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A METHOD FOR PERFORMING A HUMAN-FACTORS RELIABILITY ANALYSIS

by

A D Swain

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ABSTRACT

A method for performing a human-factors reliability analysis of a man-machine system is described. The outcome of this type of analysis is a quantitative assessment of the estimated degradation of a man-machine system resulting from human errors. The method represents an extension of a quantitative approach to reduction of human error in industrial production described by L. W. Rook, Jr., in Reduction of Human Error in Industrial Production, SCTM 93-62(14).

FOREWORD

There has been relatively little work reported on deriving quantitative estimates of the degradation to a man-machine system resulting from human errors. One approach, used in the Reliability Department of Sandia Corporation, is presented here as an example of how such estimating can be done. It is hoped that this approach will be of use to human-factors specialists and others interested in the effects of human factors on systems.

The approach presented herein uses probabilistic models and probability techniques. Both the models and techniques are elementary for those with experience or training in the theory of probability. However, since many human-factors specialists have had little training in these areas, the discussions and examples related to the application of probability theory are pitched at an elementary level. If the reader will take the time and effort to go through the mathematical models, he will have acquired at least the initial skills in estimating system effects of human errors.

Acknowledgment is due F. W. Müller, Supervisor, Reliability Training and Development Section, Sandia Corporation, for his original contributions to the probabilistic approach, for his development of certain mnemonic aids for constructing reliability equations, and for his patience in checking the equations in this report. Mr. Müller and Mr. J. M. Wiesen, Manager, Reliability Department, Sandia Corporation, worked out a method for deriving the individual equations for allocating the appropriate portion of system-failure rate among the human errors in the system.

The approach also uses a data bank of figures for estimating the probability that any given behavioral dimension of a human action will <u>not</u> lead to incorrect performance of that action. This unique data bank was developed by Dr. J. W. Altman and his colleagues at the American Institute for Research.

Finally, acknowledgment is due Dr. L. W. Rook, Jr., Advanced System Studies, Sandia Corporation, who has described a quantitative approach to reduction of human error in industrial production. This report extends Rook's quantitative approach to military operational tasks and jobs.

The present report was prepared in part as the author's contribution to Task Group 2 - Quantification of Human Performance, in the M-5.7 Military Subcommittee on Human Factors in Electronics, of the Electronics Industries Association. Task Group 2 is made up of the following human-factors specialists: Dr. Alvyn Freed, Aerojet-General Corporation, Dr. Melvin Freitag, Ryan Aeronautical Company, Dr. Charles A. Fenwick, Collins Radio Company, Mr. Robert Kinch, Western Electric Company, Dr. Edmund T. Klemmer, Bell Telephone Laboratories, Mr. Harald R. Leuba, ARINC Research Corporation, Captain Melvin S. Majesty, Hq. Ballistic Systems Division, USAF, Dr. David Meister, General Dynamics/Astronautics, and Dr. Alan D. Swain, Sandia Corporation (Chairman). Persons interested in quantifying predictions of human performance may contact any of the above men for further information on the work of Task Group 2, EIA, M-5.7.

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CHAPTER I

AN OVERVIEW OF THE METHOD

Introduction

At the 9th Military Operations Research Symposium (MORS) in early 1962, L. W. Rook, Jr., Sandia Corporation, described a method for evaluating the human error contribution to system degradation (Reference 1). This method is based partly on research on human reliability by J. W. Altman and his associates (see References 2, 3, 4, and 5) at the American Institute for Research (AIR), on research done by Rook at Sandia Corporation, and upon probability theory and other methods used by reliability engineers. This method, now called THERP (Technique for Human-Error Rate Prediction), is more fully described in Reference 6.

References 1 and 6, however, present the method in the context of predicting industrial errors and controlling degradation resulting from human errors in industrial processes. The method described in these references can also be applied to military duties in a field operational setting. However, the mathematical treatment of THERP is brief, and fuller treatment of both the mathematics and the application of THERP to field operations seems desirable. These are the primary purposes of this report.

In order to avoid security classification problems, only hypothetical job situations are discussed in illustrating the technical approach. For the reader with a security clearance, there are available two additional classified references showing the application of THERP by Sandia personnel to a military classified problem (References 7 and 8)*.

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*Reference 7 should be adequate for readers interested in human factors only. Reference 8 includes estimates of equipment reliability and total system reliability but does not contain the detailed human-factors discussion in Reference 7.

Technique for Human-Error Rate Prediction

A technique used in the Reliability Department of Sandia Corporation, THERP predicts human-error rates in a man-machine system* and evaluates the degradation to the system or any part of it likely to be caused by human errors** in association with equipment reliability, operational procedures, and other system characteristics which influence human behavior. Finally, THERP is an iterative procedure, consisting of five steps which are repeated, not always in the same order, until the system degradation resulting from human error is at an acceptable level. The five steps are listed below and described more fully on the following pages.

1. Define the system or subsystem failure which is to be evaluated.
2. Identify and list all the human operations performed and their relationships to system tasks and functions.
3. Predict error rates for each human operation or group of operations pertinent to the evaluation.
4. Determine the effect of human errors on the system.
5. Recommend changes as necessary to reduce the system or subsystem failure rate as a consequence of the estimated effects of the recommended changes.

Although most human-factors studies of man-machine systems do not attempt to predict error <u>rates</u>, it is apparent that there is nothing basically new in these five general steps. The steps are typical of the usual system reliability study if one substitutes "hardware" for "humans." In fact, as long as ten years ago (Reference 9), this general procedure was applied by Sandia Corporation in estimating the degradation to a nuclear weapon system resulting from the effects of human errors. However, since that time, the procedure has been refined, especially in steps 2, 3, and 5. Moreover, some new developments, for example the AIR method of analyzing the reliability of human-behavior components (Reference 3) and the Sandia Corporation human-error classification scheme (Reference 6), have made this whole quantitative approach to human factors more reliable and thus of greater value to system designers.

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*A man-machine system is an arrangement of men and equipment for achieving one or more goals by correctly performing functions and tasks related to each goal. The system may be broken down into subsystems or part-systems, each of which has its functions, tasks, and goals. In this report, it is often convenient to use the word "system" either to denote a complete man-machine system or any part of it.

**Human errors occur (1) when a man fails to perform a task or a part of a task (e.g., a step), (2) when he performs the task or step incorrrectly (3) when he introduces some task or step which should not have been performed, (4) when he performs some task or step out of sequence, or (5) when he fails to perform the task or step within the alloted time period. The effect of human errors in reducing the probability of the system achieving its goals is ascertained by the use of the probabilistic model described in this report. From a "system" point of view, a human behavior is an error only when it has the potential effect of reducing system or part-system reliability or otherwise reducing the likelihood that some system or part system success criterion will be met.

Define System Failure

The first step in the application of THERP is to define the system (or part-system) failure which is to be evaluated. This failure may vary from (1) such distal criteria in the life of a weapon as the probability of the weapon failing to explode within a certain area and altitude at a certain time to (2) more proximal criteria such as the failure of a component in the weapon to meet engineering specifications. As stated above, the human-factors evaluation is restricted to the influences of the human element on system failure and therefore identifies only part of the total unreliability of the system. This restriction does not remove the interactions of machine and human influences from the evaluation, but it does eliminate consideration of the influences of machine variables *per se*.

List the Human Operations

The next step is to identify and list all the human operations performed and their relationships to system tasks and functions. System and task analysis (Reference 10), a method familiar to human-factors specialists, is the basic method used in this step. Variations of this procedure are sometimes used (see Reference 11).

The system and task analysis must uncover all those possible human actions and procedures which can enter into the evaluation. They include whatever human procedures are required in the event of equipment defects or breakdowns or to compensate for other abnormal conditions. They also include human operations which are not a part of the prescribed operating procedure but which might be substituted for the required human operations.

At this point, the analyst ordinarily makes some restriction in the human operations to be considered further in the reliability analysis. That is, he drops from consideration those human operations for which it is apparent that no significant degradation to system or part-system failure rate would result as a function of their incorrect performance. Errors in human operations judged to be not relevant to this failure rate are not errors in the context of the system being evaluated. It is best to be very conservative in dropping from the analysis those human operations judged to be irrelevant to system success. If an erroneous judgment is made at this point, the entire reliability analysis can be highly misleading and the resultant recommendations (or lack of recommendations) could have a highly detrimental effect on the design and use of the system.

Predict Individual Error Rates

Next, error rates are estimated for each human operation relevant to system failure rate. Judgments are made or data are obtained on the nature of the interactions of correct and incorrect human operations in the context of the system. Finally, as discussed in the next section, the error rates are appropriately combined according to conventional probability theory. The estimates of error rates draw on actual human-error-rate data whenever available and appropriate. Two major sources of human-error-rate data are used at Sandia: (1) experimental or other empirical data and (2) the AIR Data Store (Reference 2).

The question of appropriateness of data is an important one. Usually, experimental data from behavioral laboratories in university psychology departments cannot be generalized directly to an operational situation. First of all, university experiments are often set up to generate high error rates in order to minimize the number of subjects necessary to test the statistical significance of measurable differences between experimental conditions or treatments. In the usual operational situation, on the other hand, error rates are ordinarily much lower--often at least two orders of magnitude lower. A second reason for the disparity in error rates is that the operational situation is ordinarily multitask, e.g., the task in which an investigator is interested is but one of many tasks which are competing for the attention of an operator. The nature of the competition and the frequency per unit time of the task of interest markedly affect the error rate and could make it either larger or smaller than the error rate from a corresponding laboratory experiment. A third reason is that stress conditions in the laboratory situation often bear little resemblance to high-stress conditions found in certain operational situations. Generally, under high-stress conditions (as defined in Chapter II) behavior accuracy and relevancy can be expected to deteriorate grossly.

All of these factors point to the need for the utmost caution in generalizing from laboratory data to the operational situation. However, error rates drawn from operational suitability tests or other test situations which more closely approximate operational conditions can be used with more confidence In the absence of a central data bank (or data store) of human-error rates and associated environmental and other conditions (as recommended in Reference 12), the human-factors specialist who wishes to predict error rates often must develop his own empirical data At the present time, considerable judgment is required, and, in this sense, quantification of predictions of human behavior is an art as well as a science. Even so, experience at Sandia has indicated that predictions of human-error rates made by the two Sandia human-factors specialists disagree by no more than about 30 percent.

A good start on a data bank of human-error rates has been made by AIR (Reference 2). This is the "data store" to the "index of electronic equipment operability." The AIR Data Store uses a specific step or action in a given task as the basic unit of evaluation. Each specific step or action is broken down into three aspects: (1) inputs or stimuli to the human senses, (2) mediating processes (making decisions, inferences, interpretations, or judgments, recalling information, anticipating future events, etc.), and (3) outputs or responses (e.g., motor responses of the human). In deriving this data store, major types of equipment components, behavior components, or equipment-behavior components likely to affect each aspect were identified. For example, under input (stimulus) aspects are the following components: circular scales, counters, labeling, lights, linear scales, nonspeech, scopes, semicircular scales, and speech. Under the input component "labeling" (see Table I) are three parameters: span, legibility, and size of printing. Each of these parameters is broken down into dimensions; i.e., physical descriptions of the component concerned. For example, the parameter "span" is broken down into four "digit" dimensions and three "word" dimensions. Opposite each of these dimensions appear a "time added" figure in seconds and a "success probability" figure which denotes the probability that the dimension in question will not contribute to the error rate of the step or action containing that dimension. (This report uses the more exact term "success probability figure" in place of the AIR term "reliability" which is subject to misinterpretation by reliability specialists.) This dimensional approach recognizes that human reliability is a function of the compatibility of equipment design with the capabilities and limitations of the operator, even when he is well-trained.

TABLE I

Time and Success Probability Estimates for Input Component "Labeling"
(Taken from Reference 2)

BASE TIME - 0.20 seconds		Labeling
Time added (seconds)	Success probability figure	(Includes any labeling serving as the step input)
		1. Span
		a. Digits
0	0.9998	(1) 2
0.11	0.9994	(2) 3
0.29	0.9992	(3) 4-5
0.71	0.9991	(4) 6-7
		b. Words
0	0.9999	(1) 1 or 2
0.20	0.9995	(2) 3-5
1.65	0.9985	(3) 6-11
		2. Legibility
0	0.9999	a. Clear and concise
0.25	0.9997	b. Potentially ambiguous
		3. Size of printing (height)
0	0.9997	a. 1/5" or more
0.20	0.9994	b. 1/8"

The complement of (i.e., one minus) the product of all of the relevant success probability figures for the inputs, mediating processes, and outputs for an action is the estimated error rate for that action. The sum of all of the relevant time figures for the inputs, mediating processes, and outputs for an action is the estimated time required to complete that action.

The time and success probability figures in the AIR Data Store are based on time measures and error rates from many experimental studies with a correction factor (approximately .008 x experimental error rate) applied to account for the differences between the laboratory and operational (field) situations. Both time and success probability figures assume equipment at least moderately well engineered from the human-factors standpoint and average motivation and adequate training for the operator. If the human engineering of the equipment is poor (including, for example, violations of strong populational stereotypes), then the figures in the data store would grossly underestimate both time and error-rate figures. Poor motivation or inadequate training could also result in gross inaccuracies in the estimated time and error-rate figures. However, as a rule of thumb, Sandia human-factors specialists have considered that poor human engineering can often result in error-rate increases of one or more orders of magnitude, but under usual operational conditions, they have concluded that poor motivation and training ordinarily degrade human accuracy by no more than a maximum of a factor of 5. (See the discussion on pages 8 and 9 of Reference 6.)

Chapter II illustrates the way in which Sandia Corporation human-factors specialists have used the AIR Data Store. The example in Chapter II is hypothetical, but the behaviors involved in the example and the interpretations of data made by the author are representative of those involved in the operational study described in Reference 7 .

Chapter II makes it apparent that considerable judgment is involved in accepting the figures from the AIR Data Store, especially in judging when behaviors are or are not independent* or in deciding whether the effects of stress preclude the use of the data store. Moreover, error rates derived from the data store are only as good as the basic success probability figures contained in the data store. Not nearly enough validation of predictions based on the AIR Data Store has been done. However, some comparisons of actual error rates in certain factory assembly and inspection operations with predicted error rates using the AIR Data Store have been made at Sandia. It has been found that the predicted error rates differed by no more than a factor of 3 or 4 at the most. For many applications, this degree of accuracy is sufficient. At Sandia Corporation, for example, no more accuracy in prediction than a factor of five has been claimed in human-factors reliability studies.

It is important to reiterate that the estimates of error rates derived from the AIR Data Store are for the "average military operator" trained in the operation in question and with "average" motivation and under "normal" operating conditions. (The use of quotation marks is intended to connote an unknown degree of inaccuracy.) Ordinarily, the average error rates are not accompanied with estimates of standard deviations or other measures of dispersion about the average (mean). Thus, estimated error rates based on the AIR Data Store or on other sources of data can be grossly in error when applied to a given individual. The error rates are estimates of the average error rate for an individual selected at random from the group of operators being studied. Therefore, in the Sandia Corporation human-factors reliability analyses, the assumptions state the level of stress, type of environmental conditions, the level of motivation (but not usually including malicious deviations from a standard operating procedure), and the type and extent of training (in general terms) that the operators are assumed to have had. Furthermore, the human-factors specialists feel an obligation to explain to the users of the reliability analyses the nature of the basic human-error-rate data which enter into the estimates. This is especially true in the case of estimates of human-error rates under high-stress conditions (as defined in Chapter II).

