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ARMY MATERIEL SYSTEMS ANALYSIS ACTIVITY

R&M PREDICTION IN ENGINEERING DEVELOPMENT

VOLUME I

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ERRATA

Reference 8, page 23 (and bottom of page 9) should read:

8. Stark, R. M. and Yang, C. Y., Research Study of Reliability Prediction of Mechanical and Structural Systems, Final Technical Report, US Army Contract No. DAAD05-70-C-0011, University of Delaware, SP-19, Vol II

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Valid predictions of R&M (Reliability and Maintainability) should be based on design processes as the true determinants. Failure to do this and to develop the necessary data has resulted from lack of understanding and liaison between analysts and designers. The first corrective step should be development of a data base, initially from design testing, then from better instrumentation of R&M testing, utilizing design, instrumentation, and data systems skills. Design-oriented failure-mode analysis and maintainability

20. ABSTRACT (Continued)

analysis are necessary for data classification. Proper utilization of the data for prediction depends upon an improved understanding and liaison between analysts and designers.

SUMMARY

Most attempts to apply statistical theory to prediction of "new" materiel characteristics have, by a strange rationale, neglected the design process by which they are determined. The analyst or statistician and the engineer or designer generally do not understand the interrelation of their respective disciplines and each has poor understanding of the basic concepts in the field of the other. They fail to recognize that the "cause and effect" relationships basic to most design techniques are established on sound statistical principles. The statistician tends to distrust the "deterministic" relationships used by the designer, who regards statistics as a means of evaluating tolerances and errors. In particular, the statistician does not realize that design processes constitute the "ideal" determinants of the content of populations to be used in predicting characteristics of the products of those processes. Predicting has been attempted, based on factors that are essentially unrelated to the true differences between the "old" items, which have provided the experience history or data, and the new or future items. Regardless of any opinions that might be entertained about them, design processes are the determinants of those differences, and the success of any prediction technique will depend upon how well it is correlated with these processes. Communication between designers and analysts has recently been promoted and significant progress is claimed. There is wide recognition of the value of anticipating problems in areas such as reliability before an item is produced, but as yet there is little evidence that the crux of the prediction technique has been generally recognized. While the missing ingredients are the design processes, these serve to define populations; therefore the statistician must accept the responsibility for asking the right questions and using the answers properly. As one writer puts it, "The statistician cannot excuse himself from the duty of getting his head clear on the principles of scientific inference---." Because little historical data includes information about true physical phenomena, it will be necessary to generate new data bases to support effective prediction. In this effort statisticians will also need information from designers. A fruitful source is design testing, the results of which have often been stigmatized as "laboratory data." If an effective rapport between statisticians and designers can be achieved, the resulting improvement in prediction capability will enhance the value of activities such as Maintenance Engineering Analysis, Reliability Growth Analysis, Risk Analysis, and Value Engineering.

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1. INTRODUCTION

Certain applications of statistical (and probability) theory are confused by an assumed but false dichotomy between the disciplines concerned with statistics and those concerned with the phenomena involved in its application. This is particularly true in evaluation of the development of "new" systems. The generally accepted reference books on statistics describe these disciplinary interrelationships, and in the more traditonal applications they are appropriately considered. Their proper use in statistical prediction will be defined as a prelude to a discussion of methods and techniques.

1.1 Statistics and Science.

"Statistics is a branch of scientific method which deals with the data obtained by counting or measuring the properties of populations of natural phenomena. In this definition 'natural phenomena' includes all the happenings of the external world whether human or not." (Reference 1, p. 2). Thus statistics "counts or measures the properties" of that which science "explains" in terms of cause and effect. The introduction of most reference books essentially agree with this definition (References 2 through 7, see page 23 herein). Reference 2 (pp 1 & 2) addresses the interrelationship of science and statistics in the context of the function and scope of the respective disciplines, showing that statistics provides a validation of propositions or hypotheses that are induced by science. "Statistics" as used herein includes the probability theory applicable to analyzing the effects of the characteristics of a system on its use and support. Those who are responsible for this analysis ("reliability engineers", "maintainability engineers", logisticians", etc.) will be called "statisticians" or "analysts" for brevity. Those engaged in engineering design and development will be called "designers".

1.2 The Scientific Method.

Science is assumed to mean the development of systematic knowledge by inductive reasoning, based on observations of natural

[1]Kendall, M. G., and Stuart, A., The Advanced Theory of Statistics, Vol 1, 3rd Ed. (1969), Hafner, New York.

[2]Dixon, W. J., and Massey, F. J., Jr., Introduction to Statistical Analysis, (1951), McGraw-Hill, New York.

phenomena. The following are quoted from Reference 3: "I have assumed, as the experimenter always does assume, that it is possible to draw valid inferences from the results of experimentation: that it is possible to argue from consequences to causes, from observations to hypotheses;" (p. 3); "Inductive inference is the only process known to us by which essentially new knowledge comes into the world" (p. 7); and, "The statistician cannot excuse himself from the duty of getting his head clear on the principles of scientific inference---" (p. 2).

