SCTM 93-62(14)

REDUCTION OF HUMAN ERROR IN INDUSTRIAL PRODUCTION

L. W. Rook, Jr., 1443

ABSTRACT

Within the field of nuclear ordnance there is emphasis upon both high reliability and a "no field test" design philosophy. The result of this is that human error in design and production assumes high importance with respect to nuclear weapon system degradation. An initial approach to reducing degradation from these sources has been made within Sandia Corporation by the construction of a model of human error which possesses validity with respect to both psychological concepts and operational procedures.

The model consists of two cross-cutting systems of classification, each with three categories. One system is essentially that reported by Payne and Altman in their "An Index of Equipment Operability" while the other is of our own devising and is based on the intent of the perpetrator of the error. This latter can seldom be ascertained directly, but can usually be implied from the evidence available. The two classification schemes combine to produce nine subcategories or error modes, each with unique properties which have value in diagnosing the causes of error. Error frequencies within each of these modes are combined with system parameters to produce a quantitative model which provides both evaluation of system performance and an estimate of the contribution of each potential error to system degradation.

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IN INDUSTRIAL PRODUCTION

I. QUALITATIVE CONSIDERATIONS

Training, Attitudes and Workmanship

Much has been written about the importance of workmanship in industrial production, but there are few concrete suggestions for improving it. Most suggestions have approached workmanship under the assumption that good workmanship is primarily a function of attitudes, training, and pride in work. No doubt such factors do influence quality of workmanship, but there is reason to believe that attitudes and training have received more than their fair share of emphasis as influencing factors. Under certain circumstances, the variability in the quality of workmanship resulting from nonattitudinal and nontraining factors is much greater than the variability resulting from quality of attitude and level of training. That is, while attitude and training do influence the quality of workmanship, other factors often influence it more.

For example, let us imagine a particular assembly operation in which errors are being measured as a function of such things as training or attitude. Typically, we find a relationship of the sort shown by the solid line in Figure 1.* Any influence which will change motivation upward from approximately average toward excellent will result in relatively small decreases in errors, while downward changes in the direction of poor training or motivation will result in very large increases in errors. It will be seen from this relationship that if factors such as motivation and training are in the range of average, as they usually are, only relatively minor improvements in workmanship can be affected by an upward change in such factors.

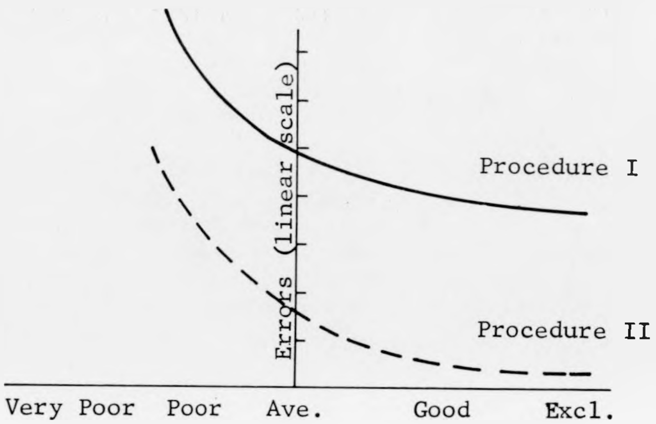

Figure 1. Typical Relationships Between Such Factors as Training and Attitudes on Production Errors

*The relationships illustrated in Figure 1 do not represent actual measurements of any particular procedures, but are representative of the sort of relationships that are typically found when such factors are investigated experimentally. They are presented here only to illustrate qualitatively the points to be discussed. (See Ryan, T. A., and Smith, P. C., Principles of Industrial Psychology, New York, The Ronald Press Co., 1954, Chapters 14 through 17.)

If really large changes are desired, some alternative method must be used. One such method is illustrated by the difference between the solid and the dotted lines in Figure 1. These two lines have the same general shape and slope, but the dotted line representing an alternative procedure is everywhere much lower on the error coordinate than its counterpart which represents Procedure I. This is to say that Procedure II, as a whole, is much less error-likely than Procedure I. Now, if these two systems represent two procedures for manufacturing the same product, it will be seen that, if we were using Procedure I, we could effect a much larger improvement in workmanship by going to Procedure II than we could by increasing the level of training and motivation while retaining Procedure I. Changes such as are represented by going from Procedure I to Procedure II can often reduce errors several orders of magnitude, while error reductions from training and motivational factors alone seldom exceed factors of three or four.

Two conclusions can be drawn:

1. It is almost always worthwhile to expend effort in improving training, motivation, and attitudes, until most of the work force is brought up in these factors to the general industrial average level. However, it is doubtful whether further improvement in workmanship (reduction in errors) can be obtained economically by further training and motivational efforts until the production procedures have been analyzed in terms of the factors which affect human error.

2. If the psychological factors of training and motivation are approximately at the average level, further substantial decreases in human errors can probably be obtained only by modification of the production procedures to minimize the probabilities of such errors. Ideally, both of these approaches should be used simultaneously.