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*THERP makes no assumptions as to the dependence or independence of behaviors. It is up to the user of THERP to make these assumptions and to use probability equations consonant with his assumptions.

The lack of precision that the above paragraph denotes is certainly not a satisfactory state of affairs. Perhaps this section of the report illustrates best why those of us who have to make estimates of human reliability hope that a large scale effort of the kind recommended in Reference 12 will soon get underway to begin the growth of the much needed computerized data bank of human-error-rate figures, including related standard deviations, characteristics of operators, and environmental and other factors affecting error rates.

Determine the Effects of Human Errors on the System

Having determined the error rates, it is necessary to determine the probability (F_i)* that each error, error class, or group of errors which have occurred will result in a failure of the system or that part of the system being evaluated. The probability of a failure condition resulting from a single incorrect performance of a human operation of Class i is then the joint probability F_iP_i, where P_i is the probability that an operation can and is supposed to occur and that it will lead to an error of Class i. A group of incorrect human operations, or incorrect human operations plus equipment defects or other factors, may be necessary for the failure condition to occur; P_i can also stand for the probability of these conditions.** It may be that a human operation or series of operations performed more than once and a single incorrect performance results in a failure condition with probability F_i. In this case we would be interested in the probability that n_i operations will result in one or more failure conditions because of errors of Class i. This probability can be evaluated as 1 minus the probability of no failure conditions from this source; it is given by $Q_i = 1 - (1 - F_iP_i)^{n_i}$,† where Q_i is the probability of one or more failure conditions existing as a result of Class i errors occurring in n_i operations.†† The total system (or subsystem) failure rate resulting from human error can be expressed as $Q_T = 1 - \left[\prod_{k=1}^{n} (1 - Q_k)\right]$† where Q_T is the probability that one or more failure conditions will result from errors in at least one of n classes of errors, and the quantity in brackets represents $(1 - Q_1)(1 - Q_2)\ldots(1 - Q_n)$.

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*P_i, F_i, Q_i, Q_T, and n_i are notations used in Reference 6. The formulas used in this section also come from Reference 6.

**For example, P_i may result from P_1 or P_2 where P_1 and P_2 are human errors. Thus $P_i = P_1 + P_2 - P_1P_2$. Or P_i may be the joint probability of P_1 and P_2, where P_1 is an error and P_2 is an equipment defect or some other factor which, when it occurs, sets up a potential failure condition only if a human error (P_1) also is made. Thus $P_i = P_1P_2$.

†The use of the exponent n_i assumes independence of the n_i operations. When this assumption would result in an unacceptable inaccuracy in a probability estimate, then the exponent should be dropped, and the calculation of F_iP_i should take the nature of the dependence into account as is done in the example in Chapter III. Often, however, independence of certain behaviors can be assumed even when it is known that the assumption is incorrect. In such cases, it is judged that the resultant calculation of F_iP_i is sufficiently accurate for the purpose at hand.

††There may be a different class, j, of failure conditions. Then $Q_j = 1 - (1-F_jP_j)^{n_j}$. The probability of one or more independent failures in either or both classes (i and j) is given as $Q_{ij} = (1 - Q_i)(1 - Q_j)$.

In determining the effects of an error, class of errors, or group of errors on the system, two major kinds of information are needed that usually require inputs from other specialists such as reliability or project engineers and operations researchers. The first is the probability, independent of the motivation of the operator , that certain procedures will or can be followed. The second is the effect of failure in a human operation on equipment-failure rates or system effectiveness . The first probability enters into the calculation of P_i and the second factor is F_i.

In the hypothetical example used in this report, we assume a pilot must receive a message while in his aircraft and that the aircraft might either be airborne or on the ground. Error rates have to be estimated for both situations. If one wishes to determine the effect of errors in these procedures upon system effectiveness, it is necessary to estimate the probability that the procedures will be done on the ground versus in the air. This type of estimation is not normally done by a human-factors specialist but can be, if he is also functioning as an operations researcher. This dual functioning is sometimes the case at Sandia Corporation.

Another estimate which should be made is the probability that a procedure can be done at all or within the required time period. In the above example, there might be environmental conditions that would preclude the possibility of the airborne pilot being able to hear a message. This type of estimate is also not normally done by a human-factors specialist. Meister (Reference 13) has pointed out that failure to consider this type of probability can lead to a gross over-estimation of system reliability. He lists five categories of "nonoperator-type discrepancies occurring insystem performance":

1. nonavailability or inadequacy of required equipment, personnel, or technical data

2. inadequacy of procedures or technical data

3. improper personnel utilization

4. failure (not due to the operator himself) to perform required preventive maintenance or setup procedures and

5. inadequate system organization.

He states that analysis of some missile systems shows that nonoperator-type discrepancies have been almost eight times as numerous as errors which can be ascribed directly to operator accuracy. Thus, it is apparent that having reliable equipment and reliable operators does not guarantee a reliable system. Human errors in support functions of a system may account for a major source of system degradation. Therefore, the human-reliability analysis either must deal with these other sources of human error or it must restrict itself to human error which can be ascribed directly to the operators who perform system tasks. If such a restriction is made, it should be clearly stated in the analysis.

Having estimated the probability that a procedure can be done, it is still necessary to determine the effect of an error in the pilot's performance of the procedures upon the failure rate of the system or subsystem in question. If the pilot incorrectly performs the procedures on the first trial and this failure means that his mission will inevitably fail, then an error in pilot performance is tantamount to system failure: F_i equals 1.0. This simple situation is not usually found. Under certain circumstances, the pilot may have a chance to correct his error. Therefore the system failure rate related to this pilot error becomes a function of the probability that he will make the initial error and fail to correct it, and the probability of each of the circumstances. Conventional probability theory is used in writing these equations, which can be quite complicated. (Table IV and Figures 1 and 2 in Chapter III are mnemonic aids for setting down the proper equations.) To make sure that every contingency is included in the model, all possible alternatives must be considered. Situation diagrams which show the possible procedural paths are particularly helpful. (Figure 1 is one type of situation diagram. Figure 2 is a more specific type.) To avoid very long and complicated equations, it is usually easier to use several shorter equations which represent part-system failures. Thus, total system failure would be some combination of these part-system failures.

Chapter III continues the hypothetical example found in Chapter II in order to illustrate how one estimates the effects of human error on a man-machine system.

Recommend Changes to System and Calculate New System Failure Rate

A logical final step in applying THERP to a man-machine system is to recommend changes, if necessary, to reduce the system or subsystem failure rate to an acceptable level and then to calculate the new failure rate which results from the estimated effects of the recommended changes. The difference between the old and new failure rates can then be balanced against the various costs of changing the system. As is usual in human-factors studies, the recommended changes can take the form of modifications to equipment, training, personnel selection, or operating procedures.*

This final step provides a common sense approach to a decision on what operations should be changed. The approach consists of ranking all Q_i values in descending order. The Q_i value reflects the extent of system degradation resulting from the operation in question rather than merely the error rate for that operation. Ordinarily, then, operations with the highest Q_i values would receive the most attention in looking for ways to increase system effectiveness. Whenever a change is considered, the related P_i values are adjusted appropriately and Q_i

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*Decisions on what changes to recommend can be aided by the use of a system of error classification devised by L. W. Rook, Jr. (Reference 6). This classification scheme subdivides human error into categories which are both manageable and suggestive of the corrective action to be taken. The classification should be especially helpful to those not formally trained in human-factors technology.

and Q_T are recomputed. Changes are made until Q_T has reached an acceptable value. As this progress is made in the iterative process of changing the system and adjusting P_i values, cost estimates of the various changes can be obtained for comparison with the gains expected from the proposed changes.

One caution must be observed when interpreting the rank order of Q_i's. When a particular Q_i has an estimated low rank, it is often tempting to omit it from further consideration, especially if available time and money limit the changes which can be made to a man-machine system at an advanced stage of development. But in the case of military man-machine systems, perhaps it should be assumed that the potential enemy is also capable of making his own analytical study. The potential enemy, especially if he would initiate an attack, may well evaluate low-probability events or events assigned low importance quite differently than the designer of a retaliatory man-machine system. One should be cautious, therefore, in deciding which Q_i's need no further consideration. This caution should be self-evident, but events in our recent and past history have made it painfully apparent that errors in judgment have been made in this regard. In terms of THERP, the above consideration of the reaction of an opponent can enter into the estimation of each F_i.

CHAPTER II

A PROCEDURE AND SOME ASSUMPTIONS FOR ESTIMATING ERROR RATES

Introduction

This chapter presents a hypothetical example to illustrate the way in which Sandia Corporation human-factors specialists have used the AIR Data Store and other sources of human-error-rate data and have made certain gross behavioral assumptions in order to estimate human-error rates in the context of a man-machine system. It is reiterated here that the approach used is strictly an empirical one: if it enables us to make predictions sufficiently accurate for the purpose at hand, we use it. However, in view of the obvious gross generalizations we must sometimes make, we are far from being complacent about the error-rate data that we use in our system reliability equations (see Chapter III). But we have reliability problems to solve and we use this data. We feel that using it is better than doing nothing, thereby either (1) forcing engineers or others not trained in human-factors technology to make their own estimates of human reliability, or (2) allowing system reliability equations to continue, as most do, to assume no degradation resulting from the human element.

Use of AIR Data

In order to illustrate the way in which human-factors specialists can use the AIR Data Store, the following hypothetical example is given. Assume that a radio operator must contact pilots by voice radio and communicate to them a five-digit number which he has never seen before. The number is written on a special form, and we assume that the number has been written correctly. The rest of the message is routine and is "second nature". We therefore decide that the only significant source of error is the operator's voicing of the number over the radio.*

If we have no operational data, we can turn to the AIR Data Store and break down this task into its aspects and components as defined in Chapter I. We then turn first to the "labeling" component (Table I in Chapter I) as the input component. If we are interested in the time required for the operator to read the number to himself (i.e., the time for the input aspect), we take the base time of 0.20 and add it to the times listed opposite the following dimensions: 4-5 digits, clear and concise legibility (assuming the number is typed rather than handwritten),

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*As stated in Chapter I, this restriction in the human operations to be considered in the reliability analysis must be made with considerable caution or the results of the analysis could be misleading.

and 1/8-inch high type. The result is 0.69 seconds. If we are interested in the probability that this input component will not lead to a reading error, take the product of 0.9992, 0.9999, and 0.9994. This product, 0.9985,* is the estimate for the operator correctly reading the number to himself once. Although we have no directly relevant evidence, we hypothesize that an immediate repetition of the number by a radio operator will not significantly reduce the estimated error probability of 0.0015. This hypothesis is based on two assumptions on nonindependence of behavioral acts. First, the operator will probably look at the number only once even though he must repeat the number. Second, even if he looks at the number when he repeats the transmission, he will have a strong tendency to "see" the original incorrect number he read and spoke on his first transmission. This perceptual error grows out of the operator's initial reading (or input) error being reinforced by his immediate speaking of the incorrect number (output error).

Next are the mediating processes, if any. For this step in the radio operator's procedure, we will assume that there are no requirements for long or short-term memory, for decision-making, or other components of thought subject to significant error. Consequently, mediating aspects can be ignored for this step.

To consider the output or response aspects, we turn to the page titled "Speaking" in the AIR Data Store (see Table II below). To the base time, 0.10 second, we add 0.45, 0, and 0.25 second to obtain 0.80 second. Adding to 2 x 0.69 second (to account for two readings), we obtain 2.18 (rounded to 2.2 seconds), the estimated time for an operator to read off a five-digit number twice.** To round out the success probability estimate for this step, we take the product of the values 0.9998 (for 5-10 numbers), 0.9999 (two or more repetitions), and 0.9997 (unfamiliar message using common language) to obtain 0.9994. The product of 0.9985, the input success probability (two repetitions), and 0.9994, the output success probability, is 0.9979, which we would ordinarily round to 0.998. Thus, the estimated error rate for this step in the operator's procedure is 0.002.

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*For numbers as large as 0.99, an approximation is suitable. Simply take the complements of each success probability figure, add them, and take the complement of the result. Thus, $1 - [(1 - 0.9992) + (1 - 0.9999) + (1 - 0.9994)] = 0.9985$. This approximation is handy inasmuch as the arithmetic manipulations can be done in one's head (with a predictable error rate, one hastens to add).

**We would know that this estimate is unrealistic inasmuch as a radio operator should pace his delivery so that the digits are spoken at a rate between 1 and 2 digits per second. So we would derive our own time estimates from other souce data. This example illustrates that one cannot apply the figures from the Data Store blindly. At Sandia, we have not needed to use the time data from the AIR Data Store because we have been able to obtain operational data or we have been able to take time measurements on simulated operational tasks.

TABLE II

Time and Success Probability Estimates for Output Component "Speaking." (Taken from Reference 2)

BASE TIME = 0.10 seconds		SPEAKING
Time added (seconds)	Success probability figure	
		1. Number of words or numbers (including repetitions)
0.	0.9999	a. One
0.10	0.9999	b. 2-5
0.45	0.9998	c. 5-10
1.00 or more	0.9996	d. More than 10
		2. Number of repetitions
0	0.9998	a. None
0 (see	0.9999	b. One
0 above)	0.9999	c. Two or more
		3. Nature of message
0	0.9999	a. Familiar message using common language
0.10	0.9998	b. Familiar message using uncommon language
0.25	0.9997	c. Unfamiliar message using common language
0.40	0.9995	c. Unfamiliar message using uncommon language

An Assumption for Monitored Behavior

Suppose, now, that the .002 error rate above were unacceptable (as determined by procedures described in Chapter III). Obviously, if two operators are used for this task, one to monitor the other, the task reliability should be improved. But by how much? If we square the .002 error rate, we have made the assumption of independence of behavior of the two operators. We know from studies in vigilance and inspection efficiency that a monitor of another's behavior does not ordinarily demonstrate such accuracy--in fact, far from it. Apparently, the monitor consciously or unconsciously assumes that the behavior he is monitoring has been done correctly. We therefore use a more conservative estimate of the error rate of the monitor and assign to him a .15 probability of not detecting an error made by the first operator. This figure is based upon an average inspection error rate taken from a number of studies of inspector accuracy in industrial assembly line situations, some of which are reported in Reference 14. If inspection errors are considered where operator errors are infrequent (like the .002 error rate above), then the assumed 15-percent inaccuracy of an inspector appears to be a reasonable gross estimate. Sandia

Corporation reliability evaluations have assumed that a monitor of another man's work has only an approximate .85 probability of recognizing the latter's errors if these errors occur infrequently. Lacking any better data, this same 15-percent error rate is applied to the second operator (monitor) in our hypothetical example. Thus, the estimated probability that the wrong code will be transmitted and go undetected by both radio operators is .002 x .15 = .0003.

An Assumption for Self-Correction of Errors

It is apparent that there are many situations in which a man's accuracy in a task is dependent upon errors he has just committed. That is, if a man makes an error, and then has to correct his mistake, he may have a greater or lesser probability of repeating the same mistake than he did of making the mistake in the first place. In order to illustrate how Sandia Corporation human-factors specialists have handled the situation, it is convenient to expand our hypothetical example to include the pilot's hypothesized role.