The "scientists" with whom we are presently concerned are not developing "new knowledge" or basic principles (research). Nevertheless, the development of anything that differs in any way from direct previous experience includes the basic inductive process.

1.3 Application of Statistics.

In most applications of statistics, assumptions requiring attention involve distributions, randomness, etc. Identification of the characteristics of prospective elements that qualify them as belonging to a particular population is usually obvious and special expertise is not required. For prediction, however, this is not true. Since the "new" system differs from those on which history is available, it is apparent that the validity of the prediction depends on the valid identification of these differences and their proper incorporation in the statistical analysis. The differences are established by the designer (to meet functional objectives). But the statistician identifies these differences primarily on the basis of names of system units and on correlations. System units (e.g., electronic "black boxes") vary drastically in content and complexity and are given functional names. The hazards of inferences drawn entirely from correlation are illustrated in Reference 4, page 52, in discussion of the "logistic distribution function". Neither method has a direct relation to the causes of failures, that is to stresses exceeding strengths.

1.4 Application of Prediction.

The Appendix describes an Engineering Reliability Program from the point of view of a contractor making a proposal to the Department of Defense. The first three sections were prepared as a guide after a study of a particular contractor's experience on several programs and a review of military standards and requirements (circa 1967). Section Four is a brief review of the most significant result of a recently completed

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[3]Fisher, R. A., The Design of Experiments, 8th Ed. (1950), Hafner, New York.

[4]Feller, Wm., An Introduction to Probability Theory and its Application, Vol 2, (1966), John Wiley, New York.

contract from AMSAA to the University of Delaware (Contract No. DAAD-70-C-0011) entitled "Research Study of Mechanical and Structural Reliability Prediction." (Reference 8) The experience of those performing the study included the field of Operations Research, and the principal application difficulty in this area and in the area of the Reliability Prediction was found to be similar - namely, the valid identification of the phenomena involved in the application, and the correlation of the analytical theory and techniques with them. The problem involves specialization as well as theory and practice. Not that there are only "theorists" on one hand and only "practitioners" on the other. The specialists in analysis and the specialists in the phenomena being analyzed generally have a good grasp of both the theoretical and practical factors, each in his own field. But each has a poor concept of the practical aspects of the other field, while viewing the ideas of specialists in that field as theoretical. A typical judgement by a designer is represented by the expression "You can prove anything with statistics." This is matched by typical judgements of statisticians, viewing the design as mainly trial and error, whereby the product is first fabricated with a "reliability" (or "MTBF") of about 10 percent of that required; the final product then being "developed" by a sequence of statistical analyses of test data, more trial and error, etc., all dignified by the expression "corrective action". The evidence used for this is failure data which does include the effects of the normal design process, but also includes other effects, some of which are not recognized. This will be discussed further in Section 5.2.

1.5 The Context of Prediction.

The difficulties of making useful and effective predictions during system design are being examined. A number of factors are involved and they are so interrelated that it is difficult to appreciate the full significance of any one without some understanding of the others. As these factors are described, reference will be made to their relevance, but this may not be too clear until viewed jointly and in perspective in Section 3.3. Prediction will be presented as it applies to Engineering Reliability, a familiar area that affects both use and support of equipment. The basic principles apply, however, to other areas, such as Maintenance Engineering, Reliability Growth, and Risk Analysis.

2. ENGINEERING RELIABILITY

2.1 History.

During the 1950's the Department of Defense recognized the need for a special effort during the design and development of materiel, in

[8] Stark, R. M. and Yang, C. Y., Research Study of Reliability Prediction of Mechanical and Structural Systems, Final Technical Report, US Army Contract No. DAAD-70-C-0011), University of Delaware.

order to achieve adequate reliability. This resulted in establishment of the Advisory Group on Reliability of Electronic Equipment (AGREE) which issued a report (Reference 9) in 1957 usually called the AGREE Report. By 1960 major system contractors were required to organize a specific department in engineering to improve reliability. This was the formal beginning of Engineering Reliability . It was often stated that reliability should be "designed into" rather than "tested into" a product, the latter referring to redesign after failure during test. The AGREE study provided a background for MIL-HDBK-217A (Reference 10), "Reliability Stress and Failure Rate Data for Electronic Equipment."

2.2 New Systems.

It is important to differentiate two Engineering Reliability activities. One provides an input to corrective action when failures occur in prototype and initial production tests. The expertise for this derives mainly from the relatively mature disciplines of quality control, supplemented by close liaison with design. The other is intended to support the design effort through analysis and reliability prediction. The primary purpose of the latter is to anticipate and avoid reliability problems created by new designs. This represents the greatest potential benefit from Engineering Reliability. A second purpose is to provide data for trade-off decisions during development and preliminary design.

What is the essence of the "new" characteristics of new systems? The answer must depend on how they are determined. The specific activity that determines them is design, mainly in response to functional requirements. Regardless of how requirements are established and constraints imposed, all characteristics, including any that might be "for reliability only", are achieved through incorporation in the design of the product. This is true although understanding of the phenomena involved is always limited by the "state-of-the-art" and techniques may be partly empirical.