The Human Factors Approach

One of the principal reasons why the workmanship problem is so difficult to assess and solve is that we do not really know what workmanship is. More specifically, we do not really know what constitutes good workmanship. The human factors approach to the workmanship problem eliminates the need for defining good workmanship, by asking different questions, which are rephrased from "What is good workmanship?" to "What are the modes of human error?" and "What are the parameters which affect error rates within these modes?" This approach to the problem has proved very useful in the field of human engineering where equipment operator error is not treated in terms of good or bad performance, but merely in terms of error rates and the factors which influence them. Moreover, this approach has been profitably extended to human engineering of electronic maintenance operations. It seems that this same approach can be profitably used to reduce human errors in industry. Such an approach must be capable of being incorporated into conventional industrial production and quality control procedures without extensive modification of these procedures. The method outlined in this paper is designed to meet these requirements.

Attitudes Toward Human Error

Before proceeding further it may be profitable to discuss some common attitudes toward human error. Writers who discuss workmanship often go to great lengths to avoid use of words such as "poor," "bad," and "faulty," in describing the kind of human behavior they wish to talk about. They feel that it is necessary to avoid these terms because of their value loading. There is really no way to describe this kind of behavior which is not value loaded. Human behavior which results in desirable output has been so firmly associated with the idea of "good," and the reverse with "bad," that there is practically no way to discuss the problem without making it a question of morals.

Words such as "human error" and "poor workmanship" are used here without any moral or ethical overtones. We are talking about an observed phenomenon which degrades the quality of our products. We consider that this phenenomon can best be approached with the same objectivity that is used in any comparable situation involving a source of degradation which is purely hardware in nature. We are forced to use value-loaded words because the language does not provide any other kind except by awkward circumlocution; this very fact is probably a clue to the reason why an objective approach to this problem is so difficult for many people.

Qualitative Considerations

To test the compatibility of the human factors approach with the established methods of quality control, we analyzed approximately 23,000 production defects observed in many aspects of nuclear weapon production. Our main data sources were defects reported in the manufacture of several major components built at the plant of an AEC prime contractor, and final weapon assembly defects detected in the Quality Evaluation Systems Test program of Sandia Corporation. Of the approximately 23,000 production defects considered, 82 percent, or about 19,200, were directly caused by human error. In our examination of these defects, we constantly asked the question, "What did the operator do to cause this error?" in an attempt to reconstruct the operator's behavior. We sometimes found that it was impossible to determine accurately this behavior from the written report of the defect. In many of these cases we talked with inspectors and production people who frequently were able to explain the kind of behavior involved in the production of errors. There were, of course, a few instances in which it was impossible to isolate the cause of error.

Behavior Categories

After looking at many thousands of defect reports we found that most of the defects could be considered, from a psychological standpoint, to be the result of three fundamentally different kinds of acts. We were unable to devise completely unambiguous names, so we have used the letters A, B, and C, to identify them.

Type A errors result from acts performed by the operator at the conscious level with the belief that the result of the act will be within the correct limits of performance, but the results of which are actually outside acceptable limits.

Type B errors result from acts which are not consciously performed.

The essential distinction between these two classes of error is one of conscious awareness by the operator. In performing a Type A error, the operator <u>intends</u> to perform the act correctly, but erroneously performs it out of limits. In performing a Type B error, there is no element of <u>intent</u> in the performance of the act; it "just happens."

A third type of error occurs when an act is completely omitted. While such acts are unintentional, and thus logically form a sub-class of Type B, they are influenced by factors different from those relevant to Type B errors. For this reason, omissions were assigned a separate category and called Type C errors. The way in which these three error categories can be used will be discussed later; first, another system of error classification will be described which cross-cuts the A, B, and C system.

Behavior Aspects and Components

In this cross-cutting system of error classification, we followed the plan reported by Payne and Altman* of the American Institute of Research (AIR) who placed all typical behaviors of electronic equipment operators into three classes: input behaviors, mediating behaviors, and output behaviors. Such classes of behavior they called aspects of behavior, which were further analyzed into smaller units called behavior components.

When we analyzed our production error data, using this conceptual framework, we found that some of the components of the AIR research were applicable, but that many of the errors with which we were dealing occurred during acts which required additional components for their description. The new components which we found necessary, together with those from the AIR study which were applicable, are given in Tables I, II, and III.

Table I gives the three input behavioral components which provide practically all of the behavioral inputs used by the production operator. These input components are pictorial or symbolic displays which normally take the form of written material or visual aids; color codes which may be used on hardware, such as resistors and wires; and labeling, such as that found on part bins, and on some parts themselves, such as capacitors.

The situational parameters which affect performance with respect to each of these input components are listed in the right-hand column under the heading, "Parameters." We see, for instance, opposite "Pictorial Displays," that the complexity, the legibility and the use of color in the pictorial or written display will significantly affect the accuracy with which the operator uses the display as an input behavior component.

In a similar manner, opposite "Labeling," it will be seen that the number of symbols (indicated as the span of digits or words), the legibility of the labeling, and the size of the printing used in the labeling, all significantly affect performance of the operator when using labeling as an input component. The input components which we have listed here are all visual in nature. If the use of audiovisual aids were to become common, it would be necessary to add at least one more input component which would, of course, be auditory in nature.