We will assume that the pilot must copy down the code transmitted to him by voice while he is simultaneously engaged in other activities. We will further assume that it is important for him to get it correctly the first time because he is not supposed to acknowledge receipt of the code. Finally, we will assume that there is a good possibility that the pilot will not be in a position to ask the radio operator for a repeat of the code if he is unable to copy it down correctly the first time. Thus, it is reasonable to believe under such conditions that if the pilot is unable to translate the code because it is not the correct code, then he will have a greater probability of incorrectly copying down the code the second time he hears it, assuming that conditions permit him a second try. But if we changed the above conditions so that there were no particular time pressures or other stimuli leading to a high degree of pilot tenseness, then a different assumption would be justified. In fact, given very good conditions, one might reasonably assume that the error rate for the second trial of the code reception task should be lower than the error rate for the first trial. And, in fact, some laboratory studies have indicated that a moderate degree of laboratory stress actually enhances accuracy in a task.* But it must not be forgotten that laboratory stress is not the same as operational stress. More is said on this subject under the next topic.

In the hypothesized example above, Sandia human-factors specialists would normally assume that the probability of incorrect code reception for the pilot's second attempt (assuming such an attempt was possible) would be double the estimated

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*The validity of this statement is partly a function of the nature of the task. Reference 15 states, "If simple conditioning and complex problem solving are thought of as being at opposite ends of a continuum of mental processes, one can postulate that stress effects are facilitative for lower-end processes and detrimental for higher-end processes. In nearly all studies involving simple conditioning, stress or anxiety was found to speed the acquisition of the conditioned response and to retard its extinction. On the other hand, most studies involving highter mental processes, such as problem-solving, thinking, discriminative learning, etc., have found that stress impairs performance."

error rate for his first attempt. This assumption is stated as follows: if a man has X probability of error for an important time-critical task on which errors occur infrequently, then his probability of making an error on Trial 2 (after he has made an error on Trial 1) is 2X, for Trial 3 (given errors on Trials 1 and 2) it is 4X, for Trial 4 (given errors on Trials 1, 2, and 3) it is 8X, and so on, until the limiting condition of a 1.0 error probability is reached. This continued doubling of his original error rate reflects the increased probability of continued error resulting from operator tenseness that occurs when it is recognized that errors are highly undesirable and that such errors might be irreversible.

To illustrate a situation where this doubling of the error rate would not be justified, let us return to the voice communication operator, and assume that he has made an error in transmitting the code and that his co-worker (i.e., the monitor) has caught this error and brought it to his attention. Due to the relatively non-stressful working conditions in a voice communication center, we would not double the voice communication operator's estimated .002 error rate of Trial 1 to obtain an estimated error rate for Trial 2. We would figure that the small amount of stress or concern that the operator felt as a result of his error on Trial 1 would probably be compensated for on Trial 2 by his greater attention and care taken in his repeat of the code. Therefore, we would normally use the same error rate for both trials so that his cumulative error rate at the end of Trial 2 would be .002 squared, or 4×10^{-6}. Thus, although we wouldn't necessarily believe that the two behaviors were really independent, we would make the assumption that squaring the error rate wouldn't introduce any important decrease in the accuracy of our estimate of the cumulative error rate.

An Assumption for Behavior Under High-Stress Conditions

There is a theoretical point where a man's ability to perform a task suddenly drops off markedly. This point is a function of many factors--fatigue, training, worry, fright, human engineering of equipment, the task itself, and so on. In everyday language, we would say that the man's breaking point has been exceeded. It is well known that different men have different breaking points and that the breaking point for any one man will vary from time to time.

Although many studies have been made of the reaction of military personnel to various kinds of stress-provoking situations, very little work in <u>quantifying</u> the degradation of human performance under operational stress has been done.* There are situations in which it is obvious that human performance should not be considered to be occurring under normal operating conditions. Assume, for example, that our hypothetical pilot were listening to and writing down a code being transmitted to him when suddenly a barrage of anti-aircraft fire begins to shake up the aircraft. Even though he had been told that he must copy down the code correctly

*Reference 15 contains 396 abstracts from the literature on stress. Nearly all of these deal with artificial stress.

the first time it is received, it seems ridiculous to assume that his error rate under normal conditions would apply now. It is reasonable to assume that his error rate under this high-stress condition would be considerably higher than his normal error rate. But how much higher? This is the question this section of the report discusses.

The importance to system reliability estimates of estimating human-error rates for tasks done under high-stress conditions is, of course, a direct function of both the probability of occurrence of these conditions and the value to the system of accurate human performance under these conditions. As stated in Chapter I, the second factor must not be overlooked. If a great deal of reliance is being placed upon accurate human performance under high-stress conditions to compensate for system perturbations, then it seems desirable to attempt to estimate, even by analogy, the degradation of this performance under these conditions.

It is well to reiterate that behavior degradation under artificial (laboratory or simulated) stress conditions may be misleading since there are real differences between the effects of stress under artificial and operational conditions. In the latter situations, the game is for keeps, and this does seem to make a difference.* For example, physiological indices of stress obtained by flight surgeons on the X15 project indicate considerably greater homeostatic deviations (in terms of physiological measures) from normal under conditions of operational stress than under conditions of artificial stress. In flight, altitude, and other types of simulators, the normal pulse rate of 72 beats per minute of X15 pilots did in fact increase to about 110, for this was a stressful situation even though it was an artificial (non-operational) situation. But their pulse rates under stressful operational conditions (such as drop-off from the mother aircraft or the loss of a windshield in flight) climbed to as much as 160 beats per minute. Therefore, flight surgeons have cautioned that behavior degradation (again in terms of physiological measures) under conditions of artificial stress may be a very conservative estimate of behavior degradation under conditions of high operational stress.

When trying to predict error rates under high-stress conditions, there are three factors which make such predictions tenuous. First, most of the available data have been taken under artificial conditions. Second, it is well known that a person's physiological degradation under stress conditions does not necessarily reflect a similar degradation in task behaviors. Some people, at least for a certain period of time, can maintain accurate task behavior even though they are doing so at a considerable physiological cost. Third, in most operational

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*In landmark World War II study entitled Men Under Stress (Reference 16), the two psychiatrist investigators concluded that for the vast majority of flight personnel, "the only valid test for endurance of combat is combat itself."

situations, time-sharing of tasks is done. Under high-stress conditions, an operator may choose to attempt to maintain his normal accuracy in one or a few tasks at the expense of accuracy on other tasks.*

All of the above factors mitigate against accurate prediction of human-error rates under high-stress conditions. Nevertheless, Sandia human-factors specialists have felt it necessary to make the best estimates they can. The error rates they have used to date are based on error rates in tasks analogous to critical behaviors of Strategic Air Command (SAC) pilots in an emergency situation in military aircraft as defined by investigators from AIR (Reference 18). These investigators defined a critical incident as a specific instance in which a crew member is called upon to handle an emergency situation. Reference 18 lists twenty-two different types of emergencies, including such conditions as complete or partial power loss, brake failures, radio equipment malfunction, and so on. In one AIR study it was found that 16 percent of all critical behaviors (e.g., behaviors which could either result in coping or not coping adequately with the emergency situation) of aircraft commanders, co-pilots, and flight engineers under emergency conditions in B-50 aircraft were ineffective. A further analysis of their data revealed that this 16 percent figure also applied to the aircraft commanders alone. The aircraft commanders had an average of about 3,000 hours flying time and averaged 885 hours in the B-50. Thus, these were well-trained personnel. At Sandia we attempted to break down the twenty-two emergency conditions into those judged to be the most and the least stress-provoking. It is interesting to note that both categories still yielded approximately 16 percent ineffective behaviors. Either the twenty-two emergency conditions are comparable in terms of generating human errors or we made an erroneous breakdown. Assuming the former explanation is more nearly correct, generalizing the above 16 percent figure to other operational situations judged to be analogous to responding to aircraft emergencies may at least suggest a basis for estimating error rates under high-stress conditions.

This treatment of high-stress is essentially the one used at Sandia. An estimate of 10 to 20 percent error rate for pilot tasks analogous to the critical behaviors identified in the AIR study is felt to be a reasonable and expedient approximation until better data can be obtained. Because of less stringent time-sharing requirements, an estimate of 5 to 15 percent has been used for high-stress error rates for in-flight tasks performed by aircrewmen other than the pilot. A range is used as a reflection of the grossness of the estimate. Thus, in the example of our hypothetical pilot, we would assign him an error-rate of 10 to 20 percent for code reception under high-stress conditions such as being shot at. In reliability

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*Some British investigators studied this phenomenon of the "lowered standard" under conditions of fatigue and stress. It was concluded (Reference 17) that within the skill being investigated, "There are always two (discrimination) thresholds--one a measure of what the observer can do, and the other of what is treated as worth doing. These can, and constantly do, vary quite independently. At the beginning of exercise they normally approximate to the same value though they are never quite identical. With continued exercise, or under a variety of other conditions, they diverge more and more. The threshold of discrimination--what the operator can do--is little affected, except in extreme cases; the threshold of indifference--what is treated as worth doing--may rise to double, treble, or quadruple its original value.... The operator may know nothing about it. He may assert that his skill is exactly as it was, and if he is stopped and his threshold of discrimination measured he may appear to be right. For a genuine measure of his skill he needs to have both these thresholds determined with the operation itself."

analyses where it has been necessary to make an estimate of behavior degradation under high-stress conditions, we feel that if our estimates of error rates for any given application are incorrect, they can probably be assumed to be on the average no more than an order of magnitude too high. We are unable to make a comparable estimate of the extent to which the estimate might be an underestimation of the operational high-stress error rate.

The question has arisen in past reliability analyses of the effect of an error in a high-stress task situation upon the operator's attempt to correct that error, assuming conditions allow such an attempt. In such cases we have kept the same assumption that we applied to tasks done under normal operational conditions. We have assumed that each repetition of a high-stress task after an error has been made in its immediately preceding performance will double the preceding error rate until the error probability of the task is 1.0. This assumption is certainly open to some question, but it appears to be a better assumption than one of independence of behavior between trials. Most behavioral scientists state that stress is a person's internal response to his perception of events, and large individual differences can be expected in responding to an error in a critical task. Thus, some people rapidly deteriorate in a situation where a high error rate occurs.

Furthermore, the more severe the stress, the sooner the point is reached at which many men begin to respond to their errors with more and more errors. In short, under highly stressful conditions, an individual may become extremely likely to continue to perform erratically with many errors. Thus, under severe stress our hypothetical pilot, having made a code reception error on Trial 1, may become so error-susceptible that his ability rapidly decreases to zero. Or, on the other hand, he may so concentrate on the reception task that his flying performance may be degraded to a danger point. In any event, it will be noted that doubling of large error rates does force the error-rate to unity after a relatively small number of trials. Implicit in this procedure, therefore, is the realistic concept that behavior will rapidly break down completely under high-stress if errors continue to be made.*

It is apparent that the estimates of high-stress error rates are certainly very gross. They depend upon several judgments made by the analyst, not the least of which is his judgment that behavior in a particular high-stress task is analogous to a SAC pilot's behavior in responding to an operational emergency. It is in this high-stress area that relevant research on operational error-rates is most urgently needed.**

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*For example, given an initial high-stress error rate of 0.10, it will take approximately five trials (original error plus four incorrect attempts to correct the error) for the error rate to reach 1.00. Note, however, that the probability of reaching the 1.00 error rate is approximately $.10 \times .20 \times .40 \times .80 \times 1.00 \approx .0064$, which we would approximate as .01 in view of the grossness of our estimates. This estimate further assumes the occurrence of the high-stress situation and its continuation for the entire corrective sequence of actions. (It will be noted that the fifth term in the above equation is 1.00 rather than $2 \times .80$ or 1.60. A probability of over 1.0 is meaningless.)

**L. W. Rook, Jr., Sandia Corporation, is currently conducting a study in which he is attempting to quantitatively relate error rates to varying levels of operational stress.

CHAPTER III

A PROCEDURE TO ESTIMATE THE EFFECTS OF HUMAN ERRORS ON A MAN-MACHINE SYSTEM

Introduction

This chapter continues the hypothetical example begun in Chapter II to show how Sandia Corporation human-factors specialists estimate the effects of human errors on a man-machine system or any part of it. The general procedure is described in Chapter I. This procedure involves the construction of an appropriate mathematical model and the assignment of Q_i values, that is, the probability of one or more failure conditions of the system, or that part of the system being evaluated, existing as a result of Class i errors occuring in n_i operations. As stated in Chapter I, Q_i has three major determinants. First, there is the error rate itself. Second, there is the probability that a human error will result in a failure to perform some procedure. Third, there is the probability that this procedure is supposed to be used and can be used in the operation of the system. The example which follows attempts to illustrate how the relevant probability figures are derived and used in arriving at an estimate of the effect of human errors on the system.

A Hypothetical Operational Situation

Assumed Operational Sequence

Over a voice radio circuit monitored by the pilots of single-place aircraft, a voice communicator reads a five-digit code aloud twice while being checked by an assistant communicator (monitor). This is an open transmission; the pilots do not break radio silence. Each pilot in his aircraft, which may be either on the ground or airborne, writes down the code as he is listening to it, unless he is forced to time-share this task with other tasks which also demand considerable attention. He is not allowed to ask for a repeat of the code at this time but must first try to translate the code he has copied down. The translation of the code is done in some specific manner which need not be hypothesized here. His answer is either obviously correct or obviously wrong, and this is immediately apparent to him. If he has obtained an incorrect answer, then he will immediately repeat the translation task, inasmuch as he might have made an error. If this repetition does not provide the correct answer, then he will attempt to contact the voice communicator and obtain a repeat of the code. If this attempt is unsuccessful, then the mission is a failure. If the attempt is successful, then he will again perform the code translation task, twice if necessary. If the answer is still incorrect, then the mission is arbitrarily considered to be a failure. (This last limitation is made to provide an ending point for the hypothetical sequence.) The mission may also fail because of events not under the control of the pilot or voice communicator.

Major Assumptions

1. The five-digit code written on a paper from which the voice communication operator reads is the correct code.

2. If the monitor correctly or incorrectly tells the voice communicator that he made a communication error, for the purpose of simplicity it is assumed that the end result will always be the correct communication. Thus, a communication error will only result if an error gets by both communicators.

3. The pilot who received the code via voice radio has received the usual training including simulated practice in all the tasks required of him.

4. Wartime conditions have just been initiated, and it is possible that all personnel on the ground may come under enemy attack. (This assumption sets the basic level of stress.)

5. The correct reception and translation of the code is necessary for the pilot's completion of his mission.

6. Certain operational circumstances might occur that make it impossible for some of the required tasks to be performed at all or within some allowable time period. (All tasks are possible unless otherwise noted.)

7. All equipment released for operational use is 100-percent reliable.*

8. Whatever conditions (high-stress/normal-medium-stress/normal-stress or air/ground operations) hold for the pilot or voice communicators on their first trials on code tasks also hold for the remainder of their operations.

9. The communication channel is either blocked completely or open completely although the signal-to-noise ratio will vary. If the channel is blocked, the mission is a failure.