2.3 Failure Classification.

Failure is defined by MIL-STD-721B as "The inability of an item to perform within previously specified limits." Criticisms of this definition have generally failed to recognize that it is "hardware" oriented to establish criteria for acceptance tests. Limited definitions are essential for most uses, but care should be used in formulating the limitations in light of ultimate use of the item, when all failures are significant.

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[9] Government Printing Office, Reliability of Military Electronic Equipment, 4 June 1957.

[10] MIL-HDBK-217 was issued on 8 August 1962 and superseded by MIL-HDBK-217A on 1 December 1965.

But are failures in ultimate use always obvious? Suppose the system was not designed to perform under the conditions in which it was used, should unsuccessful results then be classed as a failure? The answer is not obvious. Information about the conditions may not have been available before use of the system was attempted. A mission may be started when it is known that circumstances may develop that will preclude a successful outcome. If this happens the mission has failed, but not the system or its components. Thus it is essential to identify what has failed and this is not always as clear as in the example. We are concerned here mainly with equipment failures and their relation to design. Several real or apparent anomalies will be considered:

(1) A statistically specified stress requires a fixed value to be chosen as a criterion for acceptance tests. A failure from exceeding this value is or course significant for ultimate use, but is not classed as an equipment failure. Note that in a strict sense all stresses are statistical, but when the variance is very small they are assumed constant.

(2) If the skill of an operator is a factor in success, then the stress is related (inversely) to skill and the strength is the "operability" of the equipment. These are established experimentally, using adequate samples of operators and equipments. Sometimes the results can be expressed only in terms of whether stress exceeds strength, but usually strength can be related to measurable properties, thus establishing specifications to identify equipment failures.

(3) During development the relationship between a functional requirement and characteristics subject to known design techniques may be uncertain, i.e., not established by experience. In such cases the design is based on an a priori conclusion that it will perform the function. When the design is tested, usually in a "breadboard" or "prototype" form, it may fail in two ways: the intended design characteristics may not be achieved, a design failure; or the design characteristics may not enable the intended function to be performed, a failure of the analysis leading to the a priori conclusion. Both failures are in a different category from others being considered, since they do not evaluate or even relate to the ultimate form of the equipment to be produced. Instead they relate to the result of the design process, and if they occur there is a redesign. While not useful for reliability prediction, data on redesign is useful for prediction of the development process itself. This application will be considered in Section 5.

(4) When the available information about failures is not sufficient to relate them to known or determinable strengths, they are usually called random. This term does not necessarily imply a specific statistical significance, but rather that a "random" or unidentified phenomenon is involved. When random failures are a part of the history on which reliability predictions are based, they should be properly included in the analysis.

(5) Typically when a stress exceeds a strength the result is damage, but not necessarily. Stresses may render an item inoperative, but with no lasting effect. If the stresses are within previously specified limits an equipment failure is identified.

(6) A failure may be due to known and expected statistical deviations in parts. Or it may be a "debugging" failure known to have a neglible chance of affecting the delivered equipment. These failures may occur in all examples discussed above and their categorization and significance are routine and obvious.

Failures have also been classified as to mode, primarily in terms of symptom, function, or effect. The pertinent and critical aspects of failure for reliability prediction have thus been neglected. For example, a mode of failure of a mechanism might be labeled "bearing seizure, obviously an effect. If the modal classification also included a cause, such as lubrication, surface finish, alignment, etc., this would relate the failure to those design processes which determine resistance to stresses, the means of "implementing" reliability improvements.

2.4 Failure Modes of a System.

The ultimate concern of Engineering Reliability is usually with some form of aggregation called a "system". Prior to adequate tests on the complete system, determining its reliability requires that it be analyzed or dissected into appropriate elements, for which reliability indices are derived, and then synthesized to yield system reliability. The appropriate elements are identified by failure modes which are classified with respect to:

(1) Location of the modes in the system. The nominal division into subsystems, components, and parts is usually adequate for location. Some forms of redundancy and unusual inter-component or inter-subsystem interaction may require further detail. This may be provided by other aspects of classification.

(2) Relation of modes to function as required to evaluate interaction and redundancy.

(3) Relation of modes to any design processes which affect resistance to the failure. This kind of information is useful to the program on which it is generated only when changes in design are required. It is customarily collected by designers and rarely preserved for use in predicting new designs.

3. RELIABILITY PREDICTION

3.1 Prediction.

While reliability and its determination always have connotations with respect to the future, these are usually clear from the application. Therefore it is logical to limit the word prediction to determination of characteristics of equipment which is to be different in some way from that on which history is available. This is compatible with the implication of prediction as the result of inference from facts or accepted "laws of nature". Analysis of reliability of equipment identical to that which provided the data is adequately characterized as assessment.

