROCESS OR MAINTENANCE CHEMICALS OR HUMIDITY MATERIAL DEFECTS FROM MANUFACTURING PROCESS								THIS COMPONENT IS PROTECTED IN MAIN 2 GUIDE TUBE	REC. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 6 FOR SEALING OR SHIELDING AREAS WHERE LIQUIDS OR PARTICLES MAY ACCUMULATE
5.2	ROTARY DRIVE PLUG	FAILS TO MAINTAIN POSITIONAL ACCURACY	DAMAGE TO SLOT FROM COMBINED STRESS LOADS, IMPACTS, FATIGUE OR CORROSION EXCESSIVE DIFFERENTIAL THERMAL EXPANSIONS AT SLOT	LOSS OF ROTARY POSITIONING ACCURACY POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	9.205E-04	\$223.00	\$1,946.40	\$115.12	3	\$2,434.52	COMBINED LOADS, IMPACTS, CORROSION, AND TEMPERATURE EFFECTS ARE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS REC. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL
											THIS COMPONENT IS PROTECTED IN MAIN 2 GUIDE TUBE	REC. 9 FOR SEALING OR SHIELDING AREAS WHERE LIQUIDS OR PARTICLES MAY ACCUMULATE

ROTATIONAL MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION		FAILURE MODE CAUSE & EFFECT ANALYSIS			FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION		
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
5.3	ROTARY DRIVE PLUG	FAILS TO TRANSMIT POWER DUE TO LOSS OF COUPLINE WITH DRIVE TUBE	LOOSENING OF SET SCREW DUE TO REVERSING LOADS FAILURE OF SET SCREW DUE TO COMBINED LOADING, FATIGUE, CORROSION, OR IMPACTS	LOST OR REDUCED DRIVE POWER TO SYSTEM POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	9.205E-04	\$640.48	\$2,776.11	\$236.24	4	\$3,652.83	SET SCREWS ARE HIGHLY UNRELIABLE, ESPECIALLY IN REVERSING LOAD APPLICATIONS LOOSENING OF SCREWS, COMBINED LOADS, CORROSION, FATIGUE, AND IMPACTS ARE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS REC. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 9 FOR SEALING OR SHIELDING AREAS WHERE LIQUIDS OR PARTICLES CAN ACCUMULATE
6.1	ROTARY SPINDLE	FAILS TO TRANSMIT POWER DUE TO FRACTURE	COMBINED STRESS LOADS CAUSING YIELDING AND FRACTURE. SOURCES OF LOADS ARE OPERATING LOADS, MISALIGNMENTS, VIBRATIONS, AND EXTERNAL IMPACTS FATIGUE FROM ALTERNATING STRESSES DUE TO REVERSING LOADS CORROSION DUE TO PROCESS OR MAINTENANCE CHEMICALS OR HUMIDITY MATERIAL DEFECTS FROM MANUFACTURING PROCESS	LOST OR REDUCED POWER TRANSMISSION POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	9.205E-04	\$690.75	\$5,648.30	\$244.14	4	\$6,603.19	COMBINED LOADS, CORROSION, FATIGUE, AND IMPACTS ARE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN THIS COMPONENT IS PROTECTED BY MAIN Z GUIDE TUBE	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS REC. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 9 FOR SEALING OR SHIELDING AREAS WHERE LIQUIDS OR PARTICLES CAN ACCUMULATE

ROTATIONAL MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION		FAILURE MODE CAUSE & EFFECT ANALYSIS			FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION		
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
6.2	ROTARY SPINDLE	FAILS TO PROVIDE POSITIONAL ACCURACY	COMBINED STRESS LOADS CAUSING YIELDING AND FRACTURE. SOURCES OF LOADS ARE OPERATING LOADS, MISALIGNMENTS, VIBRATIONS, AND EXTERNAL IMPACTS	INACCURATE ROTARY POSITIONING POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	7.344E-03	\$338.00	\$4,746.40	\$165.12	3	\$5,249.52	COMBINED LOADING, FATIGUE, CORROSION, AND IMPACTS ARE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN THIS COMPONENT IS PROTECTED IN MAIN 2 GUIDE TUBE	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS REC. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 9 FOR SEALING AND SHIELDING AREAS WHERE LIQUIDS AND PARTICLES CAN ACCUMULATE

ROTATIONAL MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION			FAILURE MODE CAUSE & EFFECT ANALYSIS		FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION		
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
7.1	RADIAL BEARING (LOT. 2)	FAILS TO PROVIDE FREE ROTARY MOTION	LUBRICATION FAILURE DUE TO CONTAMINANTS OR CORROSIVES, OVERHEATING, AND IMPROPER OR INSUFFICIENT LUBRICANT MISALIGNED, AXIAL, OR LARGE SHOCK AND IMPACT LOADING IMPROPER MOUNTING CAUSING BALL OR RACE DAMAGE VIBRATIONS WHILE NOT ROTATING CAUSING LUBRICATION MIGRATION AND BALL/RACE DAMAGE OPERATING LIFE IN EXCESS OF DESIGN LIFE FOR BEARING	LOST OR DEGRADED POWER TRANSMISSION CAPABILITIES TO SYSTEM POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	2.011E-01	\$534.65	\$2,474.54	\$227.53	4	\$3,436.72	INSTALL./MAINT., OR DESIGN FOR NO MAINTENANCE OF THE BEARING IN ADDITION TO ALIGNMENT AND LIFE CONSIDERATIONS ARE THE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN BEARING USE IS A SCIENCE WITHIN ITSELF -- CONSULT MANUFACTURER SPECS. FOR DETAILS OR SOURCE SUCH AS SKF SERVICE GUIDE BOOKLET DESIGN FOR NO MAINTENANCE OF BEARING IF POSSIBLE OR DESIGN FOR EASY MAINTENANCE	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS REC. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 9 FOR SEALING OR SHIELDING AREAS WHERE LIQUIDS OR PARTICLES CAN ACCUMULATE

ROTATIONAL MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION			FAILURE MODE CAUSE & EFFECT ANALYSIS		FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION			
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST (\$/EVENT)	TOTAL COST RISK (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
7.2	RADIAL BEARING (QTY. 2)	FAILS TO PROVIDE POSITION AND SUPPORT	INSTALL./MAINT. ERRORS IN MOUNTING SHAFT IN BEARING OR BEARING HOUSING EXCESSIVE THERMAL EXPANSION DEGRADING FIT QUALITY EXTERNAL IMPACTS IN EXCESS OF FIT HOLDING PRESSURES	ALLOWS IMPROPER POSITIONING OF ROTARY AXIS POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	1.148E-02	\$322.00	\$2,121.40	\$180.12	2	\$2,424.52	\$30.13	INSTALL./MAINT., THERMAL EXPANSION, AND IMPACT LOADS ARE THE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN THIS COMPONENT IS PROTECTED IN MAIN 2 GUIDE TUBE	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS REC. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL
8.1	BEARING CARTRIDGE	FAILS TO MAINTAIN POSITIONING ACCURACY AND FUNCTION OF BEARINGS AND SPINDLE	COMBINED STRESS LOADS CAUSING YIELDING AND FRACTURE. SOURCES OF LOADS ARE OPERATING LOADS, MISALIGNMENTS, VIBRATIONS, AND EXTERNAL IMPACTS EXCESSIVE THERMAL DEFORMATION CAUSING LOOSENING OR EXCESSIVE TIGHTNESS CORROSION FROM PROCESS OR MAINTENANCE CHEMICALS OR HUMIDITY MATERIAL DEFECTS FROM MANUFACTURING PROCESS	LOST OR REDUCE POWER TRANSMISSION CAPABILITY INACCURATE POSITIONING OF ROTARY AXIS POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	5.740E-03	\$322.00	\$4,746.40	\$155.12	2	\$5,295.52	\$30.07	COMBINED LOADS, THERMAL DEFORMATION, CORROSION, AND IMPACTS ARE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN THIS COMPONENT IS PROTECTED IN MAIN 2 GUIDE TUBE	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS REC. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 9 FOR SEALING OR SHIELDING AREAS WHERE LUBRICANTS OR PARTICLES CAN ACCUMULATE

ROTATIONAL MOTION SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION			FAILURE MODE CAUSE & EFFECT ANALYSIS		FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION		
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST RISK (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
9.1	IC CLIPS (QTY. 2)	FAILS TO MAINTAIN SUPPORT OF ASSEMBLY	COMBINED STRESS LOADS CAUSING YIELDING AND FRACTURE. SOURCES OF LOADS ARE OPERATING LOADS, MISALIGNMENTS, VIBRATIONS, AND EXTERNAL IMPACTS FATIGUE FROM ALTERNATING STRESSES CORROSION FROM PROCESS OR MAINTENANCE CHEMICALS OR HUMIDITY MATERIAL DEFECTS FROM MANUFACTURING PROCESS	LOST OR REDUCED POWER TRANSMISSION LOST SUPPORT TO REARING CARTRIDGE ASSEMBLY POTENTIAL DAMAGE TO END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND/OR DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	5.210E-03	\$666.75	\$2,453.30	\$229.14	5	\$3,589.19	COMBINED LOADS, FATIGUE, FRICTIONAL WEAR, CORROSION, AND IMPACTS ARE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN THIS COMPONENT IS PROTECTED IN MAIN 2 GUIDE TUBE	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS REC. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 9 FOR SEALING AND SHIELDING AREA WHERE LIQUIDS AND PARTICLES CAN ACCUMULATE

PERIPHERAL EQUIPMENT SUB-SYSTEM FMEA TABLES FOR CASE STUDY

PERIPHERAL EQUIPMENT SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION		FAILURE MODE CAUSE & EFFECT ANALYSIS		FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION			
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST RISK (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
1.1	ELECTRIC POWER SUPPLY UNIT	FAILS TO SUPPLY POWER TO MOTORS	INTERNAL CIRCUIT FAILURES DUE TO OVERHEATING, CORROSION, VIBRATIONS, OR IMPACTS DEFECTIVE FUSE	LOSS OF DRIVE POWER TO ALL MOTION AXES POTENTIAL DAMAGE TO THE END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	4.836E-02	\$915.75	\$4,268.30	\$244.14	4	\$5,428.19	INSURING PROPER INSTALL./MAINT., HIGH INITIAL QUALITY, AND ISOLATION FROM THE ENVIRONMENT ARE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 15 FOR SHUTTING DOWN FEED LINES AND INTERACTING EQUIPMENT DURING ROBOT LOSS OF POWER OR ERROR SIGNAL
1.2	ELECTRIC POWER SUPPLY UNIT	FAILS TO LIMIT CURRENT TO MOTORS	INCORRECT OR DEFECTIVE FUSE INCORRECT CURRENT SET FOR OPERATION	DAMAGE TO MOTORS OR MOTOR DRIVERS WITH LOSS OF SINGLE OR MULTIPLE AXIS MOTION POTENTIAL DAMAGE TO THE END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	1.472E-03	\$774.65	\$3,899.54	\$212.53	3	\$4,886.72	INSURING PROPER INSTALL./MAINT. AND INITIAL QUALITY ARE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 16 FOR USING AN ALTERNATIVE POWER SOURCE TO SEND LOSS OF POWER SIGNAL REC. 17 FOR REQUIRING RE-CALIBRATION OF ROBOT, WITH MANUAL INITIATION, AFTER ERROR OR LOSS OF POWER EVENT

PERIPHERAL EQUIPMENT SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION			FAILURE MODE CAUSE & EFFECT ANALYSIS				FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION	
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST (\$/EVENT)	TOTAL COST RISK (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
2-1	ELECTRIC POWER SOURCE	FAILS TO PROVIDE ADEQUATE POWER	OFFSITE EVENTS BEYOND CONTROL OF ROBOT OPERATOR SUCH AS LINE MAINTENANCE, POWER LINE DAMAGE, GENERATING STATION FAILURES, ETC.	LOSS OF POWER TO ALL MOTION AXES POTENTIAL DAMAGE TO THE END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	3.168E+00	\$665.74	\$2,868.30	\$244.14	4	\$3,778.18	\$11,949.27	INSURING SAFE OPERATION AFTER THIS EVENT OR USING ALTERNATIVE POWER SUPPLY SOURCE TO CONTINUE OPERATION ARE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN.	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 15 FOR SHUTTING DOWN FEED LINES OR RELATED EQUIPMENT DURING LOSS OF POWER OR ERROR SIGNAL REC. 16 FOR USING ALTERNATE POWER SOURCE TO SEND LOSS OF POWER SIGNAL REC. 17 FOR REQUIRING RE-CALIBRATION OF ROBOT, WITH MANUAL INITIATION, AFTER ERROR OR LOSS OF POWER EVENT REC. 18 FOR CONSIDERING USING AN ALTERNATIVE POWER SUPPLY SOURCE FOR CONTINUED OPERATION

PERIPHERAL EQUIPMENT SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION			FAILURE MODE CAUSE & EFFECT ANALYSIS		FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION			
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST (\$/EVENT)	TOTAL COST RISK (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
3.1	CONTROLLING COMPUTER HARDWARE	FAILS OFF NOT ALLOWING ROBOT CONTROL OR OPERATION	INFORMATION PROCESSING AND CALCULATING SYSTEM FAILS OFF DISPLAY FAILURE NOT ALLOWING USER INTERACTION INFORMATION RETRIEVAL SYSTEM FAILS OFF KEYBOARD INPUT FAILS OFF INPUT OR OUTPUT PORTS FAIL OFF	LOSS OF OPERATION OF ROBOT POTENTIAL DAMAGE TO THE END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	2.400E-01	\$1,015.75	\$4,246.30	\$244.14	4	\$5,526.19	\$1,326.77	LOCAL TEMPERATURE, HUMIDITY, CORROSIVES AND CONTAMINANTS, AND IMPACTS ARE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 8 FOR USING A ROBOT POSITION VERIFICATION SYSTEM TO MAINTAIN ACCURACY REC. 15 FOR SHUTTING DOWN FEED LINES OR RELATED EQUIPMENT DURING LOSS OF POWER OR ERROR SIGNAL REC. 17 FOR REQUIRING RE-CALIBRATION OF ROBOT, WITH MANUAL INITIATION, AFTER ERROR OR LOSS OF POWER EVENT

PERIPHERAL EQUIPMENT SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION			FAILURE MODE CAUSE & EFFECT ANALYSIS		FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION		
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST RISK (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
3.2	CONTROLLING COMPUTER HARDWARE	CAUSES SPURIOUS CONTROL OR MOTION	PROCESSING OR CALCULATING SYSTEM ERRORS CAUSING INCORRECT SIGNALS TO BE GENERATED INPUT OR OUTPUT PORTS FAIL SENDING INCORRECT SIGNALS SPURIOUS SIGNALS FROM STRAY ELECTRIC OR MAGNETIC FIELDS OR CURRENT SURGES INCORRECT INSTALL./MAINT. IN ELECTRICAL CONNECTIONS	CAUSES SPURIOUS MOTION OF ROBOT POTENTIAL DAMAGE TO THE END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	1.200E-01	929.38	43,807.35	8204.63	3	44,051.36	TEMPERATURE, HUMIDITY, CORROSIVE AND CONTAMINANTS, IMPACTS, AND INSTALL./MAINT. ARE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 8 FOR USING A ROBOT POSITION VERIFICATION SYSTEM TO MAINTAIN ACCURACY REC. 15 FOR SHUTTING DOWN FEED LINES OR RELATED EQUIPMENT DURING LOSS OF POWER OR ERROR SIGNAL REC. 17 FOR REQUIRING RE-CALIBRATION OF ROBOT WITH MANUAL INITIATION AFTER ERROR OR LOSS OF POWER EVENT REC. 18 FOR USING RUBBER STOPS AT LIMITS OF MOTION ON EACH AXIS TO LESSEN IMPACT DAMAGES

PERIPHERAL EQUIPMENT SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION		FAILURE MODE CAUSE & EFFECT ANALYSIS			FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION			
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST (\$/EVENT)	TOTAL COST RISK (\$/YR)	FAILURE MODE COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
4.1	CONTROLLING COMPUTER SOFTWARE	ACTIVELY SENDS WRONG OR INCORRECTLY TIMED SIGNAL	IMPROPERLY CONFIGURED TO ALLOW INFORMATION RETRIEVAL, ACCESS TO OUTPUT AND INPUT PORTS, DISPLAY ON MONITOR, OR PROPER TIMING OF SIGNALS	FAILS TO PROVIDE ROBOT OPERATION OR ALLOWS SPURIOUS ROBOT OPERATION	1.670E-01	\$489.38	\$2,932.35	\$249.43	4	\$3,671.36	\$413.12	PROPER IDENTIFICATION AND LINKING OF HARDWARE TO THE SOFTWARE IS THE KEY OPERATING PARAMETER. THIS SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN
			POTENTIAL DAMAGE TO THE SEND EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY									IN TESTING OF THE DOWN FEED LINES OR PROGRAMMING, THOROUGH TESTING OF PORTS WHERE SIGNALS SHOULD NOT BE PRESENT AS WELL AS WHERE SIGNALS SHOULD BE PRESENT FOR SOME DURATION IS IMPORTANT	REC. 8 FOR USING A ROBOT POSITION VERIFICATION SYSTEM TO MAINTAIN ACCURACY
			MEMORY LIMITATIONS IN EXECUTING THE PROGRAM										REC. 15 FOR SHOOTING DOWN FEED LINES OR RELATED EQUIPMENT DURING LOSS OF POWER OR ERROR SIGNAL
			INTERNAL CALCULATING, PROCESSING, LOCATION, RETRIEVAL, OR PLACEMENT ERROR IN PROGRAMMING										REC. 17 FOR REQUIRING RE-CALIBRATION OF ROBOT WITH MANUAL INITIATION AFTER ERROR OR LOSS OF POWER EVENT
													REC. 15 FOR PROVIDING CONFIGURATION SETTING MENU OR FEATURE TO SIMPLIFY HARDWARE TO SOFTWARE INTERFACING
													REC. 20 FOR PROVIDING SLOW SPEED TEST AND VERIFICATION OF PROGRAMMED PATHS BEFORE AUTOMATIC OPERATION

PERIPHERAL EQUIPMENT SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION			FAILURE MODE CAUSE & EFFECT ANALYSIS			FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION	
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST (\$/YR)	FAILURE MODE COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
4.2	CONTROLLING COMPUTER SOFTWARE	PASSIVELY SENDS WRONG OR INCORRECTLY TIMED SIGNAL	CONFIGURATION ERRORS BETWEEN HARDWARE AND SOFTWARE "OLD" INFORMATION LEFT IN MEMORY ADDRESSES OR RETRIEVAL INFORMATION OVERWRITES CURRENT INFORMATION IN A MEMORY ADDRESS HIGH OR LOW SIGNAL INDEFINITELY LEFT ON TOO LONG	ALLOWS SPURIOUS ROBOT MOTION POTENTIAL DAMAGE TO THE END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	8.349E-01	4489.38	\$2,532.35	\$249.43	4	\$3,271.36	HARDWARE TO SOFTWARE CONFIGURATION, AND INADVERTANT PROGRAM ERRORS ARE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN REC. 15 FOR SHUTTING DOWN FEED LINES OR RELATED EQUIPMENT DURING LOSS OF POWER OR ERROR SIGNAL REC. 17 FOR RESETTING PRE-CALIBRATION OF ROBOT WITH MANUAL INITIATION AFTER ERROR OR LOSS OF POWER EVENT	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 8 FOR USING A ROBOT POSITION VERIFICATION SYSTEM TO MAINTAIN ACCURACY REC. 15 FOR SHUTTING DOWN FEED LINES OR RELATED EQUIPMENT DURING LOSS OF POWER OR ERROR SIGNAL REC. 17 FOR RESETTING PRE-CALIBRATION OF ROBOT WITH MANUAL INITIATION AFTER ERROR OR LOSS OF POWER EVENT
5.1	ROBOT BASE SUPPORT STRUCTURE	FAILS TO PROVIDE STRUCTURAL SUPPORT	FASTENERS OR MEMBER FAILURE DUE TO FATIGUE, PROCESS OR MAINTENANCE CHEMICAL CORROSION, COMBINED STRESS LOADING FROM LOADS AND MISALIGNMENTS, OR EXTERNAL IMPACTS INSTALL./MAINT. ERRORS OMITTING SOME FASTENERS OR SUPPORT MEMBERS	CATASTROPHIC ROBOT FAILURE TO MULTIPLE ROBOT COMPONENTS WITH LOSS OF MOTION POTENTIAL DAMAGE TO THE END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	7.570E-04	\$715.75	\$4,093.30	\$229.14	4	\$5,038.19	FATIGUE, CORROSION, STRESSES, ALIGNMENTS, INSTALL./MAINT., AND EXTERNAL IMPACTS ARE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT. AND DESIGN RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS RECS. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 15 FOR SHUTTING DOWN FEED LINES OR RELATED EQUIPMENT DURING LOSS OF POWER OR ERROR SIGNAL	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS RECS. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 15 FOR SHUTTING DOWN FEED LINES OR RELATED EQUIPMENT DURING LOSS OF POWER OR ERROR SIGNAL

PERIPHERAL EQUIPMENT SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION		FAILURE MODE CAUSE & EFFECT ANALYSIS		FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION				
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST (\$/EVENT)	TOTAL COST RISK (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
5.2	ROBOT BASE SUPPORT STRUCTURE	FAILS TO MAINTAIN PLACEMENT ACCURACY OF CORNER BRACKET SUPPORTS	DEFORMATION OF MEMBERS DUE TO CORROSION, WEAR, LOCAL YIELDING, OR EXTERNAL IMPACTS LOOSENING OF FASTENERS DUE TO CORROSION, WEAR, LOCAL YIELDING, OR EXTERNAL IMPACTS EXCESSIVE VIBRATION OF SUPPORT STRUCTURES CAUSING INACCURATE MOTION OF END EFFECTOR INSTALL./MAINT. ERRORS IN POSITIONING OF CORNER BRACKETS	CAUSES INACCURATE POSITIONING. POTENTIAL DAMAGE TO THE END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY MAY CAUSE BINDING OF MOTION ALONG AN AXIS	2.5E-03	\$376.28	\$3,213.59	\$158.02	4	\$3,819.89	\$9.64	CORROSION, WEAR, COMBINED STRESS LOADING, IMPACTS, AND INSTALL./MAINT. ARE KEY OPERATING PARAMETERS. THESE SHOULD BE ADDRESSED IN INSTALL./MAINT AND DESIGN	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 3 FOR RESTRICTING SOURCES OF EXTERNAL IMPACTS REC. 4 AND 5 FOR PROVIDING OPERATOR POSITION VERIFICATION AND ISOLATING ROBOT FROM OTHER EQUIPMENT AND PERSONNEL REC. 8 FOR USING A ROBOT POSITION VERIFICATION SYSTEM TO MAINTAIN ACCURACY REC. 15 FOR SHUTTING DOWN FEED LINES OR RELATED EQUIPMENT DURING LOSS OF POWER OR ERROR SIGNAL

PERIPHERAL EQUIPMENT SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION		FAILURE MODE CAUSE & EFFECT ANALYSIS			FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION		
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST (\$/YR)	FAILURE MODE COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
6.1	OPERATOR	TEACHES OR INPUTS INCORRECT PATH	INADVERTENTLY ENTERS WRONG PATH OR SEQUENCES OF PATHS OUT OF ORDER FAILS TO MAKE NECESSARY MODIFICATIONS TO AN EXISTING PATH FAILS TO BEGIN PATH COMMANDS FROM THE KEY HOME POSITION	CAUSES POSITIONING ERRORS. POTENTIAL DAMAGE TO THE END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	2.536E+00	\$665.75	\$2,343.30	\$199.14	4	\$3,208.19		REC. 20 FOR PROVIDING SLOW SPEED TEST AND VERIFICATION OF PROGRAMMED PATHS BEFORE AUTOMATIC OPERATION REC. 18 FOR USING RUBBER STOPS AT LIMITS OF MOTION ON EACH AXIS TO LESSEN IMPACT DAMAGES REC. 21 FOR MAKING ALL PATH AND POSITION MOTION PROGRAMS BEGIN AND END IN SOME HOME POSITION
6.2	OPERATOR	FAILS TO PROPERLY CALIBRATE OPERATION FOR ACCELERATION RAMPING OF LOADS	FAILS TO PROPERLY IDENTIFY AMOUNT OF LOAD FAILS TO RECOGNIZE OR RE-CALIBRATE A CHANGE IN LOAD FAILS TO PROPERLY CHANGE FACTORS AFFECTING RAMPING IN PROGRAM	INACCURATE POSITIONING. POTENTIAL DAMAGE TO THE END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	1.245E+00	\$454.10	\$1,790.16	\$151.73	3	\$2,995.99		REC. 15 FOR SHUTTING DOWN FEED LINES OR RELATED EQUIPMENT DURING LOSS OF POWER OR ERROR SIGNAL REC. 17 FOR REQUIRING RE-CALIBRATION OF ROBOT WITH MANUAL INITIATION AFTER ERROR OR LOSS OF POWER EVENT REC. 18 FOR USING RUBBER STOPS AT LIMITS OF MOTION ON EACH AXIS TO LESSEN IMPACT DAMAGES REC. 22 FOR AUTOMATING THE LOAD CALIBRATION PROCESS FOR THE ROBOT
										\$3,030.93		

PERIPHERAL EQUIPMENT SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION		FAILURE MODE CAUSE & EFFECT ANALYSIS		FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION			
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST RISK (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
6.3	OPERATOR	FAILS TO BEGIN ROBOT OPERATION FROM KEY HOME POSITION	RESUMES OPERATION AFTER FAULT WITHOUT RE-SETTING NEGLECTS TO INSURE ROBOT IS INITIALLY IN KEY HOME POSITION PREVIOUS PROGRAMMED MOTION DID NOT RETURN TO HOME POSITION NO PRECISE METHOD FOR LOCATING THE KEY HOME POSITION	INACCURATE POSITIONING. POTENTIAL DAMAGE TO THE END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	2.530E+00	4665.75	42,343.30	\$199.14	4	\$3,208.19	CREATIVE DESIGN WILL ALLOW COMBINATION OF THE ROBOT POSITION VERIFICATION SYSTEM AND THE LOCATION OF THE KEY HOME POSITION	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 18 FOR USING RUBBER STOPS AT LIMITS OF MOTION ON EACH AXIS TO LESSEN IMPACT DAMAGES REC. 17 FOR REQUIRING RE-CALIBRATION OF ROBOT WITH MANUAL INITIATION AFTER ERROR OR LOSS OF POWER EVENT REC. 20 FOR PROVIDING SLOW SPEED TEST AND VERIFICATION OF PROGRAMMED PATHES BEFORE AUTOMATIC OPERATION REC. 23 FOR AUTOMATING THE PROCESS OF LOCATING THE KEY HOME DESTINING AND ENDING POSITION

PERIPHERAL EQUIPMENT SUB-SYSTEM FOR THE UT ROBOT

FAILURE MODE EVENT IDENTIFICATION		FAILURE MODE CAUSE & EFFECT ANALYSIS		FAILURE MODE FREQUENCY AND CONSEQUENCE QUANTIFICATION					FAILURE MODE EVALUATION			
ITEM	COMPONENT DESCRIPTION	FAILURE MODE	FAILURE MODE CAUSES	FAILURE MODE SYSTEM EFFECTS	EVENT FREQUENCY (EVENT/YR)	EQUIPMENT DAMAGE COST (\$/EVENT)	BUSINESS INTERRUPTION COST (\$/EVENT)	REPAIR TIME COST (\$/EVENT)	SAFETY CAT.	TOTAL COST (\$/YR)	FAILURE MODE SAFEGUARDS AND COMMENTS	RECOMMENDED ACTIONS FOR FAILURE MODE
4.4	OPERATOR	FAILS TO SHUT DOWN SYSTEM WHEN ERROR EXISTS	OPERATOR NOT PAYING ATTENTION TO AUTOMATIC OPERATION NOT TRAINED TO DETECT ERRORS NOT ABLE TO SHUT DOWN ROBOT SYSTEM NOT ABLE TO SHUT DOWN END EFFECTOR AND LINKED EQUIPMENT OPERATION	INACCURATE POSITIONING. POTENTIAL DAMAGE TO THE END EFFECTOR, EQUIPMENT OR PARTS IN WORKSPACE, AND DAMAGE OR INJURY TO OTHER EQUIPMENT OR PERSONNEL IN VICINITY	1.25E+00	\$612.84	\$2,205.02	\$187.29	5	\$3,005.15	THE OPERATOR NEEDS A MASTER CONTROL SWITCH, SEPARATE FROM THE CONTROL SOFTWARE, TO SHUT DOWN THE SYSTEM THE OPERATOR MUST BE TRAINED TO UNDERSTAND WHAT IS A FAILURE AND WHAT ACTION SHOULD BE TAKEN	RECS. 1 AND 2 FOR INSTALL./MAINT. AND DESIGN REC. 4 FOR PROVIDING OPERATOR POSITION VERIFICATION REC. 24 FOR PROVIDING MASTER SWITCH FOR EMERGENCY SHUTDOWN OF ROBOT, END EFFECTOR, AND LINKED EQUIPMENT REC. 25 FOR LIMITING THE NUMBER OF AUTOMATIC CYCLES WHICH MAY BE EXECUTED AUTOMATICALLY WITHOUT MANUAL VERIFICATION REC. 24 FOR PROVIDING THOROUGH OPERATOR TRAINING

APPENDIX B

DERIVATION OF NUMERICAL ANALYSIS EQUATIONS

1. System Failure Rate Calculation [Fussell, 1975]

The equations for the total system expected failure rate, and corresponding Mean Time To Failure, are described by

$$\sum \lambda_{failure\ mode} \approx \lambda_{system}$$

and

$$Mean\ Time\ To\ Failure\ (MTTF)_{SYS} = \frac{1}{\lambda_{SYS}}.$$

These equations are founded on the assumptions that failure events:

- a) are statistically independent events;
- b) have constant failure rates;
- c) are based on the exponential reliability equation;
- d) all have repair times that are much less than the individual failure mode's Mean-Time-To-Failure.

