System Considerations for Establishing PreLaunch checkout Effectiveness

Theodore Taylor Jr.
Radio Corporation of America, Defense Electronic Products, Aerospace Systems Division

SYSTEM CONSIDERATIONS FOR ESTABLISHING PRELAUNCH CHECKOUT EFFECTIVENESS

Theodore Taylor, Jr.
Radio Corporation of America
Defense Electronic Products
Aerospace Systems Division
Burlington, Massachusetts

Summary

Factors contributing to the effectiveness of prelaunch testing are examined from a systems viewpoint. The complexity of manned space vehicles increases the quantity of test data that must be evaluated before launch can take place.

The effect of these factors on prelaunch checkout is to place greater emphasis in the care of establishing: (1) accuracy and error budgets, (2) test techniques and equipment design, and (3) methods, plans and procedures for carrying out the prelaunch test program.

By defining checkout effectiveness in terms of probabilities of undetected failures and false alarms at time of launch, the constraints on the above categories can be shown in numerical terms. Interrelationships between test intervals, percentage of system tested, measurement accuracy, stimulus and measurement techniques, and procedures in use of the test system are developed.

Introduction

The assignment of high probabilities for spacecraft mission success is reflected in greater desired confidence levels of system operability at the start of the mission. With mission success goals running as high as .986 for a two-week lunar mission, the effect on prelaunch testing is to place more emphasis on the engineering that goes into establishing: (1) accuracy and error budgets, (2) test techniques and equipment design, and (3) methods, plans and procedures for carrying out the prelaunch test program.

Mission reliability profiles are developed on the basis of unity reliability at the beginning of the mission or time of launch. It is presumed that at the conclusion of the last test before launch all failures have been detected and repaired. Because each measurement has associated with it certain degrees of random error, there is a statistical probability that out of a population of n measurements, that one or more measurements will falsely indicate either an in-tolerance or out-of-tolerance condition. Thus an undetected failure or false alarm situation exists. The likelihood of such an occurrence increases as a function of the total number of test parameters that define an operable system, and also, as a function of the tolerance or limits on each parameter.

Because of the quantity and high order of accuracy of test parameters dictated by complex space systems, the probability of undetected failures is significant. This probability is magnified unless the quality of the evaluating device (checkout system) and the procedure for its use are carefully specified and controlled.

This paper examines some significant factors related to prelaunch checkout effectiveness and establishes criteria by which checkout effectiveness may be defined. This criteria is further developed through the investigation of effectiveness goals and how they may be allocated between subsystems and assemblies. A prelaunch checkout system design procedure for achieving specific goals is then presented by trading off total number of test parameters, accuracy of tests, number of tests performed, interval between tests, and percentage of system tested.

Finally, methods of implementation and control at the systems level for insuring that the recommended design procedure is carried out are discussed. Reference to test requirements, checkout equipment specifications and test procedures are made.

Systems Requirements

Checkout Effectiveness

Checkout effectiveness may be defined as that accuracy or confidence by which it measures and predicts system operability. It may be expressed mathematically as a function of various parameters that are related to testing techniques and checkout system design. Its context as used in this paper is the probability of not making a checkout error while determining the existence of any failure or defect. For our purposes, a defect is defined as a system or an internal circuit parameter that is outside of specification limits because of failure or degradation. We are primarily interested in tolerance type failures as opposed to the presence or absences of discrete events such as observed when monitoring an open or closed switch or valve. The former category is significantly influenced by checkout accuracy whereas difficulty in testing for the latter condition is more apt to be attributed to a checkout system failure and not to limitations on accuracy.

Two types of checkout errors are possible: (1) failure to detect an existing defect, and (2) the detection of a failure that does not actually exist.