3.2 Statistical Populations.

Reliability is a probability. It therefore represents a fraction of a population or, in set theory, of a sample space. The content of the population obviously determines the meaning and therefore the validity of the reliability value. In many applications of probability, identification of population content is simple, even trivial. For reliability, however, a very careful examination is often required. This fact has not been widely recognized, resulting in frequent invalid conclusions, even among those who know probability theory. Statisticians typically determine populations from component labels. For assessment (based on tests of actual system components) this is sufficient. But for prediction, new or modified components must be represented by a population that is related to the source of the new or modified characteristics. This requires the joint expertise of the designer, who establishes these characteristics, and the statistician, who must interpret them so as to define a valid population. Since a population is a probabilistic concept, it is necessary for the statistician to take the initiative in correlating the two disciplines. Therefore he must understand the basic concepts of the design well enough to be able, in consultation with the designer, to interpret experience in terms of design processes and characteristics. He must also understand the significance and validity of the scientific method as quoted from Reference 3 in Section 1.2. Apparently the need for this has not lessened in some 25 years after being emphasized by Dr. Fisher.

3.3 The Perspective of Prediction.

Prediction refers to future events such as aspects of equipment operation. To be valid or accurate it must be based on antecedents or causes, as discussed in Section 1.1. The causes are critical in determining the "best" population to represent the future events, as discussed in Sections 1.3 and 3.2. One population is better than another if its elements and parameters are better known or established in relation to the scientific disciplines used in the design process. These disciplines are established by the scientific method, as discussed in Sections 1.1

and 1.2. Relating population elements or events to causes requires experience data in which events are adequately classified. Classification is the crux of the prediction process, partly because of anomalies discussed in Section 2.3, but primarily because failure modes have not been identified in relation to design, as discussed in (3) of Section 2.4. The result of disregarding physical phenomena in statistical applications is discussed in Reference 4, page 52, cited in Section 1.3. Dr. Feller concludes his illustration with "---the naive reasoning as such has not been superseded by common sense, and so it may be useful to have an explicit example of how misleading mere goodness of fit can be." The naivety in prediction is in choosing indirect population determinants (such as labels or functional identifications) with little relation to the event phenomena.

3.4 Prediction Methodology.

Although an optimization of statistical prediction cannot be strictly defined, the greatest potential improvement lies in a better understanding of the relationship of available experience data to the phenomena involved in the event or events associated with the prediction. This was interpreted statistically in terms of population definition in Section 1.3 and 3.2, and related to application of prediction, as in Section 1.4. Such applications provide a context for the detailed discussion to follow. Examples of statistical analysis in the familiar area of food products will be used to provide simple analogies to such sciences as mechanics and electronics, the principles of which are obscure to others than specialists. Some details assumed about the examples may be chosen to make them simpler or more analogous although not necessarily typical or realistic.

3.5 Direct Population Determinants.

Predicting the future yield per acre of a crop like wheat is simple if direct experience histories are available. "Direct" is used to indicate that the experience covers specifics of the future crop, such as kinds of wheat, location of acreage, etc. Acceptance of such characteristics, both for the problem and the experience, is so routine that it is rarely realized how many aspects of their validity depend on the expertise of specialists. Identification of subspecies and varieties of wheat grown in the United States requires a competent horticulturist. And yet they differ in specific morphological characteristics which are "deterministic" or "proved" as will be described in Section 3.9. But when the significance of the characteristics being identified, or the nature and function of the item, are not so well understood or so familiar, the identification may be regarded as hypothetical by statisticians. This situation is typical in reliability analysis of electronic and mechanical equipment. The attitude is reinforced by preoccupation with demonstration testing, the evaluation of which is deliberately and properly independent of all information except the test criteria and results.

3.6 Indirect Population Determinants.

Classifications in electronics and mechanics may appear superficially to be analogous to those in botany. Components such as amplifiers and motors may seem as similar to others of the same name as are, for example, different varieties of wheat. While this may be true for some items, it can be deceptively wrong for others. In general the parts of similarly-named components may differ drastically. The reason is that the names are usually related to their functional interrelationship with other components in the context of system functions. An example of the effect of a name occurred during modification of the TITAN missile to serve as a GEMINI booster. A "demodulator" in the control system had experienced a number of failures and was redesigned. But a "reliability prediction" indicated no expected improvement. It developed, however, that the analyst ("reliability engineer" or statistician) had not consulted the designer and thus the "prediction" was not even remotely related to the redesign. This particular demodulator was so named because the demodulation was functionally significant, although employing a very small fraction of the parts. This portion was not redesigned because failures had not occurred there. Instead they had occurred in an amplifier in the same enclosure, which was changed from a "transistor amplifier" to a "magnetic amplifier". A prediction using appropriate data and identifications indicated substantial improvement, later verified by experience.