2. Definition of Risk

While identifying the frequency and the cost of failure for a failure mode is valuable, the importance of each failure mode of a system is determined by the combined effects of its frequency and consequence. Failures which are catastrophic, but seldom occur, must be compared to other failures, which occur much more frequently, but have lower consequences. Calculation of the **risk** of a failure mode provides a means to compare failure modes, and a means to estimate annual costs due to system failures. Risk is calculated as shown below.

$$RISK = (FREQUENCY\ OF\ FAILURE) \times (COST\ OF\ FAILURE)$$

Furthermore, risk may be sub-divided based on contributing costs, such as Equipment Damage Costs, Business Interruption Costs, and Repair Costs. These sub-divided, and the Total Cost, equations are described by

$$\begin{aligned} RISK_{EDC} &= \lambda_{FM} \times COST_{FM-EDC} \\ RISK_{BIC} &= \lambda_{FM} \times COST_{FM-BIC} \\ RISK_{RPC} &= \lambda_{FM} \times COST_{FM-RPC} \\ RISK_{TLC} &= \lambda_{FM} \times COST_{FM-TLC} \end{aligned}$$

where EDC is the Equipment Damage Cost;
 BIC is the Business Interruption Cost;
 RPC is the Repair Cost;
 TLC is the Total Cost.

3. Numerical Evaluation of FMEA Table

As presented in the text, the exact quantification of frequencies and costs for potential failure modes in a system is quite difficult, if not impossible. In fact, most FMECA studies make no attempt to actually assign numerical frequencies, or dollar value costs, to failure modes. In these studies, a set of categories is used to estimate the quantification of the system failure modes. For instance [Ireson and Coombs, 1988, p. 13.15],

Cost Category	Description
1	Catastrophic
2	Critical
3	Marginal
4	Minor

Example of Previous Consequence "Quantification"

is an example of a consequence categorization, and

Frequency Category	Description
A	Frequent
B	Reasonable
C	Occasional
D	Remote
E	Extremely Unlikely

Example of Previous Frequency "Quantification"

is an example of a frequency categorization.

Some rating schemes are available for evaluating these types of "quantifications" for the potential failure modes. However, these evaluation schemes provide minimal numeric quantification results because of the difficulty in interpreting the combinations of frequency and consequence categories. For example, what is expected from an occasionally occurring failure event with a marginal consequence? The schemes also do not make use of potentially available data which could be used to produce more meaningful results, such as a predicted system failure rate, or an annual failure cost.

The approach developed in this research project not only makes better use of available data to generate more meaningful quantifications of the system failure modes, but also considers the uncertainty effects associated with the more direct quantifications. The numerical analysis approach presented provides two different characterizations of the system failure modes.

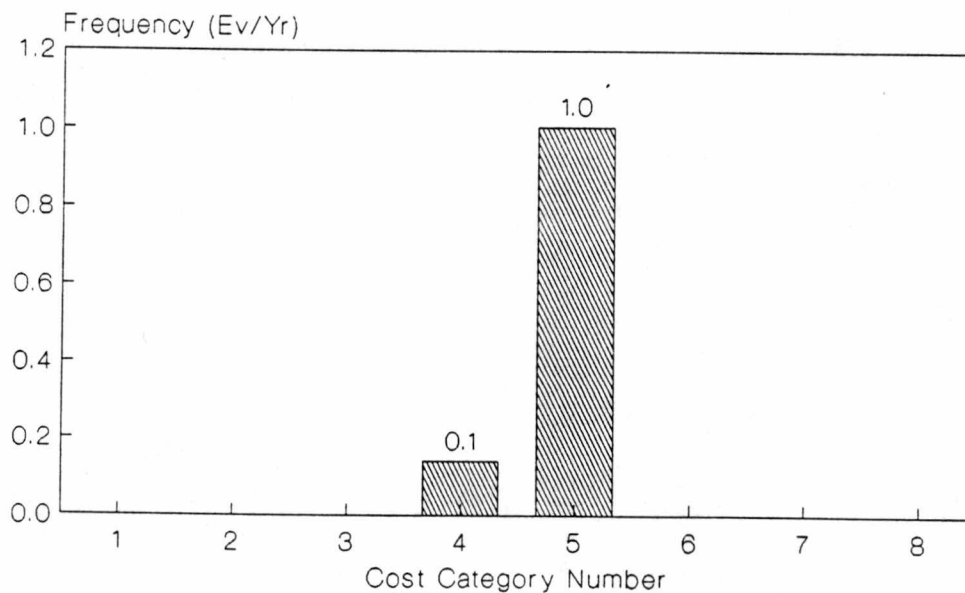
3.1 System Reliability Performance Evaluation

The first evaluation is based on the direct numerical frequency and cost data assigned to each failure mode. This data is organized into Summary Tables used to portray the predicted reliability performance. The total failure rate for each cost range considered is presented, along with a cumulative frequency for all cost categories at, or below, each cost range. The total risk for all of the events in each cost range is also presented. The following Summary Table is presented as an example.

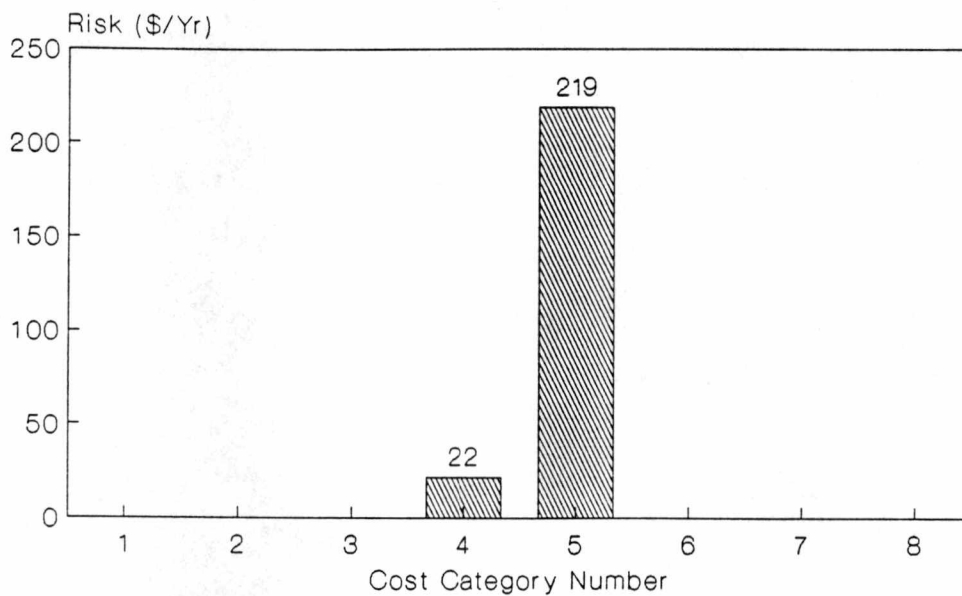
Cost Category Bounds	Category Number	Number of Events	Frequency	Cummulative Frequency	Risk
0 to 4	1				
4 to 13	2				
13 to 45	3				
45 to 158	4	4	0.138870	0.1388704	21.85
158 to 562	5	22	1.003698	1.1425688	218.66
562 to 1995	6			1.1425688	
1995 to 7079	7			1.1425688	
above 7079	8			1.1425688	

FMEA Summary Table

The frequency and risk information displayed in the Summary Table may also be depicted in histograms. The following graphs are frequency and risk histograms for the previous summary table.



a) Frequency Histogram for Summary Table



b) Risk Histogram for Summary Table

3.2 Failure Mode Importance Evaluation

The second evaluation is used to identify which failure modes are the largest contributors to the system's risk or failure frequency. This second evaluation groups frequencies by some category range definition appropriate for the expected frequencies. Failure events which are grouped in the same category are assumed to have approximately equal failure frequencies. This reduces the reliance of the importance ranking on the estimated failure frequencies for the failure modes, which have significant uncertainties in quantification, but also retains the significance of the originally input failure frequency. This procedure is repeated for each type of cost associated with the failure mode using a cost category range definition appropriate for the expected costs.

Choosing the appropriate ranges to define the categories is important. The ranges for the frequency categories, and for the cost categories, should span only the entire range of expected frequencies, or costs. A correctly focused category range definition will allow the finest division into categories. Additionally, as will be

described below in the section on Calculating Risk Based on Category Assignments and in the section on Risk Matrices, significant analysis benefits are achieved if the categories are defined such that risk is proportional to the sum of the frequency and cost categories for the failure mode.

This research effort has chosen to use a 10 category format for frequency categories, and an 8 category format for cost categories. The additional categories are used with the frequencies, because the frequencies often contribute the widest range of values. The following equations have been developed to define the ranges for the categories. The approximate frequency of a failure event in a given category is

$$EVENT\ FREQUENCY = BASE^{(-8 - SCF + FCN)}$$

where BASE is a scale parameter used for adjusting both the frequency and cost category range assignments;

SCF is a scale parameter for adjusting the ranges for determining the frequency category assignment only using the selected BASE;

and FCN is the frequency category number.

The lower bound for each category range, except for category 1, is calculated from

$$LOWER\ FREQUENCY\ BOUND = BASE^{(-8.5 - SCF + FCN)}$$

For frequency category 1, or cost category 1, the lower bound is 0, since negative frequencies, or costs, cannot occur. This equation generates the frequency category range table below with a frequency category scale parameter, SCF, of 1.0, and a BASE of 4.0.

Parameter	Frequency Category Number	Category Lower Bound (Ev/Yr)
SCF 1.0 Base 4.0	1	0
	2	3.05 E-05
	3	1.22 E-04
	4	4.88 E-04
	5	1.95 E-03
	6	7.81 E-03
	7	3.12 E-02
	8	1.25 E-01
	9	5.00 E-01
	10	2.00 E+00

Frequency Category Range Table

By definition, both the frequency and the cost category tables must have the same BASE in their definition equations. The importance of this fact is shown in the section on Calculating Risk Based on Category Assignments. However, an additional degree of freedom is provided to manipulate the cost category ranges with a cost category scale parameter, SCC. The equation for the approximate cost of a failure event in a category is

$$FAILURE\ COST = BASE^{(-SCC+CCN)}$$

where BASE is a scale parameter used for adjusting both the frequency and cost category range assignments;

SCC is a scale parameter for adjusting the ranges for determining the cost category assignment only using the selected BASE;

and CCN is the cost category number.

The lower bound for each cost category, except category 1, is given by

$$LOWER\ COST\ BOUND = BASE^{(-SCC-.5+CCN)}$$

This equation generates the cost category range table below with a cost category scale parameter, SCC, of 1.0, and a BASE of 4.0.

Parameter	Cost Category Number	Category Lower Bound (\$)
SCF 1.0 Base 4.0	1	0
	2	2
	3	8
	4	32
	5	128
	6	512
	7	2048
	8	8192

Cost Category Range Table

As an example of categorizing the failure events, three failure events are considered using the frequency and cost category tables above.

Failure Mode	Failure Frequency	Failure Cost
FM #1	1.0 E-02 /yr	\$ 1000
FM #2	1.0 E-03 /yr	\$ 300
FM #3	2.0 E-02 /yr	\$ 50

Example Failure Mode Data

The resulting categorizations for these failure modes are generated.

Failure Mode	Frequency Category	Cost Category
FM #1	6	6
FM #2	4	5
FM #3	6	4

Example Failure Mode Categorization

Safety issues are assessed in a more subjective manner. A scale is developed to identify potential safety concerns for a failure mode by a category number. The category definition used in this research is shown below.

Safety Category Number	Safety Consequence Description
1	Very Low
2	Low
3	Moderate
4	High
5	Very High

Safety Category Table

The actual classification of failure event consequences will depend on the potential hazards of the application. In some situations, some particular occurrences resulting from a failure, such as a potential for human deaths, may be used to more precisely define the safety category assignment for a failure event. The safety category assignment could also be tied to some amount of toxic release, or some level of energy dissipation, during a failure.

3.2.1 Risk Calculation Using Categories [Casada, 1989]

Risk calculations may be performed for any of the costs of failure using the category assignments for frequency and cost values. Recalling that

$$RISK = (FREQUENCY OF FAILURE) \times (COST OF FAILURE),$$

the approximate risk calculation may be written as

$$RISK \approx BASE^{(-8+FCN-SCF)} \times BASE^{(CCN-SCC)}.$$

This equation may be re-written as

$$RISK \approx BASE^{(-8-SCF-SCC)} \times BASE^{(FCN+CCN)}.$$

Since the scale parameters, BASE, SCF, and SCC, are constant during any analysis, the first term is a constant, and the equation may be written as

$$RISK \approx (CONSTANT) \times BASE^{(FCN+CCN)}.$$

Hence, the risk for an event is related to the sum of the frequency and cost categories for the failure event in the exponential equation. This is shown by

$$RISK \text{ IS RELATED TO } (FCN + CCN)$$

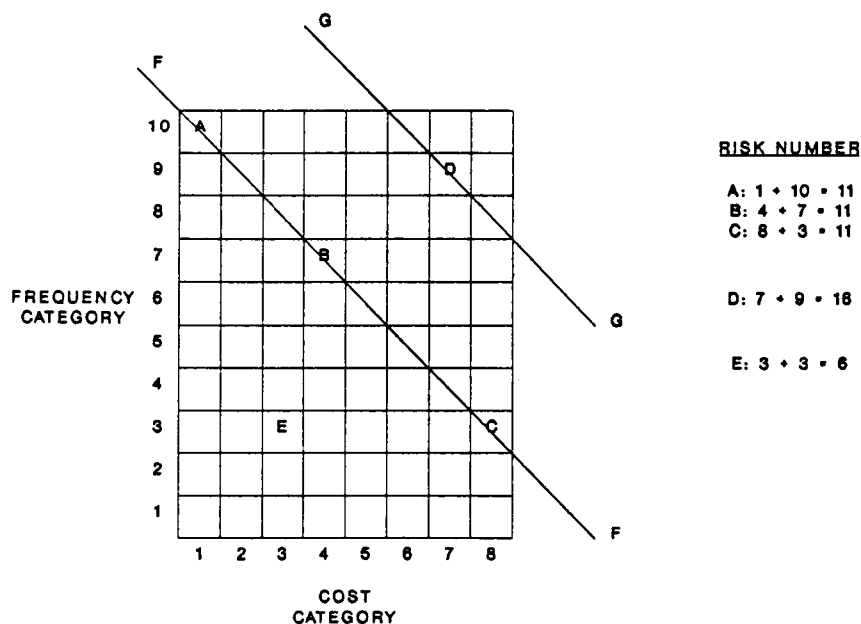
The sum of the categories forms a risk number given by

$$RISK \text{ NUMBER} = (FCN + CCN).$$

While the actual risk values for failure events are never computed using category numbers, the calculated risk numbers are very useful in determining the highest risk events of a system. Any two failure events which have the same risk number have approximately the same risk. Failure events with larger risk numbers have higher risks, and are more important than failure events with lower risk numbers. These relationships are the basis for identifying the most important contributors to the failure costs and unreliability of a system.

3.2.2 Risk Matrices

Using the risk number described, a convenient tool may be developed to quickly identify how many potential failure events significantly contribute to the failure costs of a system. This tool is the risk matrix, shown below.



Example Risk Matrix

The risk matrix is created by placing the frequency categories on the vertical axis and the consequence, cost or safety, categories along the horizontal axis. The placement of categories generates a matrix of cells which correspond to each combination of frequency and cost categories. Each combination of frequency and consequence categories prescribes a risk number. A diagonal line from the upper left to the lower right of the matrix, line FF or GG in the depiction, passes through the matrix cells which have approximately constant risk given by identical risk numbers. Lines closer to the upper right corner of

the matrix are higher risk lines. Therefore, the cells which are on line GG have higher risks than cells on line FF.

The number of potential failure events that have the corresponding frequency and consequence categories are entered in each cell. The number of events in each risk number category can be easily identified. The highest set of risk numbers may be classified as high risk events, and considered for immediate improvement action. The risk matrices may be generated for each type of consequence encountered such as Equipment Damage Costs, Business Interruption Costs, Repair Costs, Total Costs, or Safety Concerns.

3.2.3 Sorting Indices

The risk matrices determine the risk distribution of the many failure events, and allow one to define the quantity and severity of the high risk events for immediate consideration. However, the actual identification of the failure modes, which constitute the number in each matrix cell, is not available from the risk matrices. To determine which failure modes are the high risk failure modes, this research effort utilizes sorting indices to re-order the FMEA Table. The FMEA Table may be sorted by

- 1) Frequency;
- 2) Equipment Damage Risk;
- 3) Business Interruption Risk;
- 4) Repair Risk;
- 5) Total Risk;
- 6) or Safety Risk importance.

The sorting indices are created from the risk numbers of the failure events. The sorting index numbers are calculated for a particular risk, or for failure event frequency, by

$$\begin{aligned}
\text{SORTING INDEX NUMBER}_{FC} &= FCN \\
\text{SORTING INDEX NUMBER}_{EDR} &= [(CCN)_{EDC} + (FCN)] \& [.] \& [(CCN)_{EDC}] \\
\text{SORTING INDEX NUMBER}_{BIR} &= [(CCN)_{BIC} + (FCN)] \& [.] \& [(CCN)_{BIC}] \\
\text{SORTING INDEX NUMBER}_{RPR} &= [(CCN)_{RPC} + (FCN)] \& [.] \& [(CCN)_{RPC}] \\
\text{SORTING INDEX NUMBER}_{TLR} &= [(CCN)_{TLC} + (FCN)] \& [.] \& [(CCN)_{TLC}] \\
\text{SORTING INDEX NUMBER}_{SFR} &= [(SCN) + (FCN)] \& [.] \& [SCN]
\end{aligned}$$

where FCN is the Frequency Category Number;

 CCN is the Cost Category Number;

 SCN is the Safety Category Number;

 EDR is the Equipment Damage Risk;

 BIR is the Business Interruption Risk;

 RPR is the Repair Risk;

 TLR is the Total Risk;

 SFR is the Safety Risk;

 EDC refers to Equipment Damage Cost;

 BIC refers to Business Interruption Cost;

 RPC refers to Repair Cost;

 TLC refers to Total Cost;

 and SAF refers to Safety Concerns.

The sorting index numbers for every potential failure mode are placed on each line of the multiple line failure mode record as shown below.

ITEM	DESCRIPTION	FC	EQR	BIC	RCR	TCR	SFR	RESET
1.1	-----	5	7.2	9.4	6.1	9.4	8.3	1
	-----	5	7.2	9.4	6.1	9.4	8.3	2
	-----	5	7.2	9.4	6.1	9.4	8.3	3
	-----	5	7.2	9.4	6.1	9.4	8.3	4
	-----	5	7.2	9.4	6.1	9.4	8.3	5
	-----	6	7.2	9.4	6.1	9.4	8.3	6
	-----	6	7.2	9.4	6.1	9.4	8.3	7
1.2	-----	7	10.3	11.4	9.2	12.5	12.5	8
	-----	7	10.3	11.4	9.2	12.5	12.5	9
	-----	7	10.3	11.4	9.2	12.5	12.5	10
	-----	7	10.3	11.4	9.2	12.5	12.5	11
	-----	7	10.3	11.4	9.2	12.5	12.5	12
	-----	7	10.3	11.4	9.2	12.5	12.5	13
	-----	7	10.3	11.4	9.2	12.5	12.5	14
2.1	-----	7	10.3	11.4	9.2	12.5	12.5	15
	-----	3	4.1	6.3	4.1	6.3	5.2	16
	-----	3	4.1	6.3	4.1	6.3	5.2	17
	-----	3	4.1	6.3	4.1	6.3	5.2	18
	-----	3	4.1	6.3	4.1	6.3	5.2	19
	-----	3	4.1	6.3	4.1	6.3	5.2	20
	-----	3	4.1	6.3	4.1	6.3	5.2	21
		3	4.1	6.3	4.1	6.3	5.2	22
		3	4.1	6.3	4.1	6.3	5.2	23



(ETC.)

Example Sorting Index Configuration

The final column, a simple line numbering, is added to maintain the integrity of each failure mode record when the Table is sorted. This last column also provides a means to re-order the FMEA Table to the original order in which the records were input. The sorting uses a set of primary and secondary keys to list the failure mode records by the risk numbers for the selected type of risk, or by the frequency category if the frequency option is selected. After sorting, the most important events are listed highest in the FMEA Table. Within a given risk number in the sorted FMEA Table, the failure mode records with the larger consequences are listed higher. The type of sorting, primary key, and secondary key for each listing option are described in the following table.

Sort Based On:	Primary Key	Secondary Key
Frequency	Frequency Category	Line Numbering
Equipment Damage Risk	Equipment Damage Sorting Index	Line Numbering
Business Interruption Risk	Business Interruption Sorting Index	Line Numbering
Repair Risk	Repair Sorting Index	Line Numbering
Total Risk	Total Sorting Index	Line Numbering
Re-Order	Line Numbering	-----

Sorting Option Table

4. Frequency Quantification Approach for Failure Modes

The failure frequency rate is obtained from failure rate database data, actual operating experience, or engineering judgement. Using one, or a combination, of these three sources, a base expected failure rate for a potential failure mode is established. A series of multiplicative PI factors are applied to the base failure rate to customize the failure rate to the specific application. This process is shown as

$$\lambda_{FM} = \lambda_{BASE_{FM}} \times [\Pi_E \times \Pi_L \times \Pi_M \times \Pi_S \times \Pi_{OP} \dots],$$

where

λ_{FM} - PREDICTED FAILURE RATE
 λ_B - BASE FAILURE RATE
 Π_E - ENVIRONMENTAL CONDITION FACTOR
 Π_L - LOADING CONDITON FACTOR
 Π_M - MANUFACTURING QUALITY FACTOR
 Π_S - SERVICE/OPERATOR EFFECTIVENESS FACTOR
 Π_{OP} - OPERATING TIME CORRECTION
(..OTHERS AS NEEDED FOR APPLICATION..).

5. Consequence Quantification Approach for Failure Modes

The cost consequence assignments for each failure mode in the case study are calculated based on the following equations. The notation used in these equations is described below.

Each failure mode is characterized by a positioning error. The severity of the failure is generally dependant on the seriousness of the positioning error and the initiating component causing the failure. These factors are apparent in the developed quantification equations. The information necessary to perform the calculations is interpreted from the input tables shown in Figures 4-9 and 4-10 of the text.

Notation Definition:

<u>Term</u>	<u>Description</u>
AEDC	refers to an average equipment damage cost for any position error in the improved, favorable application case study
AERT	refers to an average equipment repair time for any position error in the improved, favorable application case study
BIC	refers to the business interruption cost
DT	refers to the downtime due to a failure
DTCHR	refers to the dowtime cost hourly rate for the system

EEC	refers to the end effector value
EEDC	refers to the end effector damage cost
EEDT	refers to the end effector downtime
EERT	refers to the time to repair the end effector
EDC	refers to the equipment damage cost
EIWC	refers to the process equipment inside workspace value
EIWDC	refers to the process equipment inside workspace damage cost
EIWDT	refers to the process equipment inside workspace downtime
EIWRT	refers to the time required to repair the equipment inside workspace
EOWC	refers to the process equipment outside workspace value
EOWDC	refers to the process equipment outside workspace damage cost
EOWDT	refers to the process equipment outside workspace downtime
EOWRT	refers to the time required to repair the equipment outside workspace
FM	refers to a particular failure mode
FPAT	refers to the aquisition time to obtain replacement parts for a failed system component
FPC	refers to the cost of replacement parts for a failed system component
FPRT	refers to the time required to repair the failed system component
LARGE	refers to a particular characteristic resulting from a large position error

PAT refers to total acquisition time to obtain replacement parts

RPC refers to the repair cost

RCHR refers to the repair cost hourly rate for the system

RCT refers to the time required to reset and recalibrate the system after repair

SMALL refers to a particular characteristic resulting from a small position error

TLC refers to the total cost

$\%_{LARGE}$ refers to the percentage of time a large position error occurs, given that a position error exists

VPD refers to the value of handled parts damaged during a failure event

Favorable Application Case Study

The cost quantification equations for the favorable application case study are shown.

$$\begin{aligned}
 EDC_{FM} &= (EDC_{LARGE}) \times (\%_{LARGE}) + (EDC_{SMALL}) \times (1 - \%_{LARGE}) \\
 DT_{FM} &= (DT_{LARGE}) \times (\%_{LARGE}) + (DT_{SMALL}) \times (1 - \%_{LARGE}) \\
 BIC_{FM} &= (DT_{FM}) \times (DTCHR) + (VPD) \\
 RPC_{FM} &= (DT_{FM} - PAT) \times (RCHR) \\
 TLC_{FM} &= EDC_{FM} + BIC_{FM} + RPC_{FM}
 \end{aligned}$$

The equations quantify the cost associated with large and small position errors for each failure mode, and use a weighting parameter to calculate the predicted costs. The calculations for predicting the cost of large and small positioning errors is described next. The assumption in the the favorable application case study that the business interruption cost hourly rate is zero, makes the business interruption cost dependent on only the value of production parts that may be damaged.