The first type of error is called an undetected defect and is treated here in the joint case, i.e., the probability of an undetected defect is equal to the probability that a failure or out-of-tolerance condition exist times the probability of not detecting it. The converse relation, the probability of no undetected defects, is related to the probability of mission success of the prime equipment in that the quantity of undetected defects at the conclusion of last test during prelaunch degrades the initial point on the reliability curve to some value less than unity. This is assuming, of course, that all failures that are detected during prelaunch operations are repaired.

The second type of error, the detection of a defect that does not actually exist, is called a false alarm. Though it does not have a critical effect on mission success in the same manner as an undetected defect, it does contribute to needless delays, cost, and wear on the system. The most severe manifestations of this are lengthy launch pad delays.

A trade-off exists between these two error types. A reduction of one error type cannot always be achieved without the expense of increasing the probability of the other. This is shown in Figure 1 which summarizes the relationships of the various parameters that affect the two error type probabilities at the top of the tree. The arrows indicate direction of increasing or decreasing conditions. As an example, the probability of no undetected defects at the system level can

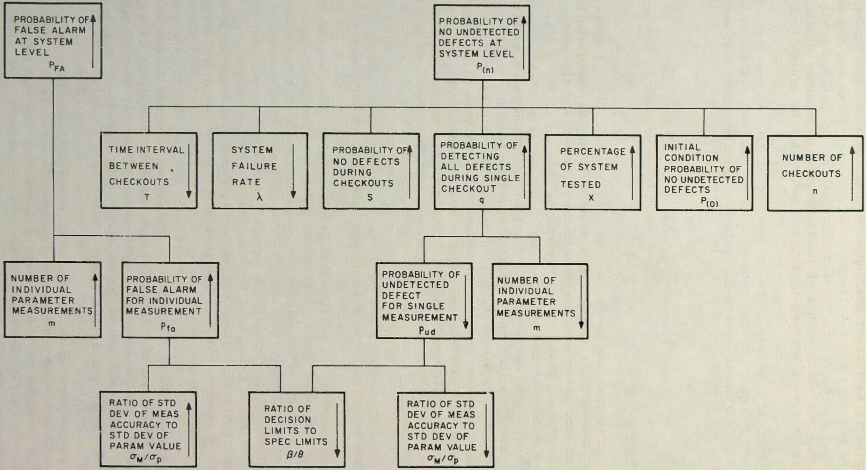

Figure 1

Parameter Trade-Off

be increased by decreasing the number of individual parameters that define an operable system, or by increasing the number of checkouts, n, and percentage of system tested, x.

A basic math model which establishes the relationship among the first row of parameters of Figure 1 is presented as follows for $P_{(n)}$, the probability of no undetected defects:

$$P_{(n)} = \left[(1 - q)\, se^{-\lambda T}\right]^{n} P_{(o)} + q \sum_{i=0}^{n-1} \left[(1 - q)\, se^{-\lambda T}\right]^{i} \qquad (1)$$

where:

$P_{(n)}$	=	probability of no undetected defects present in the system at the close of the n^{th} checkout
g	=	probability of detecting all defects in the system during checkout
s	=	probability of no defect occurrence during checkout
λ	=	system failure rate prior to activation for checkout
T	=	time interval between checkouts
n	=	number of checkouts
$P_{(o)}$	=	initial condition -- probability of no undetected defects prior to next successive checkout

The derivation of this model and subsequent ones in this paper have been developed in previous work at RCA and is covered in detail by W. Moon in reference[1]. What is significant in this model is that a quantitative value for checkout effectiveness (as expressed by $P_{(n)}$), can be computed for various values of the parameters on the first row of Figure 1. Additional models will also provide a quantitative tie-in to individual measurement accuracy contained in the bottom blocks.

Using the above model, Figures 2 through 4 illustrate how the probability of no undetected defects, $P_{(n)}$, is affected by changes in (1) initial confidence in the system prior to checkout, (2) the time period between periodic checkouts, and (3) the percentage of total system tested.