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*This assumption, made to simplify the example, actually should not be too unreasonable in a real situation because any equipment unreliability associated with the tasks as described should be so small in comparison with the human-error rates or degrading effects of certain operational circumstances that the effect of the equipment unreliability would probably be masked.

10. The voice communicators operate under normal-stress conditions at all times.

11. No malicious errors are made.

Situation Diagram

Figure 1 is a situation diagram (not a flow diagram) which represents the operational sequence described earlier. The Greek letters and related numbers stand for the probabilities of events not under the control of the communicators and pilot. The capital English letters* and related figures stand for the rates for uncaught errors (by himself) of the communicator, assistant communicator, or pilot. The meaning of each symbol is described in Table III below.

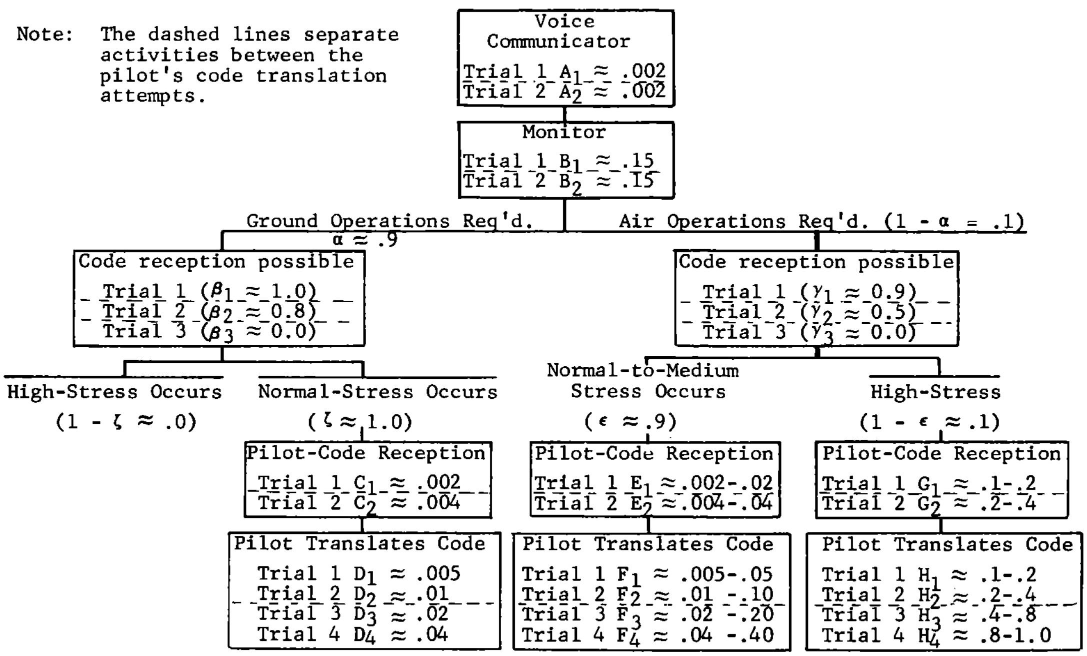

Figure 1. Situation Diagram of Hypothetical Military Sequence

Probability Estimates

All probability estimates in Table III are hypothetical approximations.

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*At Sandia Corporation, capital English letters are conventionally used for error rates or failure rates. Small English letters are conventionally used for success probabilities.

TABLE III - Probability Estimates for Hypothetical Military Sequence

Symbol	Events	Probability Estimates
α	The pilot will perform his operations on the ground	.9
$1-\alpha$	The pilot will perform his operations in the air	.1
β_1	Code reception on ground possible for Trial 1	1.0
β_2	Same for Trial 2	.8
β_3	Same for Trial 3	.0
γ_1	Code reception in air possible for Trial 1	.9
γ_2	Same for Trial 2	.5
γ_3	Same for Trial 3	.0
ζ	Normal-stress condition occurs for pilot's ground operations	1.0
$1-\zeta$	High-stress condition occurs for pilot's ground operations	.0
ϵ	Normal-to-medium-stress condition occurs for pilot's air operations	.9
$1-\epsilon$	High-stress condition occurs for pilot's air operations	.1
A_1	Voice communicator transmits wrong code, Trial 1	.002
A_2	Same, Trial 2	.002
B_1	Assistant communicator fails to catch error of voice communicator, or erroneously concludes that communicator has made an error, Trial 1	.15
B_2	Same, Trial 2	.15
C_1	Pilot on ground copies down transmitted code incorrectly, Trial 1	.002
C_2	Same, Trial 2	.004
D_1	Pilot on ground translates code incorrectly Trial 1	.005
D_2	Same, Trial 2	.01
D_3	Same, Trial 3	.02
D_4	Same, Trial 4	.04
E_1	Pilot in air, normal-to-medium stress condition, copies down transmitted code incorrectly, Trial 1	.002-.02
E_2	Same, Trial 2	.004-.04
F_1	Pilot in air, normal-to-medium stress conditions, translates code incorrectly, Trial 1.	.005-.05
F_2	Same, Trial 2	.01-.1
F_3	Same, Trial 3	.02-.2
F_4	Same, Trial 4	.04-.4
G_1	Pilot in air, high-stress condition, copies down transmitted code incorrectly, Trial 1	.1-.2
G_2	Same, Trial 2	.2-.4
H_1	Pilot in air, high-stress condition, translates code incorrectly, Trial 1	.1-.2
H_2	Same, Trial 2	.2-.4
H_3	Same, Trial 3	.4-.8
H_4	Same, Trial 4	.8-1.0

Calculation of Estimated System Degradation Resulting from Human Error

The hypothetical system criterion being evaluated is the successful translation of the five-digit code by the pilot. The probability of system success, then, is 1 minus the probability of failing to arrive at a correct translation of the code. Naturally, to estimate the degradation resulting from human error, it must be isolated from the effects of other failure events. Thus, the system failure rate resulting from human errors equals (1) the probability of not having the other failures multiplied by (2) the probability of human failure to arrive at a correct code translation.

Direct Versus Indirect Approach

In calculating the degradation resulting from human error, one can take either of two approaches when using the exact probability equations. One can directly calculate the system degradation by appropriately combining failure probabilities or one can indirectly calculate the system degradation by appropriately combining success probabilities and then subtracting the total from unity. Either model will work, but frequently one model will be considerably more complex than the other. Usually, when a man-machine system being analyzed will yield more series events than parallel events, and when one is using the exact probability equation, it is better to use the indirect approach and calculate the success probabilities. This principle can be verified readily by reference to Table IV*.

Figure 2 on page 32 and also as a fold-out page (61) at the end of this report enables one to apply this principle in determining which approach to use for the exact equation. There are a considerable number of contingent events in this hypothetical example, including a second communication attempt in case the first attempt and subsequent activities fail to result in correct translation of the code. Thus, in this example, it is simpler to use the direct approach. However, in order to fully illustrate probability technology as applied to human factors, both the direct and indirect approaches will be presented.

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*Note in the 2-switch circuit in Table IV that the success probability series equation is S = ab, whereas any of the failure equations is more complex. The opposite holds for the success probability parallel equation. Note that as the circuits contain more elements, the difference in complexity increases between the success and failure probability equations for series and parallel events.

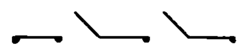
Table IV should be helpful to those who are not very familiar with probability concepts. Such persons might well study Table IV before proceeding further in the report.

TABLE IV. Mnemonic Aids for Probability Equations

Let A and B be open switches (or failure conditions) and a and b be closed switches (or success conditions). F = failure and S = success. Each cell is the product of its marginal terms, i.e., in Part I SERIES, cell AB equals the product of its marginal terms A and B.

Part 1. A 2-switch circuit

SERIES



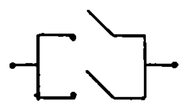
	A	a
B	F AB	F aB
b	F Ab	S ab

$S = ab$

$F = AB + aB + Ab = A + aB = B + Ab = A + B - AB = 1 - ab$

$a = 1 - A \qquad b = 1 - B$

PARALLEL



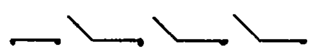
	A	a
B	F AB	S aB
b	S Ab	S ab

$F = AB$

$S = Ab + aB + ab = b + aB = a + Ab = a + b - ab = 1 - AB$

Part 2. A 3-switch circuit

SERIES



	A	A	a	a
B	F ABc	F ABC	F aBC	F aBc
b	F Abc	F AbC	F abC	S abc
	c	C	C	c

$S = abc$

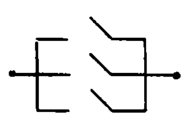
$F = ABc + ABC + aBC + aBc + Abc + AbC + abC$

$= A + a - abc = B + b - abc = C + c - abc$

$= A + aC + aBc = B + bC + Abc = C + Ac + aBc$

$= 1 - abc$

PARALLEL



	A	A	a	a
B	S ABc	F ABC	S aBC	S aBc
b	S Abc	S AbC	S abC	S abc
	c	C	C	c

$F = ABC$

$S = ABc + aBC + aBc + Abc + AbC + abC + abc$

$= a + A - ABC = b + B - ABC = c + C - ABC$

$= a + Ab + ABc = b + aB + ABc = c + aC + AbC$

$= 1 - ABC$

TABLE IV (Cont.)

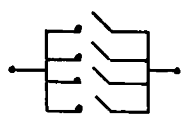
Part 3. A 4-switch circuit

SERIES 

		A	A	a	a	
B		F ABcd	F ABCd	F aBCd	F aBcd	d
B		F ABcD	F ABCD	F aBCD	F aBcD	D
b		F AbcD	F AbCD	F abCD	F abcD	D
b		F Abcd	F AbCd	F abCd	S abcd	d
		c	C	C	c	

$S = abcd$

$F = ABcd + ABCd + aBCd + aBcd + ABcD + ABCD + aBCD + aBcD$
$\quad + AbcD + AbCD + abCD + abcD + Abcd + AbCd + abCd$
$\quad = A + a - abcd = A + aC + acD + aBcd$
$\quad = B + b - abcd = B + bD + bCd + Abcd$
$\quad = C + c - abcd = C + Ac + acD + aBcd$
$\quad = D + d - abcd = D + Bd + bCd + Abcd$
$\quad = 1 - abcd$

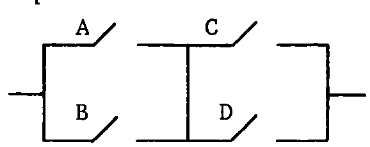
PARALLEL 

		A	A	a	a	
B		S ABcd	S ABCd	S aBCd	S aBcd	d
B		S ABcD	F ABCD	S aBCD	S aBcD	D
b		S AbcD	S AbCD	S abCD	S abcD	D
b		S Abcd	S AbCd	S abCd	S abcd	d
		c	C	C	c	

$F = ABCD$

$S = ABcd + ABCd + aBCd + aBcd + ABcD + aBCD + aBcD$
$\quad + AbcD + AbCD + abCD + abcD + Abcd + AbCd + abCd + abcd$
$\quad = a + A - ABCD = a + Ac + AbC + ABCd$
$\quad = b + B - ABCD = b + Bd + aBD + ABcD$
$\quad = c + C - ABCD = c + aC + AbC + ABCd$
$\quad = d + D - ABCD = d + bD + aBD + ABcD$
$\quad = 1 - ABCD$

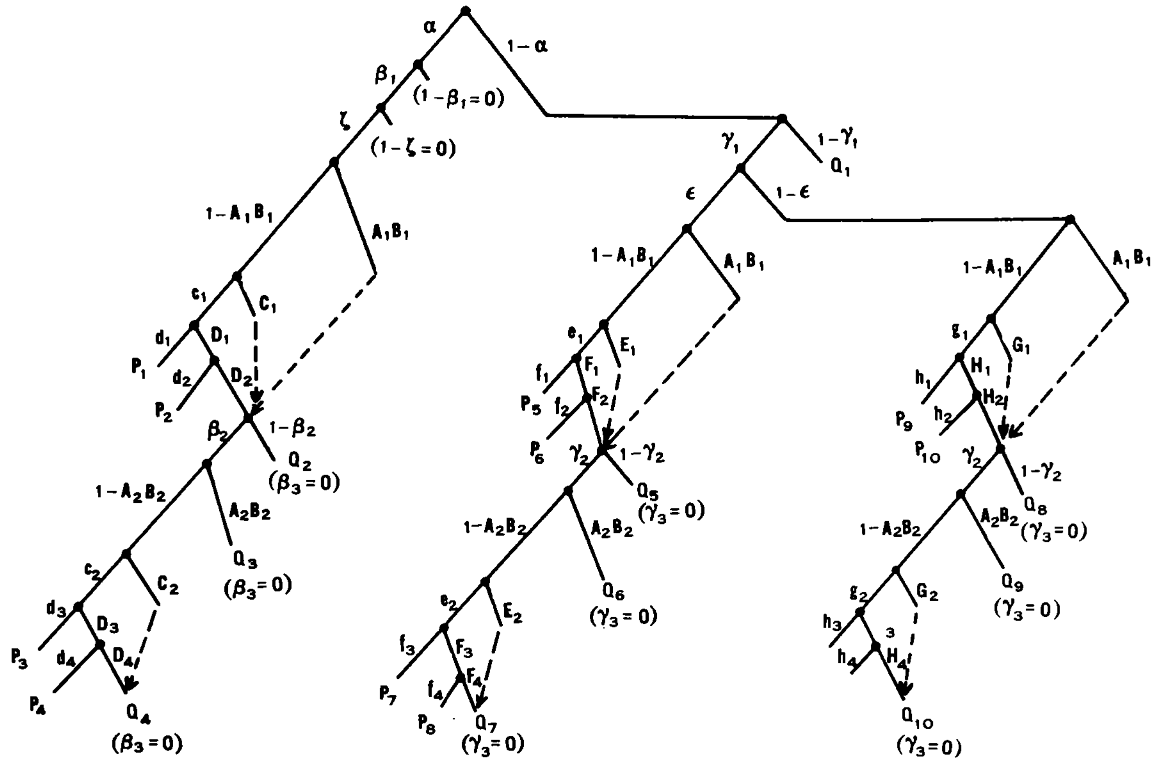
Part 4. A 4-switch series parallel circuit



		A	A	a	a	
B		ABcd F	ABCd F	aBCd S	aBcd S	d
B		ABcD F	ABCD F	aBCD F	aBcD S	D
b		AbcD S	AbCD F	abCD F	abcD S	D
b		Abcd S	AbCd S	abCd S	abcd S	d
		c	C	C	c	

$F = ABcd + ABCd + ABcD + ABCD + aBCD + AbCD + abCD$
$\quad = AB + CD - ABCD$

$S = aBCd + aBcd + aBcD + AbcD + abcD + Abcd + AbCd$
$\quad + abCd + abcd$
$\quad = ac + bd - abcd + AbcD + aBCd$



(P = success. Q = failure. Small English letters and Greek letters represent successes. Capital English letters represent failures.)

Figure 2. Probability tree illustrating branching technique

Figure 2 illustrates the branching technique used in the Reliability Department at Sandia Corporation. As stated previously, small English letters represent success probabilities and capital English letters represent failure probabilities, or, in this case, error rates of tasks. Q and P represent, respectively, failure and success of a branch of operations. The meanings of the letters and subscripts are given in Table III.