Large Position Error Cost Equations:

$$\begin{aligned}
 EDC_{LARGE} &= FPC + EEDC_{LARGE} + EIWDC_{LARGE} + EOWDC_{LARGE} \\
 EEDC_{LARGE} &= [(5\%) + (9\%) \times (90\%) + (10\%) \times (50\%) + (70\%) \times (10\%)] \times (EEC) \\
 EIWDC_{LARGE} &= [(5\%) + (9\%) \times (75\%) + (10\%) \times (25\%) + (70\%) \times (10\%)] \times (EIWC) \\
 EOWDC_{LARGE} &= [(5\%) \times (20\%) + (9\%) \times (10\%)] \times (EOWC) \\
 DT_{LARGE} &= FPAT + FPRT + RCT + EEDT_{LARGE} + EIWDT_{LARGE} + EOWDT_{LARGE} \\
 EEDT_{LARGE} &= [(5\%) + (9\%) \times (90\%) + (10\%) \times (50\%) + (70\%) \times (10\%)] \times (EERT) \\
 EIWDT_{LARGE} &= [(5\%) + (9\%) \times (75\%) + (10\%) \times (25\%) + (70\%) \times (10\%)] \times (EIWRT) \\
 EOWDT_{LARGE} &= [(5\%) \times (20\%) + (9\%) \times (10\%)] \times (EOWRT)
 \end{aligned}$$

Small Position Error Cost Equations:

$$\begin{aligned}
 EDC_{SMALL} &= FPC + EEDC_{SMALL} + EIWDC_{SMALL} + EOWDC_{SMALL} \\
 EEDC_{SMALL} &= [(0.5\%) + (9\%) \times (50\%) + (20\%) \times (20\%) + (50\%) \times (10\%)] \times (EEC) \\
 EIWDC_{SMALL} &= [(0.5\%) + (5\%) \times (50\%) + (50\%) \times (5\%) + (20\%) \times (1\%)] \times (EIWC) \\
 EOWDC_{SMALL} &= [(0.5\%) \times (10\%)] \times (EOWC) \\
 DT_{SMALL} &= FPAT + FPRT + RCT + EEDT_{SMALL} + EIWDT_{SMALL} + EOWDT_{SMALL} \\
 EEDT_{SMALL} &= [(0.5\%) + (9\%) \times (50\%) + (20\%) \times (20\%) + (50\%) \times (10\%)] \times (EERT) \\
 EIWDT_{SMALL} &= [(0.5\%) + (5\%) \times (50\%) + (50\%) \times (10\%) + (20\%) \times (10\%)] \times (EIWRT) \\
 EOWDT_{SMALL} &= [(0.5\%) \times (10\%)] \times (EOWRT)
 \end{aligned}$$

The percentages reflected in the equations are engineering estimates of the fraction of time a certain percentage of the value of the equipment is damaged, given a failure has occurred. For instance, 9% of the time that a failure occurs, 90% of the value of the end effector may be damaged for a large position error. This is a frequency weighting scheme for the consequences.

After the improvement actions suggested in Table 4-13 are instituted, drastic system advancement is expected. The improved consequences of failures are calculated using the following equations. These equations only calculate the total cost of the failure. Further sub-division into constituent costs is not warranted until the design actions are actually addressed. The goal here is to estimate potential improvement capability.

Improved System Cost Equations:

$$\begin{aligned}TLC_{FM} &= FPC + VPD + AEDC + [(RCT * FPRT_{FM} * AERT) * RCHR] \\ VPD &= \$75 \\ AEDC &= \$30.50 \\ AERT &= 0.6032 \text{ HR}\end{aligned}$$

The use of the position verification system radically limits the severity positioning error to such an extent that only small positioning errors will exist before failures are detected. The other recommendations directly affect the frequency of failures for the most important failure events, and affect some of the input data to the cost equations. These effects were considered on an individual failure mode basis.

For the Severe Application Case Study:

The cost consequence quantification equations for the severe application case study are presented next.

$$\begin{aligned}EDC_{FM} &= (EDC_{LARGE}) \times (\%_{LARGE}) + (EDC_{SMALL}) \times (1 - \%_{LARGE}) \\ DT_{FM} &= (DT_{LARGE}) \times (\%_{LARGE}) + (DT_{SMALL}) \times (1 - \%_{LARGE}) \\ BIC_{FM} &= (DT_{FM}) \times (DTCHR) + (VPD) \\ RPC_{FM} &= (DT_{FM} - PAT) \times (RCHR) \\ TLC_{FM} &= EDC_{FM} + BIC_{FM} + RPC_{FM}\end{aligned}$$

The equations similar to those for the favorable application, but the percentages are slightly different to reflect the severe application. Also, the severe application has a large business interruption cost hourly rate. The large and small positioning error cost equations are described below.

Large Position Error Cost Equations:

$$\begin{aligned}
 EDC_{LARGE} &= FPC + EEDC_{LARGE} + EIWDC_{LARGE} + EOWDC_{LARGE} \\
 EEDC_{LARGE} &= [(5\%) + (9\%) \times (90\%) + (10\%) \times (50\%) + (70\%) \times (10\%)] \times (EEC) \\
 EIWDC_{LARGE} &= [(5\%) + (9\%) \times (75\%) + (10\%) \times (25\%) + (70\%) \times (10\%)] \times (EIWC) \\
 EOWDC_{LARGE} &= [(5\%) \times (20\%) + (9\%) \times (5\%)] \times (EOWC) \\
 DT_{LARGE} &= FPAT + FPRT + RCT + EEDT_{LARGE} + EIWDT_{LARGE} + EOWDT_{LARGE} \\
 EEDT_{LARGE} &= [(5\%) + (9\%) \times (90\%) + (10\%) \times (50\%) + (70\%) \times (10\%)] \times (EERT) \\
 EIWDT_{LARGE} &= [(5\%) + (9\%) \times (75\%) + (10\%) \times (25\%) + (70\%) \times (10\%)] \times (EIWRT) \\
 EOWDT_{LARGE} &= [(5\%) \times (10\%) + (9\%) \times (5\%)] \times (EOWRT)
 \end{aligned}$$

Small Position Error Cost Equations:

$$\begin{aligned}
 EDC_{SMALL} &= FPC + EEDC_{SMALL} + EIWDC_{SMALL} + EOWDC_{SMALL} \\
 EEDC_{SMALL} &= [(0.5\%) + (9\%) \times (50\%) + (20\%) \times (20\%) + (50\%) \times (10\%)] \times (EEC) \\
 EIWDC_{SMALL} &= [(0.5\%) + (9\%) \times (50\%) + (50\%) \times (10\%) + (20\%) \times (5\%)] \times (EIWC) \\
 EOWDC_{SMALL} &= [(0.5\%) \times (10\%)] \times (EOWC) \\
 DT_{SMALL} &= FPAT + FPRT + RCT + EEDT_{SMALL} + EIWDT_{SMALL} + EOWDT_{SMALL} \\
 EEDT_{SMALL} &= [(0.5\%) + (9\%) \times (50\%) + (20\%) \times (20\%) + (50\%) \times (10\%)] \times (EERT) \\
 EIWDT_{SMALL} &= [(0.5\%) + (9\%) \times (50\%) + (50\%) \times (10\%) + (20\%) \times (5\%)] \times (EIWRT) \\
 EOWDT_{SMALL} &= [(0.5\%) \times (10\%)] \times (EOWRT)
 \end{aligned}$$

For the improved system in the severe application, the cost equations are modified as follows.

Improved System Cost Equations:

$$TLC_{PM} = FPC + (DT_{PM}) \times (DTCHR) + [(FPRT_{PM}) + (1.3)] \times (RCHR) + 125$$

$$\begin{aligned}
 125 &= EEDC + EIWDC + EOWDC \\
 EEDC &= [(0.1\%) + (1\%) \times (60\%) + (9\%) \times (30\%) + (20\%) \times (10\%) + (50\%) \times (0.1\%)] \times (EEC) \\
 EIWDC &= [(0.1\%) \times (80\%) + (1\%) \times (30\%) + (30\%) \times (10\%)] \times EIWC \\
 EOWDC &= [(1\%) \times (1\%)] \times EOWC
 \end{aligned}$$

$$\begin{aligned}
 1.3 &= RCT + EEDT + EIWRT + EOWRT \\
 EEDT &= [(0.1\%) + (1\%) \times (60\%) + (9\%) \times (30\%) + (20\%) \times (10\%) + (50\%) \times (0.1\%)] \times (EERT) \\
 EIWRT &= [(0.1\%) \times (80\%) + (1\%) \times (30\%) + (30\%) \times (10\%)] \times EIWRT \\
 EOWRT &= [(1\%) \times (1\%)] \times EOWRT
 \end{aligned}$$

Again, the costs do not depend on the $\%_{LARGE}$, because the position verification system should limit the errors to small position errors.

APPENDIX C

QUANTITATIVE EVALUATION RESULTS FOR CASE STUDY

APPLICATIONS

SEVERE APPLICATION CASE STUDY

Z AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT
EQUIPMENT DAMAGE COST MATRIX

		COST CATEGORY									
		1	2	3	4	5	6	7	8		
E V E N T S P E R Y E A R	> 13	:	:	:	:	:	:	:	:	:	10
	1.259E+01	-----	-----	-----	-----	-----	-----	-----	-----	-----	
	3.548E+00	-----	-----	-----	-----	-----	-----	-----	-----	-----	9
	1.000E+00	-----	-----	-----	-----	-----	-----	-----	-----	-----	8
	2.818E-01	-----	-----	-----	-----	-----	-----	-----	-----	-----	7
	7.943E-02	-----	-----	-----	-----	1	3	-----	-----	-----	6
	2.239E-02	-----	-----	-----	-----	4	4	-----	-----	-----	5
	6.310E-03	-----	-----	-----	-----	1	4	-----	-----	-----	4
	1.778E-03	-----	-----	-----	-----	-----	-----	-----	-----	-----	3
	5.012E-04	-----	-----	-----	-----	1	4	-----	-----	-----	2
		-----	-----	-----	-----	2	2	-----	-----	-----	1
		0	4	13	45	158	562	1995	7079	> 7079	
DOLLARS PER EVENT											

Z AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT
BUSINESS INTERRUPTION COST MATRIX

		COST CATEGORY									
		1	2	3	4	5	6	7	8		
E V E N T S P E R Y E A R	> 13	:	:	:	:	:	:	:	:	:	10
	1.259E+01	-----	-----	-----	-----	-----	-----	-----	-----	-----	
	3.548E+00	-----	-----	-----	-----	-----	-----	-----	-----	-----	9
	1.000E+00	-----	-----	-----	-----	-----	-----	-----	-----	-----	8
	2.818E-01	-----	-----	-----	-----	-----	-----	-----	-----	-----	7
	7.943E-02	-----	-----	-----	-----	-----	-----	4	-----	-----	6
	2.239E-02	-----	-----	-----	-----	-----	1	7	-----	-----	5
	6.310E-03	-----	-----	-----	-----	-----	1	4	-----	-----	4
	1.778E-03	-----	-----	-----	-----	-----	-----	-----	-----	-----	3
	5.012E-04	-----	-----	-----	-----	-----	-----	5	-----	-----	2
		-----	-----	-----	-----	-----	1	3	-----	-----	1
		0	4	13	45	158	562	1995	7079	> 7079	
DOLLARS PER EVENT											

Z AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT
REPAIR COST MATRIX

		COST CATEGORY									
		1	2	3	4	5	6	7	8		
EVENTS PER YEAR	> 13	1	1	1	1	1	1	1	1	10	
	1.259E+01	1	1	1	1	1	1	1	1	9	F
	3.548E+00	1	1	1	1	1	1	1	1	8	R
	1.000E+00	1	1	1	1	1	1	1	1	7	E
	2.818E-01	1	1	1	1	1	1	1	1	6	Q
	7.943E-02	1	1	1	1	4	1	1	1	5	E
	2.239E-02	1	1	1	2	6	1	1	1	4	N
	6.310E-03	1	1	1	1	4	1	1	1	3	C
	1.778E-03	1	1	1	1	1	1	1	1	2	A
	5.012E-04	1	1	1	1	5	1	1	1	1	T
		0	4	13	45	158	562	1995	7079	> 7079	E
DOLLARS PER EVENT											

Z AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT
TOTAL COST MATRIX

		COST CATEGORY									
		1	2	3	4	5	6	7	8		
EVENTS PER YEAR	> 13	1	1	1	1	1	1	1	1	10	
	1.259E+01	1	1	1	1	1	1	1	1	9	F
	3.548E+00	1	1	1	1	1	1	1	1	8	R
	1.000E+00	1	1	1	1	1	1	1	1	7	E
	2.818E-01	1	1	1	1	1	1	1	1	6	Q
	7.943E-02	1	1	1	1	1	1	4	1	5	E
	2.239E-02	1	1	1	1	1	1	8	1	4	N
	6.310E-03	1	1	1	1	1	1	5	1	3	C
	1.778E-03	1	1	1	1	1	1	1	1	2	A
	5.012E-04	1	1	1	1	1	1	4	1	1	T
		0	4	13	45	158	562	1995	7079	> 7079	E
DOLLARS PER EVENT											

Z AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT
SAFETY MATRIX

		SAFETY CATEGORY						
		1	2	3	4	5		
> 13		1	1	1	1	1	10	
1.259E+01		1	1	1	1	1	9	F
E		1	1	1	1	1	8	R
V	3.548E+00	1	1	1	1	1	7	E
E		1	1	1	1	1	6	Q
N	1.000E+00	1	1	1	1	1	5	E
T		1	1	1	1	1	4	N
S	2.818E-01	1	1	2	2	1	3	C
P		1	1	1	1	1	2	Y
E	7.943E-02	1	1	4	4	1	1	C
R		1	1	1	1	1	1	A
	2.239E-02	1	1	2	3	1	1	T
Y		1	1	1	1	1	1	E
E	6.310E-03	1	1	1	1	1	1	G
A		1	1	1	1	1	1	D
R	1.778E-03	1	1	1	1	2	2	R
		1	1	1	1	1	1	Y
	5.012E-04	1	1	2	1	1	1	
		VERY LOW	LOW	MODERATE	HIGH	VERY HIGH		
		SAFETY CATEGORY						

Z AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT
EQUIPMENT DAMAGE COST SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMMULATIVE FREQUENCY	RISK
0 TO 4	1				
4 TO 13	2				
13 TO 45	3				
45 TO 158	4				
158 TO 562	5	9	0.344642	0.3446428	157.4535
562 TO 1995	6	17	0.797926	1.1425688	504.7125
1995 TO 7079	7			1.1425688	
ABOVE 7079	8			1.1425688	

Z AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT
BUSINESS INTERRUPTION COST SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMMULATIVE FREQUENCY	RISK
0 TO 4	1				
4 TO 13	2				
13 TO 45	3				
45 TO 158	4				
158 TO 562	5				
562 TO 1995	6	3	0.078860	0.0788604	145.9354
1995 TO 7079	7	23	1.063708	1.1425688	3428.167
ABOVE 7079	8			1.1425688	

Z AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT
REPAIR COST SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMMULATIVE FREQUENCY	RISK
0 TO 4	1				
4 TO 13	2				
13 TO 45	3				
45 TO 158	4	4	0.138870	0.1388704	21.85621
158 TO 562	5	22	1.003698	1.1425688	218.6596
562 TO 1995	6			1.1425688	
1995 TO 7079	7			1.1425688	
ABOVE 7079	8			1.1425688	

Z AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT
TOTAL COST SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMMULATIVE FREQUENCY	RISK
0 TO 4	1				
4 TO 13	2				
13 TO 45	3				
45 TO 158	4				
158 TO 562	5				
562 TO 1995	6				
1995 TO 7079	7	25	1.141698	1.1416983	4470.144
ABOVE 7079	8	1	0.000870	1.1425688	6.640339

Z AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT
SAFETY SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMMULATIVE FREQUENCY
VERY LOW	1			
LOW	2	2	0.001362	0.0013624
MODERATE	3	11	0.475682	0.4770452
HIGH	4	11	0.663665	1.1407109
VERY HIGH	5	2	0.001857	1.1425688

X-Y AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT
EQUIPMENT DAMAGE COST MATRIX

		COST CATEGORY									
		1	2	3	4	5	6	7	8		
E V E N T S P E R Y E A R	> 13	1	1	1	1	1	1	1	1	1	10
	1.259E+01	1	1	1	1	1	1	1	1	1	9
	3.548E+00	1	1	1	1	1	2	1	1	1	8
	1.000E+00	1	1	1	1	2	5	1	1	1	7
	2.818E-01	1	1	1	1	1	8	1	1	1	6
	7.943E-02	1	1	1	1	3	2	1	1	1	5
	2.239E-02	1	1	1	1	2	1	1	1	1	4
	6.310E-03	1	1	1	1	2	6	1	1	1	3
	1.778E-03	1	1	1	1	1	3	1	1	1	2
	5.012E-04	1	1	1	1	1	1	1	1	1	1
		0	4	13	45	158	562	1995	7079	> 7079	

DOLLARS PER EVENT

X-Y AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT
BUSINESS INTERRUPTION COST MATRIX

		COST CATEGORY									
		1	2	3	4	5	6	7	8		
E V E N T S P E R Y E A R	> 13	1	1	1	1	1	1	1	1	1	10
	1.259E+01	1	1	1	1	1	1	1	1	1	9
	3.548E+00	1	1	1	1	1	1	2	1	1	8
	1.000E+00	1	1	1	1	1	1	7	1	1	7
	2.818E-01	1	1	1	1	1	1	9	1	1	6
	7.943E-02	1	1	1	1	1	2	3	1	1	5
	2.239E-02	1	1	1	1	1	1	2	1	1	4
	6.310E-03	1	1	1	1	1	1	8	1	1	3
	1.778E-03	1	1	1	1	1	1	3	1	1	2
	5.012E-04	1	1	1	1	1	1	1	1	1	1
		0	4	13	45	158	562	1995	7079	> 7079	

DOLLARS PER EVENT

REPAIR COST MATRIX

[illegible]

TOTAL COST MATRIX

[illegible]

X-Y AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT
SAFETY MATRIX

		SAFETY CATEGORY						
		1	2	3	4	5		
> 13		-----	-----	-----	-----	-----		
	1.259E+01						10	F
E	-----	-----	-----	-----	-----	-----		
V	3.548E+00						9	R
E	-----	-----	-----	-----	-----	-----		
N	1.000E+00				2		8	Q
T	-----	-----	-----	-----	-----	-----		
S	2.818E-01				2		7	N
P	-----	-----	-----	-----	-----	-----		
E	7.943E-02				2		7	Y
R	-----	-----	-----	-----	-----	-----		
	2.239E-02				4		5	C
Y	-----	-----	-----	-----	-----	-----		
E	6.310E-03				2		4	T
A	-----	-----	-----	-----	-----	-----		
R	1.778E-03				2		6	E
	-----	-----	-----	-----	-----	-----		
	5.012E-04				3		3	G
	-----	-----	-----	-----	-----	-----		
					3		2	D
	-----	-----	-----	-----	-----	-----		
							1	R
	-----	-----	-----	-----	-----	-----		
		VERY	LOW	MODERATE	HIGH	VERY		
		LOW				HIGH		
		SAFETY CATEGORY						

X-Y AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT
EQUIPMENT DAMAGE COST SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMMULATIVE FREQUENCY	RISK
0 TO 4	1				
4 TO 13	2				
13 TO 45	3				
45 TO 158	4				
158 TO 562	5	10	1.211297	1.211297	587.9518
562 TO 1995	6	26	7.115401	8.3266981	4538.137
1995 TO 7079	7			8.3266981	
ABOVE 7079	8			8.3266981	

X-Y AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT
BUSINESS INTERRUPTION COST SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMMULATIVE FREQUENCY	RISK
0 TO 4	1				
4 TO 13	2				
13 TO 45	3				
45 TO 158	4				
158 TO 562	5				
562 TO 1995	6	2	0.09026	0.09026	164.3126
1995 TO 7079	7	34	8.236438	8.3266981	26262.85
ABOVE 7079	8			8.3266981	

X-Y AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT
REPAIR COST SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMMULATIVE FREQUENCY	RISK
0 TO 4	1				
4 TO 13	2				
13 TO 45	3				
45 TO 158	4	3	0.41046	0.41046	64.52711
158 TO 562	5	33	7.916238	8.3266981	1784.594
562 TO 1995	6			8.3266981	
1995 TO 7079	7			8.3266981	
ABOVE 7079	8			8.3266981	

X-Y AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT
TOTAL COST SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMMULATIVE FREQUENCY	RISK
0 TO 4	1				
4 TO 13	2				
13 TO 45	3				
45 TO 158	4				
158 TO 562	5				
562 TO 1995	6				
1995 TO 7079	7	36	8.326698	8.3266981	33402.37
ABOVE 7079	8			8.3266981	

X-Y AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT
SAFETY SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMMULATIVE FREQUENCY
VERY LOW	1			
LOW	2			
MODERATE	3	12	1.351147	1.351147
HIGH	4	24	6.975551	8.3266981
VERY HIGH	5			8.3266981

ROTATIONAL MOTION SUB-SYSTEM FOR THE UT ROBOT
EQUIPMENT DAMAGE COST MATRIX

		COST CATEGORY									
		1	2	3	4	5	6	7	8		
E V E N T S P E R Y E A R	> 13	-----	-----	-----	-----	-----	-----	-----	-----		
	1.259E+01									10	F
	3.548E+00									9	R
	1.000E+00									8	E
	2.818E-01									7	Q
	7.943E-02					1	1			6	E
	2.239E-02						3			5	N
	6.310E-03					2	1			4	C
	1.778E-03					1	1			3	A
	5.012E-04					1	6			2	T
		-----	-----	-----	-----	-----	-----	-----	-----	1	6
		0	4	13	45	158	562	1995	7079	> 7079	Y
DOLLARS PER EVENT											

ROTATIONAL MOTION SUB-SYSTEM FOR THE UT ROBOT
BUSINESS INTERRUPTION COST MATRIX

		COST CATEGORY									
		1	2	3	4	5	6	7	8		
E V E N T S P E R Y E A R	> 13	-----	-----	-----	-----	-----	-----	-----	-----		
	1.259E+01									10	F
	3.548E+00									9	R
	1.000E+00									8	E
	2.818E-01									7	Q
	7.943E-02							2		6	E
	2.239E-02							3		5	N
	6.310E-03							3		4	C
	1.778E-03							2		3	A
	5.012E-04						1	6		2	T
		-----	-----	-----	-----	-----	-----	-----	-----	1	6
		0	4	13	45	158	562	1995	7079	> 7079	Y
DOLLARS PER EVENT											

ROTATIONAL MOTION SUB-SYSTEM FOR THE UT ROBOT
REPAIR COST MATRIX

		COST CATEGORY									
		1	2	3	4	5	6	7	8		
> 13										10	
EVENTS	1.259E+01									9	F
	3.548E+00									8	R
	1.000E+00									7	E
	2.818E-01									6	Q
	7.943E-02					2				5	E
	2.239E-02					3				4	N
	6.310E-03					3				3	C
	1.778E-03					2				2	Y
	5.012E-04					7				1	
		0	4	13	45	158	562	1995	7079	> 7079	
DOLLARS PER EVENT											

ROTATIONAL MOTION SUB-SYSTEM FOR THE UT ROBOT
TOTAL COST MATRIX

		COST CATEGORY									
		1	2	3	4	5	6	7	8		
> 13										10	
EVENTS	1.259E+01									9	F
	3.548E+00									8	R
	1.000E+00									7	E
	2.818E-01									6	Q
	7.943E-02							2		5	E
	2.239E-02							3		4	N
	6.310E-03							3		3	C
	1.778E-03							2		2	Y
	5.012E-04							7		1	
		0	4	13	45	158	562	1995	7079	> 7079	
DOLLARS PER EVENT											

ROTATIONAL MOTION SUB-SYSTEM FOR THE UT ROBOT
SAFETY MATRIX

		SAFETY CATEGORY						
		1	2	3	4	5		
> 13		-----	-----	-----	-----	-----		
	1.259E+01							10
E		-----	-----	-----	-----	-----		
V	3.548E+00							9
E		-----	-----	-----	-----	-----		
N	1.000E+00							8
T		-----	-----	-----	-----	-----		
S	2.818E-01							7
		-----	-----	-----	-----	-----		
P	7.943E-02				2			6
E		-----	-----	-----	-----	-----		
R	2.239E-02			1	1	2		5
		-----	-----	-----	-----	-----		
Y	6.310E-03		1	1	1	1		4
E		-----	-----	-----	-----	-----		
A	1.778E-03		1			1		3
R		-----	-----	-----	-----	-----		
	5.012E-04			2	5			2
		-----	-----	-----	-----	-----		
								1
		-----	-----	-----	-----	-----		
		VERY	LOW	MODERATE	HIGH	VERY		
		LOW				HIGH		
		SAFETY CATEGORY						

ROTATIONAL MOTION SUB-SYSTEM FOR THE UT ROBOT
EQUIPMENT DAMAGE COST SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMMULATIVE FREQUENCY	RISK
0 TO 4	1				
4 TO 13	2				
13 TO 45	3				
45 TO 158	4				
158 TO 562	5	5	0.226604	0.2266045	115.8952
562 TO 1995	6	12	0.314941	0.5415459	198.8216
1995 TO 7079	7			0.5415459	
ABOVE 7079	8			0.5415459	

ROTATIONAL MOTION SUB-SYSTEM FOR THE UT ROBOT
BUSINESS INTERRUPTION COST SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMMULATIVE FREQUENCY	RISK
0 TO 4	1				
4 TO 13	2				
13 TO 45	3				
45 TO 158	4				
158 TO 562	5				
562 TO 1995	6	1	0.000920	0.0009205	1.791661
1995 TO 7079	7	16	0.540625	0.5415459	1766.360
ABOVE 7079	8			0.5415459	

ROTATIONAL MOTION SUB-SYSTEM FOR THE UT ROBOT
REPAIR COST SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMMULATIVE FREQUENCY	RISK
0 TO 4	1				
4 TO 13	2				
13 TO 45	3				
45 TO 158	4				
158 TO 562	5	17	0.541545	0.5415459	117.1418
562 TO 1995	6			0.5415459	
1995 TO 7079	7			0.5415459	
ABOVE 7079	8			0.5415459	

ROTATIONAL MOTION SUB-SYSTEM FOR THE UT ROBOT
TOTAL COST SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMMULATIVE FREQUENCY	RISK
0 TO 4	1				
4 TO 13	2				
13 TO 45	3				
45 TO 158	4				
158 TO 562	5				
562 TO 1995	6				
1995 TO 7079	7	17	0.541545	0.5415459	2200.010
ABOVE 7079	8			0.5415459	

ROTATIONAL MOTION SUB-SYSTEM FOR THE UT ROBOT
SAFETY SUMMARRY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMMULATIVE FREQUENCY
VERY LOW	1			
LOW	2	2	0.01722	0.01722
MODERATE	3	4	0.069215	0.086435
HIGH	4	10	0.449892	0.5363279
VERY HIGH	5	1	0.005218	0.5415459

PERIPHERAL EQUIPMENT SUB-SYSTEM FOR THE UT ROBOT
EQUIPMENT DAMAGE COST MATRIX

		COST CATEGORY									
		1	2	3	4	5	6	7	8		
E V E N T S P E R Y E A R	> 13	1	1	1	1	1	1	1	1	10	F R E Q U E N C Y
	1.259E+01	1	1	1	1	1	1	1	1	9	
	3.548E+00	1	1	1	1	1	1	4	1	8	
	1.000E+00	1	1	1	1	1	1	1	1	7	
	2.818E-01	1	1	1	1	2	2	1	1	6	
	7.943E-02	1	1	1	1	1	1	1	1	5	
	2.239E-02	1	1	1	1	1	1	1	1	4	
	6.310E-03	1	1	1	1	1	1	1	1	3	
	1.778E-03	1	1	1	1	1	2	1	1	2	
	5.012E-04	1	1	1	1	1	1	1	1	1	
		0	4	13	45	158	562	1995	7079	> 7079	
DOLLARS PER EVENT											

PERIPHERAL EQUIPMENT SUB-SYSTEM FOR THE UT ROBOT
BUSINESS INTERRUPTION COST MATRIX

		COST CATEGORY									
		1	2	3	4	5	6	7	8		
E V E N T S P E R Y E A R	> 13	1	1	1	1	1	1	1	1	10	F R E Q U E N C Y
	1.259E+01	1	1	1	1	1	1	1	1	9	
	3.548E+00	1	1	1	1	1	1	4	1	8	
	1.000E+00	1	1	1	1	1	1	2	1	7	
	2.818E-01	1	1	1	1	1	1	3	1	6	
	7.943E-02	1	1	1	1	1	1	1	1	5	
	2.239E-02	1	1	1	1	1	1	1	1	4	
	6.310E-03	1	1	1	1	1	1	1	1	3	
	1.778E-03	1	1	1	1	1	1	2	1	2	
	5.012E-04	1	1	1	1	1	1	1	1	1	
		0	4	13	45	158	562	1995	7079	> 7079	
DOLLARS PER EVENT											

