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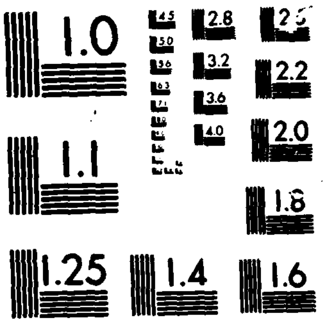

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TECHNICAL REPORT ARFSD-TR-85006

APPLICATION OF SEQUENTIAL SAMPLING PLANS FOR TEST PROGRAM SET ACCEPTANCE

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A sequential test plan for accepting test program sets is proposed. This plan is similar in basic theory to that described in MIL-STD-2077 but provides certain parameter changes as well as an operational distinction which allows for classification of faults.

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FOREWORD

In the 1940's, statistician Abraham Wald developed a statistical analysis procedure known as sequential analysis which measured the error rate of production lots. The procedure can be used on Test Program Sets (TPS) as well as production lots and, in fact, is advocated in MIL-STD-2077. It is apparent that sequential analysis is rarely used, however, in the validation of TPS's. This is probably due to two reasons: little understanding of the method of sequential analysis in the TPS community and poor choices of variables in MIL-STD-2077; namely, a TPS with 2.5% errors is considered to be good, and a TPS is not considered bad until it has in excess of 13% errors.

This report advocates the use of sequential analysis for validating TPS's, but uses variables different from MIL-STD-2077. It also describes an embellishment to the procedure which makes its use more reasonable.

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INTRODUCTION

In 1982, an analysis of Test Program Set (TPS) acceptance plans used by the Department of the Army was performed at ARDC. It indicated that most TPS acceptance plans call for the insertion of a number of faults in an otherwise known good Unit Under Test (UUT) to ensure that the test program correctly identifies these faults. The number of faults to be checked in this manner, the number of failures acceptable, or the action to be performed in case of a failure may vary from plan to plan. Often these plans are generated by intuition.

The plan in general use within ARDC is: (1) ensure that the TPS runs properly against two good UUT's; (2) ensure that the TPS properly identifies 10 faults selected from a list of 20 faults selected and tested by the developer; and (3) ensure that the TPS can find five other faults selected by the Quality Assurance (QA) representative. This plan was used to accept TPS's developed to support several weapons systems, and while the plan gave reasonable assurance that it ensured acceptance of good TPS's and rejected bad ones, actual confidence levels based on mathematical analysis were elusive. Research then commenced on application of a standard statistical theory.

This report details the results of some of this research. It includes a generalized model for developing a TPS accepance procedure. An interesting aspect of this plan is that it can be applied to a set of TPS's as well as a single TPS. This may prove invaluable for testing TPS's of the future which may be generated by artificial intelligence methods.

APPLICATION OF SEQUENTIAL SAMPLING PLANS FOR TEST PROGRAM SET ACCEPTANCE

TPS acceptance plans in use today call for inserting a specific number of faults into a UUT and ensuring that the TPS correctly locates these faults. Two problems are associated with this aspect of a TPS acceptance plan: (1) How many faults should be inserted to guarantee a certain confidence level that the TPS is good? (2) What faults should be chosen to perform the acceptance test?

MIL-STD-2077, General Requirements for Test Program Sets, addresses both of these points, but is generally not closely followed. The test plan described herein follows the essence of the plan set forth in MIL-STD-2077, but includes certain changes and some amplification.

The significant differences between this plan and that of MIL-STD-2077 are:

1. The acceptance levels herein are more stringent. MIL-STD-2077 specifies 2.5% errors as acceptable; this plan specifies 0.1% error as acceptable.

2. Classification of faults according to their criticality is taken into account in this plan, whereas MIL-STD-2077 classifies faults but does not take the classification into account.

3. The method of choosing the faults to be inserted is based upon component failure rate data in both plans, but in this plan modification of the failure rate data with a stress factor based on an engineering analysis of the circuit design is advocated.