TABLE I

Input Components

Components	Parameters
Pictorial (symbolic) displays	Complexity Legibility Use of color (not as code)
Color codes	Number of different colors Comparison standard, present or absent

Labeling**	Span
	  Digits
	  Words
	Legibility
	Size of printing

*Payne, Dan, and Altman, James W., An Index of Electronic Equipment Operability, AIR-C-43-1/62, American Institute for Research, 1962.

**From Payne and Altman.

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TABLE II

Mediating Components

Components	Parameters
Quantitative judgment	Standard present or absent Time or space judgment Required accuracy
Identification/Recognition*	Discrimination Recall Comparison (mental)
Manipulation (mental)*	Numerical Nonnumerical

TABLE III

Output Components

Components	Parameters
Probe-like tools	Length Weight Required action Required force
Pincer-like tools	Length Weight Required action Required force
Transfer of force tools	Length Weight Required force
Cable connections*	Required force Locking method Number of pins Use of tools
Cable disconnections*	Required force Locking method Use of tools
Object positioning*	Weight of object Size of object Fragileness of object Locking method Force required Use of tools
Writing*	Number of words Number of digits Familiarity of material Dispersion (one form versus many)

*From Payne and Altman

Consideration of the three sets of behavioral components shows that the input components are concerned primarily with behavior associated with sensory activity; that is, associated with perceptual behavior. The second behavioral aspect, that consisting of mediating components, is composed of those kinds of behavior which we normally associate with the process of thinking, while the third aspect, that of outputs, is normally considered as motor behavior. These two latter aspects are divided into components in a manner similar to that of the input aspect. Any single act of the production operator would normally be composed of components from all three of the aspects; that is, acts usually begin with some input component which is followed by some mediational activity which is then followed by some motor behavior or output. The final result of the act can be affected by errors at any one of these stages, and the nature of the error will depend upon where in the sequence of events the error actually occurred. Errors which occur as a part of an input component we call Type I errors, errors which occur in the mediational process, we term Type M, and those which occur in the output process we call Type O.

With these two co-existing systems, one based upon a categorization of types of acts and the other upon types of behavior, we have a means for classifying errors in terms of the sequence of elements which constitute almost all acts and, also, in terms of some of the psychological factors which influence error rates. Although, at first, this method of classification may seem unwieldy, the nature of most defects permits ready classification of the error in terms of the system.

For example, if we find a defect which consists of the reversal of two wires in an electrical connector, and we find that one of the wires has a purple tracer while the other has a blue tracer, we can be reasonably certain that the error resulted from a confusion of these two colors. The act during which this occurred is obviously intentional and the error is perceptual or input. Thus, it is a Type A error with respect to the first system of classification, and a Type I error with respect to the second.

Let us consider another example, that of an instance of burned insulation resulting from contact between the soldering iron and the insulation of a wire. The actual motor behavior which brought the soldering iron in contact with the wire was certainly not intentional on the part of the operator. Thus, the classification in the first system is Type B. Similarly, since the error resulted from motor behavior, it is, in the second system, a Type O error.

The entire system of error classification is summarized in Table IV. We wish to emphasize that this system of classification is not proposed as a means of explaining the cause of human error, but merely as a means of subdividing the phenomenon of human error into categories which are both manageable and suggestive of corrective action to be taken. Some errors may fall logically into two or more categories and some categories may contain few (or no) errors. As will be seen, however, the utility of the system is not affected. It should also be kept in mind that the purpose is not to eliminate human error (usually an impossible task), but merely to reduce it, in critical situations, to acceptable levels.

TABLE IV

System of Error Categories

Errors due to acts which are	Errors due to behavior components of		
	Input (I)	Mediation (M)	Output (O)
A -- Intentionally performed	AI	AM	AO
B -- Unintentionally performed	BI	BM	BO
C -- Omitted	CI	CM	CO

Use of the System as an Aid in Improving Workmanship

Although the system of error classifications has quantitative aspects which will be described later, the qualitative aspects of mere classification can serve as aids in the reduction of error rates. This is true because of the defining characteristics which are unique for each category. Once a particular error has been placed in an error category, reference to the definition of that category and the relevant parameters suggests what action should be taken to reduce the frequency of the error.

The general rules are these. If the error is of Type A, corrective action will be effective if it provides some means for letting the operator know that the act has been performed (or is being performed) out of limits. If the error is of Type B, two courses of action can be taken:

1. The situation can be modified so that the unintentional act will not produce an out-of-limits condition, or

2. The situation can be modified to provide a warning at the critical time that the unintentional act should be guarded against.

If the error is Type C, only the second of the two alternative fixes for a Type B error can usually be used, since, normally, no modification of the situation can prevent an omitted act from producing an out-of-limits condition.

The second system of error classification serves to point out that part of the behavioral sequence of acts to which the fix should be applied. Out-of-limits conditions which occur as the result of input errors will, in general, be reduced in frequency by appropriate modification of that part of the situation which provides the misinterpreted input information. Similarly, mediational errors can usually be reduced in frequency by providing better standards against which the results of the act can be compared. Visual aids, particularly color photographs, are of great value in providing standards of this sort. The parameters associated with each error component are the situational variables which should always be investigated first.