Pre-Checkout Confidences

A plot of the probability of no undetected defects for a system that is periodically tested is shown in Figure 2. Each curve assumes a different initial confidence of system operation prior to the start of the first test while all other parameters are held constant. For each 0%, 50% and 90% initial probabilities of no undetected defects, the curves exhibit an inherent system reliability decay between checkouts followed by an increase in the probability of no undetected defects at the close of each checkout. This increase is attributed to new knowledge gained from the checkout that there are no undetected defects. For this particular example, the values for g, s, λ, and T were chosen more to illustrate the trend for periodic testing rather than as values being representative of any particular system. λ, in this case, is associated with the standard reliability decay function and is shown as the slope between the peaks. In the case of shelf life between tests, this slope would be more nearly flat. (Any failure rate function could be used for that matter.) The vertical rise at each checkout assumes relatively negligible time to conduct the test and furthermore, that any failures or defects detected are repaired.

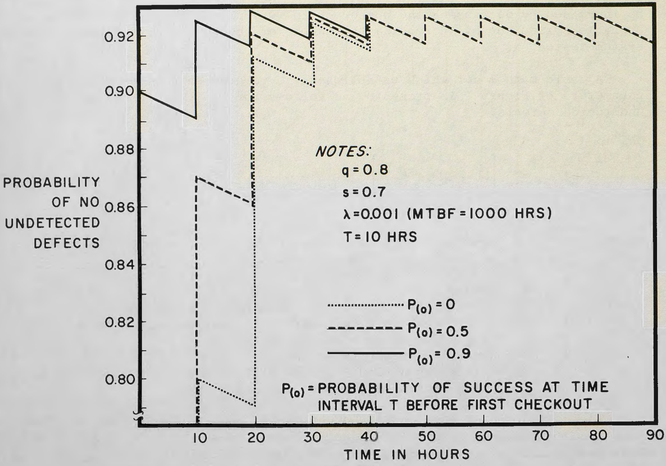

Figure 2

Probability of No Undetected Defects For Varying Initial Test Confidence Levels

It can be seen that each curve exhibits an increase in the probability of no undetected defects for the first few checkouts. Complete confidence is not gained from any single test because the probability of detecting all defects, even in the tested portion of the system, is not unity. The significant point is that all curves converge to the same value regardless of the initial confidence assumed prior to the first test. Ultimately after a given number of checkouts, confidence is gained more from the individual checkout, and less on information about the system from prior tests.

Periodic Checkout Intervals

The effect of time interval between tests is illustrated in Figure 3. Here intervals of 10 hours and 48 hours are chosen with the other parameters held constant at the same values used in the previous example. The shorter time interval between checkouts results in a higher probability of no undetected defects. The reliability decay between tests in this case has less opportunity to develop, permitting each test to maintain a higher confidence level.

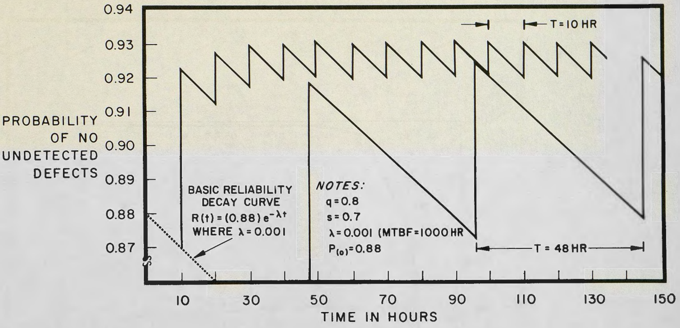

Figure 3
Probability of No Undetected Defects for Varying
Time Intervals Between Checkouts

Trade-offs, however, exist between probability of no undetected defects and system failure rate. A reduction in interval between tests improves the former while the latter becomes worse. This is particularly noticeable in the deleterious effects of system on and off operation every time a test is conducted. In general, checkout effectiveness is significantly improved by keeping the intervals short.