PERIPHERAL EQUIPMENT SUB-SYSTEM FOR THE UT ROBOT
REPAIR COST MATRIX

		COST CATEGORY									
		1	2	3	4	5	6	7	8		
E V E N T S P E R Y E A R	> 13	1	1	1	1	1	1	1	1	1	10
	1.259E+01	1	1	1	1	1	1	1	1	1	9
	3.548E+00	1	1	1	1	1	1	1	1	1	8
	1.000E+00	1	1	1	1	1	1	1	1	1	7
	2.818E-01	1	1	1	1	1	1	1	1	1	6
	7.943E-02	1	1	1	1	1	1	1	1	1	5
	2.239E-02	1	1	1	1	1	1	1	1	1	4
	6.310E-03	1	1	1	1	1	1	1	1	1	3
	1.778E-03	1	1	1	1	1	1	1	1	1	2
	5.012E-04	1	1	1	1	1	1	1	1	1	1
		0	4	13	45	158	562	1995	7079	> 7079	
		DOLLARS PER EVENT									

PERIPHERAL EQUIPMENT SUB-SYSTEM FOR THE UT ROBOT
TOTAL COST MATRIX

		COST CATEGORY									
		1	2	3	4	5	6	7	8		
E V E N T S P E R Y E A R	> 13	1	1	1	1	1	1	1	1	1	10
	1.259E+01	1	1	1	1	1	1	1	1	1	9
	3.548E+00	1	1	1	1	1	1	5	1	1	8
	1.000E+00	1	1	1	1	1	1	2	1	1	7
	2.818E-01	1	1	1	1	1	1	4	1	1	6
	7.943E-02	1	1	1	1	1	1	1	1	1	5
	2.239E-02	1	1	1	1	1	1	1	1	1	4
	6.310E-03	1	1	1	1	1	1	1	1	1	3
	1.778E-03	1	1	1	1	1	1	2	1	1	2
	5.012E-04	1	1	1	1	1	1	1	1	1	1
		0	4	13	45	158	562	1995	7079	> 7079	
		DOLLARS PER EVENT									

PERIPHERAL EQUIPMENT SUB-SYSTEM FOR THE UT ROBOT
SAFETY MATRIX

		SAFETY CATEGORY						
		1	2	3	4	5		
EVENTS PER YEAR	> 13	1	1	1	1	1	10	F
	1.259E+01	1	1	1	1	1	9	R
	3.548E+00	1	1	1	3	1	8	E
	1.000E+00	1	1	1	1	1	7	Q
	2.818E-01	1	1	1	2	1	6	E
	7.943E-02	1	1	1	1	1	5	N
	2.239E-02	1	1	1	1	1	4	C
	6.310E-03	1	1	1	1	1	3	A
	1.778E-03	1	1	1	1	1	2	T
	5.012E-04	1	1	1	1	1	1	O
		VERY LOW	LOW	MODERATE	HIGH	VERY HIGH		
SAFETY CATEGORY								

PERIPHERAL EQUIPMENT SUB-SYSTEM FOR THE UT ROBOT
EQUIPMENT DAMAGE COST SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMULATIVE FREQUENCY	RISK
0 TO 4	1				
4 TO 13	2				
13 TO 45	3				
45 TO 158	4				
158 TO 562	5	5	2.395923	2.395923	1127.657
562 TO 1995	6	10	10.32528	12.721212	6924.222
1995 TO 7079	7			12.721212	
ABOVE 7079	8			12.721212	

PERIPHERAL EQUIPMENT SUB-SYSTEM FOR THE UT ROBOT
BUSINESS INTERRUPTION COST SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMULATIVE FREQUENCY	RISK
0 TO 4	1				
4 TO 13	2				
13 TO 45	3				
45 TO 158	4				
158 TO 562	5				
562 TO 1995	6	2	1.3915	1.3915	2502.669
1995 TO 7079	7	13	11.32971	12.721212	29364.07
ABOVE 7079	8			12.721212	

PERIPHERAL EQUIPMENT SUB-SYSTEM FOR THE UT ROBOT
REPAIR COST SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMULATIVE FREQUENCY	RISK
0 TO 4	1				
4 TO 13	2				
13 TO 45	3				
45 TO 158	4	2	1.267523	1.267523	192.3371
158 TO 562	5	13	11.45368	12.721212	2467.722
562 TO 1995	6			12.721212	
1995 TO 7079	7			12.721212	
ABOVE 7079	8			12.721212	

PERIPHERAL EQUIPMENT SUB-SYSTEM FOR THE UT ROBOT
TOTAL COST SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMMULATIVE FREQUENCY	RISK
0 TO 4	1				
4 TO 13	2				
13 TO 45	3				
45 TO 158	4				
158 TO 562	5				
562 TO 1995	6				
1995 TO 7079	7	15	12.72121	12.721212	42578.68
ABOVE 7079	8			12.721212	

PERIPHERAL EQUIPMENT SUB-SYSTEM FOR THE UT ROBOT
SAFETY SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMMULATIVE FREQUENCY
VERY LOW	1			
LOW	2			
MODERATE	3	3	1.386472	1.386472
HIGH	4	9	9.52154	10.908012
VERY HIGH	5	3	1.8132	12.721212

COMPOSITE SYSTEM FOR THE UT ROBOT
EQUIPMENT DAMAGE COST MATRIX

		COST CATEGORY									
		1	2	3	4	5	6	7	8		
E V E N T S P E R Y E A R	> 13	1	1	1	1	1	1	1	1	10	
	1.259E+01	1	1	1	1	1	1	1	1	9	F
	3.548E+00	1	1	1	1	1	1	1	1	8	R
	1.000E+00	1	1	1	1	3	6	1	1	7	E
	2.818E-01	1	1	1	1	5	14	1	1	6	Q
	7.943E-02	1	1	1	1	7	10	1	1	5	E
	2.239E-02	1	1	1	1	5	5	1	1	4	N
	6.310E-03	1	1	1	1	4	7	1	1	3	C
	1.778E-03	1	1	1	1	2	15	1	1	2	A
	5.012E-04	1	1	1	1	2	2	1	1	1	Y
		0	4	13	45	158	562	1995	7079	> 7079	
DOLLARS PER EVENT											

COMPOSITE SYSTEM FOR THE UT ROBOT
BUSINESS INTERRUPTION COST MATRIX

		COST CATEGORY									
		1	2	3	4	5	6	7	8		
E V E N T S P E R Y E A R	> 13	1	1	1	1	1	1	1	1	10	
	1.259E+01	1	1	1	1	1	1	1	1	9	F
	3.548E+00	1	1	1	1	1	1	6	1	8	R
	1.000E+00	1	1	1	1	1	1	9	1	7	E
	2.818E-01	1	1	1	1	1	1	18	1	6	N
	7.943E-02	1	1	1	1	1	3	14	1	5	C
	2.239E-02	1	1	1	1	1	1	9	1	4	A
	6.310E-03	1	1	1	1	1	1	11	1	3	T
	1.778E-03	1	1	1	1	1	1	16	1	2	E
	5.012E-04	1	1	1	1	1	1	3	1	1	G
		0	4	13	45	158	562	1995	7079	> 7079	
DOLLARS PER EVENT											

COMPOSITE SYSTEM FOR THE UT ROBOT
REPAIR COST MATRIX

		COST CATEGORY									
		1	2	3	4	5	6	7	8		
EVENTS	> 13	1	1	1	1	1	1	1	1	10	FREQUENCY
	1.259E+01	1	1	1	1	1	1	1	1	9	
	3.548E+00	1	1	1	1	1	1	1	1	8	
	1.000E+00	1	1	1	1	1	1	1	1	7	
	2.818E-01	1	1	1	1	1	1	1	1	6	
	7.943E-02	1	1	1	1	1	1	1	1	5	
	2.239E-02	1	1	1	1	1	1	1	1	4	
	6.310E-03	1	1	1	1	1	1	1	1	3	
	1.778E-03	1	1	1	1	1	1	1	1	2	
	5.012E-04	1	1	1	1	1	1	1	1	1	
		0	4	13	45	158	562	1995	7079	> 7079	
DOLLARS PER EVENT											

COMPOSITE SYSTEM FOR THE UT ROBOT
TOTAL COST MATRIX

		COST CATEGORY									
		1	2	3	4	5	6	7	8		
EVENTS	> 13	1	1	1	1	1	1	1	1	10	FREQUENCY
	1.259E+01	1	1	1	1	1	1	1	1	9	
	3.548E+00	1	1	1	1	1	1	7	1	8	
	1.000E+00	1	1	1	1	1	1	9	1	7	
	2.818E-01	1	1	1	1	1	1	19	1	6	
	7.943E-02	1	1	1	1	1	1	17	1	5	
	2.239E-02	1	1	1	1	1	1	10	1	4	
	6.310E-03	1	1	1	1	1	1	11	1	3	
	1.778E-03	1	1	1	1	1	1	16	1	2	
	5.012E-04	1	1	1	1	1	1	4	1	1	
		0	4	13	45	158	562	1995	7079	> 7079	
DOLLARS PER EVENT											

COMPOSITE SYSTEM FOR THE UT ROBOT
SAFETY MATRIX

		SAFETY CATEGORY						
		1	2	3	4	5		
> 13		1	1	1	1	1	10	
1.259E+01		1	1	1	1	1	9	F
E	3.548E+00	1	1	1	1	1	8	R
V	1.000E+00	1	1	1	1	1	7	E
E	2.818E-01	1	1	1	1	1	6	Q
N	7.943E-02	1	1	1	1	1	5	E
T	2.239E-02	1	1	1	1	1	4	N
S	6.310E-03	1	1	1	1	1	3	C
P	1.778E-03	1	1	1	1	1	2	Y
E	5.012E-04	1	1	1	1	1	1	
R								
		VERY LOW	LOW	MODERATE	HIGH	VERY HIGH		
		SAFETY CATEGORY						

COMPOSITE SYSTEM FOR THE UT ROBOT
EQUIPMENT DAMAGE COST SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMMULATIVE FREQUENCY	RISK
0 TO 4	1				
4 TO 13	2				
13 TO 45	3				
45 TO 158	4				
158 TO 562	5	29	4.178467	4.1784673	1988.958
562 TO 1995	6	65	18.55355	22.7320248	12165.89
1995 TO 7079	7			22.7320248	
ABOVE 7079	8			22.7320248	

COMPOSITE SYSTEM FOR THE UT ROBOT
BUSINESS INTERRUPTION COST SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMMULATIVE FREQUENCY	RISK
0 TO 4	1				
4 TO 13	2				
13 TO 45	3				
45 TO 158	4				
158 TO 562	5				
562 TO 1995	6	8	1.561540	1.5615409	2814.709
1995 TO 7079	7	86	21.17048	22.7320248	60821.45
ABOVE 7079	8			22.7320248	

COMPOSITE SYSTEM FOR THE UT ROBOT
REPAIR COST SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMMULATIVE FREQUENCY	RISK
0 TO 4	1				
4 TO 13	2				
13 TO 45	3				
45 TO 158	4	9	1.816853	1.8168534	278.7204
158 TO 562	5	85	20.91517	22.7320248	4588.118
562 TO 1995	6			22.7320248	
1995 TO 7079	7			22.7320248	
ABOVE 7079	8			22.7320248	

COMPOSITE SYSTEM FOR THE UT ROBOT
TOTAL COST SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMULATIVE FREQUENCY	RISK
0 TO 4	1				
4 TO 13	2				
13 TO 45	3				
45 TO 158	4				
158 TO 562	5				
562 TO 1995	6				
1995 TO 7079	7	93	22.73115	22.7311543	82651.21
ABOVE 7079	8	1	0.000870	22.7320248	6.640339

COMPOSITE SYSTEM FOR THE UT ROBOT
SAFETY SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMULATIVE FREQUENCY
VERY LOW	1			
LOW	2	4	0.018582	0.0185824
MODERATE	3	30	3.282516	3.3010992
HIGH	4	54	17.61064	20.9117489
VERY HIGH	5	6	1.820275	22.7320248

FAVORABLE APPLICATION CASE STUDY

Z AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT
EQUIPMENT DAMAGE COST MATRIX

		COST CATEGORY									
		1	2	3	4	5	6	7	8		
E V E N T S P E R Y E A R	> 13	1	1	1	1	1	1	1	1	1	10
	1.259E+01	1	1	1	1	1	1	1	1	1	9
	3.548E+00	1	1	1	1	1	1	1	1	1	8
	1.000E+00	1	1	1	1	1	1	1	1	1	7
	2.818E-01	1	1	1	1	1	1	1	1	1	6
	7.943E-02	1	1	1	1	1	1	1	1	1	5
	2.239E-02	1	1	1	4	6	1	1	1	1	4
	6.310E-03	1	1	1	1	1	1	1	1	1	3
	1.778E-03	1	1	1	1	3	1	1	1	1	2
	5.012E-04	1	1	1	3	6	1	1	1	1	1
		0	4	13	45	158	562	1995	7079	> 7079	

DOLLARS PER EVENT

F
R
E
Q
U
E
N
C
Y

Z AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT
BUSINESS INTERRUPTION COST MATRIX

		COST CATEGORY									
		1	2	3	4	5	6	7	8		
E V E N T S P E R Y E A R	> 13	1	1	1	1	1	1	1	1	1	10
	1.259E+01	1	1	1	1	1	1	1	1	1	9
	3.548E+00	1	1	1	1	1	1	1	1	1	8
	1.000E+00	1	1	1	1	1	1	1	1	1	7
	2.818E-01	1	1	1	1	1	1	1	1	1	6
	7.943E-02	1	1	1	1	1	1	1	1	1	5
	2.239E-02	1	1	1	6	4	1	1	1	1	4
	6.310E-03	1	1	1	1	1	1	1	1	1	3
	1.778E-03	1	1	1	3	1	1	1	1	1	2
	5.012E-04	1	1	1	5	4	1	1	1	1	1
		0	4	13	45	158	562	1995	7079	> 7079	

DOLLARS PER EVENT

F
R
E
Q
U
E
N
C
Y

Z AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT
REPAIR COST MATRIX

		COST CATEGORY									
		1	2	3	4	5	6	7	8		
EVENTS	> 13	1	1	1	1	1	1	1	1	10	
	1.259E+01	1	1	1	1	1	1	1	1	9	F
	3.548E+00	1	1	1	1	1	1	1	1	8	R
	1.000E+00	1	1	1	1	1	1	1	1	7	E
	2.818E-01	1	1	1	1	1	1	1	1	6	Q
	7.943E-02	1	1	1	1	1	1	1	1	5	E
	2.239E-02	1	1	1	10	1	1	1	1	4	N
	6.310E-03	1	1	1	1	1	1	1	1	3	C
	1.778E-03	1	1	1	3	1	1	1	1	2	A
	5.012E-04	1	1	1	6	3	1	1	1	1	Y
		0	4	13	45	158	562	1995	7079	> 7079	
DOLLARS PER EVENT											

Z AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT
TOTAL COST MATRIX

		COST CATEGORY									
		1	2	3	4	5	6	7	8		
EVENTS	> 13	1	1	1	1	1	1	1	1	10	
	1.259E+01	1	1	1	1	1	1	1	1	9	F
	3.548E+00	1	1	1	1	1	1	1	1	8	R
	1.000E+00	1	1	1	1	1	1	1	1	7	E
	2.818E-01	1	1	1	1	1	1	1	1	6	Q
	7.943E-02	1	1	1	1	1	1	1	1	5	E
	2.239E-02	1	1	1	1	10	1	1	1	4	N
	6.310E-03	1	1	1	1	2	1	1	1	3	C
	1.778E-03	1	1	1	1	4	1	1	1	2	A
	5.012E-04	1	1	1	1	8	1	1	1	1	Y
		0	4	13	45	158	562	1995	7079	> 7079	
DOLLARS PER EVENT											

Z AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT
SAFETY MATRIX

		SAFETY CATEGORY						
		1	2	3	4	5		
> 13								
1.259E+01							10	F
E							9	R
V	3.548E+00							E
E							8	Q
N	1.000E+00							E
T							7	N
S	2.818E-01							C
							6	Y
P	7.943E-02							
E			1				5	C
R	2.239E-02							A
		5	5				4	T
Y	6.310E-03							E
E		1	1				3	G
A	1.778E-03							O
P		2	2				2	R
	5.012E-04							Y
		5	3	1			1	
		VERY LOW	LOW	MODERATE	HIGH	VERY HIGH		
		SAFETY CATEGORY						

Z AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT
EQUIPMENT DAMAGE COST SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMMULATIVE FREQUENCY	RISK
0 TO 4	1				
4 TO 13	2				
13 TO 45	3				
45 TO 158	4	10	0.085748	0.08574814	12.10992
158 TO 562	5	16	0.066954	0.15270261	12.29785
562 TO 1995	6			0.15270261	
1995 TO 7079	7			0.15270261	
ABOVE 7079	8			0.15270261	

Z AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT
BUSINESS INTERRUPTION COST SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMMULATIVE FREQUENCY	RISK
0 TO 4	1				
4 TO 13	2				
13 TO 45	3				
45 TO 158	4	16	0.109862	0.10986286	14.03063
158 TO 562	5	10	0.042839	0.15270261	6.982679
562 TO 1995	6			0.15270261	
1995 TO 7079	7			0.15270261	
ABOVE 7079	8			0.15270261	

Z AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT
REPAIR COST SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMMULATIVE FREQUENCY	RISK
0 TO 4	1				
4 TO 13	2				
13 TO 45	3				
45 TO 158	4	21	0.148104	0.14810429	16.35670
158 TO 562	5	5	0.004598	0.15270261	0.762094
562 TO 1995	6			0.15270261	
1995 TO 7079	7			0.15270261	
ABOVE 7079	8			0.15270261	

Z AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT
TOTAL COST SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMMULATIVE FREQUENCY	RISK
0 TO 4	1				
4 TO 13	2				
13 TO 45	3				
45 TO 158	4				
158 TO 562	5	25	0.152573	0.15257321	62.45757
562 TO 1995	6	1	0.000129	0.15270261	0.082508
1995 TO 7079	7			0.15270261	
ABOVE 7079	8			0.15270261	

Z AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT
SAFETY SUMMARRY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMMULATIVE FREQUENCY
VERY LOW	1	13	0.060132	0.06013286
LOW	2	12	0.092440	0.15257321
MODERATE	3	1	0.000129	0.15270261
HIGH	4			0.15270261
VERY HIGH	5			0.15270261

X-Y AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT
EQUIPMENT DAMAGE COST MATRIX

		COST CATEGORY									
		1	2	3	4	5	6	7	8		
E V E N T S P E R Y E A R	> 13	-----	-----	-----	-----	-----	-----	-----	-----	10	F
	1.259E+01	-----	-----	-----	-----	-----	-----	-----	-----	9	R
	3.548E+00	-----	-----	-----	-----	-----	-----	-----	-----	8	E
	1.000E+00	-----	-----	-----	-----	-----	-----	-----	-----	7	Q
	2.818E-01	-----	-----	-----	-----	-----	-----	-----	-----	6	E
	7.943E-02	-----	-----	-----	2	3	-----	-----	-----	5	N
	2.239E-02	-----	-----	-----	3	4	-----	-----	-----	4	C
	6.310E-03	-----	-----	-----	2	4	-----	-----	-----	3	A
	1.778E-03	-----	-----	-----	2	3	-----	-----	-----	2	T
	5.012E-04	-----	-----	-----	2	4	-----	-----	-----	1	E
		0	4	13	45	158	562	1995	7079	> 7079	G
DOLLARS PER EVENT											

X-Y AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT
BUSINESS INTERRUPTION COST MATRIX

		COST CATEGORY									
		1	2	3	4	5	6	7	8		
E V E N T S P E R Y E A R	> 13	-----	-----	-----	-----	-----	-----	-----	-----	10	F
	1.259E+01	-----	-----	-----	-----	-----	-----	-----	-----	9	R
	3.548E+00	-----	-----	-----	-----	-----	-----	-----	-----	8	E
	1.000E+00	-----	-----	-----	-----	-----	-----	-----	-----	7	Q
	2.818E-01	-----	-----	-----	-----	-----	-----	-----	-----	6	E
	7.943E-02	-----	-----	-----	3	2	-----	-----	-----	5	N
	2.239E-02	-----	-----	-----	7	-----	-----	-----	-----	4	C
	6.310E-03	-----	-----	-----	4	2	-----	-----	-----	3	A
	1.778E-03	-----	-----	-----	3	2	-----	-----	-----	2	T
	5.012E-04	-----	-----	-----	4	2	-----	-----	-----	1	E
		0	4	13	45	158	562	1995	7079	> 7079	G
DOLLARS PER EVENT											

X-Y AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT
REPAIR COST MATRIX

		COST CATEGORY									
		1	2	3	4	5	6	7	8		
E V E N T S P E R Y E A R	> 13	1	1	1	1	1	1	1	1	10	
	1.259E+01	1	1	1	1	1	1	1	1	9	F
	3.548E+00	1	1	1	1	1	1	1	1	8	R
	1.000E+00	1	1	1	1	1	1	1	1	7	E
	2.818E-01	1	1	1	1	1	1	1	1	6	Q
	7.943E-02	1	1	1	5	1	1	1	1	5	E
	2.239E-02	1	1	1	7	1	1	1	1	4	N
	6.310E-03	1	1	1	6	1	1	1	1	3	C
	1.778E-03	1	1	1	5	1	1	1	1	2	A
	5.012E-04	1	1	1	5	1	1	1	1	1	R
		0	4	13	45	158	562	1995	7079	> 7079	Y
DOLLARS PER EVENT											

X-Y AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT
TOTAL COST MATRIX

		COST CATEGORY									
		1	2	3	4	5	6	7	8		
E V E N T S P E R Y E A R	> 13	1	1	1	1	1	1	1	1	10	
	1.259E+01	1	1	1	1	1	1	1	1	9	F
	3.548E+00	1	1	1	1	1	1	1	1	8	R
	1.000E+00	1	1	1	1	1	1	1	1	7	E
	2.818E-01	1	1	1	1	1	1	1	1	6	Q
	7.943E-02	1	1	1	5	1	1	1	1	5	E
	2.239E-02	1	1	1	7	1	1	1	1	4	N
	6.310E-03	1	1	1	6	1	1	1	1	3	C
	1.778E-03	1	1	1	5	1	1	1	1	2	A
	5.012E-04	1	1	1	5	1	1	1	1	1	R
		0	4	13	45	158	562	1995	7079	> 7079	Y
DOLLARS PER EVENT											

X-Y AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT
SAFETY MATRIX

		SAFETY CATEGORY						
		1	2	3	4	5		
> 13								10
E V E N T S P E R Y E A R	1.259E+01							9
	3.548E+00							8
	1.000E+00							7
	2.818E-01							6
	7.943E-02		3		4			5
C A T E G O R Y	2.239E-02		2		4			4
	6.310E-03		3		2			3
	1.778E-03		3		3			2
	5.012E-04		1		6			1
		VERY LOW	LOW	MODERATE	HIGH	VERY HIGH		
		SAFETY CATEGORY						

X-Y AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT
EQUIPMENT DAMAGE COST SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMMULATIVE FREQUENCY	RISK
0 TO 4	1				
4 TO 13	2				
13 TO 45	3				
45 TO 158	4	12	0.441666	0.441666	67.25155
158 TO 562	5	24	0.678383	1.1200505	120.7021
562 TO 1995	6			1.1200505	
1995 TO 7079	7			1.1200505	
ABOVE 7079	8			1.1200505	

X-Y AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT
BUSINESS INTERRUPTION COST SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMMULATIVE FREQUENCY	RISK
0 TO 4	1				
4 TO 13	2				
13 TO 45	3				
45 TO 158	4	24	0.811440	0.8114402	116.5368
158 TO 562	5	12	0.308610	1.1200505	50.30347
562 TO 1995	6			1.1200505	
1995 TO 7079	7			1.1200505	
ABOVE 7079	8			1.1200505	

X-Y AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT
REPAIR COST SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMMULATIVE FREQUENCY	RISK
0 TO 4	1				
4 TO 13	2				
13 TO 45	3				
45 TO 158	4	34	1.118366	1.1183667	128.3220
158 TO 562	5	2	0.001683	1.1200505	0.279237
562 TO 1995	6			1.1200505	
1995 TO 7079	7			1.1200505	
ABOVE 7079	8			1.1200505	

X-Y AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT
TOTAL COST SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMMULATIVE FREQUENCY	RISK
0 TO 4	1				
4 TO 13	2				
13 TO 45	3				
45 TO 158	4				
158 TO 562	5	35	1.119593	1.1195937	483.1360
562 TO 1995	6	1	0.000456	1.1200505	0.259288
1995 TO 7079	7			1.1200505	
ABOVE 7079	8			1.1200505	

X-Y AXIS MOTION SUB-SYSTEM FOR THE UT ROBOT
SAFETY SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMMULATIVE FREQUENCY
VERY LOW	1	12	0.156913	0.1569136
LOW	2	24	0.963136	1.1200505
MODERATE	3			1.1200505
HIGH	4			1.1200505
VERY HIGH	5			1.1200505

ROTATIONAL MOTION SUB-SYSTEM FOR THE UT ROBOT
EQUIPMENT DAMAGE COST MATRIX

		COST CATEGORY									
		1	2	3	4	5	6	7	8		
> 13											10
E V E N T S P E R Y E A R	1.259E+01										F
	3.548E+00										R
	1.000E+00										E
	2.818E-01										Q
	7.943E-02										E
	2.239E-02				1						N
	6.310E-03				1	3					C
	1.778E-03										A
	5.012E-04				4	1					T
					2	5					E
		0	4	13	45	158	562	1995	7079	> 7079	G
DOLLARS PER EVENT											

ROTATIONAL MOTION SUB-SYSTEM FOR THE UT ROBOT
BUSINESS INTERRUPTION COST MATRIX

		COST CATEGORY									
		1	2	3	4	5	6	7	8		
> 13											10
E V E N T S P E R Y E A R	1.259E+01										F
	3.548E+00										R
	1.000E+00										E
	2.818E-01										Q
	7.943E-02										E
	2.239E-02				1						N
	6.310E-03				3	1					C
	1.778E-03										A
	5.012E-04				4	1					T
					3	4					E
		0	4	13	45	158	562	1995	7079	> 7079	G
DOLLARS PER EVENT											

ROTATIONAL MOTION SUB-SYSTEM FOR THE UT ROBOT
REPAIR COST MATRIX

		COST CATEGORY									
		1	2	3	4	5	6	7	8		
EVENTS	> 13	1	1	1	1	1	1	1	1	10	
	1.259E+01	1	1	1	1	1	1	1	1	9	F
	3.548E+00	1	1	1	1	1	1	1	1	8	R
	1.000E+00	1	1	1	1	1	1	1	1	7	E
	2.818E-01	1	1	1	1	1	1	1	1	6	Q
	7.943E-02	1	1	1	1	1	1	1	1	5	E
	2.239E-02	1	1	1	4	1	1	1	1	4	N
	6.310E-03	1	1	1	1	1	1	1	1	3	C
	1.778E-03	1	1	1	5	1	1	1	1	2	Y
	5.012E-04	1	1	1	7	1	1	1	1	1	
		0	4	13	45	158	562	1995	7079	> 7079	
DOLLARS PER EVENT											