The Indirect Approach

The left-most branch [α, β_1, ζ, $(1 - A_1B_1)$, c_1, d_1] represents one way of successfully achieving the system criterion, i.e., correct translation. Ground operations were required; normal-stress conditions prevailed; the code was communicated correctly*; and the pilot successfully performed the reception and translation tasks the first time. Other branches of the tree can be interpreted in much the same fashion.

---

*We have assumed that any communicator behaviors except A_1B_1 lead to transmission of the correct code. If this is true, then the term $(1 - A_1B_1)$ expresses the probability of successful transmission of the correct code from the point of origin. Similarly, $(1 - A_2B_2)$ represents the same sequence of events for the second communication attempt. (In either case, of course, correct transmission does not guarantee correct reception.)

The dashed lines represent shortcuts used in lieu of diagramming all of the failure branches. For example, the branch ending at C_1 indicates that the pilot made an error in code reception. From this point, whether or not he correctly performs the human activities associated with code translation makes no difference--he will not obtain the desired indication of a correct code translation because he has used an incorrect code. The dashed line shows that he will eventually wind up at the point where he tries for a repeat of the code.

Once the branches on the probability tree have been diagrammed, it is a simple matter to set down the equation which represents the degradation (Q_T) resulting from the human element. This equation is given by:

$$Q_T = 1 - (P_1 + P_2 + \ldots\ldots P_{12}) - Q_1$$

This equation assumes independence of the branches. It is necessary to remove failure Q_1 from the equation since we are restricting the equation to system failure due to human error. Q_1, which equals $(1 - \alpha)(1 - \gamma_1)$, results from air operations being required but with conditions which prohibit the pilot's receiving the code. Note that $(1 - \beta_2)$ and both $(1 - \gamma_2)$ terms are not subtracted from Q_T even though they are not human failures as defined in our analysis. This is because these terms can only occur if there has been some human error in the first half of each branch, i.e., prior to β_2 or γ_2. Therefore, these terms are considered to be parts of the human initiated system failure rate.

By substituting the appropriate terms, Q_T can be further detailed and the estimated degradation calculated. Rather than introduce this lengthy equation at this point, it will be more understandable if it is developed by degrees. Consider only the left-most third of the probability tree. To express the success probability for this part of the tree, we simply set down all the paths which lead to success and ignore those which lead to failure. Thus, the probability of success, given α, can be written as

$$P_{S|\alpha} = (1 - A_1B_1)\, c_1 \left[d_1 + D_1d_2 + D_1D_2\,\beta_2 (1 - A_2B_2)\, c_2\, (d_3 + D_3d_4)\right]$$
$$+ \left[A_1B_1 + (1 - A_1B_1)\, C_1\right]\left[\beta_2(1 - A_2B_2)\, c_2\, (d_3 + D_3d_4)\right]$$

β_1 and ζ are omitted because they both equal 1.0. Note also that the behaviors denoted by the dashed lines (but not shown in the probability tree) are not included in the above equation. One dashed line runs from C_1 to β_2. Since the behaviors denoted by this dashed line equal unity, they are omitted from the equation.*

---

*Given C_1, no matter what the pilot does, he will not obtain the indication for a correct translation of the code. Thus, he will have to attempt recommunication of the code. The equation for this set of events, given α, is given as

$$(1 - A_1B_1)\, C_1 \left[d_1d_2 + d_1D_2 + D_1d_2 + D_1D_2\right]\beta_2 \text{ etc.}$$

The expression in brackets can be written as $d_1d_2 + D_1d_2 + d_1D_2 + D_1D_2$ or

$$d_2(d_1 + D_1) + D_2(d_1 + D_1) \text{ or } (d_2 + D_2)\,(d_1 + D_1).$$

The latter two quantities both equal unity.

Another dashed line runs from A_1B_1 to β_2. The behaviors denoted by this dashed line also equal unity and again are omitted from the equation.*

If we wanted to obtain an estimate of system degradation, given α (that is, given ground operations), the appropriate probability estimates could be substituted for the terms in the equation. Using the estimates listed earlier,

$$\begin{aligned} Q_S &= 1 - P_S \\ &= 1 - \{.9997 \times .998 [.995 + (.005 \times .99) + (.005 \times .01 \\ &\quad \times .8 \times .9997 \times .996)(.98 + .02 \times .96)] \\ &\quad + [.0003 + .9997 \times .002][.8 \times .9997 \times .996 (.98 + .02 \times .96)]\} \\ &\approx 1 - .99948 \approx .00052 \approx 5 \times 10^{-4} \end{aligned}$$

This estimated degradation due to the human element indicates that if all of our assumptions are correct, then the hypothetical system is in good shape, given ground operations for all pilots. If our assumption--given D_3, then there is sufficient time for d_4--is not correct, then our estimate of system degradation would be too small, but probably not an important amount in an operational situation. If our assumed values for β_1 and β_2 are overestimates, then the estimated degradation of 5×10^{-4} would be overoptimistic.

On the other hand, if our assumption that β_1 is 1.0 is correct, the system would still be fairly reliable even if β_2 were zero. That is,

---

*While practice enables one to write down the above equation directly from the probability tree (but usually with one or more errors on the first attempt), fewer errors are likely to be made if all of the terms in the equation are written out and then the equation is simplified by appropriate factoring. Thus, the following terms would lead to the equation above.

$$\begin{aligned} P_{S|\alpha} &= \beta_1 \zeta (1 - A_1B_1) c_1 d_1 + \beta_1 \zeta (1 - A_1B_1) c_1 D_1 d_2 \\ &+ \beta_1 \zeta (1 - A_1B_1) c_1 D_1 D_2 \beta_2 (1 - A_2B_2) c_2 d_3 \\ &+ \beta_1 \zeta (1 - A_1B_1) c_1 D_1 D_2 \beta_2 (1 - A_2B_2) c_2 D_3 d_4 \\ &+ \beta_1 \zeta (1 - A_1B_1) C_1 \beta_2 (1 - A_2B_2) c_2 d_3 \\ &+ \beta_1 \zeta (1 - A_1B_1) C_1 \beta_2 (1 - A_2B_2) c_2 D_3 d_4 \\ &+ \beta_1 \zeta A_1B_1 \beta_2 (1 - A_2B_2) c_2 d_3 \\ &+ \beta_1 \zeta A_1B_1 \beta_2 (1 - A_2B_2) c_2 D_3 d_4 \\ &= (1 - A_1B_1) c_1 [d_1 + D_1 d_2 + D_1 D_2 \beta_2 (1 - A_2B_2) c_2 (d_3 + D_3 d_4)] \\ &+ (1 - A_1B_2) C_1 \beta_2 (1 - A_2B_2) c_2 (d_3 + D_3 d_4) \\ &+ A_1B_1 \beta_2 (1 - A_2B_2) c_2 (d_3 + D_3 d_4) \\ &= (1 - A_1B_1) c_1 [d_1 + D_1 d_2 + D_1 D_2 \beta_2 (1 - A_2B_2) c_2 (d_3 + D_3 d_4)] \\ &+ [A_1B_1 + (1 - A_1B_1) C_1][\beta_2 (1 - A_2B_2) c_2 (d_3 + D_3 d_4)] \end{aligned}$$

$$
\begin{aligned}
Q_{S|\alpha|(\beta_2 = 0)} &\approx 1 - [(1- A_1B_1)\ c\ (d_1 + D_1d_2)] \\
&\approx 1 - [.9997 \times .998 \times (.995 + .005 \times .99)] \\
&\approx .0003 + .002 + .0001^{*} \\
&\approx .0024 \approx 2 \times 10^{-3}
\end{aligned}
$$

However, in some operational situations, this increase in system unreliability by a factor of four might not be acceptable.

Let us now turn to the calculation of the estimated Q_T, the total system degradation per system resulting from human error in this hypothetical example. The following equation brings in all of the success probabilities (except the ones that equal 1.0) in the probability tree of Figure 2. The low range, Q_{T_1}, is calculated first.

$$
\begin{aligned}
Q_{T_1} \approx 1 - \Big[&\alpha \Big\{(1 - A_1B_1)\ c_1\ [d_1 + D_1d_2 + D_1D_2\beta_2\ (1 - A_2B_2)\ c_2\ (d_3 \\
&+ D_3d_4)] + [A_1B_1 + (1 - A_1B_1)\ C_1]\ [\beta_2(1 - A_2B_2)\ c_2\ (d_3 \\
&+ D_3d_4)]\Big\} + (1 - \alpha)\ \Big[\gamma_1\ [\epsilon \Big\{(1 - A_1B_1)e_1 \{f_1 + F_1f_2 \\
&+ F_1F_2\gamma_2\ (1 - A_2B_2)e_2\ (f_3 + F_3f_4)\} + \{A_1B_1 + (1 - A_1B_1)E_1\} \\
&\{\gamma_2(1 - A_2B_2)e_2\ (f_3 + F_3f_4)\}\Big\} \\
&+ (1 - \epsilon)\Big\{(1 - A_1B_1)g_1\{h_1 + H_1h_2 + H_1H_2\gamma_2\ (1 - A_2B_2) \\
&\times g_2(h_3 + H_3h_4)\} + \{A_1B_1 + (1 - A_1B_1)\ G_1\}\ \{\gamma_2(1 - A_2B_2)g_2 \\
&\times (h_3 + H_3h_4)\}\Big\}] + (1 - \gamma_1)\Big]\Big] \\
\approx 1 - \Big[&.9 \Big\{.9997 \times .998\ [.995 + (.005 \times .99) + (.005 \times .01 \times .8 \\
&\times .9997 \times .996)\ (.98 + .02 \times .96)] + [.0003 + (.9997 \times .002)] \\
&\times [.8 \times .9997 \times .996\ (.98 + .02 \times .96)]\Big\} \\
&+ .1\ \Big[.9\ [.9 \Big\{.9997 \times .998\ \{.995 + (.005 \times .99) + (.005 \times .01 \\
&\times .5 \times .9997 \times .996)\ (.98 + .02 \times .96)\} + \{.0003 + (.9997 \times .002)\} \\
&\times \{.5 \times .9997 \times .996\ (.98 + .02 \times .96)\}\Big\} + .1 \Big\{.9997 \times .9\ \{.9 \\
&+ (.1 \times .8) + .1 \times .2 \times .5 \times .9997 \times .8\ (.6 + .4 \times .2)\} + \{.0003 \\
&+ (.9997 \times .1)\}\{.5 \times .9997 \times .8\ (.6 + .4 \times .2)\}\Big\}] + .1\Big]\Big] \\
\approx 1 - \Big[&.9\ \{.9995\} + .1\ \Big[.9\ [.9\ \{.9990\} + .1\ \{.9121\}] + .1\Big]\Big] \\
\approx 1 - &.9987 \approx .0013 \approx 10^{-3}
\end{aligned}
$$

$\approx$ The low range of the estimated average total system degradation per system due to human error.

---

*This method of approximation was explained in Chapter II. It saves the multiplication of large numbers, and can ordinarily be used when the error rates are in the neighborhood of 1 percent or less.

The high range of Q_T is calculated by substituting the high range of probability estimates where appropriate. This Q_{T_2} equals approximately 4×10^{-3}*. Thus, Q_T, the estimated total system degradation due to human error, is between 0.1 and 0.4 percent regardless of whether one uses the high or low probability estimates from Table III. The reason for this relative insensitivity to large variations in some error rates can be traced to the relatively low estimated probability of the occurrence of the middle branch of the probability tree, $(1 - \alpha)\gamma_1\epsilon = .1 \times .9 \times .9 = .081$, and the even lower estimated probability of the righthand branch, $(1 - \alpha)\gamma_1 (1 - \epsilon) = .1 \times .9 \times .1 = .009$, as compared with the estimated probability of the lefthand branch, $\alpha\beta_1 = .9 \times 1.0 = .9$.

It should be recalled that it was necessary to subtract $(1 - \alpha)(1 - \gamma_1)$ from the equation of system failure due to human error, to account for the fact that $(1 - \alpha)(1 - \gamma_1)$ is not a failure due to human error as defined. If this term (which equals .01) is added back into the equation, the result, $10^{-3} + 10^{-2} \approx 10^{-2}$, shows clearly that the failure rate due to pilot and communicator human error is only about 1/10th of the total failure rate of that part of the system evaluated.

Some operational personnel object to the above type of system calculation. They would prefer to estimate (1) the system degradation due to human error, given α; (2) this degradation, given $1 - \alpha$ and ϵ; and (3) this degradation, given $1 - \alpha$ and $1 - \epsilon$. Their argument may be summarized as follows: "Although there may be conditions not under the control of the operator which seriously degrade system reliability, we want to make sure that if these conditions are favorable, then the operator will have a high probability of success." Without commenting on the validity of this argument, it should be apparent that the approach described herein permits these calculations.

The Direct Approach

As stated earlier, in calculating the exact failure equation for the hypothetical example in this report, it is simpler to use failure probabilities rather than success probabilities. This section of the report illustrates the calculations using failure probabilities and the following section shows and discusses an approximation using approximate failure probabilities.

$$\begin{aligned} Q_T = \alpha\, & [A_1B_1 + (1 - A_1B_1)\, C_1 + (1 - A_1B_1)c_1D_1D_2] \\ & [(1 - \beta_2) + \beta_2A_2B_2 + \beta_2(1 - A_2B_2)\, C_2 + \beta_2(1 - A_2B_2)\, c_2D_3D_4] \\ & + (1 - \alpha)\, \gamma_1 \Big[\epsilon[A_1B_1 + (1 - A_1B_1)\, E_1 + (1 - A_1B_1)\, e_1F_1F_2] \\ & [(1 - \gamma_2) + \gamma_2A_2B_2 + \gamma_2(1 - A_2B_2)\, E_2 + \gamma_2(1 - A_2B_2)e_2F_3F_4] \end{aligned}$$

$$* \quad Q_{T_2} \approx 1 - \Big[.9\ \{.9995\} + .1\ \Big[.9\ [.9\ \{.9859\} + .1\ \{.7516\}] + .1\Big]\Big]$$
$$\approx 1 - .9962 \approx .0038 \approx 4 \times 10^{-3}$$

$$+ (1 - \epsilon) [A_1B_1 + (1 - A_1B_1) G_1 + (1 - A_1B_1)g_1H_1H_2]$$

$$[(1 - \gamma_2) + \gamma_2A_2B_2 + \gamma_2(1 - A_2B_2) G_2 + \gamma_2(1 - A_2B_2)g_2H_3H_4]]$$

Note that in this equation $(1 - \alpha)(1 - \gamma_1)$ is not included. This omission is made because the equation is dealing directly with failure events due to human error, and therefore it is not necessary to subtract the failure event labeled Q_1 in Figure 2. Also note that $(1 - \beta_2)$ and both $(1 - \gamma_2)$ terms are included, for reasons given under the discussion of the indirect approach.