It is perhaps appropriate here to explain why integrated audio-visual systems can produce such striking improvement in workmanship if the programs are prepared carefully. The audio channel provides an ideal means for bringing into conscious awareness the fact that the process is approaching a condition in which either a Type B or a Type C error will result in an out-of-limits condition. Experiments have shown repeatedly that audible warnings are much more insistent than visual warnings. For this reason it is seldom necessary even to place an auditory warning in the form of a "WARNING!" as it is for a visual warning. The mere giving of an auditory instruction has the attention-getting impact of a very elaborately prepared visual warning. Another advantage of the auditory input is that its impact does not decline with repetition nearly as rapidly as does a visual input. These considerations make the audio channel an ideal means for reducing Type B and Type C errors if the program is prepared with this purpose in mind.

The visual channel, on the other hand, provides an excellent means for reducing errors of Type A. The presentation of a color photograph of the result of a correctly performed act provides a standard against which the operator can continuously make comparisons. The ready availability of a standard removes the necessity for making comparisons against memory images which are bound to change with time. The visual channel is thus an excellent means for reducing errors of Type A, but again only if the program is prepared with this purpose in mind.

A third, somewhat subsidiary advantage of an integrated audio-visual method, is its training value. The manner in which learned material recedes after learning is well known. The classical "forgetting curve" is illustrated in Figure 2 by the broken line. The effect of constant reinforcement of learned material by an integrated audio-visual system is illustrated by the solid line. At each presentation, the material forgotten is again brought into consciousness with the result that there is less loss the next time. The effect is to maintain the level of learning at a remarkably high level throughout the time during which the system is used.

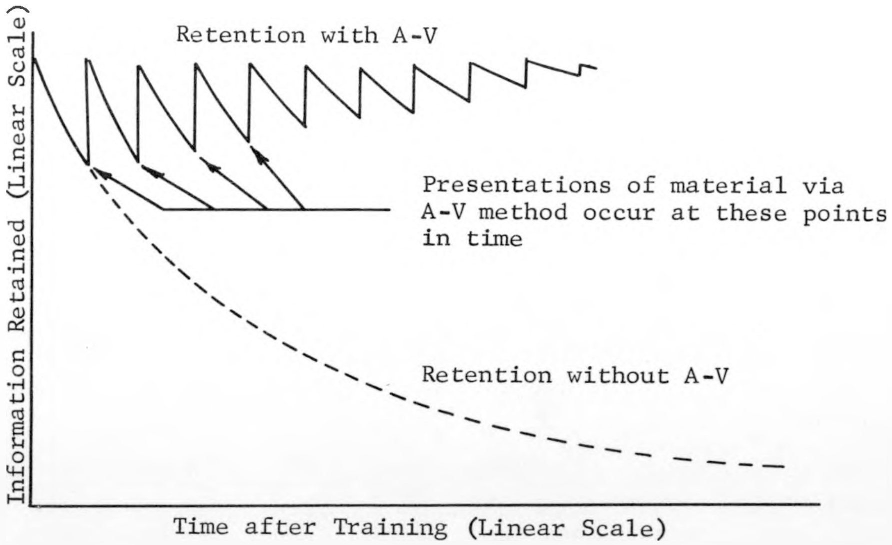


Figure 2. Relative Retention With and Without A-V Method

Sample "Fixes"

Using the examples previously cited, if an operator reverses a pair of wires while making a solder connection to an electrical connector, and if the wires reversed are color coded by, say, purple and blue tracers, an error of Type AI has occurred. The designation AI indicates that the error is the result of an act intentionally, but wrongly, performed, and that the error occurs in the input phase of the act. The most reasonable course of action to eliminate this error is therefore associated with some modification of the input situation which will:

1. Eliminate the possibility that the two wires can be transposed, or, if this is not possible,

2. Reduce the similarity between the two stimuli, purple and blue, or

3. Provide some standard of reference so that the operator will not have to identify either blue or purple from only its memory image.

The other example given, that of inadvertent burning of insulation by accidental contact with a soldering iron, was classified as an error of Type BO. It is thus an output error and is the result of an act unintentionally performed. Since unintentional acts are performed at a subconscious level; no amount of training or appeal to reason, and no quantity of instructions, can effectively prevent them. Such acts are just "emitted." People differ widely in the tendencies to perform such acts; and, if the situation cannot be modified to prevent accidental contact between the soldering iron and the wire in question, it may be necessary to consider such things as modification of the tool itself or selection for this operation of personnel who are not likely to commit acts of this type.

In general, when an error occurs frequently enough to be troublesome, two methods are available to reduce the rate with which it occurs. One is to supply additional inputs to the operator at appropriate times so that these inputs will interact with the error situation in such a way as reduce the likelihood of error. Precautionary notices in production procedures are an example. The other course of action lies in modifying the situation. Changing the order in which an assembly operation occurs, so as to bring components susceptible to damage on to the scene as late as possible, would be an example of this second method. The latter method is to be preferred, but is sometimes not practical.