The foundation of the test plan to be followed is based upon established prediction methodologies, known as sequential analysis, set down by A. Wald (ref 1) and others during the late 1940's. This procedure will predict acceptance or rejection of manufactured lots based on an attribute sampling plan. This sequential sampling plan is an accepted sampling technique utilized by the business community as well as the armed services.

Sequential analysis is simply "... a method of statistical inference whose characteristic feature is that the number of observations required by the procedure is not determined in advance of the experiment" (ref 1).

Some of the variables associated with this plan need to be clearly defined.

Inspection lot - The TPS is considered to be an inspection lot.

Unit of product - A unit of product is the item inspected to determine its classification as defective or non-defective. In the TPS, each definable failure mode is a unit of product.

Acceptable quality level (AQL) - The maximum percent of defective items within a lot (a TPS) that, for purposes of sampling, can be considered satisfactory to accept that lot. The value used in this plan is 0.1%.

Lot tolerance percent defective (LTPD) - The lowest quality level that the customer is willing to accept. The value used in this plan is 10%.

[Note: Since all possible faults cannot be tested, and there will be probabilities of errors associated with any sampling tests, the developer will strive for more stringent requirements (AQL) in order to assure that the customer's requirements (LTPD) are met.]

Producer's risk - The chance that a good lot could be rejected.

Customer's risk - The chance that a bad lot could be accepted.

Sample - Units of product selected from the inspection lot. The number of units of product is the sample size. For the purposes of this study, these are the faults to be inserted.

The acceptance sampling plan herein has many similarities with the sampling plan presented in MIL-STD-2077, both of which are sequential sampling plans based on Wald's work. We wish to accept a TPS with 0.1% defectives or less (AQL), and we wish to set a 5% limit to the chance of rejecting a TPS that meets this standard (producer risk); also we may wish to reject a TPS that has 10% or more defectives (LTPD), and we wish to set a variable limit (from 1% to 25%) on the chance of accepting a TPS with this ratio of defectives (customer risk). In this plan, P_1 will equal AQL and P_2 will equal LTPD. The AQL and LTPD are terms used in MIL-STD-2077; P_1 and P_2 are terms used in the mathematical equations.

Another view of the meanings and interrelations of AQL, LTPD, customer risk, and producer risk is as follows: a TPS will have a certain error rate, P, which we want to measure; but, since the number of possible faults in the UUT that the TPS tests may easily number in the hundreds, and since we cannot afford to check them all, we want to measure this error rate using sequential analysis. We are going to set two error rates as boundaries for our test. AQL (P_1) is 0.1%. If the TPS has only one error or less in 1,000, we will consider it acceptable. LTPD (P_2) is 10%. If the TPS has 10 errors or more out of 100, we want to reject it. We realize that because we are going to test less than 1,000 or even 100 faults, there will be some uncertainty as to where our measurement of P will fall with respect to P_1 and P_2. We hope we don't measure P to be less than AQL when it is not, but this could happen, and we set a limit on the risk we are willing to take that this does happen. This, the customer risk, we will choose from 1% to 25%. This means that 1% to 25% of the TPS's we buy may have more than one out of 1,000 errors in them. The producer hopes that we don't measure P to be more than LTPD and reject a TPS that is actually good. We set the producer risk at 5%. This means that of the TPS's that are rejected by this plan, 5% of them could actually be good.

MIL-STD-2077 sets LTPD at 13% and AQL at 2.5%; here we have chosen LTPD to be set at 10% and AQL at 0.1%; these values are commensurate with modern industrial standards. Also, MIL-STD-2077 sets the consumer risk and producer risk as equal but they are based upon mean time between failure of the UUT. Here we have set the producer risk at 5% and advocate selecting consumer risk based upon mean time between failure (MTBF) from table 1 which is similar to table 1 of MIL-STD-2077.*

For this plan, P_1 is the acceptance limit specified by AQL, α is the producer risk, $1-\alpha$ is the probability of accepting a TPS that is good, P_2 is the LTPD, and β represents consumer risk from table 1. The relationship between α, β, P_1, and P_2 is shown in figure 1.