Percentage of System Tested

A checkout that covers only portions of a system results in lower test confidences. In Figure 4, the curves represent the upper envelopes of the sawtooth functions in the previous examples with x being the percentage of system tested. This situation is typical of the testing environment on launch pads where accessibility limits the amount of testing desired. With shrouds in place at vertical assembly, such equipment as radar antennas and stable platforms receive only cursory checks. The mission, effectively, for these systems has already started days prior when they received a last thorough checkout at an assembly area or boresight range.

From the curve illustrated, untested portions of the system ultimately exhibit a decay in the probability of no undetected defects in spite of continued periodic testing. The continuous reliability decay of the untested portion eventually begins to dominate the course of the curve.

Individual Measurement Level

The three figures just discussed concern undetected defect and false alarm goals as related to periodic checkout and other criteria shown in the first row of parameters of the tree in Figure 1. To find the significant effects on prelaunch checkout detailed design, the interrelationship of the effectiveness goals must be considered further at the individual measurement level.

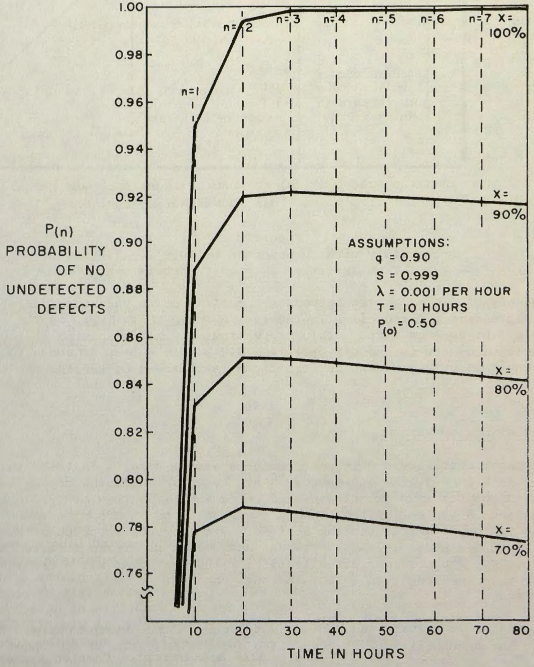

Figure 4

Probability of No Undetected Defects
Versus Time for Partial Test

The probability of detecting all defects, g, in a system during a single checkout is as follows:

$$q = \prod_{i=1}^{m} \left[1 - (p_{ud})_i\right] \qquad (2)$$

where: m = number of individual parameter measurements per checkout
$(p_{ud})_i$ = probability of an undetected defect for the i^{th} individual measurement

The probability of a false alarm, P_{FA}, in the same manner, is defined as:

$$P_{FA} = 1 - \prod_{i=1}^{m} \left[1 - (p_{fa})_i\right] \qquad (3)$$

where: $(p_{fa})_i$ = probability of false alarm at the i^{th} individual measurement

If we assume that the probabilities of undetected defects and false alarms (p_{ud} and p_{fa}) are nearly the same among all individual measurements, then equations (2) and (3) become:

$$g = (1-p_{ud})^m \qquad (4)$$

$$P_{FA} = 1-(1-p_{fa})^m \qquad (5)$$

g may also be expressed as $(1-P_{UD})$, where P_{UD} is defined as the probability of undetected defects at system level for a single checkout. With effectiveness goals for P_{FA} and P_{UD} established as initial conditions, individual measurement levels for p_{ud} and p_{fa} may be obtained from:

$$p_{ud} = 1-(1-P_{UD})^{1/m} \qquad (6)$$

and

$$p_{fa} = 1-(1-P_{FA})^{1/m} \qquad (7)$$

Figures 5 and 6 are parametric plots of equations (4) and (5). Figure 5 relates the probability of detecting all defects in a group of measurements to the number of measurements. The group, in this case, may constitute a complete system, subsystem, or even an assembly. The number of measurements are the minimum number of parameters which unambiguously define the operability of the system or subsystem. The three curves select different levels of probability of undetected defects at the measurement level. The effect on g, probability of detecting all defects, by increasing number of individual measurements, m, is clearly indicated. It is important to keep m small. The ideal situation is one where the complete operability of a system is defined by a single measurement. Complex systems involving large numbers of test parameters force higher levels of undetected defects. Subsequent curves will show how compensation of this effect may be obtained through increased measurement accuracy and adjustment of decision limits.