There is nothing really revolutionary in the proposed scheme of error reduction. It merely breaks down the phenomenon called poor workmanship into discrete manageable parts and classifies them in such a way that the error classification suggests its own fix. In all probability, after the system of classification is used for some time, the kind of trouble diagnosis illustrated in the two previous examples would be accomplished almost automatically without recourse to formal classification of errors, but the system of classification does serve to illustrate the practice by which this diagnosis is most easily accomplished; and it is recommended that formal classification of errors be done initially to prevent the obscuring of error causes by irrelevant considerations.

II. QUANTITATIVE CONSIDERATIONS

The second use which may be made of the error classification system is, unlike the first, quantitative in nature. By using the quantitative aspects of the system, human error reduction can take its place in the over-all quality control program alongside those problems essentially concerned with hardware which have been handled quantitatively for some time. The key to utilizing the system within the present quality control framework lies in thinking of the commission of a particular kind of an error as an attribute of the product.

Of course, the error itself is not truly an attribute of the product, but, rather, the attribute is the defect caused by the error. However, since we must deal with human behavior in terms of defect causation, it is necessary, in the case of human error, to move one step farther back from the product to the interaction between operator and product. In the practical sense, it makes very little difference whether the error resides in the product itself or is considered as the cause of the defect in the product. The standard methods of attributes sampling and attribute evaluation now in use in quality control procedures can be applied without substantial change to the system of error classification here described. What we are proposing is that the statistical procedures now used with data obtained from product attribute measurements be applied to human errors classified according to the procedures described. This involves keeping a record of the relative frequency with which errors occur in each of the error categories. Such a procedure serves a dual purpose. It permits the recording of the critical aspects of workmanship on a time-series basis, analogous to that used in other aspects of quality control, and at the same time provides the production engineer with the information he needs to reduce those human errors which are particularly troublesome.

It will be found useful in this connection to adopt some of the procedures used by the reliability analyst. The effect of various kinds of errors on the product can be determined in a manner similar to the way in which component failure rates are used to predict system failure rates. Such procedures provide the means for evaluating the relationship of each potential error to over-all product quality. They also permit the evaluation of the human error contribution to product degradation in such a way that cost can be compared against potential gain, before production starts. For an ongoing production process, they enable an analysis to be made which will point out where and how effort should be expended to improve product quality.

Wider Applicability of the Method

Although the proposed method was derived primarily from an analysis of electrical assembly defects, it has more general applicability. When extended to other fields, such as mechanical assembly and inspection, it will, of course, be necessary to define new behavioral components to accommodate the acts peculiar to those fields; and, further, it will be necessary to define the parameters associated with those behavioral components. Once such determinations are made, however, almost any human error situation can be analyzed by using the procedures of the method. For this reason, the following discussion of the mathematical procedures presents a somewhat more general perspective.

Quantitative Method

The following method provides a means for quantitatively evaluating the contribution of human error to the degradation of product quality. A failure condition is defined as any condition which, by itself, will result in product failure. Product failure is considered to be any condition of unacceptability. If the product is a component considered alone, this condition might be defined as one in which the component was outside acceptance specifications. For a complete weapon, the evaluation might be performed with an unacceptable condition defined as one in which the weapon will detonate prematurely. Once the failure is defined, values must be assigned to the following variables in terms of that definition, and the ensuing evaluation made with respect to only that definition of failure.

Let P_i represent the probability that a particular operation will result in an error of Class i and that this class of error will result in a failure condition with a probability of F_i. From this it follows that the probability of the existence of a failure condition resulting from a single performance of the operation is F_iP_i. If the operation is performed n_i times in the assembly of the product, each time can result in a failure condition or no failure condition, and the number of failure conditions can range from zero to n_i. But a single failure condition causes product failure; hence, we are interested only in the probability that the n_i operations will result in one or more failure conditions due to errors of Class i.

This probability can most easily be evaluated as one minus the probability of no failure conditions from this source which is given by

$$Q_i = 1 - (1 - F_iP_i)^{n_i} \tag{1}$$

where Q_i is the probability of one or more failure conditions existing as a result of errors of Class i occurring in the n_i operations.

The quantity P_i can represent either the probability of a single error or may be considered a joint probability as when two errors can combine to produce a failure condition. When this latter situation exists

$$P_i = P_1 \cdot P_2 \tag{2}$$

where P_1 and P_2 are the probabilities with which the two errors occur.

If we also consider the effect of another class of errors, Class j, we can evaluate the probability of one or more failure conditions in either or both classes as

$$Q_{ij} = 1 - (1 - Q_i)(1 - Q_j) \qquad (3)$$

and

$$Q_T = 1 - \left[\prod_{k=1}^{N} (1 - Q_k) \right] \qquad (4)$$

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.

The quantity Q_i is the contribution of errors of Class i to Q_T, the total predicted product failure rate from those human errors evaluated. By computing Q_i for each error class and ranking the values in decreasing order of magnitude, a list is obtained which indicates the order of importance of error classes to product quality. Such a list provides a guide for selecting those errors which contribute most to product degradation and which should therefore receive the most attention.