$P_1 = 0.1\% = 0.001$	AQL
$P_2 = 10\% = 0.10$	LTPD
$\alpha = 5\% = 0.05$	Producer risk
$1-\alpha = 1-0.05 = 0.95$	Acceptance probability
$\beta = 10\% = 0.10$	Customer risk

---

* Table 1 of this report incorporates a more detailed correlation between consumer risk and UUT MTBF; namely, a linear relation which is derived from two specification points:

$$\text{MTBF} = 50 \text{ hr} \rightarrow \beta = 1\% \text{ and MTBF} = 5{,}000 \text{ hr} \rightarrow \beta = 25\%.$$

To construct a chart for use in a sequential sampling plan, we need to draw a graph with a horizontal axis, n, which will represent the number of faults to be inserted in the UUT to verify the TPS, and a vertical axis which will represent the score or defects, d, obtained by the test subject (fig. 2). On these axes we draw the parallel lines:

$$d = h_1 + sn$$

$$d = h_2 + sn$$

The variables describing these lines, as derived by Wald, are related to the parameters P_1, P_2, α, and β.

To find the Y intercepts - h_1 and h_2 and the common slope s, we first compute the auxiliary quantities (ref 2):

$$g_1 = \mathrm{LOG}[p_2/p_1]$$

$$g_2 = \mathrm{LOG}[(1 - p_1)/(1 - p_2)]$$

$$a = \mathrm{LOG}[(1 - \beta)/\alpha]$$

$$b = \mathrm{LOG}[(1 - \alpha)/\beta]$$

and then

$$h_1 = - b/(g_1 + g_2)$$

$$h_2 = a/(g_1 + g_2)$$

$$s = g_2/(g_1 + g_2)$$

The values for the above-mentioned conditions are shown in table 2. β, or consumer's risk, is highlighted, as is the number of faults (n), for easier reference.

Once the graph has been drawn, its use is simple; for each fault inserted, the point (n,d) is plotted. If at any time the point meets or falls below the lower of the parallel lines, we accept the lot. If it meets or crosses the upper line, we reject the lot. As long as it remains between the lines, we continue testing.

At this point we will be diverging somewhat from the plan presented by Wald in that we will be using a scoring system to rate the defects. We should note that the score will be based on faults inserted on a circuit board to test the TPS.

The minimum number of faults to determine acceptance can be calculated by setting d = 0 and solving for n, where $n = h_1/s$. As can be seen from figure 3 and table 1, this can range from 13 faults for a 25% consumer risk to 44 faults for a 1% consumer risk. As indicated by Crow et al (ref 3), the test can be of faults. If we have tested 1.5 times the minimum faults and we are still in the "continue testing" area with a gradual slope toward acceptance, a decision should be made to stop testing for economic reasons. At this time if we are still in the continue testing range, we must make a decision whether or not to accept or reject the board based on previous tests.

FAULT SCORING

Should a fault occur (the TPS cannot find a fault or improperly finds a fault), there must be some consideration as to the criticality of the fault. At the verification and validation (V&V) testing, there are several types of faults that might show up in a TPS:

A critical fault is one which prohibits continuation of sample testing. Failure of the TPS to pass a performance test is considered a critical defect. If this defect can be corrected at the time of testing with a minor programming change (tolerances are too tight to pass a good board or too loose to call out a defective board), then we will consider the fault a corrected fault and a penalty will be assigned to that particular fault.

A major fault is a fault other than critical that is likely to result in failure or reduce materially the usability of the TPS for its intended purpose. Failure to isolate an inserted fault is considered a major fault. Once again, if the fault could be corrected during the V&V with a minimum of action on the part of the programmer, then this would be considered a major fault corrected.

Minor faults are ones that will not materially reduce the ability of the TPS to be used for its intended purpose. Wording and spelling errors in display messages or in the test program instructions are considered minor defects. Again, we could consider this in a minor fault corrected category.

The next question that arises is: Why consider the corrected categories or even rank them differently? When using the previous sampling plan, two errors in grammar (commas, for instance) would reject the entire TPS. Although they would in no way affect the running of the program, without ranking we are forced to reject a functional TPS on the basis of two errors in grammar! The ranking of two misspellings with a critical defect is unjustifiable. This sampling plan is designed to take the seriousness of the fault into account with a scoring system that we feel fairly considers the seriousness of a fault in the V&V process.