ROTATIONAL MOTION SUB-SYSTEM FOR THE UT ROBOT
TOTAL COST MATRIX

		COST CATEGORY									
		1	2	3	4	5	6	7	8		
EVENTS	> 13	1	1	1	1	1	1	1	1	10	
	1.259E+01	1	1	1	1	1	1	1	1	9	F
	3.548E+00	1	1	1	1	1	1	1	1	8	R
	1.000E+00	1	1	1	1	1	1	1	1	7	E
	2.818E-01	1	1	1	1	1	1	1	1	6	Q
	7.943E-02	1	1	1	1	1	1	1	1	5	E
	2.239E-02	1	1	1	4	1	1	1	1	4	N
	6.310E-03	1	1	1	1	1	1	1	1	3	C
	1.778E-03	1	1	1	5	1	1	1	1	2	Y
	5.012E-04	1	1	1	7	1	1	1	1	1	
		0	4	13	45	158	562	1995	7079	> 7079	
DOLLARS PER EVENT											

ROTATIONAL MOTION SUB-SYSTEM FOR THE UT ROBOT
SAFETY MATRIX

		SAFETY CATEGORY						
		1	2	3	4	5		
> 13		-----						
								10
1.259E+01		-----						
E								9
V		-----						
E								8
N		-----						
T								7
S		-----						
								6
P		-----						
E								5
R		-----						
			1	3				4
Y		-----						
E								3
A		-----						
R			3	1	1			2

			2	5				1

		VERY	LOW	MODERATE	HIGH	VERY		
		LOW				HIGH		
		SAFETY CATEGORY						

ROTATIONAL MOTION SUB-SYSTEM FOR THE UT ROBOT
EQUIPMENT DAMAGE COST SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMMULATIVE FREQUENCY	RISK
0 TO 4	1				
4 TO 13	2				
13 TO 45	3				
45 TO 158	4	8	0.046212	0.0462122	6.214842
158 TO 562	5	9	0.023214	0.0694269	5.543564
562 TO 1995	6			0.0694269	
1995 TO 7079	7			0.0694269	
ABOVE 7079	8			0.0694269	

ROTATIONAL MOTION SUB-SYSTEM FOR THE UT ROBOT
BUSINESS INTERRUPTION COST SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMMULATIVE FREQUENCY	RISK
0 TO 4	1				
4 TO 13	2				
13 TO 45	3				
45 TO 158	4	11	0.060901	0.0609013	7.981202
158 TO 562	5	6	0.008525	0.0694269	1.389672
562 TO 1995	6			0.0694269	
1995 TO 7079	7			0.0694269	
ABOVE 7079	8			0.0694269	

ROTATIONAL MOTION SUB-SYSTEM FOR THE UT ROBOT
REPAIR COST SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMMULATIVE FREQUENCY	RISK
0 TO 4	1				
4 TO 13	2				
13 TO 45	3				
45 TO 158	4	17	0.069426	0.0694269	8.199942
158 TO 562	5			0.0694269	
562 TO 1995	6			0.0694269	
1995 TO 7079	7			0.0694269	
ABOVE 7079	8			0.0694269	

ROTATIONAL MOTION SUB-SYSTEM FOR THE UT ROBOT
TOTAL COST SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMMULATIVE FREQUENCY	RISK
0 TO 4	1				
4 TO 13	2				
13 TO 45	3				
45 TO 158	4				
158 TO 562	5	17	0.069426	0.0694269	29.32922
562 TO 1995	6			0.0694269	
1995 TO 7079	7			0.0694269	
ABOVE 7079	8			0.0694269	

ROTATIONAL MOTION SUB-SYSTEM FOR THE UT ROBOT
SAFETY SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMMULATIVE FREQUENCY
VERY LOW	1	6	0.011593	0.011593
LOW	2	10	0.057322	0.0689157
MODERATE	3	1	0.000511	0.0694269
HIGH	4			0.0694269
VERY HIGH	5			0.0694269

PERIPHERAL EQUIPMENT SUB-SYSTEM FOR THE UT ROBOT
EQUIPMENT DAMAGE COST MATRIX

		COST CATEGORY									
		1	2	3	4	5	6	7	8		
E V E N T S P E R Y E A R	> 13	1	1	1	1	1	1	1	1	10	F R E Q U E N C Y C A T E G O R Y
	1.259E+01	1	1	1	1	1	1	1	1	9	
	3.548E+00	1	1	1	1	2	1	1	1	8	
	1.000E+00	1	1	1	2	1	1	1	1	7	
	2.818E-01	1	1	1	1	2	1	1	1	6	
	7.943E-02	1	1	1	2	1	1	1	1	5	
	2.239E-02	1	1	1	1	1	1	1	1	4	
	6.310E-03	1	1	1	1	1	1	1	1	3	
	1.778E-03	1	1	1	1	1	1	1	1	2	
	5.012E-04	1	1	1	1	2	1	1	1	1	
		0	4	13	45	158	562	1995	7079	> 7079	
DOLLARS PER EVENT											

PERIPHERAL EQUIPMENT SUB-SYSTEM FOR THE UT ROBOT
BUSINESS INTERRUPTION COST MATRIX

		COST CATEGORY									
		1	2	3	4	5	6	7	8		
E V E N T S P E R Y E A R	> 13	1	1	1	1	1	1	1	1	10	F R E Q U E N C Y C A T E G O R Y
	1.259E+01	1	1	1	1	1	1	1	1	9	
	3.548E+00	1	1	1	1	2	1	1	1	8	
	1.000E+00	1	1	1	2	1	1	1	1	7	
	2.818E-01	1	1	1	2	1	1	1	1	6	
	7.943E-02	1	1	1	2	1	1	1	1	5	
	2.239E-02	1	1	1	1	1	1	1	1	4	
	6.310E-03	1	1	1	1	1	1	1	1	3	
	1.778E-03	1	1	1	1	1	1	1	1	2	
	5.012E-04	1	1	1	1	1	1	1	1	1	
		0	4	13	45	158	562	1995	7079	> 7079	
DOLLARS PER EVENT											

PERIPHERAL EQUIPMENT SUB-SYSTEM FOR THE UT ROBOT
REPAIR COST MATRIX

		COST CATEGORY								
		1	2	3	4	5	6	7	8	
E V E N T S P E R Y E A R	> 13	1	1	1	1	1	1	1	1	10
	1.259E+01	1	1	1	1	1	1	1	1	9
	3.548E+00	1	1	1	2	1	1	1	1	8
	1.000E+00	1	1	1	3	1	1	1	1	7
	2.818E-01	1	1	1	3	1	1	1	1	6
	7.943E-02	1	1	1	3	1	1	1	1	5
	2.239E-02	1	1	1	1	1	1	1	1	4
	6.310E-03	1	1	1	1	1	1	1	1	3
	1.778E-03	1	1	1	1	1	1	1	1	2
	5.012E-04	1	1	1	2	1	1	1	1	1
		0	4	13	45	158	562	1995	7079	> 7079
DOLLARS PER EVENT										

PERIPHERAL EQUIPMENT SUB-SYSTEM FOR THE UT ROBOT
TOTAL COST MATRIX

		COST CATEGORY								
		1	2	3	4	5	6	7	8	
E V E N T S P E R Y E A R	> 13	1	1	1	1	1	1	1	1	10
	1.259E+01	1	1	1	1	1	1	1	1	9
	3.548E+00	1	1	1	1	2	1	1	1	8
	1.000E+00	1	1	1	1	3	1	1	1	7
	2.818E-01	1	1	1	1	2	1	1	1	6
	7.943E-02	1	1	1	1	2	1	1	1	5
	2.239E-02	1	1	1	1	1	1	1	1	4
	6.310E-03	1	1	1	1	1	1	1	1	3
	1.778E-03	1	1	1	1	1	1	1	1	2
	5.012E-04	1	1	1	1	1	1	1	1	1
		0	4	13	45	158	562	1995	7079	> 7079
DOLLARS PER EVENT										

PERIPHERAL EQUIPMENT SUB-SYSTEM FOR THE UT ROBOT
SAFETY MATRIX

		SAFETY CATEGORY					
		1	2	3	4	5	
E V E N T S P E R Y E A R	> 13	1	1	1	1	1	10
	1.259E+01	1	1	1	1	1	9
	3.548E+00	1	1	1	2	1	8
	1.000E+00	1	1	2	1	1	7
	2.818E-01	1	1	1	1	1	6
	7.943E-02	1	1	2	1	1	5
	2.239E-02	1	1	1	1	1	4
	6.310E-03	1	1	1	1	1	3
	1.778E-03	1	1	1	1	1	2
	5.012E-04	1	1	1	1	1	1
		VERY LOW	LOW	MODERATE	HIGH	VERY HIGH	
		SAFETY CATEGORY					

PERIPHERAL EQUIPMENT SUB-SYSTEM FOR THE UT ROBOT
EQUIPMENT DAMAGE COST SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMMULATIVE FREQUENCY	RISK
0 TO 4	1				
4 TO 13	2				
13 TO 45	3				
45 TO 158	4	6	1.879647	1.8796475	238.7063
158 TO 562	5	9	4.017731	5.8973787	734.0322
562 TO 1995	6			5.8973787	
1995 TO 7079	7			5.8973787	
ABOVE 7079	8			5.8973787	

PERIPHERAL EQUIPMENT SUB-SYSTEM FOR THE UT ROBOT
BUSINESS INTERRUPTION COST SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMMULATIVE FREQUENCY	RISK
0 TO 4	1				
4 TO 13	2				
13 TO 45	3				
45 TO 158	4	8	2.024666	2.0246664	261.8556
158 TO 562	5	7	3.872712	5.8973787	631.2521
562 TO 1995	6			5.8973787	
1995 TO 7079	7			5.8973787	
ABOVE 7079	8			5.8973787	

PERIPHERAL EQUIPMENT SUB-SYSTEM FOR THE UT ROBOT
REPAIR COST SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMMULATIVE FREQUENCY	RISK
0 TO 4	1				
4 TO 13	2				
13 TO 45	3				
45 TO 158	4	15	5.897378	5.8973787	497.0034
158 TO 562	5			5.8973787	
562 TO 1995	6			5.8973787	
1995 TO 7079	7			5.8973787	
ABOVE 7079	8			5.8973787	

PERIPHERAL EQUIPMENT SUB-SYSTEM FOR THE UT ROBOT
TOTAL COST SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMMULATIVE FREQUENCY	RISK
0 TO 4	1				
4 TO 13	2				
13 TO 45	3				
45 TO 158	4				
158 TO 562	5	11	5.716199	5.7161998	2234.906
562 TO 1995	6	4	0.181178	5.8973787	127.9435
1995 TO 7079	7			5.8973787	
ABOVE 7079	8			5.8973787	

PERIPHERAL EQUIPMENT SUB-SYSTEM FOR THE UT ROBOT
SAFETY SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMMULATIVE FREQUENCY
VERY LOW	1	2	0.145018	0.1450189
LOW	2	8	1.595859	1.7408767
MODERATE	3	3	3.625	5.5658787
HIGH	4	1	0.255	5.8208787
VERY HIGH	5	1	0.0765	5.8973787

COMPOSITE SYSTEM FOR THE UT ROBOT
EQUIPMENT DAMAGE COST MATRIX

		COST CATEGORY									
		1	2	3	4	5	6	7	8		
E V E N T S P E R Y E A R	> 13										10
	1.259E+01										9
	3.548E+00					2					8
	1.000E+00				2	1					7
	2.818E-01				3	5					6
	7.943E-02				7	5					5
	2.239E-02				7	14					4
	6.310E-03				3	4					3
	1.778E-03				8	8					2
	5.012E-04				6	19					1
		0	4	13	45	158	562	1995	7079	> 7079	
DOLLARS PER EVENT											

COMPOSITE SYSTEM FOR THE UT ROBOT
BUSINESS INTERRUPTION COST MATRIX

		COST CATEGORY									
		1	2	3	4	5	6	7	8		
E V E N T S P E R Y E A R	> 13										10
	1.259E+01										9
	3.548E+00					2					8
	1.000E+00				2	1					7
	2.818E-01				5	3					6
	7.943E-02				11	1					5
	2.239E-02				13	8					4
	6.310E-03				4	3					3
	1.778E-03				12	4					2
	5.012E-04				12	13					1
		0	4	13	45	158	562	1995	7079	> 7079	
DOLLARS PER EVENT											

COMPOSITE SYSTEM FOR THE UT ROBOT
REPAIR COST MATRIX

		COST CATEGORY									
		1	2	3	4	5	6	7	8		
EVENTS	> 13	1	1	1	1	1	1	1	1	10	
	1.259E+01	1	1	1	1	1	1	1	1	9	F
	3.548E+00	1	1	1	2	1	1	1	1	8	R
	1.000E+00	1	1	1	3	1	1	1	1	7	E
	2.818E-01	1	1	1	8	1	1	1	1	6	Q
	7.943E-02	1	1	1	12	1	1	1	1	5	E
	2.239E-02	1	1	1	21	1	1	1	1	4	N
	6.310E-03	1	1	1	6	1	1	1	1	3	C
	1.778E-03	1	1	1	14	2	1	1	1	2	A
	5.012E-04	1	1	1	21	4	1	1	1	1	T
		0	4	13	45	158	562	1995	7079	> 7079	E
DOLLARS PER EVENT											6

COMPOSITE SYSTEM FOR THE UT ROBOT
TOTAL COST MATRIX

		COST CATEGORY									
		1	2	3	4	5	6	7	8		
EVENTS	> 13	1	1	1	1	1	1	1	1	10	
	1.259E+01	1	1	1	1	1	1	1	1	9	F
	3.548E+00	1	1	1	1	2	1	1	1	8	R
	1.000E+00	1	1	1	1	3	1	1	1	7	E
	2.818E-01	1	1	1	1	7	1	1	1	6	Q
	7.943E-02	1	1	1	1	11	1	1	1	5	E
	2.239E-02	1	1	1	1	20	1	1	1	4	N
	6.310E-03	1	1	1	1	7	1	1	1	3	C
	1.778E-03	1	1	1	1	16	1	1	1	2	A
	5.012E-04	1	1	1	1	22	3	1	1	1	T
		0	4	13	45	158	562	1995	7079	> 7079	E
DOLLARS PER EVENT											6

COMPOSITE SYSTEM FOR THE UT ROBOT
SAFETY MATRIX

		SAFETY CATEGORY						
		1	2	3	4	5		
> 13		1	1	1	1	1	10	
1.259E+01		1	1	1	1	1	9	F
E	3.548E+00	1	1	1	1	1	8	R
V	1.000E+00	1	1	2	1	1	8	E
E	2.818E-01	1	2	1	1	1	7	Q
N	7.943E-02	1	1	6	1	1	6	E
T	2.239E-02	1	3	8	1	1	5	N
S	6.310E-03	1	8	13	1	1	4	C
P	1.778E-03	1	4	3	1	1	3	A
E	5.012E-04	1	8	7	1	1	2	T
R		1	9	15	1	1	1	E
		VERY	LOW	MODERATE	HIGH	VERY		G
		LOW				HIGH		O
		SAFETY CATEGORY						R
								Y

COMPOSITE SYSTEM FOR THE UT ROBOT
EQUIPMENT DAMAGE COST SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMMULATIVE FREQUENCY	RISK
0 TO 4	1				
4 TO 13	2				
13 TO 45	3				
45 TO 158	4	36	2.453274	2.45327444	324.2826
158 TO 562	5	58	4.786284	7.23955871	872.5758
562 TO 1995	6			7.23955871	
1995 TO 7079	7			7.23955871	
ABOVE 7079	8			7.23955871	

COMPOSITE SYSTEM FOR THE UT ROBOT
BUSINESS INTERRUPTION COST SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMMULATIVE FREQUENCY	RISK
0 TO 4	1				
4 TO 13	2				
13 TO 45	3				
45 TO 158	4	59	3.006870	3.00687076	400.4043
158 TO 562	5	35	4.232687	7.23955871	689.9281
562 TO 1995	6			7.23955871	
1995 TO 7079	7			7.23955871	
ABOVE 7079	8			7.23955871	

COMPOSITE SYSTEM FOR THE UT ROBOT
REPAIR COST SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMMULATIVE FREQUENCY	RISK
0 TO 4	1				
4 TO 13	2				
13 TO 45	3				
45 TO 158	4	87	7.233276	7.23327659	649.8822
158 TO 562	5	7	0.006282	7.23955871	1.041331
562 TO 1995	6			7.23955871	
1995 TO 7079	7			7.23955871	
ABOVE 7079	8			7.23955871	

COMPOSITE SYSTEM FOR THE UT ROBOT
TOTAL COST SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMMULATIVE FREQUENCY	RISK
0 TO 4	1				
4 TO 13	2				
13 TO 45	3				
45 TO 158	4				
158 TO 562	5	88	7.057793	7.05779361	2809.829
562 TO 1995	6	6	0.181765	7.23955871	128.2853
1995 TO 7079	7			7.23955871	
ABOVE 7079	8			7.23955871	

COMPOSITE SYSTEM FOR THE UT ROBOT
SAFETY SUMMARY TABLE

COST CATEGORY BOUNDS	CATEGORY NUMBER	NUMBER OF EVENTS	FREQUENCY	CUMMULATIVE FREQUENCY
VERY LOW	1	33	0.373658	0.37365836
LOW	2	54	2.708759	3.08241811
MODERATE	3	5	3.825640	6.90805871
HIGH	4	1	0.255	7.16305871
VERY HIGH	5	1	0.0765	7.23955871

APPENDIX D

IMPORTANCE LISTINGS FOR ALL FAILURE MODES

IN BOTH CASE STUDY APPLICATIONS

**Severe Application Listing of Failure Events
by Financial Risk Importance**

<u>Risk Index</u>	<u>Description</u>	<u>Item Number</u>
15.7	Peripheral	2.1
15.7	Peripheral	6.1
15.7	Peripheral	6.2
15.7	Peripheral	6.3
15.7	Peripheral	6.4
15.7	X-Y Axis Motion	6.2
15.7	X-Y Axis Motion	11.2
14.7	Peripheral	4.2
14.7	Peripheral	6.5
14.7	X-Y Axis Motion	1.3
14.7	X-Y Axis Motion	7.2
14.7	X-Y Axis Motion	7.3
14.7	X-Y Axis Motion	9.1
14.7	X-Y Axis Motion	10.2
14.7	X-Y Axis Motion	10.3
14.7	X-Y Axis Motion	12.3
13.7	Peripheral	3.1
13.7	Peripheral	3.2
13.7	Peripheral	4.1
13.7	Peripheral	6.6
13.7	X-Y Axis Motion	4.3
13.7	X-Y Axis Motion	5.1
13.7	X-Y Axis Motion	6.1
13.7	X-Y Axis Motion	6.4
13.7	X-Y Axis Motion	11.1
13.7	X-Y Axis Motion	11.4
13.7	X-Y Axis Motion	12.2
13.7	X-Y Axis Motion	13.1
13.7	X-Y Axis Motion	13.2
13.7	Z Axis Motion	4.2
13.7	Z Axis Motion	5.2
13.7	Z Axis Motion	6.3
13.7	Z Axis Motion	10.2
13.7	W Axis Motion	1.2
13.7	W Axis Motion	7.1
12.7	Peripheral	1.1
12.7	X-Y Axis Motion	2.2
12.7	X-Y Axis Motion	3.2
12.7	X-Y Axis Motion	6.3
12.7	X-Y Axis Motion	11.3
12.7	X-Y Axis Motion	12.1
12.7	Z Axis Motion	2.1
12.7	Z Axis Motion	3.3

12.7	Z Axis Motion	4.1
12.7	Z Axis Motion	5.3
12.7	Z Axis Motion	7.2
12.7	Z Axis Motion	9.1
12.7	Z Axis Motion	9.2
12.7	Z Axis Motion	10.3
12.7	W Axis Motion	1.3
12.7	W Axis Motion	2.1
12.7	W Axis Motion	2.2
11.7	X-Y Axis Motion	8.2
11.7	X-Y Axis Motion	9.2
11.7	Z Axis Motion	1.2
11.7	Z Axis Motion	4.3
11.7	Z Axis Motion	4.4
11.7	Z Axis Motion	7.1
11.7	Z Axis Motion	10.1
11.7	W Axis Motion	1.1
11.7	W Axis Motion	6.2
11.7	W Axis Motion	7.2
10.8	Z Axis Motion	8.1
10.7	Peripheral	5.2
10.7	X-Y Axis Motion	1.1
10.7	X-Y Axis Motion	1.2
10.7	X-Y Axis Motion	2.1
10.7	X-Y Axis Motion	3.1
10.7	X-Y Axis Motion	4.1
10.7	X-Y Axis Motion	4.2
10.7	X-Y Axis Motion	14.1
10.7	X-Y Axis Motion	14.2
10.7	W Axis Motion	8.1
10.7	W Axis Motion	9.1
9.7	Peripheral	1.2
9.7	Peripheral	5.1
9.7	X-Y Axis Motion	7.1
9.7	X-Y Axis Motion	8.1
9.7	X-Y Axis Motion	10.1
9.7	Z Axis Motion	1.1
9.7	Z Axis Motion	6.1
9.7	Z Axis Motion	6.2
9.7	Z Axis Motion	6.4
9.7	W Axis Motion	1.1
9.7	W Axis Motion	3.2
9.7	W Axis Motion	4.1
9.7	W Axis Motion	5.1
9.7	W Axis Motion	5.2
9.7	W Axis Motion	5.3

9.7	W Axis Motion	6.1
8.7	Z Axis Motion	3.1
8.7	Z Axis Motion	3.2
8.7	Z Axis Motion	5.1
8.7	Z Axis Motion	8.2

**Severe Application Listing of Failure Events
by Safety Risk Importance**

<u>Risk Index</u>	<u>Description</u>	<u>Item Number</u>
13.5	Peripheral	6.4
12.5	Peripheral	6.5
12.4	Peripheral	2.1
12.4	Peripheral	6.1
12.4	Peripheral	6.3
12.4	X-Y Axis Motion	6.2
12.4	X-Y Axis Motion	11.2
11.5	Peripheral	6.6
11.4	Peripheral	4.2
11.4	X-Y Axis Motion	7.2
11.4	X-Y Axis Motion	7.3
11.4	X-Y Axis Motion	9.2
11.4	X-Y Axis Motion	10.2
11.4	X-Y Axis Motion	10.3
11.3	Peripheral	6.2
10.4	Peripheral	3.1
10.4	Peripheral	4.1
10.4	X-Y Axis Motion	6.1
10.4	X-Y Axis Motion	6.4
10.4	X-Y Axis Motion	11.1
10.4	X-Y Axis Motion	11.4
10.4	X-Y Axis Motion	12.2
10.4	X-Y Axis Motion	13.1
10.4	X-Y Axis Motion	13.2
10.4	Z Axis Motion	4.2
10.4	Z Axis Motion	5.2
10.4	W Axis Motion	1.2
10.4	W Axis Motion	7.1
10.3	X-Y Axis Motion	1.3
10.3	X-Y Axis Motion	12.3
9.4	Peripheral	1.1
9.4	X-Y Axis Motion	12.1
9.4	Z Axis Motion	4.1
9.4	Z Axis Motion	5.3
9.4	Z Axis Motion	9.1
9.4	Z Axis Motion	9.2
9.4	W Axis Motion	2.1
9.4	W Axis Motion	2.2

9.3	Peripheral	3.2
9.3	X-Y Axis Motion	4.3
9.3	X-Y Axis Motion	5.1
9.3	Z Axis Motion	6.3
9.3	Z Axis Motion	10.2
8.5	W Axis Motion	9.1
8.4	Z Axis Motion	4.4
8.4	Z Axis Motion	7.1
8.4	Z Axis Motion	10.1
8.4	W Axis Motion	1.1
8.3	X-Y Axis Motion	2.2
8.3	X-Y Axis Motion	3.2
8.3	X-Y Axis Motion	6.3
8.3	X-Y Axis Motion	11.3
8.3	Z Axis Motion	2.1
8.3	Z Axis Motion	3.3
8.3	Z Axis Motion	7.2
8.3	Z Axis Motion	10.3
8.3	W Axis Motion	1.3
7.5	Z Axis Motion	6.1
7.5	Z Axis Motion	8.1
7.4	Peripheral	5.2
7.4	X-Y Axis Motion	1.1
7.4	X-Y Axis Motion	2.1
7.4	X-Y Axis Motion	3.1
7.4	X-Y Axis Motion	4.1
7.4	X-Y Axis Motion	14.1
7.4	X-Y Axis Motion	14.2
7.3	X-Y Axis Motion	8.2
7.3	X-Y Axis Motion	9.2
7.3	Z Axis Motion	1.2
7.3	Z Axis Motion	4.3
7.3	W Axis Motion	6.2
6.4	Peripheral	5.1
6.4	X-Y Axis Motion	7.1
6.4	X-Y Axis Motion	8.1
6.4	X-Y Axis Motion	10.1
6.4	Z Axis Motion	1.1
6.4	W Axis Motion	3.1
6.4	W Axis Motion	4.1
6.4	W Axis Motion	5.1
6.4	W Axis Motion	5.3
6.4	W Axis Motion	6.1

6.3	X-Y Axis Motion	1.2
6.3	X-Y Axis Motion	4.2
6.2	W Axis Motion	7.2
5.4	Z Axis Motion	5.1
5.3	Peripheral	1.2
5.3	Z Axis Motion	6.4
5.3	W Axis Motion	3.2
5.3	W Axis Motion	5.2
5.2	W Axis Motion	8.1
4.3	Z Axis Motion	3.1
4.3	Z Axis Motion	8.2
4.2	Z Axis Motion	6.2
3.2	Z Axis Motion	3.2

**Favorable Application Listing of Failure Events
by Financial Risk Importance**

<u>Risk Index</u>	<u>Description</u>	<u>Item Number</u>
13.5	Peripheral	6.1
13.5	Peripheral	6.3
12.6	Peripheral	3.2
12.5	Peripheral	2.1
12.5	Peripheral	6.2
12.5	Peripheral	6.4
11.6	Peripheral	3.1
11.5	Peripheral	4.2
11.5	Peripheral	6.5
11.5	X-Y Axis Motion	6.2
11.5	X-Y Axis Motion	7.2
11.5	X-Y Axis Motion	9.1
11.5	X-Y Axis Motion	10.2
11.5	X-Y Axis Motion	11.2
10.6	Peripheral	1.1
10.5	Peripheral	4.1
10.5	Peripheral	6.6
10.5	X-Y Axis Motion	1.3
10.5	X-Y Axis Motion	4.3
10.5	X-Y Axis Motion	6.1
10.5	X-Y Axis Motion	7.3
10.5	X-Y Axis Motion	10.3
10.5	X-Y Axis Motion	12.2
10.5	X-Y Axis Motion	12.3
10.5	Z Axis Motion	4.2
10.5	W Axis Motion	7.1
9.5	X-Y Axis Motion	2.2
9.5	X-Y Axis Motion	6.4
9.5	X-Y Axis Motion	11.3
9.5	X-Y Axis Motion	11.4
9.5	X-Y Axis Motion	13.1
9.5	X-Y Axis Motion	12.2
9.5	Z Axis Motion	2.1
9.5	Z Axis Motion	3.3
9.5	Z Axis Motion	4.1
9.5	Z Axis Motion	5.2
9.5	Z Axis Motion	5.3
9.5	Z Axis Motion	6.3
9.5	Z Axis Motion	9.1

9.5	Z Axis Motion	9.2
9.5	Z Axis Motion	10.2
9.5	Z Axis Motion	10.3
9.5	W Axis Motion	1.2
9.5	W Axis Motion	1.3
9.5	W Axis Motion	2.1
9.5	W Axis Motion	2.2
8.5	X-Y Axis Motion	3.2
8.5	X-Y Axis Motion	6.3
8.5	X-Y Axis Motion	9.2
8.5	X-Y Axis Motion	11.1
8.5	X-Y Axis Motion	12.1
8.5	Z Axis Motion	4.4
8.5	Z Axis Motion	7.2
7.6	Peripheral	1.2
7.6	X-Y Axis Motion	3.1
7.6	Z Axis Motion	8.1
7.5	Peripheral	5.2
7.5	X-Y Axis Motion	1.2
7.5	X-Y Axis Motion	2.1
7.5	X-Y Axis Motion	5.1
7.5	X-Y Axis Motion	8.2
7.5	X-Y Axis Motion	14.1
7.5	X-Y Axis Motion	14.2
7.5	Z Axis Motion	1.2
7.5	Z Axis Motion	4.3
7.5	Z Axis Motion	7.1
7.5	Z Axis Motion	10.1
7.5	W Axis Motion	1.1
7.5	W Axis Motion	6.2
7.5	W Axis Motion	7.1
7.5	W Axis Motion	8.1
7.5	W Axis Motion	9.1
6.5	Peripheral	5.1
6.5	X-Y Axis Motion	1.1
6.5	X-Y Axis Motion	4.1
6.5	X-Y Axis Motion	4.2
6.5	X-Y Axis Motion	7.1
6.5	X-Y Axis Motion	8.1
6.5	X-Y Axis Motion	10.1
6.5	Z Axis Motion	1.1
6.5	Z Axis Motion	3.1
6.5	Z Axis Motion	3.2
6.5	Z Axis Motion	5.1
6.5	Z Axis Motion	6.1
6.5	Z Axis Motion	6.2