The effect of false alarms for a group of measurements at the systems level versus the number of measurements is shown in Figure 6. As in the previous case, various values for false alarms at the individual measurement level are plotted parametrically using equation (5). Again, false alarm probability is a direct function of the number of measurements, m.

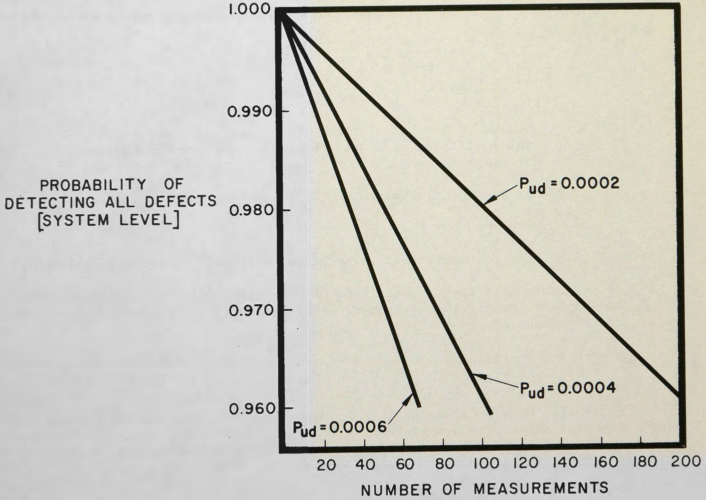

Figure 5

Probability of No Undetected Defects Versus Total Number Of Measurements for Varying Undetected Defect Probabilities At Individual Measurement Level

Measurement Accuracy

The effect of measurement accuracy on effectiveness goals may be considered from the criteria that defines in or out-of-tolerance conditions. As was mentioned under Checkout Effectiveness, we are primarily interested in measurements which have tolerances and limits.

A typical checkout parameter would have upper and lower specification limits inside of which the actual or true value must fall in order to be acceptable. To minimize chances of error or an undetected defect, tighter decision limits may be established within the specification limits inside of which the measured value must fall in order to be acceptable. These bounds are defined by θ and B in Figure 7.

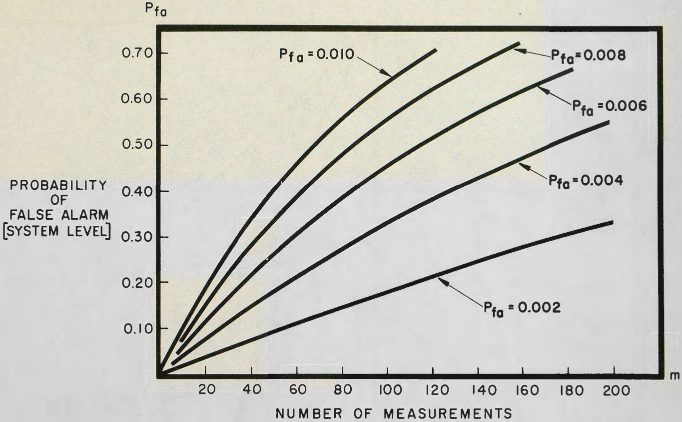

Figure 6

Probability of False Alarm Versus Total Number of Measurements for Varying Probabilities of False Alarm at Individual Measurement Level

The probabilities of error are a combined function of the distribution of the true parameter value and the distribution of measurement error. The normal or Gaussian distribution for measurement error has been fairly firmly established in the measurement field. Distributions of the true parameter are not as easily determined due primarily to certain individualistic characteristics existent among some test parameters which lessens the validity for a single distribution that is applicable to all. However, for establishing goals for checkout design, the Gaussian distribution provides a good enough approximation and is used in this analysis. For the true parameter case, the nominal value is considered to be located midway between the specification limits S_L and S_U. For a given checkout, the true parameter value is then distributed about the nominal in a normal or Gaussian manner.