Determination of P_i

The quantity P_i, the probability that a particular operation will result in an error of class i, can be evaluated by referring to information from a number of sources. The most obvious of these is the past record of human performance on this or similar operations. The desirability of maintaining records from which such data may be obtained is obvious. Error rates of some frequently observed electrical assembly errors are given in Appendix C.

Determination of F_i

The value of F_i, the probability that a failure condition will exist, given that an error of class i occurs, will depend upon how the condition "failure" is defined. If this condition is defined as placing the product outside acceptance specifications, F_i can be evaluated by referring to those specifications. If "failure" means premature weapon detonation or weapon dud, it may be necessary to refer to reliability studies of the hardware to determine the effect of the particular error on the weapon.

There is no general method for evaluating F_i. The specific failure definition adopted will dictate how the error will interact with the product to produce failure. This interaction must be analyzed to obtain an estimate of F_i. The best source of data is probably to be found in the record of past rejections of similar items.

Summary of the Method

1. Define the failure with respect to which the evaluation is to be made.

2. Identify and list all human operations performed and their associated errors. The level of specificity of this list may vary from use to use, but in general the more specific the operation descriptions are, the easier it will be to evaluate P_i and F_i.

3. As outlined above, determine P_i and F_i for each error.

4. Compute Q_i for each error class and Q_T for the product (see Appendix A).

5. If Q_T exceeds an acceptable value, refer to error classes with the highest values of Q_i. The error categories (from Part I) in which these errors fall will suggest ways of changing the operations to decrease values of P_i.

6. Adjust P_i values downward by an amount which may be expected from the proposed procedural changes and recompute Q_i and Q_T.

7. Continue changing operations and adjusting P_i values until Q_T is reduced to an acceptable value.

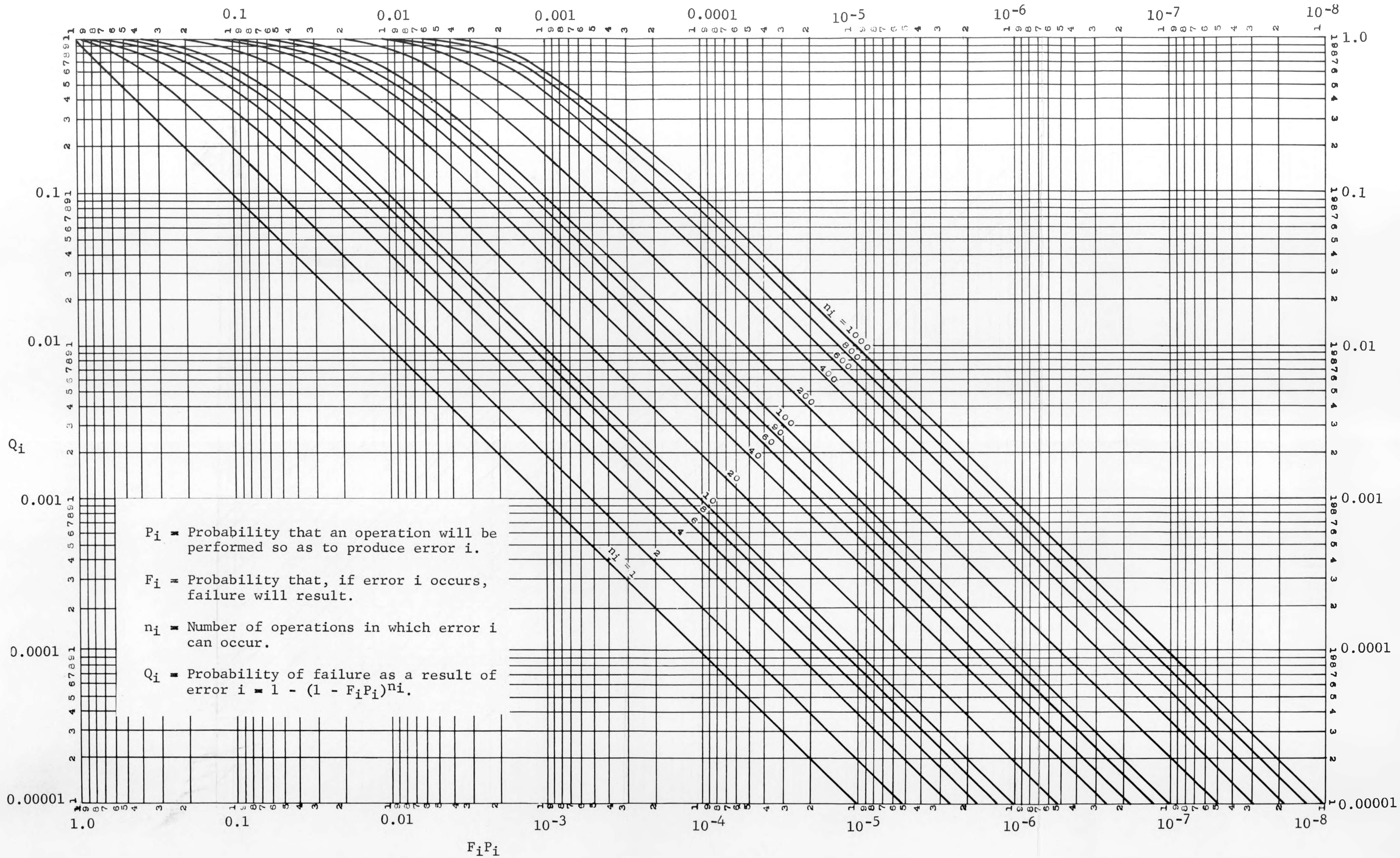
8. As the iterative process of changing procedures and adjusting P_i progresses, cost estimates of the various procedures can be obtained for comparison with the quality gains expected from the proposed changes.