6.5	Z Axis Motion	6.4
6.5	Z Axis Motion	8.2
6.5	W Axis Motion	3.1
6.5	W Axis Motion	3.2
6.5	W Axis Motion	4.1
6.5	W Axis Motion	5.1
6.5	W Axis Motion	5.2
6.5	W Axis Motion	5.3
6.5	W Axis Motion	6.1

**Favorable Application Listing of Failure Events
by Safety Risk Importance**

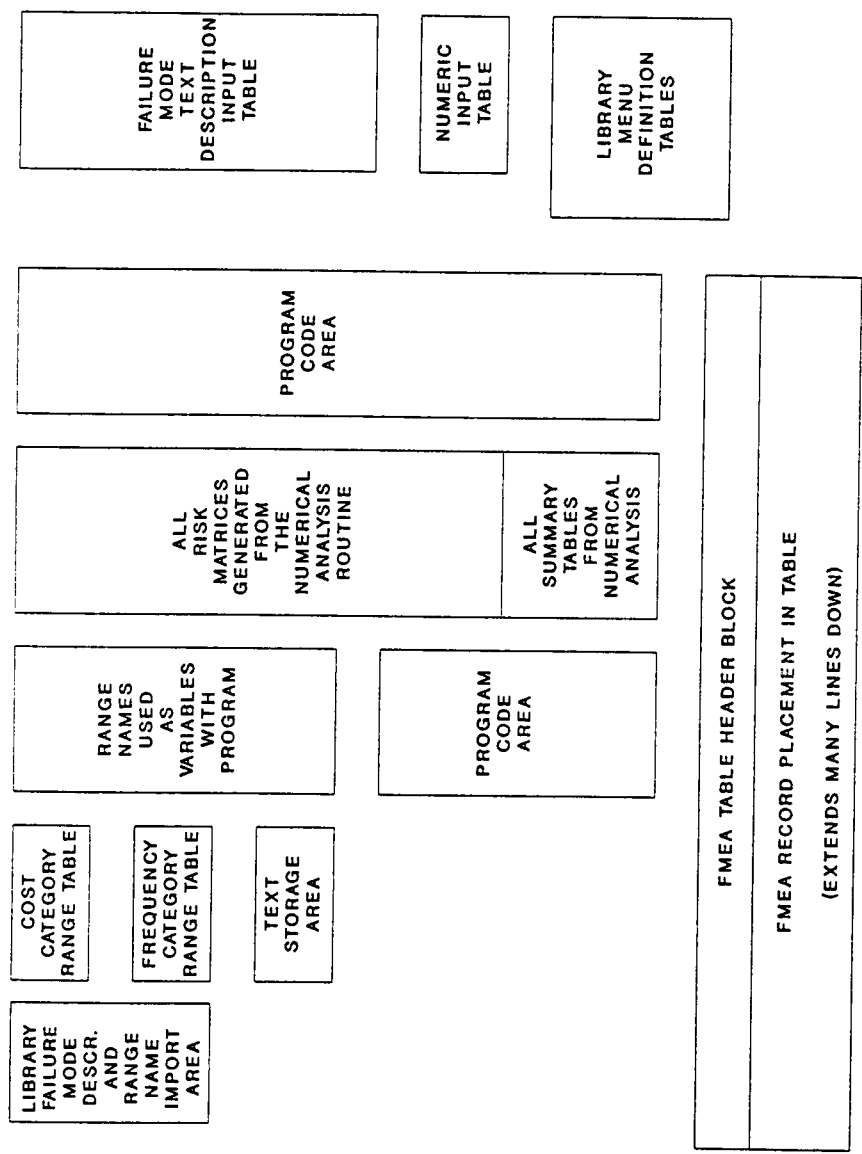
<u>Risk Index</u>	<u>Description</u>	<u>Item Number</u>
11.3	Peripheral	6.1
11.3	Peripheral	6.3
10.5	Peripheral	6.6
10.4	Peripheral	6.5
10.3	Peripheral	6.4
9.2	Peripheral	2.1
9.2	Peripheral	6.2
8.2	Peripheral	4.2
8.2	X-Y Axis Motion	6.2
8.2	X-Y Axis Motion	7.2
8.2	X-Y Axis Motion	9.1
8.2	X-Y Axis Motion	10.2
8.2	X-Y Axis Motion	11.2
7.2	Peripheral	3.1
7.2	Peripheral	4.1
7.2	X-Y Axis Motion	6.1
7.2	X-Y Axis Motion	7.3
7.2	X-Y Axis Motion	10.3
7.2	X-Y Axis Motion	12.2
7.2	Z Axis Motion	4.1
7.2	W Axis Motion	7.1
7.1	Peripheral	3.2
6.2	Peripheral	1.1
6.2	X-Y Axis Motion	6.4
6.2	X-Y Axis Motion	11.4
6.2	X-Y Axis Motion	13.1
6.2	X-Y Axis Motion	13.2
6.2	Z Axis Motion	4.1
6.2	Z Axis Motion	5.2
6.2	Z Axis Motion	5.3
6.2	Z Axis Motion	9.1
6.2	Z Axis Motion	9.2
6.2	W Axis Motion	1.2
6.2	W Axis Motion	2.1
6.2	W Axis Motion	2.2
6.1	X-Y Axis Motion	1.3
6.1	X-Y Axis Motion	4.3

6.1	X-Y Axis Motion	12.3
5.3	W Axis Motion	9.1
5.2	X-Y Axis Motion	11.1
5.2	X-Y Axis Motion	12.1
5.2	Z Axis Motion	4.4
5.1	X-Y Axis Motion	2.2
5.1	X-Y Axis Motion	11.3
5.1	Z Axis Motion	2.1
5.1	Z Axis Motion	3.3
5.1	Z Axis Motion	6.3
5.1	Z Axis Motion	10.2
5.1	Z Axis Motion	10.3
5.1	W Axis Motion	1.3
4.3	Z Axis Motion	8.1
4.2	Peripheral	5.2
4.2	X-Y Axis Motion	2.1
4.2	X-Y Axis Motion	14.1
4.2	X-Y Axis Motion	14.2
4.2	Z Axis Motion	7.1
4.2	Z Axis Motion	10.1
4.2	W Axis Motion	1.1
4.1	X-Y Axis Motion	3.2
4.1	X-Y Axis Motion	6.3
4.1	X-Y Axis Motion	9.2
4.1	Z Axis Motion	7.2
3.2	Peripheral	5.1
3.2	X-Y Axis Motion	1.1
3.2	X-Y Axis Motion	3.1
3.2	X-Y Axis Motion	4.1
3.2	X-Y Axis Motion	7.1
3.2	X-Y Axis Motion	8.1
3.2	X-Y Axis Motion	10.1
3.2	Z Axis Motion	1.1
3.2	Z Axis Motion	5.1
3.2	Z Axis Motion	6.1
3.2	W Axis Motion	3.1
3.2	W Axis Motion	4.1
3.2	W Axis Motion	5.1
3.2	W Axis Motion	5.3
3.2	W Axis Motion	6.1
3.1	X-Y Axis Motion	1.2
3.1	X-Y Axis Motion	5.1

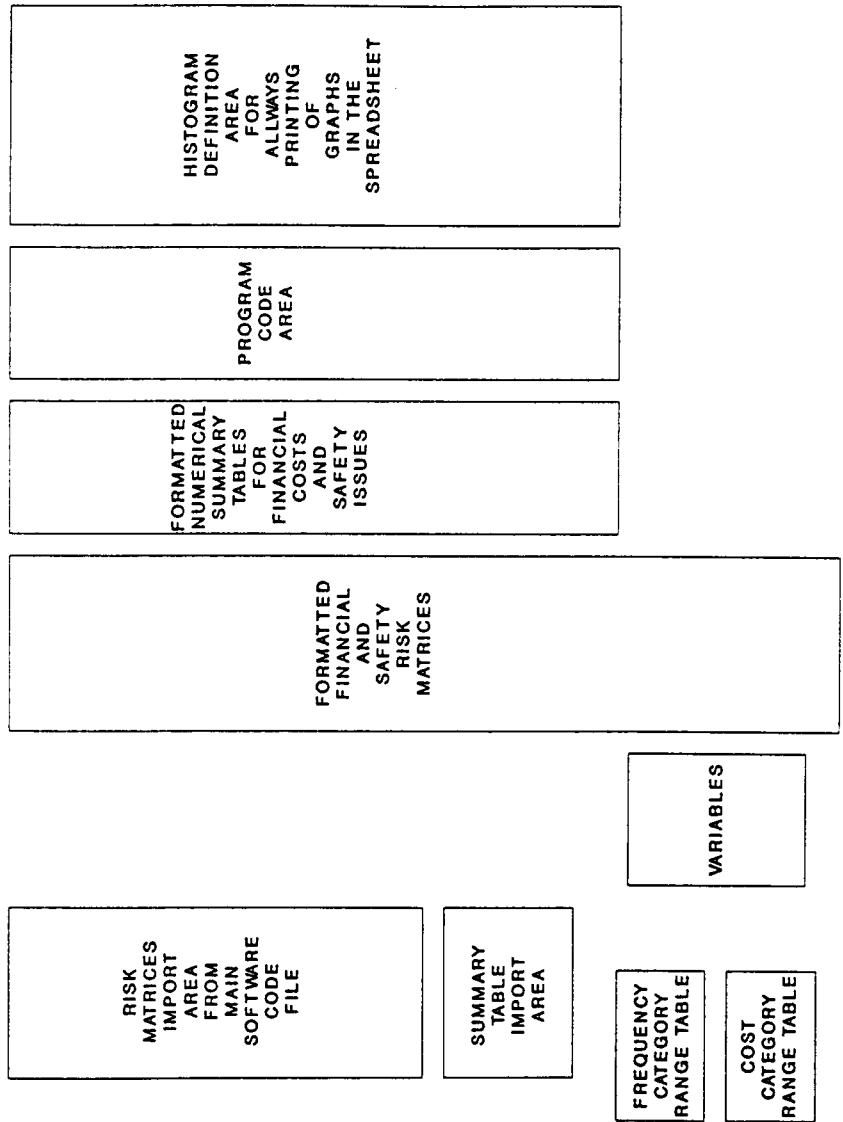
3.1	X-Y Axis Motion	8.2
3.1	Z Axis Motion	1.2
3.1	Z Axis Motion	4.3
3.1	W Axis Motion	6.2
3.1	W Axis Motion	7.2
3.1	W Axis Motion	8.1
2.1	Peripheral	1.2
2.1	X-Y Axis Motion	4.2
2.1	Z Axis Motion	3.1
2.1	Z Axis Motion	3.2
2.1	Z Axis Motion	6.2
2.1	Z Axis Motion	6.4
2.1	Z Axis Motion	8.2
2.1	W Axis Motion	3.2
2.1	W Axis Motion	5.2

APPENDIX E

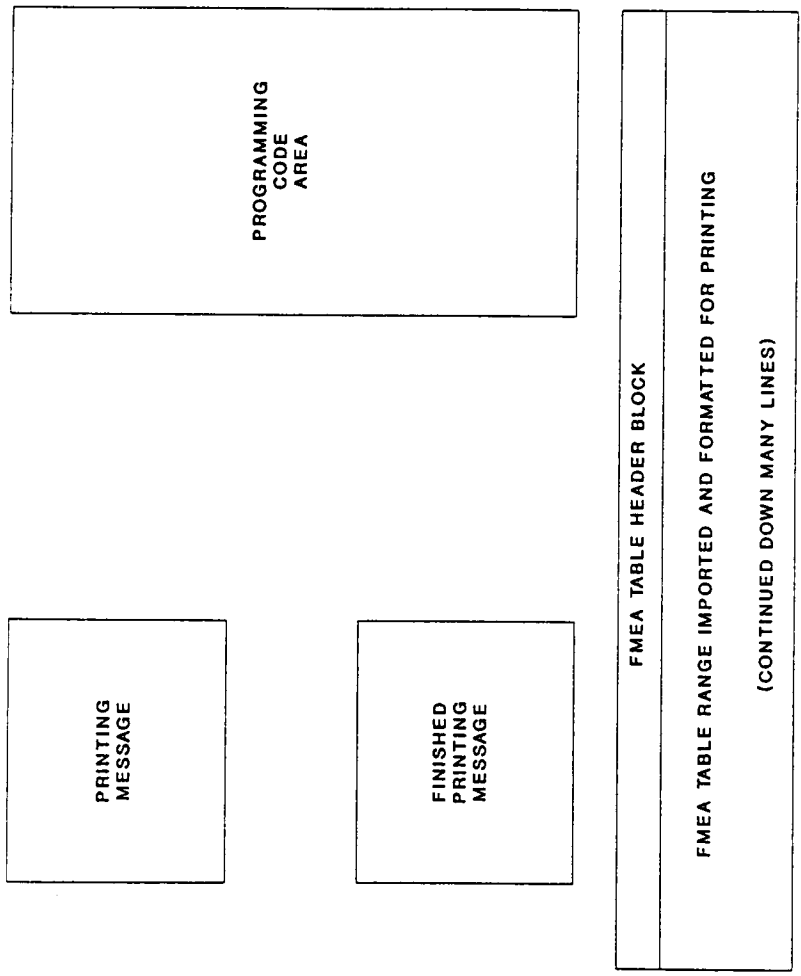
FMEA SOFTWARE SPREADSHEET FILE DEPICTIONS



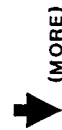
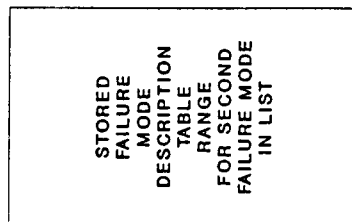
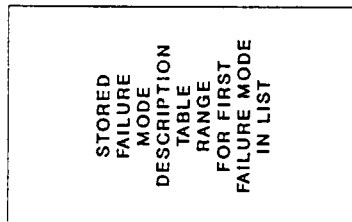
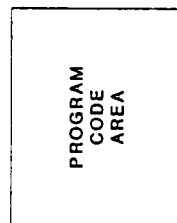
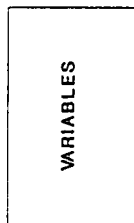
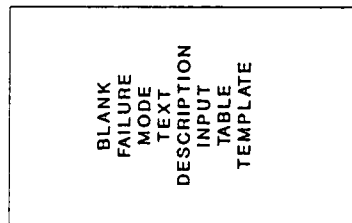
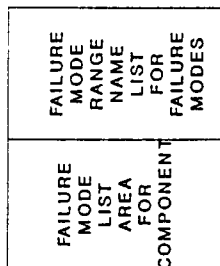
Pictorial Representation of Spreadsheet Program File ZETA8.WK1 Which is Used for Managing the FMEA Study



Pictorial Representation of Spreadsheet Program File MATRICES.WK1 which is Used for Viewing and Printing Numerical Results from the FMEA Table



Pictorial Representation of Spreadsheet Program File FMTprt.wk1 Which is Used for Formatting and Printing FMEA Tables

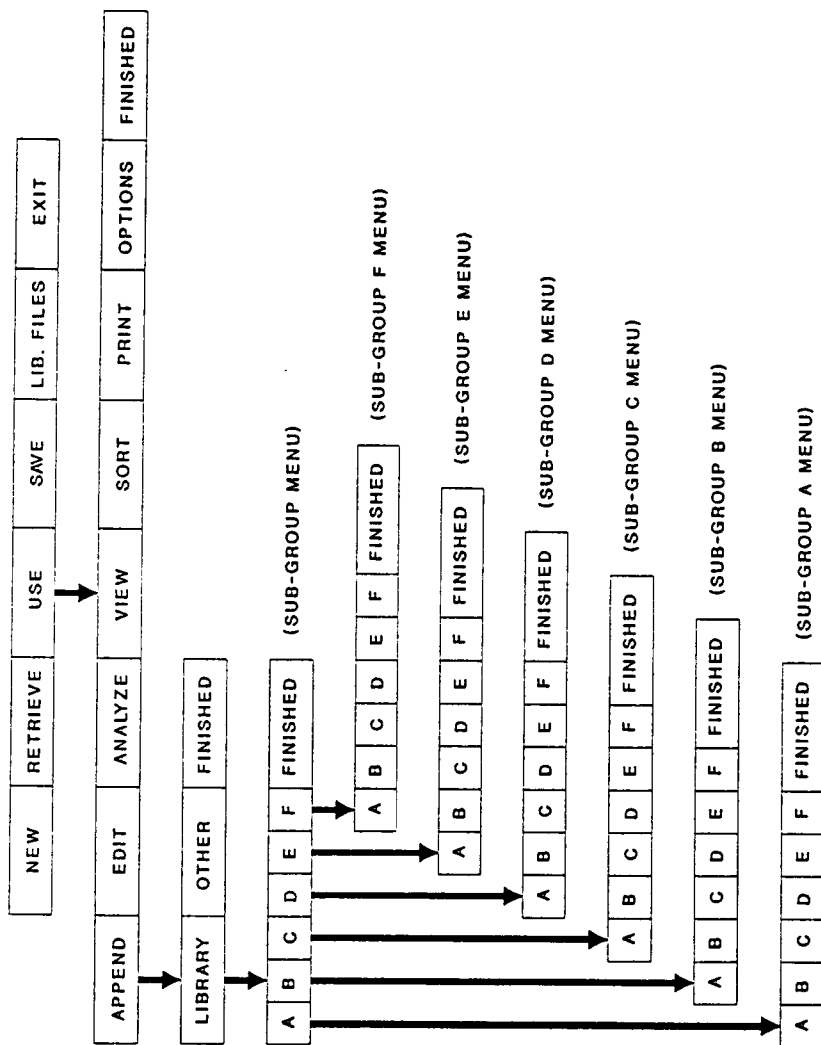


(MORE)

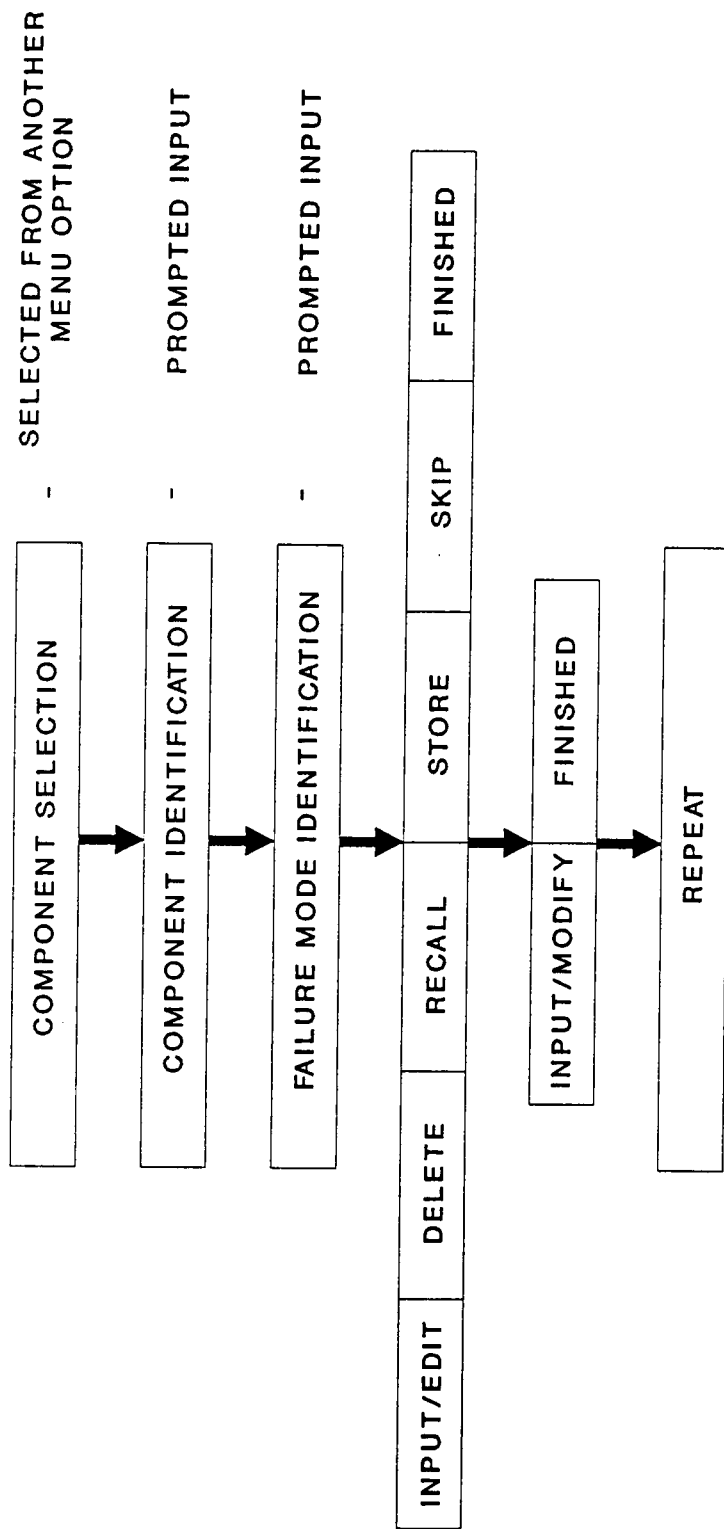
Pictorial Representation of Spreadsheet Program File LIBCRT.WK1 Which is Used for Creating and Storing Library Data Files for Components

APPENDIX F

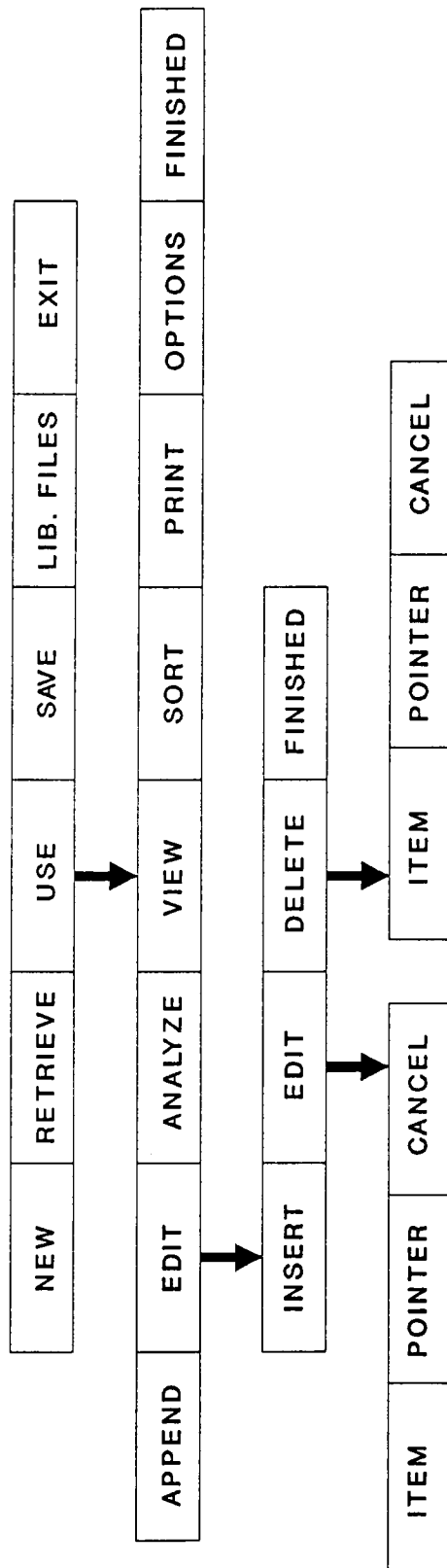
FMEA SOFTWARE MENU STRUCTURE



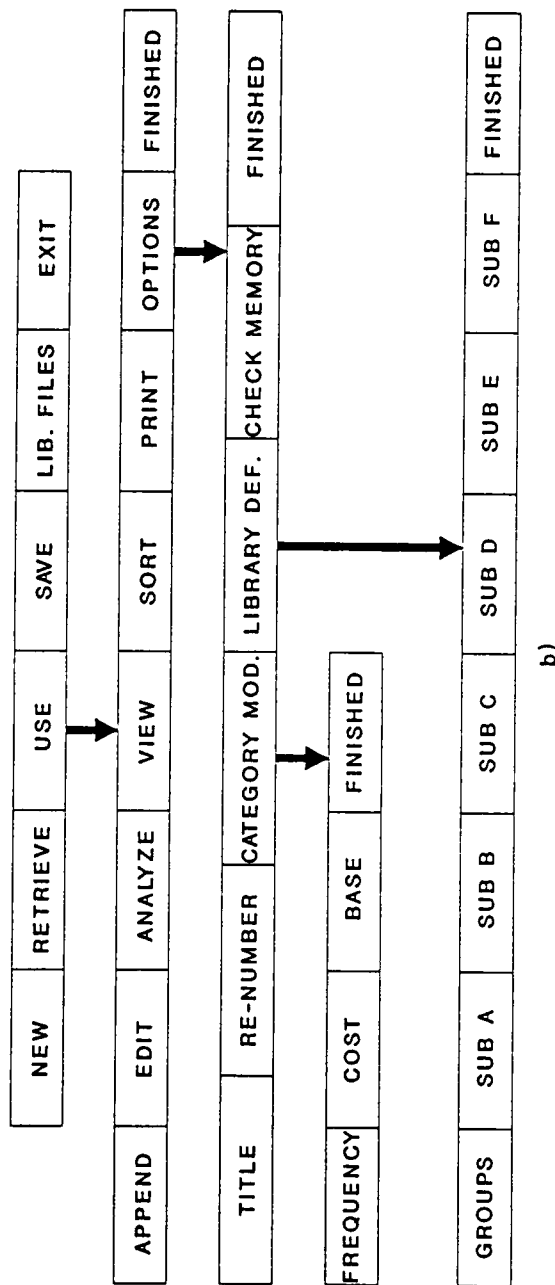
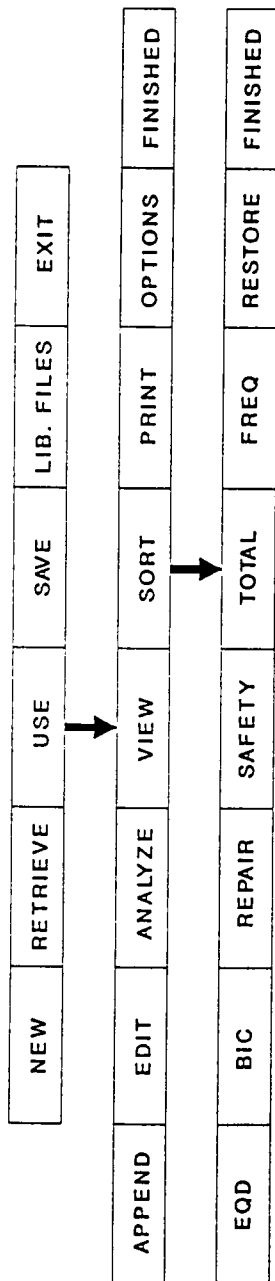
FMEA Software Menu Structure Options for Adding Components to the FMEA Table



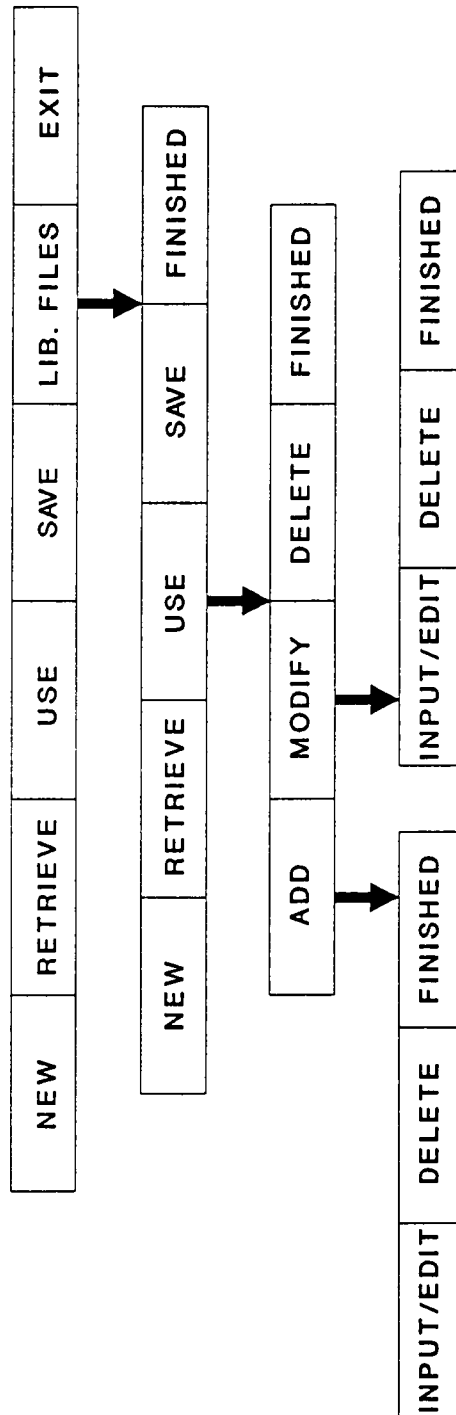
FMEA Software Menu Structure Options for Modifying Text and Numeric Values in the FMEA Table



FMEA Software Menu Structure Options for Editing the Failure Mode Records in the FMEA Table



FMEA Software Menu Structure Options for a) Sorting the FMEA Table Records by Importances and b) Changing the FMEA Study Options



APPENDIX G

FMEA SOFTWARE ROUTINE ALGORITHMS

\0 or \W

- 1) Checks logical variables and transfer program to some menu if program file was exited from one of these menus.
- 2) If not, Present menu options to begin NEW Component Library File, RETRIEVE previously created Library File, Use the selected Library File, Save the currently selected Library File, or exit to the Main FMEA program file.