Q_{T_1}, the system degradation due to human error using the low-range figures from Table III, is calculated as

$$Q_{T_1} = .9\ [.0003 + .9997 \times .002 + .9997 \times .998 \times .00005]$$

$$[.2 + .8 \times .0003 + .8 \times .9997 \times .004 + .8 \times .9997 \times .996 \times .0008]$$

$$+ .1 \times .9 \Big[.9\ [.0003 + .9997 \times .002 + .9997 \times .998 \times .00005]$$

$$[.5 + .5 \times .0003 + .5 \times .9997 \times .004 + .5 \times .9997 \times .996 \times .0008]$$

$$+ .1\ [.0003 + .9997 \times .1 + .9997 \times .9 \times .02]$$

$$[.5 + .5 \times .0003 + .5 \times .9997 \times .2 + .5 \times .9997 \times .8 \times .32]\Big]$$

$$= .9 \times .00048 + .09\ [.9 \times .00118 + .1 \times .08611]$$

$$= .0013 \approx 10^{-3}$$

Q_{T_2}, the system degradation due to human error using the high-range figures from Table III, is calculated as

$$Q_{T_2} = .9\ [.0003 + .9997 \times .002 + .9997 \times .998 \times .00005]$$

$$[.2 + .8 \times .0003 + .8 \times .9997 \times .004 + .8 \times .9997 \times .996 \times .0008]$$

$$+ .1 \times .9 \Big[.9\ [.0003 + .9997 \times .02 + .9997 \times .98 \times .005]$$

$$[.5 + .5 \times .0003 + .5 \times .9997 \times .04 + .5 \times .9997 \times .96 \times .08]$$

$$+ .1\ [.0003 + .9997 \times .2 + .9997 \times .8 \times .08]$$

$$[.5 + .5 \times .0003 + .5 \times .9997 \times .4 + .5 \times .9997 \times .6 \times .8]\Big]$$

$$= .9 \times .00048 + .09\ [.9 \times .01407 + .1 \times .24837]$$

$$= .0038 \approx 4 \times 10^{-3}$$

It should not be surprising that the answers for Q_{T_1} and Q_{T_2} using the failure probabilities are identical to the answers obtained by using the success probabilities.

An Approximation of the Exact Failure Equation

Unless one has statistical clerks at his disposal, the above calculations can be tedious. A shortcut approximation can be used and usually will be sufficiently accurate as long as the success probabilities of nearly all events equal at least .99. (The more success probabilities not reaching .99, the less accurate the approximation will be.) Consider the left-hand branch of Figure 2. Failure of this branch, given ground operations, can be approximated as:

$$Q_{S|\alpha} \approx (A_1B_1 + C_1 + D_1D_2)\ (1 - \beta_2 + A_2B_2 + C_2 + D_3D_4)$$

$$\approx (.0003 + .002 + .00005)\ (.2 + .0003 + .004 + .0008)$$

$$\approx .00048 \approx 5 \times 10^{-4}$$

The answer, .00048, is identical to the answer obtained with the exact equation.

Note that each term in this approximation is the approximate first or second order failure term in the exact failure equation. This approximation is derived by summing the first- and second-order terms which are combinations of failure probabilities in a series part of the system where these terms are both sufficient and necessary.* The failure probabilities for the parallel parts of the system must, of course, be multiplied to account for the system redundancy (parallelism). Thus, in the approximate equation above, the first set of terms in parentheses represents a failure on Trial 1 while the second set of terms in parentheses represents a failure on Trial 2. System failure requires a failure on both Trial 1 and Trial 2. Thus, the two sets of terms are multiplied to give total system failure rate resulting from human error, given that ground operations occur.

If the approximate equation is used to calculate the probability of failure resulting from human error of the middle branch of the tree, given $(1 - \alpha)$, γ_1, and ϵ, the following equation is relevant:

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*In a series combination, only first-order terms would ordinarily be used. For example, in the two-switch series circuit in Table IV, the exact equation for F (failure) is AB + aB + Ab. But if the probabilities associated with a and b are both about .99, then, as stated above, a and b can be dropped from the equation without introducing a large error in the estimated failure rate. Furthermore, the term AB is sufficient but not necessary for failure. That is, either A or B alone will result in a failure. Therefore, the approximate failure equation is $F \approx A + B$. In a simple parallel combination, an approximation is not appropriate. For example, in the two-switch parallel circuit shown in Table IV, F = AB. Of course, if the probability of one of these failure events is close to 1.0, it may be sufficient to use the lower probability figure as an approximation of F.

$$Q_{S|(1-\alpha),\ \gamma_1,\ \epsilon} \approx (A_1B_1 + E_1 + F_1F_2)\ (1 - \gamma_2 + A_2B_2 + E_2 + F_3F_4)$$

and

$$Q_{\text{Low Range}} \approx (.0003 + .002 + .00005)\ (.5 + .0003 + .004 + .0008)$$

$$\approx .0012 \approx .001$$

$$Q_{\text{High Range}} \approx (.0003 + .02 + .005)\ (.5 + .0003 + .04 + .08)$$

$$\approx .0157 \approx .016$$

The unrounded estimates, .0012 and .0157, can be compared with the corresponding estimates, .0012 and .0141, using the exact failure equations. Thus, the approximation for the low range would be considered adequate even though one of the success probabilities, γ_2, is considerably less than .99. The approximation is less accurate for the high range since four of the seven terms do not meet the criterion of .99 for their related success probabilities. However, many human-factors specialists would probably consider this approximation to be sufficiently accurate, especially in view of the assumption discussed in Chapter II of doubling error rates after an error has been made.

If the approximate equation is used to calculate the probability of failure resulting from human error of the right-hand branch of the tree, given $(1 - \alpha)$, γ_1, and $(1 - \epsilon)$, the following equation is relevant:

$$Q_{S|(1-\alpha),\ \gamma_1,\ (1-\epsilon)} \approx (A_1B_1 + G_1 + H_1H_2)\ (1 - \gamma_2 + A_2B_2 + G_2 + H_3H_4)$$

and

$$Q_{\text{Low Range}} \approx (.0003 + .1 + .02)\ (.5 + .0003 + .2 + .32)$$

$$\approx (.1203)\ (1)^* \approx .1203 \approx .1$$

$$Q_{\text{High Range}} \approx (.0003 + .2 + .08)\ (.5 + .0003 + .4 + .8)$$

$$\approx (.2803)\ (1)^* \approx .2803 \approx .3$$

The unrounded estimates, .1203 and .2803, can be compared with the corresponding unrounded estimates, .0861 and .2484, using the exact failure equations. These differences are fairly substantial and some reliability specialists would prefer to

---

*A probability of error greater than 1.0 is meaningless; therefore 1.0 is used even though the sum of the individual probabilities is greater than 1.0. As discussed earlier, the value greater than one merely means that the average performance beginning with γ_2 or $1 - \gamma_2$ under high-stress conditions, after a failure has been experienced following γ_1 under high-stress conditions, will not lead to a successful translation of the code.

avoid this additional error in the estimate and use the exact equations. Others would note that the differences in error rates, i.e., about .03 for each comparison, are probably not significant in view of the grossness of the estimated error rates for tasks performed under high-stress conditions. In any event, the use of the above type of approximation does yield higher estimates of system degradation, and this fact should be kept in mind.

The following calculation illustrates that when high error rates are associated with events which in themselves have a low probability of occurrence and vice versa, the use of the approximation for estimating total system degradation due to human error does not lead to substantially different results than when using the exact failure equation.

$$Q_T \approx \alpha(A_1B_1 + C_1 + D_1D_2)(1 - \beta_2 + A_1B_2 + C_2 + D_3D_4)$$
$$+ (1 - \alpha)\,\gamma_1\,[\epsilon(A_1B_1 + E_1 + F_1F_2)(1 - \gamma_2 + A_2B_2 + E_2 + F_3F_4)$$
$$+ (1 - \epsilon)(A_1B_1 + G_1 + H_1H_2)(1 - \gamma_2 + A_2B_2 + G_2 + H_3H_4)]$$

$$Q_{T_1} \approx .9\ (.0003 + .002 + .00005)\ (.2 + .0003 + .004 + .0008)$$
$$+ .1 \times .9\ [.9\ (.0003 + .002 + .00005)\ (.5 + .0003 + .004 + .0008)$$
$$+ .1\ (.0003 + .1 + .02)\ (.5 + .0003 + .2 + .32)^*]$$
$$\approx .0016 \approx 2 \times 10^{-3}$$

$$Q_{T_2} \approx .9\ (.0003 + .002 + .00005)\ (.2 + .0003 + .004 + .0008)$$
$$+ .1 \times .9\ [.9\ (.0003 + .02 + .005)\ (.5 + .0003 + .04 + .08)$$
$$+ .1\ (.0003 + .2 + .08)\ (.5 + .0003 + .4 + .8)^*]$$
$$\approx .0042 \approx 4 \times 10^{-3}$$

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*See footnote on previous page.

Recommend Changes to System and Calculate New System Failure Rate

This topic heading provides the final logical step in our application of THERP to a hypothetical operational system. As explained in Chapter I under the same topic heading, the initial procedure in this step is to calculate all Q_i values and order them from largest to smallest. Q_i is the probability that the system will fail due to some P_i, the probability that an operation can and is supposed to occur and that it will lead to an error of Class i. Thus, in this section of the report, the estimated 10^{-3} to 4×10^{-3} system degradation resulting from human errors will be allocated among the various human error terms in Figure 2.

Calculation of Q_i Values

We will let n_i equal 1.0, since each P_i must be computed separately. Therefore, the equation from Chapter I, $Q_i = 1 - (1 - F_iP_i)^{n_i}$, can be simplified to $Q_i = F_iP_i$ for each Q_i. In calculating P_i, however, certain dependencies in the probability tree in Figure 2 must be taken into account. These dependencies stem from the dependence of Trial 2 on the failure of Trial 1. If the dependencies are not taken into account, the sum of all the Q_i values, ΣQ_i, would not equal Q_T, the total system degradation resulting from human error.

In order to illustrate how the individual Q_i equation can be derived, we will first consider only ground operations, that is, the left-most branch of the probability tree. The best way to avoid errors in deriving the Q_i equations is to start out by writing down all of the possible paths to failure, given α. The twelve such paths, the sum of which equals $Q_{T|\alpha}$, are listed below. For simplification each of these twelve is set equal to a single symbol.

$$L = (A_1B_1)\,(1 - \beta_2)$$
$$M = (A_1B_1)\beta_2(A_2B_2)$$
$$N = (A_1B_1)\beta_2\,(1 - A_2B_2)C_2$$
$$R = (A_1B_1)\beta_2\,(1 - A_2B_2)c_2D_3D_4$$
$$S = (1 - A_1B_1)C_1\,(1 - \beta_2)$$
$$T = (1 - A_1B_1)C_1\beta_2A_2B_2$$
$$U = (1 - A_1B_1)C_1\beta_2(1 - A_2B_2)C_2$$
$$V = (1 - A_1B_1)C_1\beta_2(1 - A_2B_2)c_2D_3D_4$$
$$W = (1 - A_1B_1)c_1D_1D_2(1 - \beta_2)$$
$$X = (1 - A_1B_1)c_1D_1D_2\beta_2A_2B_2$$
$$Y = (1 - A_1B_1)c_1D_1D_2\beta_2(1 - A_2B_2)C_2$$
$$Z = (1 - A_1B_1)c_1D_1D_2\beta_2\,(1 - A_2B_2)c_2D_3D_4{}^*$$

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* β_1 and ζ are dropped from the twelve paths because they both equal 1.0.

Consider first the effect of the four error terms ($1 - \beta_2$, A_2B_2, C_2, and D_3D_4) in the second half of the branch, i.e., the Trial 2 terms.* F_i for each of these four error terms must equal 1.0 because, in our hypothetical model, there is no chance for system success once any one of them has occurred. All that is left, therefore, is to work out the P_i values for each of the four error terms in Trial 2.

Let us turn to the system failure rate resulting from D_3D_4, the last chance for failure. This Q_i will be identified as Q_7. D_3D_4 occurs in three paths, R, V, and Z. But one cannot ascribe to D_3D_4 alone the blame for the failures denoted by these three paths.** Note that error terms A_1B_1, C_1, and D_1D_2 are associated, respectively, with R, V, and Z. All the other terms in R, V, and Z (except, of course, D_3D_4) are success terms. Therefore, the system failure rate ascribed to these three paths must be allocated among D_3D_4 and these three Trial 1 error terms. Thus, D_3D_4 gets the blame for

$$\frac{D_3D_4}{D_3D_4 + A_1B_1} \text{ of R, for } \frac{D_3D_4}{D_3D_4 + C_1} \text{ of V, and for } \frac{D_3D_4}{D_3D_4 + D_1D_2} \text{ of Z.}$$

and the Q_i for D_3D_4 can be written as:

$$Q_7 = \frac{D_3D_4R}{D_3D_4 + A_1B_1} + \frac{D_3D_4V}{D_3D_4 + C_1} + \frac{D_3D_4Z}{D_3D_4 + D_1D_2}$$

It can be noted, by appropriate factoring, that R + V + Z contains the probability of failure on Trial 1, that is, $A_1B_1 + (1 - A_1B_1)C_1 + (1 - A_1B_1)c_1D_1D_2$. This probability expression reflects the fact that D_3D_4 will not occur unless Trial 1 has failed to produce a successful code translation.

Similarly, the Q_i equations for the other Trial 2 error terms are written as:

$$Q_6\text{, the } Q_i \text{ for } C_2 = \frac{C_2N}{C_2 + A_1B_1} + \frac{C_2U}{C_2 + C_1} + \frac{C_2Y}{C_2 + D_1D_2}$$

$$Q_5\text{, the } Q_i \text{ for } A_2B_2 = \frac{A_2B_2M}{A_2B_2 + A_1B_1} + \frac{A_2B_2T}{A_2B_2\ 2\ C_1} + \frac{A_2B_2X}{A_2B_2 + D_1D_2}$$

$$Q_4\text{, the } Q_i \text{ for } 1 - \beta_2 = \frac{(1 - \beta_2)L}{(1 - \beta_2) + A_1B_1} + \frac{(1 - \beta_2)S}{(1 - \beta_2) + C_1} + \frac{(1 - \beta_2)W}{(1 - \beta_2) + D_1D_2}$$

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*It will be recalled that $1 - \beta_2$ is regarded as an error term because it can occur only if successful code translation is not attained on Trial 1.

**If this type of calculation error is made for all the error terms in this branch, then $\Sigma Q_i|\alpha = 2Q_T|\alpha$ which is obviously false since $\Sigma Q_i|\alpha$ must equal $Q_T|\alpha$. The incorrect answer of $2Q_T|\alpha$ results from failure to reflect the dependencies in the probability tree between Trial 1 and Trial 2 error terms. Thus, if we denote F_i as the probability of failure in Trial 2, and F_j as the probability of failure in Trial 1,

$$\begin{aligned}\Sigma Q_i|\alpha &= A_1B_1F_i + (1 - A_1B_1)C_1F_i \\ &\quad + (1 - A_1B_1)c_1D_1D_2F_i + F_j(1 - \beta_2) + F_j\beta_2A_2B_2 + F_j\beta_2(1 - A_2B_2)C_2 \\ &\quad + F_j\beta_2(1 - A_2B_2)c_2D_3D_4 \\ &= F_i\,[A_1B_1 + (1 - A_1B_1)(C_1 + c_1D_1D_2)] \\ &\quad + F_j\left\{(1 - \beta_2) + \beta_2[A_2B_2 + (1 - A_2B_2)(C_2 + c_2D_3D_4)]\right\} \\ &= F_iF_j + F_jF_i = 2F_iF_j = 2Q_T\end{aligned}$$

It can be noted that each of the above equations contains the Trial 1 failure probability expression.