3.7 Choosing Population Determinants.

Direct or deterministically correlated information will improve prediction, even for "very similar components. This will be illustrated by use of an example of prepared foods. Assume that nutritionists have developed "new" foods for some particular and critical use such as for an expedition or exploration. Assume that there is much nutritional data available on the effects of foods on health in terms of maintaining various indices at least as high as accepted standards. Statisticians then make an analysis to predict the probability that the newly "designed" foods will maintain these indices. Two kinds of data may be used. One is "field data" in which the food is identified by labels of "dishes" as found on a menu. The other is "laboratory data", the results of studies by nutritionists, in which the effects of foods are evaluated with respect to ingredients, processing, etc. of the foods. The "ingredients" are not those identified by the names found in recipes. Instead they are the result of the science of nutrition and are based on deterministic identification of the need for and utilization of various constituents of foods by the body. It is doubtful if any statistician would use the "field data" as described. Everyone is familiar with proteins, carbohydrates, the multiplicity of vitamins, etc., and it would be obvious that the names of dishes, especially with modified or "new" recipes, would correlate poorly with nutrition. But to those who do not understand electronics, the inside of "black boxes" is something like magic and wizardry of the designer must be examined in the independent light of the real world.

Field data or experience becomes the "proof of the pudding", or the real world, and design information is considered "hypothetical" or "laboratory". But the determination of the pudding is definitely independent of the eating, and the greatest potential for improvement lies in influencing the cook during its preparation.

3.8 Modified Assessment Data.

Typical reliability data classifies failure modes in terms of location in the system, or in relation to functions, as indicated in (1) and (2) of Section 2.4. Prediction of new designs have been made with such data by using certain "modification factors" labeled "state-of-the-art", "complexity", etc., or an attempt has been made to identify "analogous equipment", essentially based on nomenclature. The point of view represented in this simplistic approach is illustrated by the following intended commendation: "Prediction is based on actual field data rather than hypothetical or laboratory data." Although field data is essential for assessment, stresses are rarely instrumented and design/strength related modes are usually not identified. In contrast, "laboratory" data results from design testing in which well-instrumented stresses, both functional and environmental, are typically increased to measure critical strength factors such as yield point, ultimate strength, etc.

3.9 Prediction Data.

Occasionally the relation of a failure mode to the function of an item identifies the design process affecting reliability. This occurs mainly for electronic equipment and is virtually the only data preserved which is directly applicable to prediction of new or modified designs. A recent study referenced in Section 1.4 (Reference 8, see page 23) found lack of such data to be the most critical present problem limiting reliability prediction, in particular for structures and mechanisms. Those who are skilled in the disciplines of statistics and analysis, and are therefore able to use the data, generally do not appreciate the interrelations of their disciplines with those of the physical sciences. Several widely accepted texts on applications of statistics, such as those mentioned in Section 1.1, have recognized this. Reference 2, page 1 (see page 23 herein), describes the disciplinary interrelations explicitly, beginning with the statement that "Natural and physical laws are hypotheses which have been subjected to various tests and have become accepted or, as some say, proved." The conclusion is that "---statistical proof is the basic form of proof used in the investigation of all sciences." A prevalent and naive idea that law indicates rigorous certainty is then addressed, showing that this is confusing statistical proof with mathematical proof, and that the latter is "---available only in the framework of mathematics itself but cannot be applied outside that field." Thus a law is accepted when experience indicates that the probability of accepting it if false ("error of the second kind") is small enough to be considered negligible.

3.10 Prediction Analysis.

Most design processes are based primarily on scientific principles which (Section 3.9) have been established beyond reasonable doubt. The sources of unreliability (with respect to design) therefore lie elsewhere. They may be described as follows:

(1) Variation in properties of the materials or constituents of components that affect resistance to failure. Related failures were discussed in (2) and (6) of Section 2.3.

(2) Uncertainty of stress determination. Stresses corresponding to those described in (2) and (3) of Section 2.3, may be dominant in determining reliability.

(3) Empirical design processes. These are relatively rare and relate to phenomena that are beyond the "state-of-the-art" in that they are not "understood" in terms of scientific principles. Though rare, they may be a source of serious design problems. A notable example occurred in the Apollo program, consisting of certain forms of instability in the large booster engines. For obvious reasons these problems attract much attention, giving a false impression of prevalence. They do not necessarily result in an unreliable product, as indicated by performance of the Apollo engines.

(4) Distribution of stresses. Except where heat is critical, this is easily determined for electronic equipment. It is more important for mechanisms and is usually dominant for structures.

(5) Empirical configuration factors. A "part" is that which may be utilized by a designer in terms of its characteristics as an entity. A "component" is an assembly of parts, integrated to perform a more complex function than a part. Typically component reliability can be predicted by evaluating stresses on component parts, even when the configuration introduces factors that are not a simple composite of the individual parts factors. But there are exceptions where the configuration factors are not sufficiently understood (as affecting reliability) and can only be treated empirically. When the component is produced, its reliability is measured from test and use data. Why not preserve such data for prediction? It is preserved, but is related to component nomenclature or function and not identified with design-related failure modes, as discussed in Section 2.4 under (3).