Measurement error, on the other hand, is the difference between the true value of the parameter and what the measurement device says it is. The true value is then Gaussian distributed about the measured value, M. The combined distribution of both true parameter values about the nominal and true parameter value about the measured value, are contained in Figure 7. Back-to-back exponentials were used to approximate the distribution to simplify solutions.

The definition of the probability of two error types, undetected defects and false alarms, is shown in Figure 7. The conditional probability of an undetected defect is the probability that the true parameter value falls outside of the specification limits when the measured value falls inside of the decision limits. This probability is the shaded area contained under the small curve on the right. The

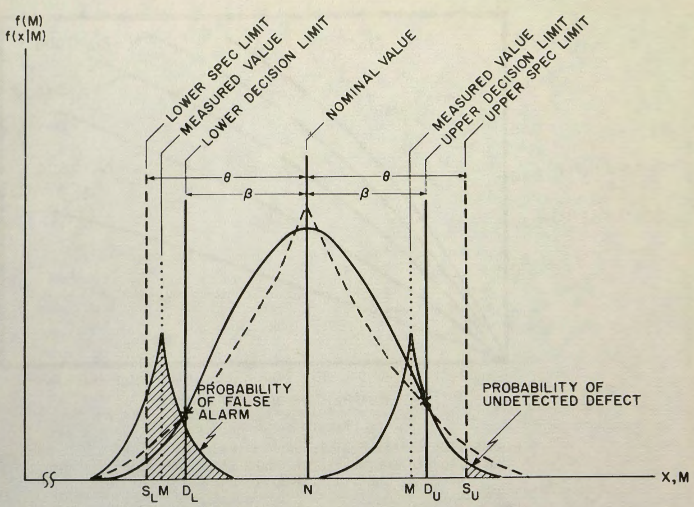

Figure 7

Probability Density Distributions for True Parameter and Measured Values

conditional probability of false alarm is the probability that the true parameter value falls inside of the specification limits when the measured value falls outside of the decision limits. This condition is shown as the shaded area under the small curve on the left.

The mathematical relationships of Figure 7 for probabilities of undetected defects, p_{ud}, and false alarms, p_{fa}, at the individual measurement level are as follows:

$$p_{ud} = \left[\frac{\sigma_m}{2(\sigma_p - \sigma_m)}\right] e^{-1.15(\theta\sigma_p - \beta\sigma_p + \beta\sigma_m / \sigma_p\sigma_m)} - \left[\frac{\sigma_m}{2(\sigma_p + \sigma_m)}\right] e^{-1.15(\theta\sigma_p + \beta\sigma_p + \beta\sigma_m / \sigma_p\sigma_m)} - \left[\frac{\sigma_m^2}{\sigma_p^2 - \sigma_m^2}\right] e^{-1.15(\theta/\sigma_m)}$$

$$p_{fa} = e^{-1.15^{(\beta/\sigma_p)}} - \left[\frac{\sigma_p^2}{\sigma_p^2 - \sigma_m^2}\right] e^{-1.15^{(\theta/\sigma_p)}}$$

$$+ \left[\frac{\sigma_m}{2(\sigma_p - \sigma_m)}\right] e^{-1.15^{(\theta\sigma_p - \beta\sigma_p + \beta\sigma_m/\sigma_p\sigma_m)}} \qquad (9)$$

$$- \left[\frac{\sigma_m}{2(\sigma_p + \sigma_m)}\right] e^{-1.15^{(\theta\sigma_p + \beta\sigma_p + \beta\sigma_m/\sigma_p\sigma_m)}}$$

where: σ_p = standard deviation of density function for distribution of true parameter, x.