When we turn to the Trial 1 error terms, it is obvious from the probability tree that any Trial 1 error is not a sufficient cause of system failure. It is still possible for the code translation to be achieved on Trial 2. Thus, F_i for each of the three Trial 1 error terms is the probability of failure on Trial 2. Again, in order to avoid errors, it is best to work out the Q_i equations by careful reference to the possible failure paths. Consider the Q_i for D_1D_2. D_1D_2 occurs in four paths, W, X, Y, and Z. But we cannot assign the blame to D_1D_2 alone for these failure paths. The four error terms from Trial 2, i.e., $(1 - \beta_2)$, A_2B_2, C_2 and D_3D_4, are also associated with, respectively, W, X, Y, and Z. Therefore, the system failure rate ascribed to these four paths must be allocated among D_1D_2 and the four Trial 2 error items. Thus, D_1D_2 gets the blame for

$\frac{D_1D_2}{D_1D_2 + (1 - \beta_2)}$ of W, for $\frac{D_1D_2}{D_1D_2 + A_2B_2}$ of X, for $\frac{D_1D_2}{D_1D_2 + C_2}$ of Y and for $\frac{D_1D_2}{D_1D_2 + D_3D_4}$ of Z; and the Q_i and D_1D_2 can be written as:

$$Q_3 = \frac{D_1D_2W}{D_1D_2 + (1 - \beta_2)} + \frac{D_1D_2X}{D_1D_2 + A_2B_2} + \frac{D_1D_2Y}{D_1D_2 + C_2} + \frac{D_1D_2Z}{D_1D_2 + D_3D_4}$$

It can be noted, by appropriate factoring, that W + X + Y + Z contains the expression for F_i, or the probability of failure on Trial 2, i.e., $(1 - \beta_2) + \beta_2A_2B_2 + \beta_2(1 - A_2B_2)(C_2 + \beta_2(1 - A_2B_2)c_2D_3D_4$. This same expression is also found in the Q_i equations for C_1 and A_1B_1.

Similarly, the Q_i equations for the other Trial 1 error terms are written as:

$$Q_2\text{, the } Q_i \text{ for } C_1\text{, } = \frac{C_1S}{C_1 + (1 - \beta_2)} + \frac{C_1T}{C_1 + A_2B_2} + \frac{C_1U}{C_1 + C_2} + \frac{C_1V}{C_1 + D_3D_4}$$

$$Q_1\text{, the } Q_i \text{ for } A_1B_1 = \frac{A_1B_1L}{A_1B_1 + (1 - \beta_2)} + \frac{A_1B_1M}{A_1B_1 + A_2B_2} + \frac{A_1B_1N}{A_1B_1 + C_2} + \frac{A_1B_1R}{A_1B_1 + D_3D_4}$$

The proof is that $\Sigma Q_i|\alpha = Q_T\,\alpha$.

$$\Sigma Q_i|\alpha = Q_1 + Q_2 + \ldots\ldots + Q_7\text{; or collecting like terms,}$$

$$= \frac{A_1B_1 + D_3D_4}{A_1B_1 + D_3D_4} R + \frac{A_1B_1 + C_2}{A_1B_1 + C_2} N + \frac{A_1B_1 + A_2B_2}{A_1B_1 + A_2B_2} M$$

$$+ \frac{A_1B_1 + (1 - \beta_2)}{A_1B_1 + (1 - \beta_2)} L + \frac{C_1 + D_3D_4}{C_1 + D_3D_4} V + \frac{C_1 + C_2}{C_1 + C_2} U$$

$$+ \frac{C_1 + A_2B_2}{C_1 + A_2B_2} T + \frac{C_1 + (1 - \beta_2)}{C_1 + (1 - \beta_2)} S + \frac{D_1D_2 + D_3D_4}{D_1D_2 + D_3D_4} Z$$

$$+ \frac{D_1D_2 + C_2}{D_1D_2 + C_2} Y + \frac{D_1D_2 + A_2B_2}{D_1D_2 + A_2B_2} X + \frac{D_1D_2 + (1 - \beta_2)}{D_1D_2 + (1 - \beta_2)} W$$

$$= L + M + N + R + S + T + U + V + W + X + Y + Z$$

$$= Q_T|\alpha\ .$$

There is one final correction to the above set of equations that should be made. Although $1 - \beta_2$ was regarded as an error term in the calculation of $Q_T|\alpha$, a Q_i value for $1 - \beta_2$ is not too meaningful if we are concerned primarily with human errors.* It is more reasonable to allocate the Q_i calculated for $1 - \beta_2$ to the Q_i values for A_1B_1, C_1, and D_1D_2. This allocation reflects the fact that if any of these three Trial 1 error terms occur, the system automatically has a .2 probability of failing since $1 - \beta_2 = .2$. Therefore, the above equations for Q_1, Q_2, and Q_3 are changed, respectively, to drop the fractional modifiers of L, S, and W. The new Q_i equations for A_1B_1, C_1, and D_1D_2 now become:

$$Q_1 = L + \frac{A_1B_1M}{A_1B_1 + A_2B_2} + \frac{A_1B_1N}{A_1B_1 + C_2} + \frac{A_1B_1R}{A_1B_1 + D_3D_4}$$

$$Q_2 = S + \frac{C_1T}{C_1 + A_2B_2} + \frac{C_1U}{C_1 + C_2} + \frac{C_1V}{C_1 + D_3D_4}$$

$$Q_3 = W + \frac{D_1D_2X}{D_1D_2 + A_2B_2} + \frac{D_1D_2Y}{D_1D_2 + C_2} + \frac{D_1D_2Z}{D_1D_2 + D_3D_4}$$

The Q_i equations for the other two branches of the probability tree are similarly derived. Table V presents all the failure paths in the system due to human error. Table VI presents all the Q_i equations (in a form suitable for machine calculations) for the reader who wishes to check his own derivations. Table VII presents the Q_i values and the data used to determine the values.** Finally, Table VIII presents selected, rounded Q_i values ordered from high to low numbers. Where there is a range for an error rate or for F_i or F_j†, both values are used and are reflected in Tables VI and VII. The Q_i for A_1B_1 independent of tree branch is obtained by summing all the Q_i values for the A_1B_1 terms in each branch. The Q_i for A_2B_2 independent of branch is similarly calculated.

Using the 8-place Q_i values in Table VII, it can be shown that the sum of the Q_i low-range values (.0013) equals Q_{T_1} (.0013) and the sum of the Q_i high-range values (.0038) similarly equals Q_{T_2} (.0038). When the rounded figures in Table VIII are used, there is an inconsequential rounding error, but agreement is still obtained at the third decimal place.

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*However, one may, if interested, calculate the degradation due to $1 - \beta_2$ *per se*.

**All of the values shown in the tables were obtained by using 8-decimal-place probability figures throughout the calculations and doing the final rounding at the end. This pseudoaccuracy was used merely to check on the closeness of agreement of ΣQ_i with Q_T.

†F_i is the probability of failure on Trial 2, given a failure on Trial 1, and F_j is the probability of failure on Trial 1 given α, ϵ, or $1 - \epsilon$.

TABLE V

The Failure Paths Due to Human Error

Left Branch	Middle Branch	Right Branch
$L = \alpha A_1B_1(1 - \beta_2)$	$L' = (1 - \alpha)\gamma_1\epsilon_1A_1B_1(1 - \gamma_2)$	$L'' = (1 - \alpha)\gamma_1(1 - \epsilon)A_1B_1(1 - \gamma_2)$
$M = \alpha A_1B_1\beta_2A_2B_2$	$M' = (1 - \alpha)\gamma_1\epsilon A_1B_1\gamma_2A_2B_2$	$M'' = (1 - \alpha)\gamma_1(1 - \epsilon)A_1B_1\gamma_2A_2B_2$
$N = \alpha A_1B_1\beta_2(1-A_2B_2)C_2$	$N' = (1 - \alpha)\gamma_1\epsilon A_1B_1\gamma_2(1-A_2B_2)E_2$	$N'' = (1 - \alpha)\gamma_1(1 - \epsilon)A_1B_1\gamma_2(1-A_2B_2)G_2$
$R = \alpha A_1B_1\beta_2(1-A_2B_2)c_2D_3D_4$	$R' = (1 - \alpha)\gamma_1\epsilon A_1B_1\gamma_2(1-A_2B_2)e_2F_3F_4$	$R'' = (1 - \alpha)\gamma_1(1 - \epsilon)A_1B_1\gamma_2(1-A_2B_2)g_2H_3H_4$
$S = \alpha(1-A_1B_1)C_1(1 - \beta_2)$	$S' = (1 - \alpha)\gamma_1\epsilon(1-A_1B_1)E_1(1 - \gamma_2)$	$S'' = (1 - \alpha)\gamma_1(1 - \epsilon)(1-A_1B_1)G_1(1 - \gamma_2)$
$T = \alpha(1-A_1B_1)C_1\beta_2A_2B_2$	$T' = (1 - \alpha)\gamma_1\epsilon(1-A_1B_1)E_1\gamma_2A_2B_2$	$T'' = (1 - \alpha)\gamma_1(1 - \epsilon)(1-A_1B_1)G_1\gamma_2A_2B_2$
$U = \alpha(1-A_1B_1)C_1\beta_2(1-A_2B_2)C_2$	$U' = (1 - \alpha)\gamma_1\epsilon(1-A_1B_1)E_1\gamma_2(1-A_2B_2)E_2$	$U'' = (1 - \alpha)\gamma_1(1 - \epsilon)(1-A_1B_1)G_1\gamma_2(1- A_2B_2)G_2$
$V = \alpha(1-A_1B_1)C_1\beta_2(1-A_2B_2)c_2D_3D_4$	$V' = (1 - \alpha)\gamma_1\epsilon(1-A_1B_1)E_1\gamma_2(1-A_2B_2)e_2F_3F_4$	$V'' = (1 - \alpha)\gamma_1(1 - \epsilon)(1-A_1B_1)G_1\gamma_2(1-A_2B_2)g_2H_3H_4$
$W = \alpha(1-A_1B_1)c_1D_1D_2(1 - \beta_2)$	$W' = (1 - \alpha)\gamma_1\epsilon(1-A_1B_1)e_1F_1F_2(1 - \gamma_2)$	$W'' = (1 - \alpha)\gamma_1(1 - \epsilon)(1-A_1B_1)g_1H_1H_2(1 - \gamma_2)$
$X = \alpha(1-A_1B_1)c_1D_1D_2\beta_2A_2B_2$	$X' = (1 - \alpha)\gamma_1\epsilon(1-A_1B_1)e_1F_1F_2\gamma_2A_2B_2$	$X'' = (1 - \alpha)\gamma_1(1 - \epsilon)(1-A_1B_1)g_1H_1H_2\gamma_2A_2B_2$
$Y = \alpha(1-A_1B_1)c_1D_1D_2\beta_2(1-A_2B_2)C_2$	$Y' = (1 - \alpha)\gamma_1\epsilon(1-A_1B_1)e_1F_1F_2\gamma_2(1-A_2B_2)E_2$	$Y'' = (1 - \alpha)\gamma_1(1 - \epsilon)(1-A_1B_1)g_1H_1H_2\gamma_2(1-A_2B_2)G_2$
$Z = \alpha(1-A_1B_1)c_1D_1D_2\beta_2(1-A_2B_2)c_2D_3D_4$	$Z' = (1 - \alpha)\gamma_1\epsilon(1-A_1B_1)e_1F_1F_2\gamma_2(1-A_2B_2)e_2F_3F_4$	$Z'' = (1 - \alpha)\gamma_1(1- \epsilon)(1-A_1B_1)g_1H_1H_2\gamma_2(1-A_2B_2)g_2H_3H_4$

TABLE VI

Equations for Q_i*

$$Q_1 = L + \frac{A_1B_1M}{A_1B_1 + A_2B_2} + \frac{A_1B_1N}{A_1B_1 + C_2} + \frac{A_1B_1R}{A_1B_1 + D_3D_4}$$

$$Q_2 = S + \frac{C_1T}{C_1 + A_2B_2} + \frac{C_1U}{C_1 + C_2} + \frac{C_1V}{C_1 + D_3D_4}$$

$$Q_3 = W + \frac{D_1D_2X}{D_1D_2 + A_2B_2} + \frac{D_1D_2Y}{D_1D_2 + C_2} + \frac{D_1D_2Z}{D_1D_2 + D_3D_4}$$

$$^{**}Q_4 = \frac{(1 - \beta_2)L}{(1 - \beta_2) + A_1B_1} + \frac{(1 - \beta_2)S}{(1 - \beta_2) + C_1} + \frac{(1 \;\; \beta_2)W}{(1 - \beta_2) + D_1D_2}$$

$$Q_5 = \frac{A_2B_2M}{A_2B_2 + A_1B_1} + \frac{A_2B_2T}{A_2B_2 + C_1} + \frac{A_2B_2X}{A_2B_2 + D_1D_2}$$

$$Q_6 = \frac{C_2N}{C_2 + A_1B_1} + \frac{C_2U}{C_2 + C_1} + \frac{C_2Y}{C_2 + D_1D_2}$$

$$Q_7 = \frac{D_3D_4R}{D_3D_4 + A_1B_1} + \frac{D_3D_4V}{D_3D_4 + C_1} + \frac{D_3D_4Z}{D_3D_4 + D_1D_2}$$

$$Q_8 = L' + \frac{A_1B_1M'}{A_1B_1 + A_2B_2} + \frac{A_1B_1N'}{A_1B_1 + E_2} + \frac{A_1B_1R'}{A_1B_1 + F_3F_4}$$

$$Q_9 = S' + \frac{E_1T'}{E_1 + A_2B_2} + \frac{E_1U'}{E_1 + E_2} + \frac{E_1V'}{E_1 + F_3F_4}$$

$$Q_{10} = W' + \frac{F_1F_2X'}{F_1F_2 + A_2B_2} + \frac{F_1F_2Y'}{F_1F_2 + E_2} + \frac{F_1F_2Z'}{F_1F_2 + F_3F_4}$$

$$^{**}Q_{11} = \frac{(1 - \gamma_2)L'}{(1 - \gamma_2) + A_1B_1} + \frac{(1 - \gamma_2)S'}{(1 - \gamma_2) + E_1} + \frac{(1 - \gamma_2)W'}{(1 - \gamma_2) + F_1F_2}$$

$$Q_{12} = \frac{A_2B_2M'}{A_2B_2 + A_1B_1} + \frac{A_2B_2T'}{A_2B_2 + E_1} + \frac{A_2B_2X'}{A_2B_2 + F_1F_2}$$

$$Q_{13} = \frac{E_2N'}{E_2 + A_1B_1} + \frac{E_2U'}{E_2 + E_1} + \frac{E_2Y'}{E_2 + F_1F_2}$$

$$Q_{14} = \frac{F_3F_4R'}{F_3F_4 + A_1B_1} + \frac{F_3F_4V'}{F_3F_4 + E_1} + \frac{F_3F_4Z'}{F_3F_4 + F_1F_2}$$

$$Q_{15} = L'' + \frac{A_1B_1M''}{A_1B_1 + A_2B_2} + \frac{A_1B_1N''}{A_1B_1 + G_2} + \frac{A_1B_1R''}{A_1B_1 + H_3H_4}$$

$$Q_{16} = S'' + \frac{G_1T''}{G_1 + A_2B_2} + \frac{G_1U''}{G_1 + G_2} + \frac{G_1V''}{G_2 + H_3H_4}$$

$$Q_{17} = W'' + \frac{H_1H_2X''}{H_1H_2 + A_2B_2} + \frac{H_1H_2Y''}{H_1H_2 + G_2} + \frac{H_1H_2Z''}{H_1H_2 + H_3H_4}$$

$$^{**}Q_{18} = \frac{(1 - \gamma_2)L''}{(1 - \gamma_2) + A_1B_1} + \frac{(1 - \gamma_2)S''}{(1 - \gamma_2) + G_1} + \frac{(1 - \gamma_2)W''}{(1 - \gamma_2) + H_1H_2}$$

$$Q_{19} = \frac{A_2B_2M''}{A_2B_2 + A_1B_1} + \frac{A_2B_2T''}{A_2B_2 + G_1} + \frac{A_2B_2X''}{A_2B_2 + H_1H_2}$$

$$Q_{20} = \frac{G_2N''}{G_2 + A_1B_1} + \frac{G_2U''}{G_2 + G_1} + \frac{G_2Y''}{G_2 + H_1H_2}$$

$$Q_{21} = \frac{H_3H_4R''}{H_3H_4 + A_1B_1} + \frac{H_3H_4V''}{H_3H_4 + G_1} + \frac{H_3H_4Z''}{H_3H_4 + H_1H_2}$$

*The first term in the denominator or numerator in the fraction in equation is the error term for that Q_i.