Designers are generally aware of these factors affecting reliability and give them consideration within the limits of general techniques. The real potential for reliability improvement however lies in the details of multiple applications to highly complex systems. Techniques for resolving these are being continually developed in the design of ongoing programs, but the problem is preservation of this experience for future use. When systems were relatively simple, experience was preserved and easily located in the literature. A parallel problem has been preserving functional design techniques, and some companies have attempted to solve this by requiring "official" designers notebooks. But there have been no resources to provide indexing for retrieving the new from a preponderance of routine techniques in the mass of stored notebooks. It is obvious that a program cannot bear the cost of preserving experience for future programs. Data banks are provided, however, within the Department of Defense to store and retrieve information for reliability analyses. These should include prediction data.

4. DEVELOPING AN EXPERIENCE BASE

4.1 Information Required.

As described in Section 3.2, reliability prediction requires that a population, a statistical concept, be defined in terms of characteristics established by the physical sciences. But these characteristics are those that relate to failure modes in a probabilistic sense and are not those that are of primary interest to designers, whose major concern is functional capability. In order to utilize the expertise of designers, which is essential to defining the population, it is necessary for the statistician to interpret the designers concepts properly. Thus he must understand the principles of scientific inference well enough to identify the determinants of reliability. The crux of this identification for the statistician is that "deterministic relationships, which he is inclined to distrust, are the essential identifiers for the "probabilistic" emements of the populations that determine reliability.

4.2 Design Testing.

Data from design testing is usually deliberately ignored by statisticians. Some refer to it as "laboratory data" with the implication that conditions are favorable. In fact the opposite is true, as described in Section 3.8. The tests are often criticized as numerically inadequate to be statistically significant. This is quite true if they are to be regarded as independent assessments. But typically these tests are only partly "statistical". In addition they identify reliability determinants related to known populations. The statistical aspects consist primarily of "safety margins" which, with identified strength distributions, provide reliability assessment equivalent to much more extensive "independent" testing. Occasionally designs are tested which include empirical factors, as described under (3) of Section 3.10. These designs, as well as some with complex deterministic phenomena, may include very involved statistical factors. If statisticians could correlate their expertise with that of designers and achieve a rapport, they would not only obtain data for analyses, but could often make a contribution that would improve reliability during the design process. Communication between designers and analysts has been stressed recently as part of the current emphasis on integrated logistics support, and evidence of success is being cited. There is, however, no evidence that this has led to recognition of design processes as the direct source of the characteristics of the product being designed.

4.3 Reliability Testing.

Most of the testing that is specifically for reliability is qualification or acceptance testing. Instrumentation is typically that required to establish the specified test conditions. For the test results to be useful for valid prediction, it is necessary to determine the stresses significant for all failure modes. Thus additional instrumentation should be provided as required to measure them.

As explained in Section 2.4, a system "consists" of failure modes with respect to reliability. These modes, when identified with respect to strengths and stresses, represent those "elements" of a system that are most basic with respect to reliability analysis. Thus when modification factors are derived to assess the effects of various operating conditions on reliability, they will be correlated with the characteristics that are directly affected by these conditions. The point of view that ignores the physical phenomena probably arises from the criteria for demonstration testing, where it is quite proper. But it is misplaced when applied to prediction, where modification factors must be used. When these factors are not associated with true physical properties, they are usually associated with names or labels. Thus if competing designs used the same component labels, the prediction for each would be the same.

5. DEVELOPMENT PREDICTION

Occasionally during development of a system a design proves to be unacceptable, resulting in a redesign. Such an event must be properly identified in evaluating data for reliability prediction in order <u>not</u> to class it inadvertently as a "failure" in that context (see (3), Section 2.3). If this experience were preserved, however, it would provide a data base for evaluating and predicting future development programs. The classification would include characteristics similar to those for reliability prediction. Experience should reveal others, related to the development process. This information would enable meaningful predictions to be made in two important areas of development.

5.1 Risk Analysis.

A development program involves many risks. Among the more difficult to determine are those related to design of "new" items. Note that the newness does not include unknown or purely theoretical factors, otherwise the program is research, not engineering development. Thus it is primarily the application that is new and is the source of the risk. Typically only a small percentage of those items that are nominally new are actually so. Unfortunately analysts do not look deeply enough to identify these few items. Only in rare instances is there found in the literature on prediction even the suggestion that scientific knowledge be utilized. One example has been found in a report on mechanical reliability prediction (Reference 11, Section 4.1, page 10) in which the influences on reliability are defined mathematically as "independent variables". The analyst is to determine the "best set of variables". The method for this is described as multiple linear regression, but then it is pointed out that for effective application of this, "...careful preliminary planning and engineering analysis are required." It is further stated that "...the analyst must not depend too heavily on the computerized statistical screening procedure. Rather, he must make full use of his scientific insight, judgement, and experience in selecting the best prediction equation from the many mathematical possibilities that may appear equally good." Presumably "engineering analysis", "scientific insight", and "experience", are exercised by examining the design of the equipment being analyzed. But why should the analyst attempt to do this? It is in fact more difficult to deduce the stress-strength relationships from a description of the results of a design (intended to provide information for fabrication) than to produce the design itself. When a prediction is being made, the design would normally be just completed and information readily available from the designer. Otherwise, the analyst's "engineering analysis" would necessarily be based on functional characteristics and nomenclature, which obviously would not correlate as well with failures as would stress-strength relationships.