New:

- a) Check logical variable to see if file has been saved since change were made. If not, verify intention question.
- b) Option to save if needed.
- c) Retrieve blank FMEA Table File spreadsheet.

Retrieve:

- a) Check logical variable to see if file has been saved since change were made. If not, verify intention question.
- b) Option to save if needed.
- c) Retrieve previously created FMEA Table spreadsheet.

Use:

- a) Change logical save variable to indicate that changes are being made to the selected FMEA Table File.
- b) Branch to the FMEA Table File program options.

Save:

- a) Uses Lotus save feature to save spreadsheet file.
- b) Changes logical save variable to indicate the file has been saved since changes were made.

Finished:

- a) Check logical variable to see if file has been saved since change were made. If not, verify intention question.
- b) Option to save if needed.
- c) Exits LOTUS and transfer program control to batch file.

TXTPPLACE

- 1) Indicate "Placing Text in the FMEA Table."
- 2) Place the Failure Mode Item Number in column A on the first line of the current Failure Mode Record.
- 3) Place the Component Description from the FMEA Text Input Table in column C on the first line of the current Failure Mode Record.
- 4) Justify the Component Description in column C.
- 5) Place the Failure Mode Description from the FMEA Text Input Table in column E on the first line of the current Failure Mode Record.
- 6) Justify the Failure Mode Description in column E.
- 7) Place the first Failure Mode Cause from the FMEA Text Input Table in column G on the first line of the current Failure Mode Record.
- 8) Justify the Failure Mode Cause in column G.
- 9) Place the next Failure Mode Cause from the FMEA Text Input Table in column G one blank line below the last line of the previously justified Failure Mode Cause.
- 10) Justify the Failure Mode Cause in column G.
- 11) Update the row number, two blank line below the lowest point, necessary for the next Failure Mode Record to be place below the current Failure Mode Record.
- 12) Repeat 9-11 for the remaining Failure Mode Causes.
- 13) Repeat 7-11 in column I for the Failure Mode System Effects in the FMEA Text Input Table.
- 14) Repeat 7-11 in column Y for the Failure Mode Comments and Safeguards in the FMEA Text Input Table.
- 15) Repeat 7-11 in column AA for the Failure Mode Recommended Actions in the FMEA Text Input Table.
- 16) Returns to the routine from which it was called.

NUMPLACE

- 1) Indicate "Placing Numeric Information in the Main FMEA Table."
- 2) Place Equipment Damage Cost, if present, in column M on the first line of the Failure Mode Record.
- 3) Place Business Interruption Cost, if present, in column O on the first line of the Failure Mode Record.
- 4) Place Repair Cost, if present, in column Q on the first line of the Failure Mode Record.
- 5) Place Safety Category, if Present, in column S on the first line of the Failure Mode Record.
- 6) If numeric cost values are present, add the failure costs to calculate the Total Cost, and place the Total Cost in column U on the first line of the Failure Mode Record.
- 7) If a Total Cost and Failure Frequency are present, multiply the two to calculate the Total Cost Risk, and place the Risk in Column W on the first line of the Failure Mode Record.
- 8) Return to routine which called NUMPLACE.

APPEND

- 1) Indicate "Append Menu."
- 2) Set the row for the newly appended Failure Mode Record to begin at the end of the FMEA Table.
- 3) Erase the text and the numeric values in the FMEA Text Input Table and the FMEA Numeric Input Table.
- 4) Present menu option to add component from Library files or user input.

For Adding A Component from the Library Files:

- 5) Indicate "Library Sub-group Menu."
- 6) User selects component from Library Menus.
- 7) Read the Component Library File name for the chosen component.
- 8) Import the list of Failure Mode Descriptions, and corresponding information storage range names, into the spreadsheet file.
- 9) Place the FMEA Text Input Table on the screen.
- 10) Prompt for a specific Component Description.
- 11) Copy the first imported failure mode into the FMEA Text Input Table. Increment the Failure Mode Number counter.
- 12) Import the stored text descriptions from the range defined in the Component Library File which corresponds to the current failure mode in the FMEA Text Input Table.
- 13) Use the MODTXT routine to Input/Edit information in the FMEA Text Input Table.
- 14) Use the TXTPLACE routine to properly place the text descriptions in the Main FMEA Table.
- 15) Use the NUMENT routine to Input/Edit information in the FMEA Numeric Input Table.

- 16) Use the NUMPLACE routine to properly place the numeric descriptions in the Main FMEA Table.
- 17) Erase the descriptions for this Failure Mode from the Input Tables.
- 18) Repeat 11-17 until no more Failure Modes from the Library File are left.
- 19) Option presented to add any additional Failure Modes not already addressed. Increment Failure Mode Counter.
- 20) If chosen, perform steps 13-17.
- 21) Repeat steps 19 and 20 until all Failure Modes have been addressed.

For Non-Library Supported Components:

- 4) Perform Steps 19-21 until satisfied.

RETRVE

- 1) Indicate "Compiling Selected Entry Into Input Table."
- 2) Store the Component and Failure Mode Counters.
- 3) Read Component Number for selected Failure Mode Record.
- 4) Read Failure Mode Number for selected Failure Mode Record.
- 5) Store the row number on which Failure Mode Records would be added to the end of the FMEA Table.
- 6) Store the row number of the first line of the selected Failure Mode Record.
- 7) Find the highest line number for the selected Failure Mode Record.
- 8) Expand the selected Failure Mode Record to its default maximum number of line by adding blank lines to the end of the Record.

- 9) Erase the information in the FMEA Text and Numeric Input Tables.
- 10) Use the CONCATEN routine to concatenate the Failure Mode Record entries into long text strings or numbers, and place them in the Input Tables.
- 11) Use the MODTXT and NUMENT routines to Input/Edit information in the FMEA Text Input Table and the FMEA Numeric Input Table.
- 12) Erase the old information for the Failure Mode Record in the Main FMEA Table, if the Skip Option is zero. If not, keep the old information in the FMEA Table, and eliminate the additional lines.
- 13) Use the TXTPLACE and NUMPLACE routines to place the modified text and numeric descriptions in the FMEA Table.
- 14) Delete the unnecessary rows from the expanded Failure Mode Record so that two blank lines exist between subsequent Failure Mode Records.
- 15) Restore the previous failure mode counters and the bottom row the FMEA Table counter.

CONCATEN

- 1) Store the first line of the Component Description.
- 2) In the next line below in the same column is not blank, concatenate the lower line to the end of the stored string.
- 3) Repeat 1 and 2 until a blank line is found.
- 4) Place the concatenated string in the FMEA Text Input Table space for the Component Description. Erase the string in the Concatenation variable.
- 5) Repeat 1-4 for the Failure Mode Description.
- 6) Repeat 1-4 for each Failure Mode Cause.
- 7) Repeat 1-4 for each Failure Mode System Effect.
- 8) Repeat 1-4 for each Failure Mode Comment/Safeguard.

- 9) Repeat 1-4 for each Failure Mode Recommended Action.
- 10) If the Equipment Damage Cost is not blank, place the Equipment Damage Cost in the FMEA Numeric Input Table.
- 11) If the Business Interruption Cost is not blank, place the Business Interruption Cost in the FMEA Numeric Input Table.
- 12) If the Repair Cost is not blank, place the Repair Cost in the FMEA Numeric Input Table.
- 13) If the Safety Category is present, place the Safety Category in the FMEA Numeric Input Table.

ANLYZE

- 1) Insure FMEA Table is not sorted by logical variable check.
- 2) Set logical variable to identify that the ANLYZE routine has been run.
- 3) Erase the current Matrices, Summary Tables, and Sorting Indices.
- 4) Place cursor on first Failure Mode Record Item Number.
- 5) If the Failure Frequency on this row is not blank, calculate the Frequency Category for the Event.
- 6) Store the Frequency Category in the Frequency Sorting Index column on the first line of the Failure Mode Record.
- 7) If the Equipment Damage Cost on this row is not blank, calculate the Equipment Damage Cost Category.
- 8) Increment the cell in the Equipment Damage Risk Matrix for the appropriate Equipment Damage Cost Category and the Frequency Category.
- 9) Add the Failure Frequency and Equipment Damage Risk values to the appropriate categories in the Equipment Damage Summary Table.

- 10) Store the Equipment Damage Sorting Index in the correct column on the first line of the Failure Mode Record.
- 11) Repeat 7-10 for the Business Interruption Cost.
- 12) Repeat 7-10 for the Repair Cost.
- 13) Repeat 7-10 for the Total Cost.
- 14) Repeat 7-10 for the Safety Category.
- 15) Copy the sorting indices from the first line of the Failure Mode Record to the subsequent lines for the same Category.
- 16) Repeat 5-15 for each Failure Mode Record in the FMEA Table.
- 17) Place the line numbering index in the last column.

MODTXT

Input:

- 1) Indicate "Input/Edit Text Entries."
- 2) Position the FMEA Text Input Table on the screen.
- 3) Set screen borders.
- 4) Define input cells of the FMEA Text Input Table as Input Range to allow user to easily enter information in Table.
- 5) Returns to the MODTXT menu options.

Delete:

- 1) Prompt user to highlight cell in the FMEA Text Input Table to erase.
- 2) Verify the intention to delete the entry.
- 3) Erase the contents of the cell.
- 4) Returns to the MODTXT menu options.

Recall:

- 1) Present menu options for using stored text strings in the FMEA Text Input Table.
- 2) Allows users to position cursor on any cell to place the stored text string.

- 3) Returns to the MODTXT menu options.

Store:

- 1) Present menu options to allow user to select in which storage location to store text.
- 2) Positions text label storage table on screen.
- 3) Prompt user to enter text string for storage location.
- 4) Stores text in storage location.
- 5) Returns screen to top of the FMEA Text Input Table.
- 6) Returns to the MODTXT menu options.

Skip:

- 1) Erase information in the FMEA Text Input Table.
- 2) Increment the Failure Mode Counter.
- 3) Set logical variable to detecting Skip option to one.
- 4) Return to Routine which called MODTXT.

NUMENT

- 1) Position the FMEA Numeric Input Table on the screen.
- 2) Indicate "Input Quantification Data."
- 3) Set screen borders.
- 4) Define cells in the FMEA Numeric Input Table as an input range allowing the user to complete the numeric quantifications easily.
- 5) Returns to NUMENT menu options.

INSERT-FM

- 1) Verify Intention to insert a new Failure Mode in the FMEA Table.
- 2) Indicate "Insert Failure Mode."
- 3) If adding a Failure Mode after the last Failure Mode Record in the FMEA Table, move cursor to the end of

the FMEA Table to row position indicated for next Failure Mode record.

- 4) Else, allow user to position cursor on the item number of the existing Failure Mode Record that will follow the inserted Failure Mode Record.
- 5) Test to insure the cursor is placed correctly on an existing Failure Mode Item Number, if not got to step 1.
- 6) Insert three blank lines below cursor.
- 7) Store the row number of the cursor position.
- 8) Prompt for an Failure Mode Item Number with the appropriate component number with a failure mode number different from those already existing.
- 9) Prompt for a Component Description for the inserted Failure Mode.
- 10) Prompt for a Failure Mode Description for the inserted Failure Mode.
- 11) Update bottom row number for the FMEA Table to reflect the addition of three rows.
- 12) Use the RETRVE, NUMENT, TXTMOD, TXTPLACE, and NUMPLACE routines to complete and place the remaining information for the inserted Failure Mode in the FMEA Table.
- 13) Return to the Edit the FMEA Table menu options.

Editing--FM

- 1) Indicate "Edit A Failure Mode."
- 2) Use the WHICH routine to identify which Failure Mode Record Item to edit.
- 3) Check to determine if cancel command was selected in the WHICH option.
- 4) Prompt to Modify the numeric information only.

- 5) If modifying numeric information only, use the NUMREAD and NUMENT to read numeric information into the FMEA Numeric Input Table, modify the information, and replace the new information in the FMEA Table. Return to the Edit the FMEA Table menu options.
- 6) Use RETRVE and TXTPLACE routines to concatenate, edit, and replace the Failure Mode Record in the FMEA Table.
- 7) Return to the Edit the FMEA Table menu options.

Delete--FM

- 1) Indicate "Delete a Failure Mode."
- 2) Use the WHICH routine to identify which Failure Mode Record to delete from the FMEA Table.
- 3) Check to determine if cancel command was selected in the WHICH option.
- 4) Verify intention to delete the Failure Mode Record. If negative, return to Edit the FMEA Table menu options.
- 5) Delete the lines from the row number of the first line of the Failure Mode Record to the first line before the next Failure Mode Record.
- 6) Modify the stored value of the row number on which the next Failure Mode should be placed at the end of the FMEA Table due to the deleted lines.
- 7) Return to the Edit the FMEA Table menu options.

WHICH

Item:

- 1) Display FMEA Table on screen.
- 2) Prompt for Failure Mode Record Item Number to be selected.
- 3) Move cursor to Failure Mode Record Item Number, and compare to entered value.
- 4) If a match is found, return to the routine that called WHICH.

- 5) Repeat 3-4 for next Failure Mode Record until the end of the FMEA Table is found.
- 6) In no match, selected item not found in FMEA Table, begin WHICH again.

Pointer:

- 1) Display the FMEA Table.
- 2) Prompt the user to position the cursor on the Failure Mode Number Item Number to be selected.
- 3) Verify that cursor is in the correct column and on a valid item number, if not begin WHICH again.
- 4) Return to the routine that called WHICH.

Cancel:

- 1) Store Cancel logical variable and return to routine which called WHICH.

SORT

- 1) Menu option to select what type of sorting is desired.
- 2) Indicate "Sorting Table Entries."
- 3) Test to be certain ANALYZE routine has been performed by testing logical variable definition from ANALYZE routine, if not, return to Use menu options.
- 4) Define logical variable status to indicate if the FMEA Table has been sorted.
- 5) Define range to be sorted from column A in the first line of the FMEA Table to the last line of the FMEA Table in the AG column. This includes all columns of the FMEA Table and all of the sorting index columns.
- 6) Define the primary key to appropriate sorting index column.
- 7) Define secondary key to line numbering column.
- 8) Perform the sorting operation.
- 9) Return to the Use Menu options.

View FMEA Table

- 1) Indicate "Viewing FMEA Table."
- 2) Move cursor to display the upper left corner of the FMEA Table.
- 3) Define screen borders.
- 4) Allow the user to view the FMEA Table by moving the cursor to display other areas of the FMEA Table until a carriage return is entered.
- 5) Display the FMEA Text Input Table.
- 6) Return to the View options menu.

View Numerical Summary Information

- 1) Define the logical variable to one for branching the program to the current mode after re-initiating when this file is re-activated after working in the MATRICES.WK1 file.
- 2) Temporarily save this FMEA file in XXXXXXXX.WK1.
- 3) Indicate "Generating Numerical Summary."
- 4) Retrieve MATRICES.WK1 for displaying and printing formatted numerical summary results.
- 5) Indicate "Numerical Summary Main Menu."
- 6) Retrieve Numerical results from the ANALYZE routine into the MATRICES spreadsheet file.
- 7) Prompt to combine the numerical results from multiple FMEA Tables

Yes:

- a) Prompt to be certain the files have the same category definition ranges, if no, do not combine.
- b) Prompt to change the title of the study
- c) Combine the numeric information from *.WK1 file by adding to the existing results.

- d) Repeat if other files to added.
- 8) Provide menu options to view Matrices, Summary Tables, Histograms, or Print numeric results.

View:

- a) Select what type of Numeric information to be viewed.
- b) Select specific cost or safety aspect for the selected type of numeric summary presentation.
- c) Display the table or figure on the screen allowing the user to view areas of the table not displayed on the screen using the cursor keys until a carriage return is pressed.
- d) Return to the Numerical Summary View Menu.

Print:

- a) Select Matrices, Sumamry Tables, or Histograms
 - b) Print pre-defined ranges for selected type of numeric summary to be presented.
 - c) Return to Print Numeric Summary menu options.
- 9) Repeat View options and Print options until satisfied.
- 10) Retrieve FMEA Table file XXXXXXXX.WK1.
- 11) Transfer program operation to the View menu because the logical variable detecting that program execution terminated on this menu previously.

LIB. MOD.

- 1) Prompt menu options to change the Sub-Group definition or the listing of Components in each Sub-Group.
- 2) Verification of Intention to Modify Selected Library menu definitions.
- 3) Position selected Library Sub-menu Defintion Table.

- 4) Allow user to position cursor on item in the menu definition table which is to be modified.
- 5) Prompt Inactive or Active.

Inactive:

- 1) Replace the description with the menu location name.
- 2) Place Inactive in the file name range.
- 3) Return to the Library Menu Definition Range.

Active:

- 1) Prompt to enter a brief Component Description which is placed in the Library Definition Table.
- 2) Prompt for filename of the Component File.
- 3) Enter Active in last column if the Sub-Group menu option is chosen.
- 4) Return to Library Menu Definition Range.

TITLE

- 1) Indicate "Title."
- 2) Prompt for new FMEA Table Title.
- 3) Return to OPTIONS menu options.

CHECK MEMORY

- 1) Indicate "Memory Check."
- 2) Display LOTUS Worksheet Status Table until a carriage return is pressed.
- 3) Return to OPTIONS menu options.

CATEGORY MOD.

- 1) Indicate "Category Range Modification."
- 2) Present menu options to change the Base, Frequency Category Scale Factor, or the Cost Category Scale Factor which are adjusting parameters in the equations which define the categories.

Base:

- a) Prompt to enter the new BASE number.
- b) Return to the CATEGORY MOD. menu options.

Frequency Category Scale Factor:

- a) Display the Frequency Category Range Table.
- b) Prompt for new Frequency Category Scale Factor.
- c) Return to CATEGORY MOD. menu options.

Cost Category Scale Factor:

- a) Display the Cost Category Range Table.
- b) Prompt for new Cost Category Scale Factor.
- c) Return to CATEGORY MOD. menu options.

RE-NUMBER

- 1) Indicate "Re-numbering the FMEA Table."
- 2) Move to the first line below the header of the FMEA Table.
- 3) Set the Component and Failure Mode Counters to one.
- 4) Move to the first Failure Mode Item Number.
- 5) Store the Component Number of the first Failure Mode Record.
- 6) Number the first Failure Mode record in the FMEA Table "COMPNUM"."FMNUM" .
- 7) Move to the next Failure Mode Record Item Number.
 - a) If the new Component Number is the same as the previous Component Number:

- i) increment the Failure Mode Counter,
 - ii) renumber the item number as "COMPNUM"."FMNUM" .
- b) If the new Component Number is different from the previous Component Number:
 - i) store the new Component Number,
 - ii) increment the Component Number Counter,
 - iii) set the Failure Mode Counter to one,
 - iv) renumber the item number as "COMPNUM"."FMNUM" .
- 8) Repeat until all Failure Mode Record Item Numbers have been modified.
- 9) Return to the OPTIONS menu options.

PRINT FMEA TABLE

- 1) Indicate "Print Main FMEA Table."
- 2) Store logical variable to identify that this option should be selected when the program control return to this file after working in the FMTPRT.WK1 file.
- 3) Prompt for the amount of the FMEA Table to be printed.

Entire:

- a) Defines the lowest and highest row numbers in the FMEA Table automatically for printing.

Selected:

- a) Prompt for the lowest row number in the FMEA Table to be printed.
- b) Prompt for the highest row number in the FMEA Table to be printed.

Cancel:

- a) Changes text variable to indicate the cancel option was chosen, returns to Main menu options.

- 4) Extract the FMEA Table Title into the file XXXXTITLE.WK1.
- 5) Extract the range defined by column A and the lowest row number in the FMEA Table to be printed to column AA and the highest row number in the FMEA Table to be printed into the file XXXXXPRT.WK1.
- 6) Temporarily save the current FMEA Table file in XXXXXXXX.WK1.
- 7) Retrieve the formatting and printing file, FMTTPRT.WK1.
- 8) Activate the ALWAYS add-in.
- 9) Combine the title file, XXXXTITLE.WK1, into the print file above the header block for the FMEA Table.
- 10) Combine the print range, XXXXXPRT.WK1, into the print file below the header block for the FMEA Table.
- 11) Delete the extra spacing columns between the Failure Mode Description columns of the FMEA Table.
- 12) Find the highest row number in the FMEA Table.
- 13) Move the cursor to the first Failure Mode Record Item Number.
- 14) Save this location as the first line of the printed FMEA Table page.
- 15) Move the cursor to the next Failure Mode Record Item Number and identify its row number.
- 16) If the difference between the current row number and the first row number for the page is larger than the maximum difference that may be printed on one page, the entry before the current Failure Mode Record will not fit on this page.
 - a) If only one entry was considered for placement on the page, this entry will have to be split between pages because of its length.
 - i) Move the cursor up, one line at a time, until a blank line all the way across the FMEA Table is found within the Failure Mode Record of interest. A sufficient number of

blank lines will be inserted at this point to force the rest of this record onto the top of the next page. The variable which records the highest row number in the FMEA Table is update to reflect the addition of rows. This will try to avoid splitting any single description between pages.

- ii) If this is impossible, the page is broken naturally by the LOTUS print routine where ever the page break falls. (CONT) is placed in the Item Number column of the record at the line which will occur on the first line of the next printed page. This line is now considered the first line on the top of the next printed page and the process is repeated.
 - b) If multiple Failure Mode Records had been considered for the printed page, the last one considered would not fit on the page. The cursor moves to the previous Failure Mode Record Item Number. The number of lines to force this entry to the top of the next page is calculated and inserted. The highest row number in the FMEA Table is updated.
- 17) If the difference is exactly the number of lines for the printed page, the current Failure Mode Record is considered the top of the next page. The process is repeated from step 13.
 - 18) If the difference is too small, additional Failure Mode Records may fit on the page. Move to the next lowest Failure Mode Record Item Number until 16 or 17 is satisfied and performed.
 - 19) Repeat until the entire FMEA Table is properly spaced.
 - 20) Add ALWAYS lines from the top of the FMEA Table to the end of the FMEA Table, and define the printing borders.
 - 21) Print the FMEA Table Range in ALWAYS.
 - 22) Detach ALWAYS.
 - 23) Retrieve the FMEA Table file stored in XXXXXXXX.WK1.

- 24) Program execution is transferred to the Main menu options.

LIB FILES

- 1) Temporarily Save FMEA Table file as XXXXXXXX.WK1.
- 2) Retrieve Library program file LIBCRT.WK1.
- 3) Indicate "Library File Creation."
- 4) Present menu options to begin NEW Component Library File, RETRIEVE previously created Library File, Use the selected Library File, Save the currently selected Library File, or exit to the Main FMEA program file.

New:

- a) Check logical variable to see if file has been saved since change were made. If not, verify intention question.
- b) Option to save if needed.
- c) Retrieve blank Component Library File spreadsheet.

Retrieve:

- a) Check logical variable to see if file has been saved since change were made. If not, verify intention question.
- b) Option to save if needed.
- c) Retrieve previously created Component Library File spreadsheet.

Use:

- a) Change logical save variable to indicate that changes are being made to the selected Library File.
- b) Branch to the Library File program options.

Save:

- a) Uses Lotus save feature to save spreadsheet file.
- b) Changes logical save variable to indicate the file has been saved since changes were made.

Finished:

- a) Check logical variable to see if file has been saved since change were made. If not, verify intention question.
 - b) Option to save if needed.
 - c) Retrieve FMEA program file XXXXXXXX.WK1.
 - d) Program transfer to Main menu options.
- 5) Presents Library file modification features to ADD, MODIFY, or DELETE Failure Modes from the Component Library File.

Add:

- a) Indicate "Adding Additional Failure Mode."
- b) Copy blank FMEA Text Input Table to information storage area.
- c) Define the blank FMEA Text Input Table as a range name.
- d) Place the range name in the Table of Failure Mode Descriptions for the supported components next to the description for the Failure Mode.
- e) Use the MODTXT routine to complete the Failure Mode Descriptions in the FMEA Text Input Table for the added Failure Mode.
- f) Places the Failure Mode Description in the Table of Failure Mode Descriptions.
- g) Returns to the Library File modification features.

Modify:

- a) Indicate "Modifying Existing Failure Mode."
- b) Allow user to highlight Failure Mode to be modified using the cursors in the Table of Failure Mode Descriptions.
- c) Check the cursor position to be certain it is placed in the correct column in an acceptable row.
- d) Move the the range defined next the the Failure Mode Description in the Table of Failure Mode Descriptions. Display FMEA Text Input Table on the screen.
- e) Use the MODTXT routine to complete the Failure Mode Descriptions in the FMEA Text Input Table for the added Failure Mode.
- f) Places the Failure Mode Description in the Table of Failure Mode Descriptions.

- g) Returns to the Library File modification features.

Delete:

- a) Indicate "Deleting a Failure Mode."
- b) Allow user to highlight Failure Mode to be modified using the cursors in the Table of Failure Mode Descriptions.
- c) Check the cursor position to be certain it is placed in the correct column in an acceptable row.
- d) Delete the Failure Mode Description and Range Name from the Table of Failure Mode Descriptions for the Component Library File, and move the remaining entries in the table to fill the void.
- e) Delete the completed FMEA Text Input Table for the deleted Failure Mode from the information storage area, and move the other FMEA Text Input Tables to fill the void.
- f) Returns to the Library File modification features.