**These equations are provided for reference purposes. See discussion in text.

TABLE VII

Hypothetical Q_i Values and Rank Order from High to Low

Q_i Rank*						Error Rank	
L	H	Q_i	and Value**	Error Term	Error Rate**	L	H
-	-	Q_1	.00005414	$A_1B_1 \| \alpha$	3×10^{-4}	-	-
2	3	Q_2	.00036492	C_1	2×10^{-3}	6	9
6	8	Q_3	.00000898	D_1D_2	5×10^{-5}	9	12
-	-	Q_4	.00041922	$(1 - \beta_2)$	.2	-	-
-	-	Q_5	.00000010	$A_2B_2 \| \alpha$	3×10^{-4}	-	-
7	9	Q_6	.00000478	C_2	4×10^{-3}	5	8
9	10	Q_7	.00000048	D_3D_4	8×10^{-4}	7	10
-	-	Q_8	.00001216	$A_1B_1 \| \epsilon$	3×10^{-4}	-	-
4	2	Q_9	.00008115 .00083322	E_1	2×10^{-3}, 2×10^{-2}	6	6
8	5	Q_{10}	.00000202 .00020022	F_1F_2	5×10^{-5}, 5×10^{-3}	9	7
-	-	Q_{11}	.00009482 .00098718	$(1 - \gamma_2) \| \epsilon$	.5	-	-
-	-	Q_{12}	.00000001	$A_2B_2 \| \epsilon$	3×10^{-4}	-	-
10	7	Q_{13}	.00000027 .00002912	E_2	4×10^{-3}; 4×10^{-2}	5	5
12	6	Q_{14}	.00000003 .00006500	F_3F_4	8×10^{-4}; 8×10^{-2}	7	4
-	-	Q_{15}	.00000135	$A_1B_1 \| 1 - \epsilon$	3×10^{-4}	-	-
1	1	Q_{16}	.00050739 .00110628	G_1	.1, .2	3	3
4	4	Q_{17}	.00008369 .00031975	H_1H_2	2×10^{-2}; 8×10^{-2}	4	4
-	-	Q_{18}	.00045410 .00089221	$(1 - \gamma_2) \| (1 - \epsilon)$	.5	-	-
-	-	Q_{19}	.000000001	$A_2B_2 \| (1 - \epsilon)$	3×10^{-4}	-	-
5	4	Q_{20}	.00007495 .00033634	G_2	.2, .4	2	2
3	3	Q_{21}	.00010757 .00047164	H_3H_4	.32, .8	1	1
5	6	Q_{22}	.00006765	A_1B_1	3×10^{-4}	8	11
11	11	Q_{23}	.00000011	A_2B_2	3×10^{-4}	8	11

*L refers to the rank order based on lower estimates of Q_i values or error terms, while H refers to rank order based on the higher estimates. Ranking is based on rounded first significant number. Ranks are not given for $(1 - \beta_2)$, and both $(1 - \gamma_2)$ terms as these are not human errors and their effects have been included in Trial 1 error terms as discussed in the text. Ranks are given for the complete A_1B_1 and A_2B_2 terms but not for their parts because our interest is in the error terms *per se*.

**Where two numbers appear, the first is the lower estimate and the second is the higher. The values have been carried to 8-decimal places, merely to aid anyone who wishes to calculate Q_i values as an exercise.

TABLE VIII

Ranks of High and Low Hypothetical Q_i Values

Low Range			High Range			
Q_i Rank	Error Term	Q_i Value	Q_i Rank	Error Term	Q_i Value	Factor of Increase*
1	G_1	5×10^{-4}	1	G_1	10^{-3}	2
2	C_1	4×10^{-4}	2	E_1	8×10^{-4}	10
3	H_3H_4	10^{-4}	3	H_3H_4	5×10^{-4}	5
4	E_1	8×10^{-5}	4	C_1	4×10^{-4}	0
4	H_1H_2	8×10^{-5}	5	H_1H_2	3×10^{-4}	4
5	G_2	7×10^{-5}	5	G_2	3×10^{-4}	4
5	A_1B_1	7×10^{-5}	6	F_1F_2	2×10^{-4}	100
6	D_1D_2	9×10^{-6}	7	A_1B_1	7×10^{-5}	0
7	C_2	5×10^{-6}	7	F_3F_4	7×10^{-5}	>70
8	F_1F_2	2×10^{-6}	8	E_2	3×10^{-5}	>30
9	D_3D_4	$< 10^{-6}$ **	9	D_1D_2	9×10^{-6}	0
9	E_2	$< 10^{-6}$	10	C_2	5×10^{-6}	0
9	A_2B_2	$< 10^{-6}$	11	A_2B_2	$< 10^{-6}$	0
10	F_3F_4	$<< 10^{-6}$ **	11	D_3D_4	$< 10^{-6}$	0
		$\Sigma Q_i = 1.3 \times 10^{-3}$			$\Sigma Q_i = 3.7 \times 10^{-3}$ ***	

*The increase in Q_i values as a function of going from low to high range.

**In most human factors applications, one is not justified in expressing any greater accuracy than $< 10^{-6}$ or $<< 10^{-6}$ to indicate, respectively, $< 10^{-6} \geq 10^{-7}$ and $< 10^{-7}$.

***The correct answer is 3.8×10^{-3}. The difference is due to rounding errors.

Discussion of Q_i Values

The ranking of Q_i values shows the weakest human link very clearly. This is the pilot's reception of the code. If one sums the Q_i values for the pilot's reception terms (C_1, C_2, E_1, E_2, G_1, G_2), this conclusion becomes abundantly clear. This sum for the low-range values is approximately 10^{-3} and for the high-range values is approximately 2.5×10^{-3}. These sums constitute roughly from two-thirds to three-quarters* of the total system degradation resulting from human error. But if only the pilot's reception in the air is considered, reception errors (E_1, E_2, G_1, G_2) account for roughly one-half to two-thirds of the total system degradation due to human error. If this amount of degradation were considered unacceptable, then system planners would undoubtedly seek ways either to increase the reliability of the pilot's reception, to bypass him, or change the system in some other way, such as eliminating the requirement to receive the code in the air. The latter

*In discussing Q_i values, it is necessary to keep in mind that our best estimate of certain of the Q_i values is a range of values.

change, of course, would pay high dividends inasmuch as it would reduce the system failure rate brought about by $(1 - \alpha)(1 - \gamma_1)$, i.e., a nonhuman contribution of .01 to system failure. But such gains would have to be balanced against the loss of flexibility introduced by a requirement to receive the code on the ground.

It is interesting to note that the G terms alone constitute roughly one-third of the total system degradation due to human error, and this despite the fact that the right-hand third of the events in the probability tree (which contain the G terms) are estimated to occur with a probability of only $(1 - \alpha)\gamma_1(1 - \epsilon) \approx .009$, or roughly one time in a hundred. It is the experience at Sandia Corporation that uncovering the sometimes unexpected system importance of low probability events is one major benefit from taking the time to set down a complete probability tree and working out the probabilities for each branch. There is an all-too-common tendency to dismiss low probability events, such as the right-hand third of Figure 2, as being unimportant. The use of the probability tree can bring biases and preconceptions back into line with reality.

In making the recommendations for reducing Q_T to some acceptable level, one would have to remember that the Q_T estimated for the hypothetical example is for <u>each</u> system. If one were trying to estimate the total degradation resulting from human errors for <u>all</u> of the systems, he would, of course, have to take into account the estimated number of systems in operation and would have to decide how to assign the probabilities denoted by Greek symbols in Table III to each of these systems and then how to combine these probabilities appropriately for estimating degradation for all of the systems. For example, some of these probabilities might pertain to one, a few, or many of the systems. Obviously, the single estimated degradation for all systems would be greatly affected by such relationships.

CHAPTER IV

SUMMARY AND CONCLUSIONS

A technique (THERP) is used to predict human-error rates in a man-machine system and to estimate quantitatively the degradation to the system or any part of it likely to be caused by or associated with the human element. Although the technique is quantitative in nature, its application requires many qualitative judgments by persons who are trained and experienced in the psychology of human behavior. However, the close agreement in predictions obtained by two users of THERP indicates that the judgments that are required may not unduly reduce the consistency of the technique itself. The validity of predictions made with THERP is another question. Very little work has been done in this area, but here, too, there is some evidence that, at least for many applications, validity of the technique and its predictions is adequate. THERP is in its infancy, however, and there is an urgent need for a large data bank of human-error rates taken from operational use and practice exercising of man-machine systems and from the entire manufacturing process related to weapon systems. Along with this need, there is a requirement for continually validating the method and the data upon which it depends.

Several classified applications of THERP have been made to estimate the reliability loss resulting from human errors in selected Air Force aircraft/nuclear-weapon systems. These applications have shown a number of human-factors problems and have led to suggestions for revising equipment, procedures, and operations which should reduce these problems to an acceptable level. Even though, in these applications, no attempt has been made to claim more accuracy of prediction than a factor of five for tasks performed under normal operational stress (and an order of magnitude accuracy for tasks performed under high-stress conditions), the results of the human-factors reliability analyses have been accepted and recognized by a number of designers and military planners as having value in system planning.

Finally, the mere attempt to be quantitative forces one to avoid vagueness and to be concrete in thinking about human performance. In applying THERP to analyze man-machine system reliability, Sandia human-factors specialists have often been forced to decide, sometimes to their surprise, that although certain design features deviated considerably from accepted human-engineering practices, their effect upon system reliability would not be important. (Of course, one should strive for as good a human-engineered design as possible, consistent with other system considerations.) Thus, the quantitative approach has forced them to pay more than mere lip service to systems considerations. Perhaps all of us in the human-factors field can benefit from this kind of quantitative approach.

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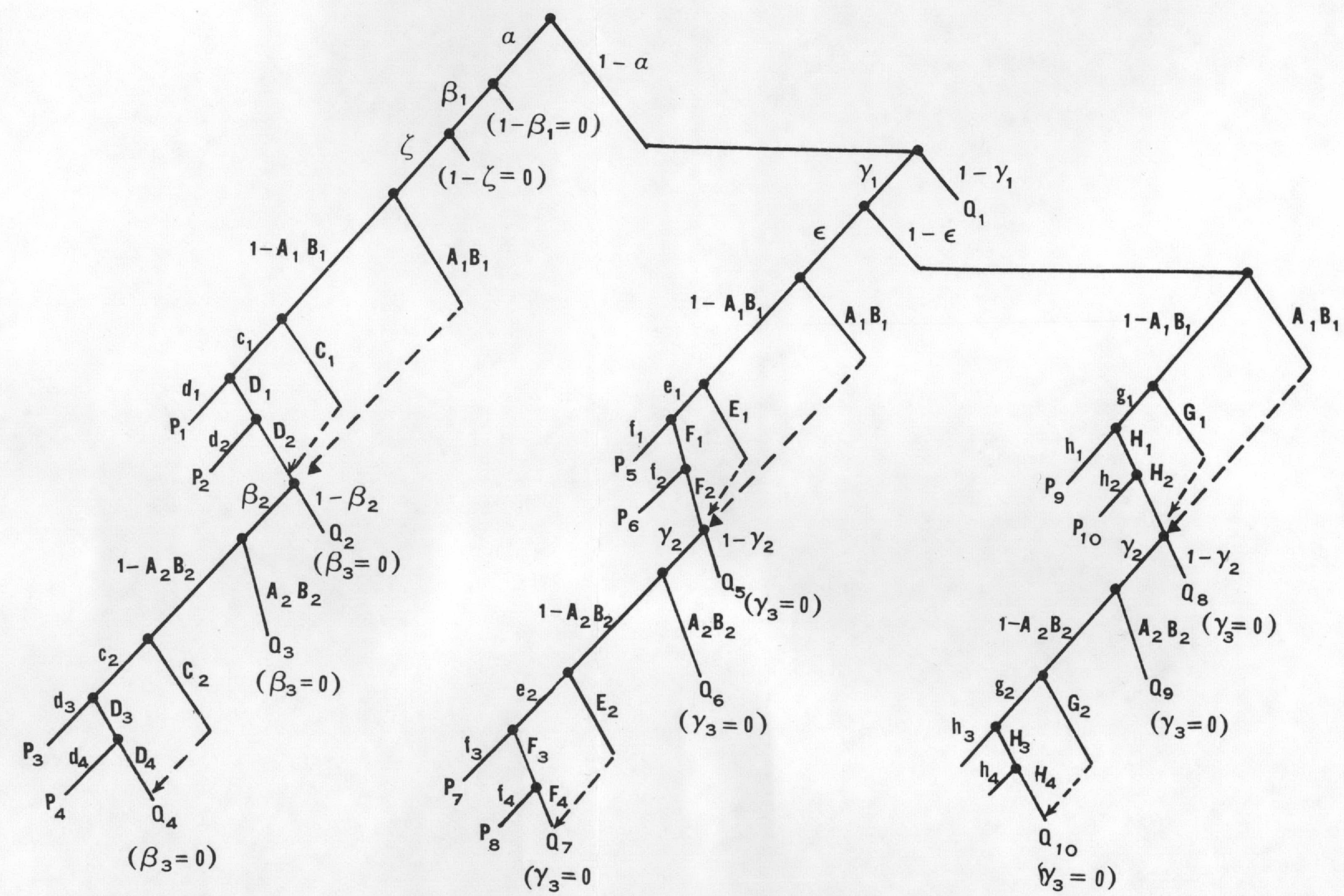
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