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ESTIMATION OF HIGH AND LOW
PROBABILITY EED FUNCTIONING LEVELS

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ESTIMATION OF HIGH AND LOW PROBABILITY
EED FUNCTIONING LEVELS

By
L. D. Hampton, J. N. Ayres, I. Kabik

ABSTRACT: Predicting very high or low EED response probabilities usually requires extrapolation from limited data. Extrapolation errors will be increased by inappropriate test plans or statistical treatment. Various test plans are discussed. Possible new prediction techniques are suggested. The necessity for careful design of experiment is stressed.

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U. S. NAVAL ORDNANCE LABORATORY
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Estimation of High and Low Probability EED Functioning Levels

The present report, with minor variations, was presented at the 4th Electric Initiator Symposium, 1 & 2 October 1963. Because the subject material is of broad interest it warrants a wider distribution than it might get by appearing only in the Proceedings of the Symposium. The concepts dealt with are equally of interest in weapon safety and weapon reliability considerations.

The work leading to the writing of this report was supported by Task NOL-443/NWL.

R. E. ODENING
Captain, USN
Commander

(C. J. Aronson)
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By direction

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I. INTRODUCTION

In this paper the authors wish to address themselves to the problem where, with a limited number of samples, it is desired to predict the stimulus corresponding to an extreme functioning probability level for a given electric initiator population, or conversely the estimated response at a stipulated stimulus. This problem is becoming increasingly important to both the military and the space agencies. In the past the military could frequently tolerate weapons having a relatively large degree of unreliability and then compensate for this unreliability by firing large numbers of weapons to attain the desired target kill; for example, the firing of projectiles or the dropping of bombs in large quantities. However, complex modern weapons, their high cost and their great destructive power often preclude firings in large numbers. High reliability (and safety) must be achieved and demonstrated for the individual weapon. As for space ventures the complexity of operations, the necessity for accuracy, the high cost, the prestige value, and the stake in human lives make it mandatory that components have a high level of reliability and safety.

High reliability (or safety) in the sense that we will use it here is a functioning probability of 99.5% or higher at a specified input level. Such reliabilities are not excessive for electro-explosive devices. Experience based on thousands of manufacturers' firings of conventional primers and detonators show that such reliabilities are in fact usually exceeded by ordinary production techniques. During the course of development, however, it is often necessary to predict the response of EED's to given stimuli. For example, in assessing hazards of electro-magnetic radiation it may be necessary to predict the response at a very low stimulus level. To determine whether a given power supply in a particular weapon is capable of reliably firing an EED it is necessary to estimate the response of the EED to the input stimulus of the power supply.

The direct demonstration of a 99.5% or better response at 95% confidence of an EED to a given stimulus is often too costly in material, time, and manpower to be seriously considered. It would require the firing of approximately 750 items without a failure.

Before discussing the general philosophy for making, logically, the required estimates, some discussion appears warranted about the present most frequently used method. This is the Bruceton method.

It is the authors' observation that the Bruceton test method is being used extensively for determining the response (sensitivity) of electric initiators. When properly used it is

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a good method. It is rapid and economical. The algebraic manipulations required to produce the statistical quantities are simple to carry out. It is because of these features that the Bruceton test has found such widespread application. Unfortunately it has been frequently used in situations where the results obtained are inaccurate and misleading.

For making studies around the 50% response level the test is most often highly acceptable and advantageous. When estimates are made by the Bruceton method beyond the 75% response level difficulties can be anticipated. The authors have spelled out in detail the reasons for the difficulty in a paper presented before the last HERO Congress¹. The salient reasons, without detail, are worthy of repetition:

- a. The Bruceton method gives a very poor estimate of the standard deviation. Even Bruceton tests of 100 samples will often underestimate the true standard deviation by 50 per cent or more.
- b. Since most all of the data are collected between the 25 and 75% firing points, long extrapolations must be made to the points of interest along a curve which is usually unknown.

When it is not feasible to demonstrate directly a response at an extreme firing point, estimates of the response are usually made by a process of extrapolation and curve fitting. The extrapolation process is basic to the approach. This principle should be kept firmly in mind. All of us as technical people are very familiar with making extrapolations and the principles involved. The statistical problems are really no different. What is desired is an extrapolation from measured response points to points removed from the region of measurement. Our extrapolations become better as the length of the extrapolation becomes smaller. They also become better when the general shape of the curve being extrapolated is known. From the statistical standpoint, when the response function or distribution function is known in the region of extrapolation.

There is no single best method for making estimates of extreme functioning probability points. Various methods are available for use. Those which can be used for best results depend on such factors as sample size available, the degree of accuracy needed, data available from other tests, and the remoteness of the desired functioning level.

¹References are given on page iii.

II. PRESENT SENSITIVITY TESTING METHODS

Sensitivity tests are of different types. Each type has certain advantages and disadvantages. These should be considered to make an intelligent selection of the test to be used. In certain situations one test would be selected while in others a different test would be chosen. We shall consider some of the tests which are frequently used along with their advantages and disadvantages. First, however, it would be wise to state some principles which will be general in their applications.