9. The values of P_i finally arrived at suggest upper limits which, when exceeded during production, indicate an out-of-control human process for the operation concerned.

10. Maintain quality control charts of observed values of P_i during production for the more critical (high Q_i) error classes, and occasionally determine P_i for all error classes as a means of monitoring them and of adding to the store of data to be used in future estimations of P_i.

APPENDIX A

GRAPH OF EQUATION FOR Q_i



0.1
0.01
0.001
0.0001
10^{-5}
10^{-6}
10^{-7}
10^{-8}
1.0
0.1
0.01
0.001
0.0001
0.00001
Q_i
$n_i = 1000$
800
600
400
200
100
80
60
40
20
10
8
6
4
2
$n_i = 1$
P_i = Probability that an operation will be performed so as to produce error i.
F_i = Probability that, if error i occurs, failure will result.
n_i = Number of operations in which error i can occur.
Q_i = Probability of failure as a result of error i = $1 - (1 - F_iP_i)^{n_i}$.
1.0
0.1
0.01
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
F_iP_i

APPENDIX B

SAMPLE EVALUATION

The following is a sample evaluation of the contribution of human error in the assembly of a typical component. This unit is a relatively complex electronic device containing approximately 20 subminiature vacuum tubes. Almost all interconnections are by means of printed circuits on six printed-circuit boards. The errors evaluated are those which were actually detected during a carefully observed production run of five weeks.

The values assigned to F_i for the various errors were obtained from the best source available, usually from specialists in the field of concern, such as soldering, capacitors, etc. Since the kind of data necessary for determining F_i has not been methodically gathered as has data concerning P_i, the values of F_i must be considered largely as estimates. As pointed out in the body of this report, if such information were conscientiously gathered, a body of data would soon be accumulated from which values of P_i could be determined for most production errors. Data could also be obtained which could be combined with situational parametersto provide estimates of F_i.

The values used for P_i are the predicted rates at which the various errors are made and not caught by the assembly operator. They thus represent the amount of unreliability which is built into the product. Subsequent testing and inspection must be sufficient to remove enough of the defects to achieve acceptable reliability. No attempt has been made to include the effects of formal testing and inspection. These factors could be included in the evaluation by changing the values of F_i to include the probability that the particular error would go uncaught. The P_i values were obtained from the same sources used to determine the error rates cited in Appendix C.

TABLE I-B

Errors Observed

Symbol	Definition of error	Error rate	Predicted F_i	Predicted n_i
P_1	Soldering operation results in solder splash.	0.001	0.08	596
P_2	Soldering operation results in excess solder.	0.0005	0.00005	596
P_3	Soldering operation results in insufficient solder.	0.002	0.0001	596
P_4	Soldering operation results in hole in solder.	0.07	0.0001	596
P_5	Component is damaged by burn from soldering iron.	0.001	0.05	213
P_6	Two wires which can be transposed are transposed.	0 0006	1.0	22
P_7	A polarized component (diode, etc.) is wired backwards.	0.001	1.0	27
P_8	A capacitor with preferred polarity is wired backwards.	0.001	0.5	24
P_9	A solder joint is omitted.	0.00005	1.0	596
P_{10}	A component is omitted.	0.00003	1.0	213
P_{11}	A component of wrong value is used.	0.0002	1.0	213
P_{12}	A lead is left unclipped.	0.00003	0.01	551
P_{13}	Staking is omitted on fastener.	0.00003	0.0001	48
P_{14}	Staking omitted on adjustment.	0.00003	0.01	11
P_{15}	Small item such as lockwasher is omitted.	0.00003	0.00005	73

TABLE II-B

Errors Ordered by Value of Q_i
(Q_i Determined from Graph in Appendix I)

Q_i and Value	Abbreviated description of error
$Q_1 = 0.045$	Solder splash
$Q_{11} = 0.04$	Wrong value
$Q_7 = 0.022$	Reversal of polarized component
$Q_9 = 0.02$	Omitted solder joint
$Q_6 = 0.012$	Transposed wires
$Q_5 = 0.011$	Damaged component
$Q_8 = 0.011$	Reversed capacitor
$Q_{10} = 0.006$	Omitted component
$Q_{12} = 0.00014$	Un-clipped lead
$Q_3 = 0.00011$	Too little solder
$Q_4 = 0.0001$	Hole in solder
$Q_{13} < 0.00001$	No fastener staking
$Q_{14} < 0.00001$	No adjustment staking
$Q_{15} < 0.00001$	Small item omitted
$Q_2 < 0.00001$	Excess solder

Combining the preceding values of Q_1 in accordance with equation (4) gives

$$Q_T = 1 - \left[\prod_{i=1}^{15} (1 - Q_i) \right] = 0.16$$

This indicates that, if there were no inspection or testing to catch assembly errors, 16 percent of the units would fail from the "built-in" defects alone. If this figure is considered to be unacceptable, the list of errors ordered according to values of Q_i should be consulted as a guide to locating the most important sources of error. Those errors with highest values of Q_i should be classified according to the system discussed in Part I of this report. This classification would suggest where fixes should be applied and what kind of fixes would probably be effective.