5.2 Reliability Growth.

Certain anomalies exist in the data used for reliability growth, usually resulting in early estimates that are too low and ultimately an indication of more growth than actually occurs. Obviously errors of fabrication (e.g., wiring errors) that are corrected by routine checking are not a source of true equipment failures. Obvious errors are recognized as such, but due to inattention to failure phenomena, many errors that require an understanding of the equipment are not recognized. If a conservative "lower limit" is used, then "improvement" due to more data should be identified as information growth, not reliability growth. In general, true growth should reflect changes in the equipment. If better fabrication methods are developed, this is also growth, but the source should be identified. The principle difference between reliability growth and risk as described in Section 5.1, is that the planned effort allowed for corrective action is not considered a "risk". Thus a more accurate prediction of reliability will reduce both the risk and the necessary growth.

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[11] ARINC Research Corporation, Development of a Reliability Prediction Procedure for Shipboard Mechanical Equipments - Phase I, ARINC Research Publication No. 933-01-2-1079, ARINC Research Corporation, Anapolis, MD, November 1970.

6. CONCLUSIONS AND RECOMMENDATIONS

In Section 3.10 under (5), reference was made to prediction of component reliability from data on parts. Techniques for this were presented in MIL-HDBK-217A (cited in Section 2.1). Simple design procedures for parts selection were included, for example the derivation of semi-conductor junction temperature (under 7.4.3), usually the primary reliability factor for these devices. Parts selection techniques have been expanded and updated in the RADC Reliability Notebooks. (Reference 12). These techniques have been used mainly in the aerospace industry, and lack of general acceptance is indicated in the literature on reliability prediction where use of data on parts, if mentioned, is usually considered unrealistic. But this is only one factor in such prediction, and is usually not the critical factor. Instead the potential unreliability of "new" designs lies in design configuration factors discussed in Section 3.10 under (5). The one recognition of this found in the literature (See Section 5.1) failed to recognize designers as the logical source of information on which to base reliability determinants of the designs they produce.

In order to further develop a valid approach to prediction of reliability, and to extend it to other areas, three things are necessary: (1) analysts must learn enough about the scientific method of engineering design to ask designers pertinent questions and to use the answers properly; (2) the information obtained must be used to collect and preserve histories of events and to relate them to design procedures; (3) it must be further used to develop methods of analyzing new designs and to make predictions based on the data.

6.1 Correlating Analysis with Design.

It should be obvious that any analysis which attempts to predict some characteristic expected to result from a design should consider all available evidence relating to the effect of the design on that characteristic. It should further be obvious that the prime design processes to be considered are those having the explicit purpose of determining the characteristic. In order to do this, analysts must understand and accept the statistical significance of natural and physical laws as cited in Section 3.9 from Reference 2, and be able to differentiate these from factors in the design process that are subject to significant statistical variation. The primary obstacle to overcome is apparently a misapplication of a principle of "independence", which properly applies to testing a product after it is produced.

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[12] RADC Reliability Notebooks, Vol I (AD 845304) and Vol II (AD 821640).

6.2 Developing Prediction Methodology.

A "good" prediction technique must identify the more significant "causes" of the "effect" that is being predicted. When considering reliability, the phenomenon of failure can always be interpreted in terms of a "stress" exceeding a "strength". The techniques that have been used have usually identified conventional strengths, as those of parts listed in MIL-HDBK-217A. But in a more general sense, a strength may be any property or characteristic of a part or an interrelated assembly of parts that has an effect on successful operation of a system. The word "balance" may represent such a characteristic in either electronic or mechanical design. A complex of factors may contribute to an essential characteristic of balance and thus determine success or failure. A true advance in the state of the art of reliability prediction must correlate failures with such failure determinants of the design process rather than with functionally oriented nomenclature of components.

6.3 Preserving Experience History.

The basis of any prediction technique must be a properly correlated experience history. The correlation must be with whatever identifies, defines, or determines that which is being predicted. Thus a data base for predicting the expected reliability of equipment from a design, must relate failures to design processes that affect the probability of failure. This was done in MIL-HDBK-217A for selection of parts, but should be extended to other factors of the design process. Such factors often dominate determination of reliability in mechanical design. The task of developing a data base must precede analytical methods in order that the latter be application oriented. Reference 8 (see page 23) states in Section 1, page 1: "The first step in the application of mathematics to a physical problem is the construction of a mathematical model which embodies the main observational and theoretical features of the phenomenon." Thus it is necessary to obtain experience data from which the phenomena may be identified before they may be embodied in the models. Such identification requires that expertise be provided by experienced designers in all fields related to the systems of interest. Thus the initial task in developing a prediction capability should be carried out by a team of specialists in design, instrumentation, and data collection. Only elementary aspects of statistics will be involved.