In most tests the analysis involves fitting a frequency distribution function to the observed data. In other words the test consists of an experiment in which the sensitivity is determined at each of two or more stimulus levels. From these data we attempt to predict either the response at some other level or the level which will have some desired response. In order to do this we must assume some frequency distribution function. One which has been widely used in the explosives field is the log-normal function. Experience has shown that this is a fairly good fit and entirely adequate for many purposes. However, recent work at The Franklin Institute² and at the Naval Ordnance Laboratory³ has shown that the log-logistic function gives a somewhat better fit. Even this is not a perfect fit.

In general, predictions based upon interpolation from observed data are fairly safe since the function assumed in the interpolation will ordinarily coincide closely with the true function over the range of the observed data. On the other hand the assumed and true functions may differ considerably outside this range. For this reason extrapolation is always dangerous because of the uncertainty in the choice of distribution function. The larger the extrapolation the greater the resulting error is likely to be. The use of extrapolation cannot be avoided in estimates of very high or low response points. However it can be kept small by proper choice of test plan at the cost of testing an increased number of items.

A second point to be considered is the possibility of bias. Some tests have a tendency to over or underestimate the quantity which is being determined. This tendency is known as bias. Some bias might be tolerated, if it were in the direction of making a more conservative estimate.

Another point to be considered in planning sensitivity experiments is the allocation of items to the stimulus test levels. A trial made at a stimulus level at which almost all trials are expected to result in fires or fails gives us less information than one made near the fifty per cent point. To obtain an equal amount of information at each level we must

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assign larger numbers of items at levels farther from the fifty per cent point. By this method we can give each of the levels equal weight.

Another consideration is the total number of items to be tested. Of course, the larger this number the more information we obtain. This, then, usually becomes a compromise between the amount of information we would like to have and what we can afford to spend in time and money in order to get it. Some tests are more efficient than others in obtaining information from a given number of trials.

One type of test which is quite largely used is the up-and-down or stair-step test, the best known being the Bruceton test. This test concentrates the trials near the fifty per cent point. All, or nearly all, of the data will be from observations concentrated between the 25 and 75 per cent points. The weights of the observations at the test levels will show an even greater concentration around the fifty per cent point. Investigations in England and at the Naval Ordnance Laboratory have indicated that the Bruceton test has a serious bias in the estimation of the standard deviation, giving a value which is too small. The effect of this bias would be to predict too much reliability and safety for an item which is tested in this way. The error becomes even more serious since the concentration of trials near the fifty per cent point makes the prediction of reliability or safety depend upon extreme extrapolation. Consideration of the characteristics of the Bruceton test shows that it is a good test for anyone who is interested in determining the fifty per cent point but a poor test for determining high or low per cent points.

Another test which has some of the characteristics of an up-and-down test is the Bartlett test. Stimulus levels are set up and testing continued at each level until two reversals are observed. A reversal is a fire, or fail, when the other response is expected. The Bartlett plan gives an increasing number of trials as we get farther from the fifty per cent point. Thus the weights of the observations at the different levels are made approximately equal. It also reduces the extrapolation required for very high or low response points and therefore is a good test for making estimates of extreme functioning levels. It is fairly easy to show, however, that estimates of sensitivity obtained by this plan are biased. Sixty per cent of the tests will give estimates of the sensitivity which are too low at the upper end of the range and too high in the lower end. This bias is not as serious as that shown by the Bruceton test since it is in the direction of conservatism. It should be emphasized that the Bartlett test requires very large samples. In two instances^{2, 3} the sample sizes were approximately 8000.

A third type of test is one which has been analyzed by Golub and Grubbs⁴ of the Ballistic Research Laboratory at Aberdeen, Maryland. In this type of test a comparatively small number of items is tested at different levels of stimuli with possibly only one item at each level. This type of plan is especially applicable to tests in which the stimulus level cannot be exactly controlled but can be measured. Ford Motor Company⁵ has recently done some work on a similar type of test. Since the sample size for either of these tests is usually small, the results are subject to the uncertainty always associated with small samples.

Finally, a plan which is quite frequently used is one that has been called the run-down test. This type and the up-and-down tests include most of the sensitivity tests which are made. The plan calls for making a specified number of trials at each of two or more stimulus levels. We shall describe here in detail, as an example of tailoring tests to specific situations, a run-down test plan which calls for testing at two stimulus levels. This plan was devised to determine high probability of firing estimates for electro-explosive devices of one of the Navy's most important missiles. Only 200 EED's per sample were available for test. This test plan was optimized to fit the specific needs but may be useful to others faced with a similar problem. The probability points of interest are estimated by extrapolation based on observed responses measured in the neighborhood of the 65 and 90 per cent points. If we have previous experience with similar items we may use this experience as the basis for choosing these two test levels. Lacking this experience, we can use a short Bruceton test. Suppose that we use twenty of the two hundred items in the preliminary Bruceton test. Then the remaining one hundred eighty are used for the main test at the two levels. Fifty items will be allocated at the expected 65 per cent level, and the remaining one hundred thirty will be tested at the expected 90 per cent level. If, after testing the fifty items at the first level, it appears that the response is much higher than the expected 65 per cent point we can revise our plan by using this as the second level rather than the first. In this case a new level is selected as the first, somewhat nearer the 50 per cent point, and fifty items tested at the new level. The following is a step-by-step procedure for firing the two hundred items.