Inspection of the errors with high Q_i values shows that four of them are associated with acts involving component selection and manipulation. Wrong valued components, component reversal and component omission are all input errors and would yield to a fix which would provide appropriate input information at the correct time. A simple fixture could be constructed to do this. It should hold the proper number of parts in the relative position they occupy on the printed-circuit board and should have value markings for comparison with the held components. Such a fixture could be expected to reduce errors 7, 8, 10, and 11 greatly. A further reduction in reversal and transposition errors would be provided by modifying the board and/or components (perhaps by bending or clipping the leads) so as to prevent them from being mounted backwards. Omitted solder joints on the board could be almost precluded by requiring the operator to inspect the finished board in a fixture which provides back-lighting and masks which cast shadows on all holes which are supposed to be present. With this fixture, any light seen through the board indicates a missed solder joint.

Damaged components and solder splashes are the most difficult errors to treat. Both are the result of inadvertent acts and hence are difficult to bring to the attention of the operator. Efforts to place the operator "on guard" are almost certain to fail in the long run because of the well-known tendency for parts of acts to drop out if these parts do not frequently produce observable results. Since solder splashes and component damage occur with relative infrequency we can expect that attempts to reduce errors of this kind by any form of self-inspection will produce reductions of not more than 1/2 to 1/3 in error rates, and even these will probably be temporary. Since people differ greatly in their tendencies to make errors of this sort it might be useful to use personnel selection methods if the observed error rates are considered to be too high, (But even with this fix a cut in error rate of about 1/5 is the greatest reduction that can be expected.)

TABLE III-B

Analysis of Errors with Values of P_i
Which Could be Expected From the Proposed Changes

Error	P_i old	P_i new	F_i	n_i	Q_i
6*	0.006	0.00001	1.0	22	0.0002
7	0.001	0.00001	1.0	27	0.0002
8	0.001	0.00001	0.5	24	0.0001
9	0.00005	0.00001	1.0	596	0.006
10	0.00003	0.00001	1.0	213	0.002
11	0.0002	0.00001	1.0	213	0.002

*All unlisted errors are unchanged.

TABLE IV

Errors With Appreciable Contribution to Failure
Rearranged in Order of New Value of Q_i

$Q_1 = 0.045$

$Q_5 = 0.011$

$Q_9 = 0.006$

$Q_{10} = 0.002$

$Q_{11} = 0.002$

$Q_4 = 0.001$

$Q_6 = 0.0002$

$Q_7 = 0.0002$

$Q_{12} = 0.00014$

$Q_3 = 0.00011$

$Q_8 = 0.0001$

Computing Q_T for the contribution of human error under an assembly procedure which incorporates the suggested changes gives a value of $Q_T = 0.07$. It is seen that by the application of relatively simple methods the number of defective units has been more than cut in half. Further reduction could be effected by attacking the problem of solder splashes and component damage. Just how this would be done depends to a great extent upon the specific situation. It should be mentioned that, since solder splashes are such a large contributor to defect conditions, it would probably be worth while to consider the development of special tools to reduce the probability that solder will be splashed during the operation. It seems probable that the proportion of defective units could be cut to at least 0.02.

It should be kept in mind that the preceding discussion has been presented primarily for illustration purposes. It should be considered as an actual evaluation only to a limited extent. However, the order of seriousness indicated by the ordering of values of Q_i is probably accurate for the most serious errors evaluated.

APPENDIX C

PREDICTED ERROR RATES OF CERTAIN CLASSES OF ERROR*

Error	Number of observations on which estimate of P is based	P_i
Two wires which can be transposed are transposed.	13,083	0.0006
A component is omitted.	10,388	0.00003
A solder joint is omitted.	47,075	0.00005
An operation such as applying staking is omitted.	59,435	0.00003
A component is wired backwards (diodes, capacitors, etc.).	2,610	0.001
Wrong valued component is used.	10,388	0.0002
A lead is left unclipped.	33,000	0.00003
A component is damaged by burn from soldering iron.	10,388	0.001
Soldering operation produces a solder splash.	13,080	0.001
Soldering operation results in excess solder.	47,075	0.0005
Soldering operation results in insufficient solder.	47,075	0.002
Soldering operation results in hole in solder.	47,075	0.07

*The data upon which these predictions are based were obtained from an analysis of slightly over 23,000 production defects detected in assembly operations of electronic equipment.