σ_M = standard deviation of density function for distribution of measured value, M.

and β, θ as defined in Figure 7.

The derivation of these functions is contained in reference[1] and is beyond the scope of this paper to be presented here. However, an error in reference[1] has been corrected in the second term of equation (9). The significance of these equations are their solutions presented parametrically in Figure 8. Here probability of false alarm versus probability of undetected defects are plotted for combinations of decision limits and measurement accuracy ratios. Checkout effectiveness goals for p_{ud} and p_{fa} derived from total system level using equations (6) and (7) can be entered and accuracy requirements for individual measurements determined. Accuracy is shown as the ratio of the standard deviations. This is similar to the order of magnitude of measurement accuracy in percent over parameter tolerance. For the calculation of Figure 8, it was postulated that the parameter tolerance (specification limit) fell at the three sigma point for the true parameter value distribution. This is typical for current equipment specifications.

The solid curves, σ_m/σ_p, indicate that various combinations of probabilities of undetected defect and false alarms can be obtained by shifting the decision limits while holding σ_m/σ_p constant. As p_{ud} decreases, p_{fa} can become quite large. On the other hand, for the region of relative flatness for σ_m/σ_p, a large shift in decision limits significantly changes undetected defects but has little affect on probability of false alarm. In the same region, accuracy change has little affect on undetected defects but does cause quite a change on false alarms. In general, this indicates that the manner in which the decision limits (β and θ) are changed to optimally reduce error situations is a function of where the area of interest lies. A reduction of probability of undetected defects without corresponding increase in false alarms cannot be undertaken without consideration in the selection of both accuracy as well as decision limit ratios.

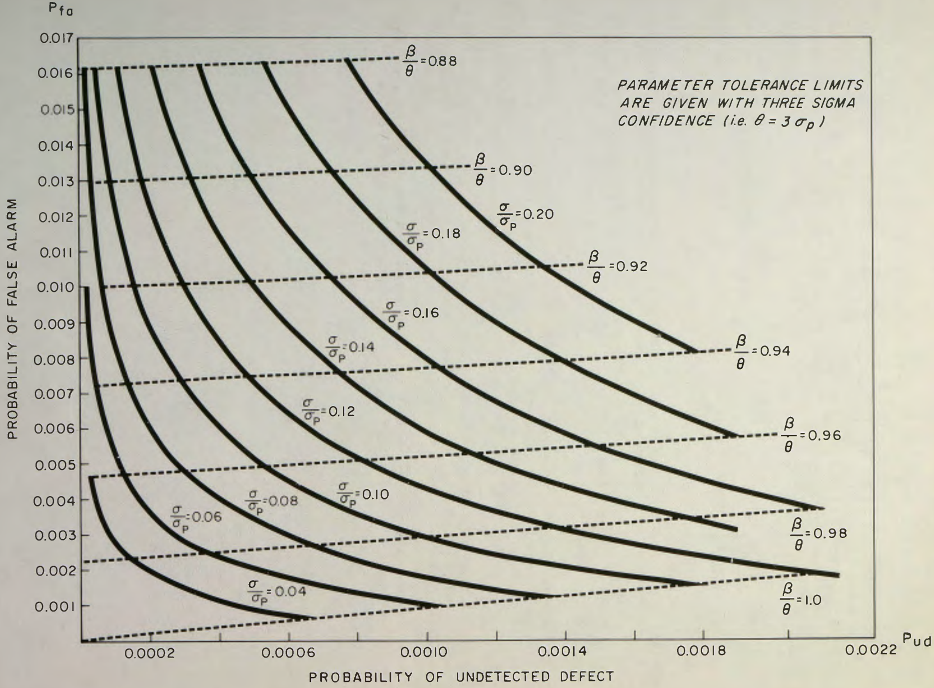

Figure 8

Probabilities of False Alarms Versus Undetected Defects for Varying Accuracy and Decision Limit Ratios