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APPENDIX

ENGINEERING RELIABILITY PROGRAM

1. OBJECTIVE

When products were relatively simple and design latitudes generous, adequate reliability was achieved by careful conservative design. Except for such design parameters as these associated with safety factors, reliability was mainly good intentions of a general nature, rarely quantified. Increasing complexity and constraint have revealed the limitations of the older approach, and the advantage of a rigorous discipline using statistical methods has been demonstrated. It is the objective of a reliability program to produce a statistical quantification of design, test, and use information, to determine the interrelation among these by appropriate analyses, and to use the results as a basis for design, component, and integration control in order to achieve a high probability of correlation of the final product with the design intent and the test and use indices.

2. SCOPE

The reliability effort is accomplished by specific tasks (listed later under the heading of "Method") which may be divided into three general areas as follows:

(1) Reliability of design, Tasks 8 and 9.

(2) Selection and control of components, Tasks 2, 3, 4, 5, and 6.

(3) Appraisal of reliability achievement and potential, Tasks 1 and 7.

3. METHOD

The following tasks are required to carry out the reliability program and are listed under three categories which identify the major method involved.

a. Reliability Control and Documentation

Task 1, Program Review. The proposal would describe the establishment of data control procedures for information on: component reliability experience; design analysis and reviews; time/cycle and storage sensitive components. The purpose is to provide information to assess the reliability status of the product and to contribute the reliability portion of program reports.

Task 2, Review of Test Program and Procedures. This effort will ensure that the testing is compatible with reliability requirements and that data is provided for assessment.

Task 3, Failure Analysis and Corrective Action. Failure analysis will provide the basis for corrective action appropriate to achievement of adequate reliability. The proposal should describe the means of executing this operation.

b. Vendor Selection and Component Control

Task 4, Review and Evaluation of Vendor Reliability Programs and Activities. This task determines the adequacy of vendor reliability programs and provides an input to vendor selection.

Task 5, Identification and Control of Time/Cycle and Storage Sensitive Components. The proposal would show how this task ensures that components are not degraded prior to actual use.

Task 6, Component Selection and Control. The objective of this task is selection of components with demonstrated reliability or with potential reliability to be achieved through diligent application of testing, reliability, and quality control programs. The proposal should show how these programs are integrated and coordinated and how component control provides a close statistical correlation between the tested samples and the components used in the final product.

c. Reliability Analysis

Task 7, Reliability Prediction and Assessment. The proposal would describe how an initial prediction and allocation is made and revised as changes are made in preliminary designs. Later in the program, data from testing actual hardware will provide the basis of assessments.

Task 8, Reliability Design Analysis. The proposal should show how this effort which is concurrent with designs, results in reliability being "designed into" the subsystems. The analyses include evaluation of reliability problem areas, use of redundancy, and trade-offs involving reliability. Participating in design reviews is part of this task.

Task 9, Review of Proposed Design Changes. Continuous monitoring of subsystem design provides the background for review of changes for effect on reliability.

4. IMPLEMENTATION

Information and techniques are generally available for carrying out most of the tasks described. The state-of-the-art for reliability prediction and design analysis (Tasks 7 and 8) for structures and mechanisms is, however, seriously lagging, and for electronics is out of date. Improvement is needed in three areas, failure mode analysis, reliability design analysis, and preservation of the resulting information or data. These will be discussed in some detail.

(1) Failure mode analysis. In order to use failure data as a basis of predicting the reliability of an item that has not yet been fabricated, it is essential that the failure modes be determined in terms of identified strengths that have been exceeded by identified stresses. Only then is it applicable to the design constants and specifications that describe a proposed item.

(2) Reliability design analysis. The strengths significant to failure modes must be related to design "outputs" or constants which establish them, and the constants in turn related to the design disciplines and techniques by means of which they are derived. This includes a statistical analysis resulting in probability of identified stresses being exceeded by identified strengths. In some cases failure mode and reliability design analyses will not establish the required identifications. If these failures can be assigned some kind of modal classification, then a statistical correlation may be sought with known design constants. If such is found the mode is thus identified for use in prediction. Correlations so discovered provide potential clues for designers to look for a means to control strengths related to these failure modes. Finally a failure analysis may not reveal sufficient information for any modal classification. Such failures, sometimes called "random", can be identified only with respect to the "type" of item to which they are applicable and used for prediction in this manner. Thus three "kinds" of failures are recognized which may be labeled, in order of discussion, as intrinsic, empirical, and random.

(3) Data system. The information generated by the analyses described must be preserved along with the usual "assessment" data. A design engineer might point out that information of this kind is generated by "design" testing. Such tests are often made on some parts of an item with simulated functional and/or environmental stresses. Typically very extensive instrumentation is used and stresses are usually increased to determine points of failure. Results of such testing should be included in the data system. Although it is not feasible to instrument reliability testing as extensively as design testing, it should be done to the extent practicable in order to identify more "intrinsic" failures.

In summary, reliability testing should be more like design testing with complete records preserved, failures should be analyzed to identify the physical phenomena involved, and the phenomena should be related to the design processes and outputs. While these relations are probabilistic, in the form of distributions, it is essential that the form and parameters of the distributions be identified as closely as possible with the deterministic physical relationships that form the basis of the design disciplines being used.

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