For a critical fault not corrected, we would add two to the defect score on the graph. This would effectively reject the lot by positioning the point in the reject area of the graph. A critical fault corrected would add one to the defect score on the graph, and testing would continue if the point falls between the two parallel lines. A major fault not corrected would result in a score of one being added to the graph, and once again testing may or may not continue. A major fault corrected would add 0.5 to the score total and testing, again, may or may not continue. Minor faults would add 0.4 or 0.2 to the defect score depending on whether or not they are corrected. The values of these defect scores are based upon engineering judgment of the relative weights of their seriousness.

FAULT SELECTION

The next item that should be considered is the placement of the faults we will insert into the board. It will behoove us to test those faults that will actually occur to the UUT in the field. Is it possible to locate the built-in weaknesses of a particular board? The answer to this question, in many cases, is yes. What is needed at this time is additional data which will allow us to predict and isolate those components most likely to fail in actual operation. Those components will be faulted and used to verify the ability of a TPS to correctly isolate faults on a given circuit board using the procedure outlined above. These data would probably come from the depot level and would include data such as board type and serial number, parts called out for repair, parts actually replaced, errors called out by TPS, last station calibration check, etc.

In lieu of such data, the prediction of failures can be accomplished by using generic failure rates and part stress analysis of the components on the board. These calculations will show the components most likely to fail first. Fault insertion should center around these items initially and diverge to other areas of lower reliability during the testing based on this analysis.

To determine the most logical faults to be inserted on the UUT, we must first determine the relative reliability of each of the components. This can be done through the individual equations in Military Handbook 217D or the relative generic reliabilities can be used. If the circuit board is very large, the calculation of each individual component on the board may not be practical. In this case, one would group the components into small sets; e.g., resistors, ceramic capacitors, IC's, electrolytic capacitors, etc. The generic failure rates are found and recorded. The component with the highest generic failure rates should be targeted for the initial testing during V&V. Should there be two or more groups with the same generic failure rates, the faults tested should incorporate equal percentages of these parts.

A key feature to examine is the stress on the individual component. A component may be operating at the edge of its performance limit. Questions evoking unusual conditions should be asked: What would happen if a spike were to come down an input pin? Is the circuit connected to a high impedance load, such as a motor, which will generate considerable back EMF when the unit is cycled through its various phases? Factors such as these will need to be addressed before the faults are chosen.

With the generic reliability data on hand along with the circuit diagram, the engineer can estimate which components are subjected to the highest stress and from there, which have the highest failure rates.

IMPLICATIONS OF EXPANDED USE

This acceptance plan will provide the desired results of rejecting only 5% of the time, lots containing 0.1% deffective items; but will reject at least 90% of the time, lots containing 10% defective items. With the fault selection technique described, meaningful V&V testing can be accomplished. This procedure is valid and can be applied to the testing of TPS's as well as manufactured lots. It can also be applied to "lots" of TPS's. In this case, a lot of TPS's would be defined as a group of TPS's produced and used commonly; for instance, a group of TPS's procured for a certain weapon system. Of course, one should be convinced that the TPS's are produced similarly: same programming style guidelines, same test equipment, perhaps the same programmer. But even one individual programmer may display various techniques throughout various test programs. However, consider test programs that are generated by Automatic Test Program Generators (ATPG), or test programs of the future which may be generated by artificial intelligence machines. If a weapon system with 120 UUT's had been targeted for TPS's which would all be generated under a common system, it would be perfectly valid to test only a portion of the 120 TPS's using a test plan of this nature and accept or reject the entire lot based on the outcome.

It is recommended that the Army continue the use of this type of sampling plan to test TPS's and consider its use for accepting or rejecting ATPG or AI systems for generating TPS's.