APPENDIX H

FMEA SOFTWARE RANGE NAME DESCRIPTIONS

Range Name Definitions For ZETA8.WK1

Name	Range	Description
A	P8	defines the appropriate column for displaying the chosen menu definition table
ABRN	T17	defines the row number of the last line in the expanded failure mode record during the RETRVE subroutine
AMOUNT	BH29	marks a routine for determining the range of the FMEA Table to be printed
ANALYZE	BB1	marks a routine for analyzing the numerical quantifications for the failure mode records
ANBIC	BB15	branch location within the ANALYZE routine marking the code for interpreting the business interruption cost data for a failure mode record
ANBOT	P14	defines the row number of the last line of the current failure mode record during the ANALYZE routine. Used for copying the sorting indicies to all of the rows in the current failure mode record
ANFIN	BB35	branch location within the ANALYZE routine marking the code for copying the sorting indicies to all of the rows in the current failure mode record
ANNEXT	BB4	branch location within the ANALYZE routine marking the code for repeating the numerical analysis for another failure mode record
ANRC	BB20	branch location within the ANALYZE routine marking the code for interpreting the repair cost data for a failure mode record
ANS	BB25	branch location within the ANALYZE routine marking the code for interpreting the safety issue data for a failure mode record
ANSTOP	BB40	branch location within the ANALYZE routine marking the code for ending the numerical analysis routine
ANTOT	BB30	branch location within the ANALYZE routine marking the code for interpreting the total cost data for a failure mode record
ANYL	T13	defines logical variable to determine is the FMEA Table has been numerically analyzed since changes have been made

Range Name Definitions For ZETA8.WK1

Name	Range	Description
APPEND	AI12	marks routine to add additional components to the FMEA Table
B	P9	defines the appropriate column for displaying the chosen menu definition table
BASE	R10	defines the base number for the category assignment range equations
BEGIN	AS84	marks the MAIN FMEA menu choices
BIC	CB48	defines the business interruption cost input cell in the numerical input table
BICCAT	P20	defines the business interruption cost category number calculated for an event during the ANALYZE routine
BICMAT	V18..AE27	defines the business interruption cost risk matrix generated during the ANALYZE routine
BLDCNT	R21	defines the number of the entry, among the other entires for the same failure mode record in the same column, being placed in the failure mode input table during the CONCATEN routine
BLDRNG	R22	defines the initial letters of the range location in the input table where the text being concatenated will be placed. The number from BLDRNG is used to complete the name of the variable location such as "REC" & "1" resulting in REC1
BOTROW	T16	temporarily, during the RETRVE routine, defines the begining of the next failure mode record which would be added to the end of the FMEA Table
BRANGE	R23	defines the letter of the column for which text will be concatenated during the CONCATEN routine
BTPRT	P4	defines the bottom row of the range of the FMEA Table defined for printing in the AMOUNT routine
BTROW	P26	defines the begining of the next failure mode record which would be added to the end of the FMEA Table, and temporarily used to define the end of an interior failure mode record during editing

Range Name Definitions For ZETA8.WK1

Name	Range	Description
BUILD	AS41	marks the routine for joining the justified entries into a single long text entry
C	P7	defines the appropriate column for displaying the chosen menu definition table
CAS1	CE5	defines the location in the failure mode input table for storing the first cause description of the failure mode record
CAS2	CE6	defines the location in the failure mode input table for storing the second cause description of the failure mode record
CAS3	CE7	defines the location in the failure mode input table for storing the third cause description of the failure mode record
CAS4	CE8	defines the location in the failure mode input table for storing the fourth cause description of the failure mode record
CAS5	CE9	defines the location in the failure mode input table for storing the fifth cause description of the failure mode record
CAS6	CE10	defines the location in the failure mode input table for storing the sixth cause description of the failure mode record
CAS7	CE11	defines the location in the failure mode input table for storing the seventh cause description of the failure mode record
CAS8	CE12	defines the location in the failure mode input table for storing the eighth cause description of the failure mode record
CCOL	P30	defines the column letter for the current column during the TXTPLACE operation
CCT	R29	logical variable to identify if the component to be added under the append feature is from the library
CIROW	P24	defines the row number of the first line of a failure mode record during the current operation in several routines
COMM1	CE21	defines the location in the failure mode input table for storing the first comment description of the failure mode record

Range Name Definitions For ZETA8.WK1

Name	Range	Description
COMM2	CE22	defines the location in the failure mode input table for storing the second comment description of the failure mode record
COMM3	CE23	defines the location in the failure mode input table for storing the third comment description of the failure mode record
COMM4	CE24	defines the location in the failure mode input table for storing the fourth comment description of the failure mode record
COMM5	CE25	defines the location in the failure mode input table for storing the fifth comment description of the failure mode record
COMP	CE3	defines the location in the failure mode input table for storing the component description of the failure mode record
COMPEN	AI19	marks the choices for the COMPONENT menu for adding the components to the FMEA Table
COMPNUM	P27	defines the component number for the failure mode record. The component number precedes the period in the item number
CONCAT	R20	defines variable used to accumulate concatenated strings into one long text entry
CONCATEN	AS31	marks a routine for concatenating the justified entries in an FMEA Table record into the long text entries of the input table
COSTTAB	I6..K13	defines the component consequence category range table
COUNTER	R24	defines counting variable for FOR loops
CSTVW	G1..G1	defines a position marker for positioning cost category table on the screen
DELS	AI69	marks a routine for deleting a failure mode record from the FMEA Table
DIFF	T15	defines the difference between the current row position and the lowest row position during RETRVE routine
DODEL	AS22	branch location in RETRVE routine which deletes excess rows after an expanded failure mode record has been modified

Range Name Definitions For ZETA8.WK1

Name	Range	Description
DONTDEL	AS26	branch location when it is not necessary to delete rows after an expanded failure mode record has been replaced
EDT	AS55	marks a routine for editing, inserting, and deleting failure mode records in the FMEA Table
EFF1	CE13	defines the location in the failure mode input table for storing the first system effect description of the failure mode record
EFF2	CE14	defines the location in the failure mode input table for storing the second system effect description of the failure mode record
EFF3	CE15	defines the location in the failure mode input table for storing the third system effect description of the failure mode record
EFF4	CE16	defines the location in the failure mode input table for storing the fourth system effect description of the failure mode record
EFF5	CE17	defines the location in the failure mode input table for storing the fifth system effect description of the failure mode record
EFF6	CE18	defines the location in the failure mode input table for storing the sixth system effect description of the failure mode record
EFF7	CE19	defines the location in the failure mode input table for storing the seventh system effect description of the failure mode record
EFF8	CE20	defines the location in the failure mode input table for storing the eighth system effect description of the failure mode record
EMPTY	R19	defines a logical variable to determine if the contents of a cell during the CONCATEN routine is empty
ENDSRCH	P54	marks a routine for searching for the last line of multiple line text description in a column
ENTCOMP	AI33	marks the routine for entering new components in the FMEA Table. Interprets whether the information will be input from library file or from the user

Range Name Definitions For ZETA8.WK1

Name	Range	Description
EQD	CB47	defines the equipment damage cost input cell in the numerical input table
EQDCAT	P19	defines the equipment damage cost category number calculated for an event during the ANALYZE routine
EQDMAT	V3..AE12	defines the equipment damage cost risk matrix generated during the ANALYZE routine
ERFILE	AI77	branch location and routine for continuing program execution when a "File Not Found Error" occurs
F	CB46	defines the frequency input cell in the numeric input table
FMCOUNT	T14	defines the row number of the next failure mode in the FMTABLE for a component which is retrieved from a component library file
FMD	CE4	defines the location in the failure mode input table for storing the failure mode description of the failure mode record
FMDATA	CE4..CE29	defines the range of descriptive text information for a failure mode record in the input table, excluding the component description
FMNUM	P28	defines the failure mode number for the failure mode record. The failure mode number follows the period in the item number
FMTABLE	C3..D50	defines the range reserved for importing the list of failure modes, and the failure mode description range names in the component library file, from the selected component library file
FREQCAT	P13	defines the frequency category number calculated for an event during the ANALYZE routine
FREQTAB	I26..K35	defines the component frequency category range table
FRQVW	G21..G21	defines a position marker for positioning frequency category table on the screen
HIGH	T22	defines the lowest row number, highest line on the screen, for a failure mode record during the CONCATEN routine

Range Name Definitions For ZETA8.WK1

Name	Range	Description
INTGR1	R11	defines the component number, based on the actual item number, for the previous failure mode record during the RENUM routine
INTGR2	T11	defines the component number, based on the actual item number, for the current failure mode record during the RENUM routine
ITEM	R18	defines the item number as a label during the CONCATEN routine
JUST	P57	branch location and routine for justifying a long text entry in a column withing the maximum number of lines allotted for any failure mode record
LIBABB	R30	defines the range name for the failure mode description in the library file for the current failure mode record while adding records from the library feature
LIBCALL	AI42	marks a routine for retrieving a library failure mode description into the text input table
LIBCHG	BB82	marks a routine for modifying the library menus to access different library files
LIBFILE	R28	defines the library file name of the currently selected component if the component is supported by a library file
LIBGRP	BB71	marks the menu choices for modifying the grouping of library components into sub-groups
LIBMAIN	BB66	marks the menu choices for selecting the sub-group of components while adding a component to the FMEA study
LIBMEN1	BO1	marks the menu choices for selecting a component from sub-group A of components while adding a component to the FMEA study
LIBMEN2	BO7	marks the menu choices for selecting a component from sub-group B of components while adding a component to the FMEA study
LIBMEN3	BO13	marks the menu choices for selecting a component from sub-group C of components while adding a component to the FMEA study

Range Name Definitions For ZETA8.WK1

Name	Range	Description
LIBMEN4	B019	marks the menu choices for selecting a component from sub-group D of components while adding a component to the FMEA study
LIBMEN5	B025	marks the menu choices for selecting a component from sub-group E of components while adding a component to the FMEA study
LIBMEN6	B031	marks the menu choices for selecting a component from sub-group F of components while adding a component to the FMEA study
LNGTH	P12	defines the length of a label entry encountered
LOW	T23	defines the begining point of the next failure mode record during the RETRVE routine
MACROS	P11..Z83	defines the range of cells which contain the macros, necessary for recalculating the formulas in the macros
MAIN	A15	marks the menu choices for manipulating the currently selected FMEA Table
MATRICES	U3..AE72	defines the range which contains all of the risk matrices generated from the ANALYZE routine
MAXC	R26	defines the maximum number of separate causes, effects, comments, or recommendations to be considered during the TXTPLACE routine
MODTXT	A162	marks the menu choices for modifying or entering text in the input table
MULT	P46	branch location which adds multiple descriptions for the same failure mode record in the same column, such a causes, effect, comments, recommendations
MULTBLD	AS48	branch location generates seperate long text descriptions when the failure mode record has multiple descriptions for the same failure mode record in the same column, such a causes, effect, comments, recommendations
MULTTYPE	R25	defines the initial letters of the range location in the input table where the text being concatenated will be placed. The number from BLDRNG is used to complete the name of the variable location such as "REC"

Range Name Definitions For ZETA8.WK1

Name	Range	Description
		& "1" resulting in REC1
NEXTFM	AI35	branch location in the ENTCOMP routine for iterating the procedure for the next failure mode
NOTHERE	P48	branch location in MULT to skip the placement of text from storage locations in the input table which are blank
NUMCHC	P68	marks the menu choices for entering the numeric information in the input table
NUMDATA	CB46..CB50	defines the range of numerical information for a failure mode record in the numeric input table
NUMENT	P63	marks the routine for quantifying the current failure mode record
NUMIN	CB46..CB51	defines the range of numerical information for a failure mode record in the numeric input table
NUMPLACE	P76	marks the routine for placing the information in the numeric input table in the FMEA Table
NUMREAD	P85	marks the routine for placing the quantification data in the FMEA Table in the numeric input table for modification
NUMVIEW	CA41..CA41	defines a position range for positioning numeric input table on the screen
NUMXTRCT	U3..AD82	defines the range which includes all of the numeric summary information and risk matrices from the ANALYZE routine
NXT	BH18	branch location in RENUM for iterating to the next failure mode record item number
NXTBLD	AS42	branch location in BUILD for iterating to next description in same column that is part of the same failure mode record
NXTITM	AS78	branch location under WHICH to iterate through item numbers looking for item which has been selected
OPTIONS	BG1	marks menu choices for modifying the FMEA Table options

Range Name Definitions For ZETA8.WK1

Name	Range	Description
OPTS	AS59	marks menu choices under EDT routine for editing, entering, and deleting failure mode records for existing components
OTHER	AI54	marks the routine for manually entering the failure mode records for a component
PLROW	P25	defines the current row number of the cell being evaluated
PLS	P53	marks routine to determine the last row of a justified entry in a column
PLSRCH	P53	marks routine to determine the last row of a justified entry in a column
PPS	P11	defines the location of the "." in the item number description
PRTVAR	P6	defines a logical variable to determine if the macro execution should begin at the print option after the main software code file is retrieved
RC	CB49	defines the repair cost input cell in the numerical input table
REC1	CE26	defines the location in the failure mode input table for storing the first recommended action description of the failure mode record
REC2	CE27	defines the location in the failure mode input table for storing the second recommended action description of the failure mode record
REC3	CE28	defines the location in the failure mode input table for storing the third recommended action description of the failure mode record
REC4	CE29	defines the location in the failure mode input table for storing the fourth recommended action description of the failure mode record
REC5	CE30	defines the location in the failure mode input table for storing the fifth recommended action description of the failure mode record
REC6	CE31	defines the location in the failure mode

Range Name Definitions For ZETA8.WK1

Name	Range	Description
		input table for storing the sixth recommended action description of the failure mode record
REC7	CE32	defines the location in the failure mode input table for storing the seventh recommended action description of the failure mode record
REC8	CE33	defines the location in the failure mode input table for storing the eighth recommended action description of the failure mode record
RECALL	AI87	marks menu choices for recalling text from the storage feature to avoid retyping
REINST	AS62	branch location for trapping incorrectly defined location in the insert failure mode record routine under OPTS
RENUM	BH14	marks a routine for re-numbering the failure mode records in the FMEA Table
REPCAT	P21	defines the repair cost category number calculated for an event during the ANALYZE routine
REPMAT	V32..AE41	defines the repair cost risk matrix generated during the ANALYZE routine
RETN	T12	defines a logical variable to determine if the macro execution should begin at the view option after the main software code file is retrieved
RETRVE	AS11	marks a routine for placing the text descriptions for a failure mode record from the FMEA Table into the text input table for modification
ROWADD	T19	defines the number of lines to be added at the end of a selected failure mode record to expand the record to the maximum size allotted for records. Used during RETRVE
ROWDEL	T18	defines the number of lines to be deleted at the end of a selected failure mode record to reduce the record leaving only two blank lines to the next records. Used during RETRVE
S	CB50	defines the safety category input cell in the numerical input table

Range Name Definitions For ZETA8.WK1

Name	Range	Description
SAFCAT	P15	defines the safety category number calculated for an event during the ANALYZE routine
SAFMAT	V46..AE55	defines the safety risk matrix generated during the ANALYZE routine
SCC	P16	defines the parameter used to modify the cost category table for a specific appliation range
SCF	P17	defines the parameter used to modify the frequency category table for a specific appliation range
SCFS	BH7	marks the menu choices for modifying the frequency and cost category range tables
SDEF	P3	defines the path to the program default directory. Read from the default file
SKPTST	R17	defines logical variable to determine whether to skip a failure mode which is prompted from the library file listing
SPACE	P29	defines the maximum number lines that a failure mode record can have
SRT	P18	defines logical variable to determine if the FMEA Table is in a sorted configuration
SRTMEN	BB47	marks the menu choices for sorting the failure records by importance
START	A99	defines a placement location for the cursor at the first column on the blank line under the header block in the FMEA Table
STORA	I42	defines the first text storage location to store labels used multiple times
STORB	I43	defines the second text storage location to store labels used multiple times
STORC	I44	defines the third text storage location to store labels used multiple times
STORD	I45	defines the fourth text storage location to store labels used multiple times
STORE	AI82	marks the menu choices for storing text labels which will be used multiple times

Range Name Definitions For ZETA8.WK1

Name	Range	Description
STOREE	I46	defines the fifth text storage location to store labels used multiple times
STORTAB	G39	defines a position marker for positioning stored text table on the screen
STRCMCNT	R15	defines a location for storing the failure mode counter for event to be added at the end of the FMEA Table while modifications are being made to existing events
STRFCMCNT	R16	defines a location for storing the component number counter for event to be added at the end of the FMEA Table while modifications are being made to existing events
STRT	AS18	branch locations which intitates the process of COCACATEN in the RETRVE routine
SUBS	R10	defines logical variable to determine if the group option or a particular group has been selected in the library menu modification procedure
SVECHK	R12	defines logical variable to determine if the FMEA Table file has been saved before exiting
TEMP	R27	defines a variable used to reflect responses to prompts
TITLE	A90	defines the title of the FMEA Table above the FMEA Table header
TNRN	T20	defines the row number of the last line in the expanded failure mode record, plus one blank line, during the RETRVE subroutine
TOP	P10	defines the row number of the first line of the particular menu definition table selected
TOTCAT	P22	defines the total cost category number calculated for an event during the ANALYZE routine
TOTCST	R14	defines the total cost value of each failure mode record during the numeric entry stage
TOTMAT	V60..AE69	defines the total cost risk matrix generated during the ANALYZE routine
TOTRSK	R13	defines the risk value based on the total cost of each failure mode record during the

Range Name Definitions For ZETA8.WK1

Name	Range	Description
		numeric entry stage
TOTS	V75..AD82	defines the range containing all of the numeric summary information for the numeric summary tables
TPPRT	P5	defines the top row of the range of the FMEA Table defined for printing in the AMOUNT routine
TXTDATA	CE3..CE33	defines the range of descriptive text information for a failure mode record in the input table, including the component description
TXTPPLACE	P31	marks the routine for placing the text from the input table into the FMEA Table
TXTVIEW	CD1	defines a position marker for positioning text failure mode input table on the screen
USEROW	P23	defines the row which will contain the first line of text in an inserted failure mode record
VWMEN	BB57	marks the menu choices for viewing the FMEA Table or Numerical Summary Information
WHICH	AS74	marks the menu choices for selecting which item will be chosen for modification or deletion
YRN	AS65	branch location within the insert a failure mode routine
\0	AI1	automatic execution macro definition for beginning program
\W	AI1	manual execution macro definition for beginning program

Range Name Definitions For MATRICES.WK1

Name	Range	Description
BACKSUP	BJ2	branch location for accessing the CHOICE menu from the superimposing option
BASE	R10	defines the base number for the category assignment range equations
BIGBIC	O35..AI62	defines range for large, formatted business interruption cost risk matrix
BIGEQD	O1..AI28	defines range for large, formatted equipment damage cost risk matrix
BIGREP	O69..AI96	defines range for large, formatted repair cost risk matrix
BIGSAF	O137..AC167	defines range for large, formatted safety cost risk matrix
BIGTOT	O103..AI130	defines range for large, formatted total cost risk matrix
CHC	L101	defines the first letters of the range location to be displayed. Example CHC="BIC" then "BIG"&CHC is "BIGBIC"
CHOICE	BJ6	marks menu choices for viewing matrices, summary tables, or histograms, or for printing options
COSTTAB	D116..E123	defines same cost category range table as in ZETA8.WK1
CST1	B116	defines lowest cost bound for the first cost category
CST2	B117	defines lowest cost bound for the second cost category
CST3	B118	defines lowest cost bound for the third cost category
CST4	B119	defines lowest cost bound for the fourth cost category
CST5	B120	defines lowest cost bound for the fifth cost category
CST6	B121	defines lowest cost bound for the sixth cost category
CST7	B122	defines lowest cost bound for the seventh cost category

Range Name Definitions For MATRICES.WK1

Name	Range	Description
CST8	B123	defines lowest cost bound for the eighth cost category
EEND	L104	defines the last letter of the graph name for display in the graph options
ER	BJ67	marks the routine handling a "File Not Found" error
FREQTAB	D102..E111	defines same frequency category range table as in ZETA8.WK1
FRQ1	B102	defines lowest frequency bound for the first frequency category
FRQ10	B111	defines lowest frequency bound for the tenth frequency category
FRQ2	B103	defines lowest frequency bound for the second frequency category
FRQ3	B104	defines lowest frequency bound for the third frequency category
FRQ4	B105	defines lowest frequency bound for the fourth frequency category
FRQ5	B106	defines lowest frequency bound for the fifth frequency category
FRQ6	B107	defines lowest frequency bound for the sixth frequency category
FRQ7	B108	defines lowest frequency bound for the seventh frequency category
FRQ8	B109	defines lowest frequency bound for the eighth frequency category
FRQ9	B110	defines lowest frequency bound for the ninth frequency category
GRFS	BJ22	marks the menu choices for the type of graph to display
HISTOGRAMS	BZ1..CG236	defines the range reserved for storing ALWAYS depictions of graphs in the spreadsheet
NOPRT	BJ70	marks the routine for handling a "Printer Not Ready" error
OPTS	BJ13	marks the menu choices for selecting which

Range Name Definitions For MATRICES.WK1

Name	Range	Description
		matrix or summary table to view
PRT	BJ35	marks the menu choices for printing the matrices, summary tables, or histograms
RNG	L102	defines the last three letters of the option to be displayed
SCC	I105	same parameter value in ZETA8.WK1 for varying the cost category range table
SCF	I102	same parameter value in ZETA8.WK1 for varying the frequency category range table
SUMMBIC	AV27..BG40	formatted summary table for business interruption cost quantifications
SUMMEQD	AV3..BG16	formatted summary table for equipment damage cost quantifications
SUMMREP	AV53..BG66	formatted summary table for repair cost quantifications
SUMMSAF	AV109..BE119	formatted summary table for safety issue quantifications
SUMMTOT	AV81..BG94	formatted summary table for total cost quantifications
SUPER	BJ54	marks routine for superimposing results from other FMEA Table files
TEMP	L103	variable for storing responses to prompts
TITLE	B1	defines the title of the FMEA Table from file ZETA8.WK1
TOTS	C79..K86	defines all of the numeric summary table information for the FMEA
TWO	BJ29	marks menu choices for frequency or risk viewing of histograms
\0	BJ1	marks automatically executing macro for initiating program
\W	BJ1	marks manually executing macro for initiating program

Range Name Definitions For FMTPRT.WK1

Name	Range	Description
BOTTOM	AB7	marks routine to identify the last row in the FMEA Table range imported for printing
CURRENT	AF5	defines the row number of the current failure mode record
DWN	AF3	defines the number of failure mode records which are being placed on the page, counts the record trying to be added but that may not fit
END	AB45	marks routine to complete the formatting process for the FMEA Table range imported for printing
ENDPRT	AF6	defines location of last row to be printed after the FMEA Table range has been formatted for printing
ENDROW	AF2	defines the last row in the unformatted FMEA Table range
ERRPRT	AB54	marks routine for trapping the "Printer Not Ready" error
LINES	AB49	marks the routine for adding ALWAYS lines for columns
N	AF1	defines the maximum number of printed lines from the FMEA Table range, not counting the header, on a page for the printer selected
ONE	AB37	marks routine for formatting a failure mode record that is too long to fit on a single page
ONE1	AB38	branch location in ONE for identifying the most appropriate place to separate the long failure mode record, trying not to separate any single description between pages
SP1	AB19	branch location for iteratively considering whether the next failure mode record will fit on the current printed page
SP2	AB28	branch location for adding blank rows to make the following failure mode record appear on the next printed page
SP3	AB32	branch location for adding blank rows at the selected position within a long failure mode record so that the record is appropriately divided between two pages

Range Name Definitions For FMTPR.T.WK1

Name	Range	Description
SPACETOP	AB16	marks routine to correctly space failure mode records of the FMEA Table for formatted printing
SPACING	AB17	branch location in SPACETOP for re-initializing to begin considering a new printed page
TEMP	AF7	defines a variable for storing the response to prompts
TOP	AF4	defines the row number of the line which will appear at the top of the printed page being generated
\0	AB1	marks automatically executing macro to initiate program operation
\W	AB1	marks manually executing macro to initiate program operation
\A	AB3	marks manually executing macro to initiate program operation without importing the FMEA Table range

Range Name Definitions For LIBCRT.WK1

Name	Range	Description
BEGIN	L73	marks menu choices for retrieving or creating library files
BLANKTAB	K8..L40	defines range for blank template failure mode input table
BOTFM	L50	defines row number of the line in the FMTABLE in which the title and range for a newly added failure mode will be displayed
BTROW	L46	defines the row number of the lowest line in the arrangement of stored failure modes description tables. Used for locating the position of the next table
DELS	L109	marks routine for deleting text entries in a currently selected failure mode table
FMNUM	L44	defines the number of the failure mode. Used to define the range name of the failure mode description table when stored such as FAIL3
FMTABLE	A4..B63	defines of list of failure modes and the range name under which each description table for the failure mode is stored
HERE	L54	defines current cell address while deleting a failure mode description table
LNGTH	L47	defines the number of rows in the failure mode description table
MAIN	L81	marks menu choices for adding, modifying, or deleting failure modes from a library file
MODENT	L94	marks routine for adding a failure mode to the library file
MODRET	L96	marks routine for placing the failure mode description in the FMTABLE
MODTXT	L99	marks menu choices for adding, editing, and deleting descriptions in a failure mode description table
PDIR	L55	defines library default directory from the default configuration file
PLACE	L51	stores the range name of the failure mode description table for the failure mode being considered

Range Name Definitions For LIBCRT.WK1

Name	Range	Description
PLACE2	L53	stores range name of the failure mode description below the one being deleted. Used to reposition other tables
POS	L52	defines the current row number of the cursor in several routines
SPACE	L48	defines the amount of vertical lines left blank between subsequent failure mode description tables
SVECHK	L43	defines a logical variable to determine if the library files has been saved since changes have been made
TEMP	L45	defines a variable to store responses to prompts
TOP	L49	defines the row number of the first line in the range where the failure mode description for a failure mode will be stored
\0	L69	defines an automatically executing macro for initiating program operation
\w	L69	defines an manually executing macro for initiating program operation

Range Name Definitions For FMEACNFG.WK1

Name	Range	Description
DIRS	C3..C6	defines range which contains the default directories for the program
ERRS	G11	marks routing for handling the "FILE NOT FOUND" error
PFD	C4	defines the program file directory
STD	C6	defines the saved tables directory
TEMP	G16	defines a variable for storing the response to prompts
\0	G1	defines an automatically executing macro for initiating program operation
\W	G1	defines an manually executing macro for initiating program operation

VITA

David Alan Walker was born in Knoxville, Tennessee on January 21, 1967. He attended schools in that city and graduated from Doyle High School in June 1985. The following September he entered The University of Tennessee, Knoxville in the Mechanical and Aerospace Engineering Department, and earned a Bachelor of Science degree in Mechanical Engineering in the Spring of 1989. He immediately accepted a graduate research assistantship, as a part of the Superior Engineering Design Program, at The University of Tennessee, Knoxville and began study toward a Master's degree.

Mr. Walker has employment experience in risk/reliability/safety studies with a highly respected firm, JBF Associates, Inc. He has worked on several major projects including Fault Tree Analysis (FTA), Failure Modes and Effects Analysis (FMEA), and Hazard Operability Studies (HAZOP) projects for prominent manufacturers and government agencies.

The author is a member of Tau Beta Pi, Phi Kappa Phi, Pi Tau Sigma, and the American Society of Mechanical Engineering. Mr. Walker has previously authored a paper on using laser holographic interferometry and naphthalene sublimation to measure convective heat transfer

coefficients, as well as an award winning paper on International Technology Exchange. Additionally, Mr. Walker undertook a detailed study of reliability assessment and improvement procedures at Texas Instruments Johnson City facility as a class project. The author has received a prestigious DuPont Graduate Fellowship, an ALCOA Foundation Scholarship, a Martin Marietta Scholarship, and has been named an Eastman Kodak Scholar. Mr. Walker will be employed by JBF Associates, Inc. in Knoxville after graduation.