Table 1. Plan guide for sampling--recommended consumer risk versus mean time between failure

Consumer risk (%)	MTBF range (hr)	
	From	To
1.0	0	50
2.0	50	256
3.0	256	463
4.0	463	669
5.0	669	875
6.0	875	1081
7.0	1081	1288
8.0	1288	1494
9.0	1494	1700
10.0	1700	1906
11.0	1906	2113
12.0	2113	2319
13.0	2319	2525
14.0	2525	2731
15.0	2731	2938
16.0	2938	3144
17.0	3144	3350
18.0	3350	3556
19.0	3556	3763
20.0	3763	3969
21.0	3969	4175
22.0	4175	4381
23.0	4381	4588
24.0	4588	4794
25.0	4794	5000

Note: The values given here will be found different from those in table 1 of MIL-STD-2077. The values in this study are derived from two specification points:

MTBF = 50 hr --> 1%, and MTBF = 5000 hr --> 25%, which results in the relationship.

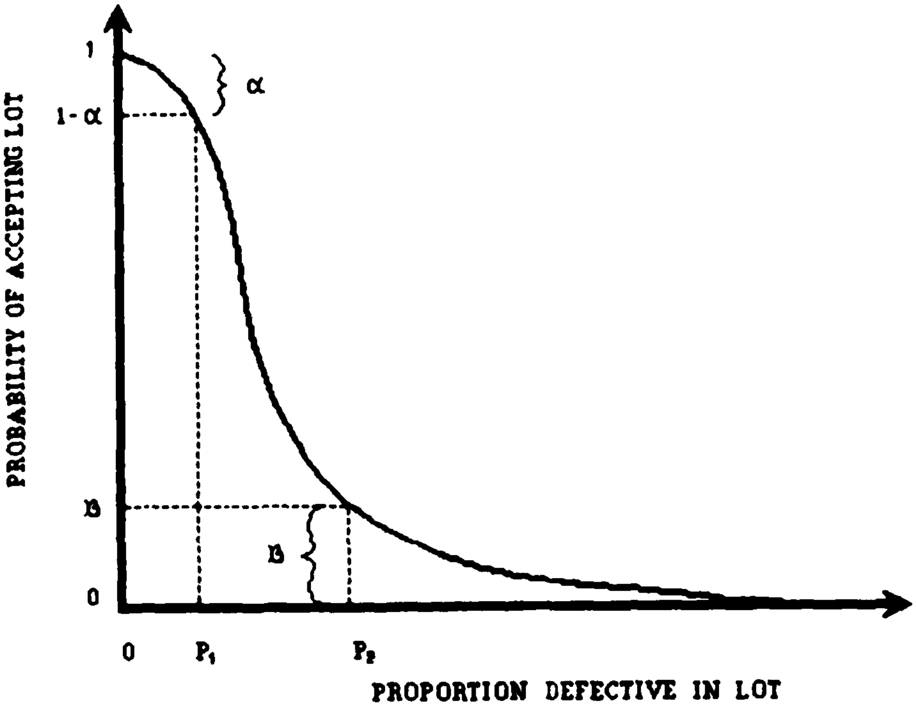
Consumer risk = [24(MTBF) + 3750]/4950

This is suggested by Logistics Support Analysis Office, Missile Logistics Center in Disposition Form: DRSMI-SL to DRSMI-SL, dated 10 April 1984.

Table 2. Proposed acceptance sampling plan

P1	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
P2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
ALPHA	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
1-ALPHA	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
BETA	***0.01***	***0.02***	***0.03***	***0.04***	***0.05***	***0.06***	***0.07***	***0.08***	***0.09***	***0.1***	***0.11***	***0.12***	***0.13***	***0.14***
G1	2	2	2	2	2	2	2	2	2	2	2	2	2	2
G2	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045
a	1.297	1.292	1.288	1.283	1.279	1.274	1.27	1.265	1.26	1.255	1.25	1.246	1.241	1.236
b	1.978	1.677	1.501	1.376	1.279	1.2	1.133	1.075	1.023	0.978	0.936	0.899	0.864	0.832
h1	0.967	0.82	0.734	0.673	0.625	0.587	0.554	0.525	0.5	0.478	0.458	0.439	0.422	0.407
h2	0.634	0.632	0.63	0.627	0.625	0.623	0.621	0.618	0.616	0.614	0.611	0.609	0.607	0.604
SLOPE(S)	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022
FAULTS(N)	***43.7***	***37***	***33.1***	***30.4***	***28.2***	***26.5***	***25***	***23.7***	***22.6***	***21.6***	***20.7***	***19.8***	***19.1***	***18.4***

P1	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
P2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
ALPHA	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
1-ALPHA	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
BETA	***0.15***	***0.16***	***0.17***	***0.18***	***0.19***	***0.2***	***0.21***	***0.22***	***0.23***	***0.24***	***0.25***
G1	2	2	2	2	2	2	2	2	2	2	2
G2	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045
a	1.23	1.225	1.22	1.215	1.21	1.204	1.199	1.193	1.188	1.182	1.176
b	0.802	0.774	0.747	0.722	0.699	0.677	0.656	0.635	0.616	0.598	0.58
h1	0.392	0.378	0.365	0.353	0.342	0.331	0.32	0.311	0.301	0.292	0.283
h2	0.602	0.599	0.597	0.594	0.591	0.589	0.586	0.583	0.581	0.578	0.575
SLOPE(S)	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022
FAULTS(N)	***17.7***	***17.1***	***16.5***	***15.9***	***15.4***	***14.9***	***14.5***	***14***	***13.6***	***13.2***	***12.8***



α - Producer Risk
β - Consumer Risk
P_1 - Acceptable Quality Level (AQL)
P_2 - Lot Tolerance Percent Defective (LTPD)

Figure 1. Relation of producer and consumer risks, AQL, and LTPD

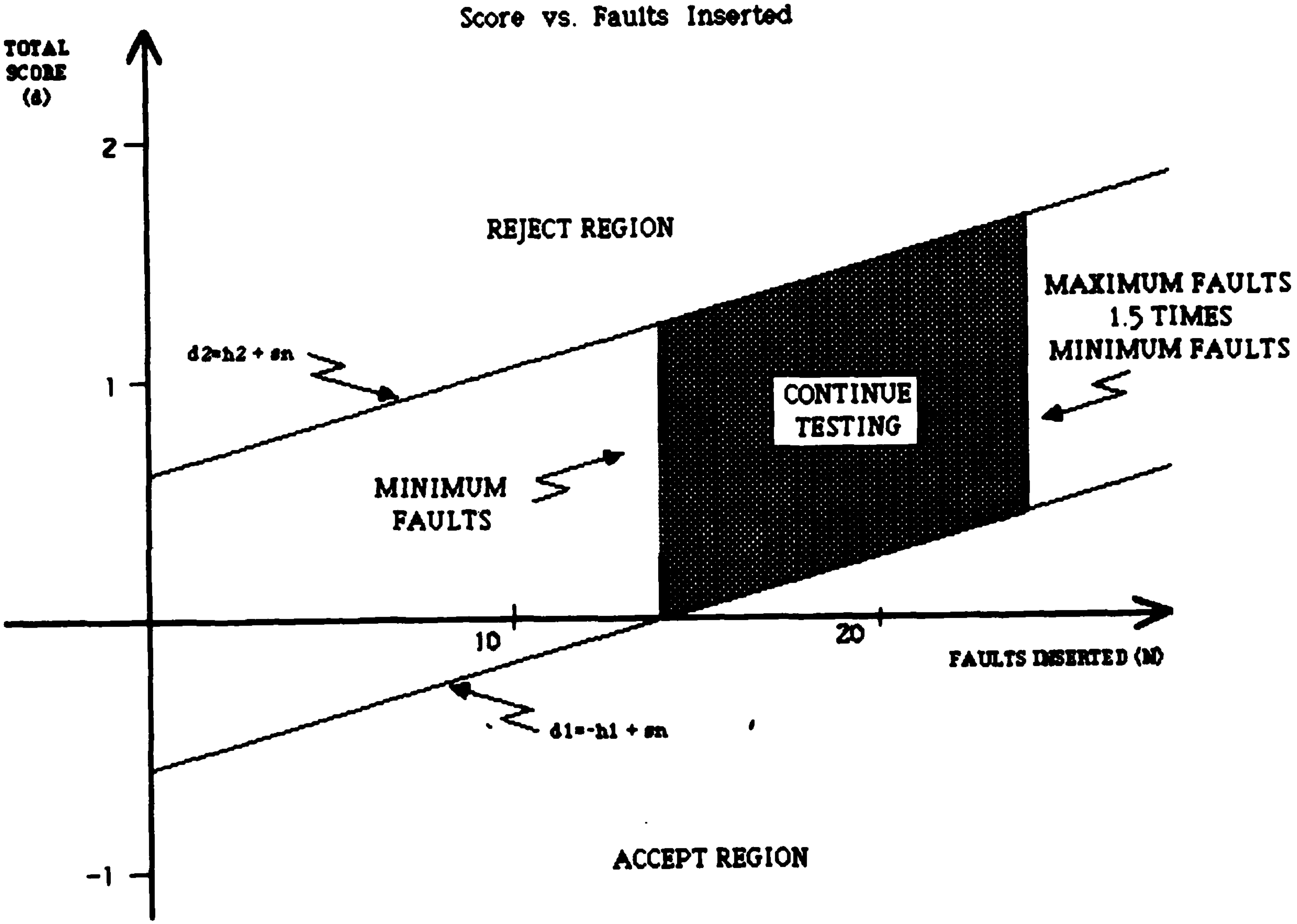


Figure 2. Implementing sequential sampling

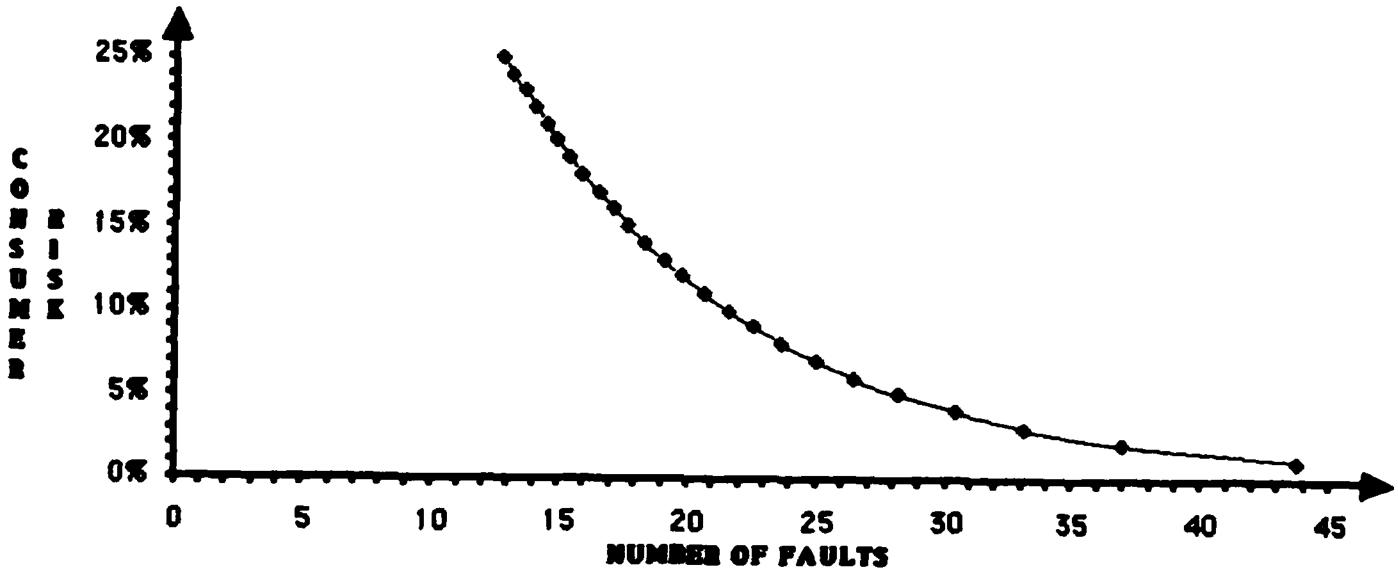


Figure 3. Number of faults versus risk

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