- a. Fire twenty items in a Bruceton test to obtain preliminary estimates of the mean, m , and the standard deviation, s . A log-transform of the dosage (current, potential, energy) is taken as the stimulus.

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- b. Compute the first and second test levels as the mean of the Bruceton test plus 0.4s and 1.3s respectively.
- c. Test fifty items at the first stimulus level.
 - (1) If five or fewer fails are observed, redefine the first level as the second and continue firing at this level until one hundred thirty are tested. Test the remaining fifty at a stimulus level $m + 0.2s$.
 - (2) If more than five fails are observed (the usual case) test the remaining one hundred thirty units at the original second level.

The analysis of the data obtained from a test of this kind would require fitting a frequency distribution function, as was pointed out earlier in this paper. As was also pointed out the log-logistic function is the preferable one. The procedure for fitting this function to these data would be as follows. First, convert the observed number of fires, x , and fails, y , for each level into logits by the relation

$$L = \ln \frac{x}{y} .$$

Plot these values of L against the stimulus (log-current, log-potential, or log-energy). Draw a straight line through these two points. To interpret the graph in terms of per cent response for any stimulus read the result in logits and change to per cent by the relation

$$L = \ln \frac{p}{100 - p}$$

where p is the desired per cent.

A test of this general type has the good feature of minimizing the necessary extrapolation. It is free from bias such as is found in the Bruceton or Bartlett tests. The items are allocated to the test levels so as to give nearly equal weight to the observations. Two hundred items is about as small a number as can be used in order to give a good estimate of a high or low per cent point.

III. NEW APPROACHES

NOL is looking for ways for improving extreme-probability estimation methods by using information in addition to Go/No-Go firing data.

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As has been pointed out, the estimation of very high or low probabilities on the basis of Go/No-Go data always requires extrapolation towards the asymptotic All-Fire and No-Fire limits. The extrapolation is a risky business. Can we avoid this extrapolation? We think that it is possible. By using data from such sources as nondestructive measurements of EED thermal parameters in conjunction with sensitivity data we can interpolate rather than extrapolate.

For instance, we can show with the Mk 1 Squib that a current of 50 milliamperes through the bridge would cause a maximum elevation of the bridgewire temperature above ambient of about 10° Centigrade. By figuring backwards from a maximum acceptable elevation of the bridgewire temperature, we can deduce an even higher maximum current which would be acceptable not only as a safe current but also one which will not deteriorate the EED. In this fashion we can establish a true No-Fire current level.

Once a non-zero No-Fire level is available we should be able to estimate a very low probability of firing by interpolation between the No-Fire level and experimentally observed low-probability firing data.

A similar use of the electro-thermal data in conjunction with limits of variability of EED configuration and explosive ignition temperatures should permit the computation of a finite All-Fire point (provided there are no Q-C defects). With this All-Fire point and appropriate firing data we should be able to interpolate to find a high reliability point.

In either case, the interpolation can be carried out only if some distribution function can be assumed to connect the data. There are many expressions which can be devised to describe a distribution which is (1) approaching zero probability tangentially at a non-zero positive No-Fire point, (2) approaching a probability of 1 at a finite All-Fire point, and (3) a fit through observed firing data. What basis do we have for selecting the proper function?

To handle this problem, we are investigating the field of non-parametric or distribution-free statistics. The general approach in this technique is to find facts which apply to whole classes of distributions. It is assumed, on the basis of experience, that the EED distribution, though unknown, falls in a general class. If appropriate boundaries or limits for the class of distributions can be found then it will be possible to set conservative bounds on the EED probability estimates.

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For instance, if it can be assumed that:

- (a) The Probability Density Function is unimodal, i.e., the Cumulative Distribution Function (C.D.F.) has a single inflection point which corresponds to the mode above, and
- (b) The two distribution functions are zero at the true No-Fire level,

then we can say that a straight line drawn on the C.D.F. from the No-Fire point to the inflection point will always be more conservative for safety estimates than any distribution which satisfies the above criteria. This is because the C.D.F. will always be concave upward in this range.

The trouble with the above example is the difficulty in experimentally locating the point of inflection of the C.D.F.

IV. CONCLUSIONS

We advise caution and forethought in carrying out sensitivity determinations. Ready made test plans (such as those previously mentioned) have been devised to answer specific needs and have been based on assumptions which are often implicit. If these needs and assumptions are not relevant to the current problem, trouble can arise. A cookbook firing plan, applied blindly, can be a waste of time, money, and material.

The experimental and computational procedures should therefore be carefully designed before the investigation is started. The questions to be answered should be clearly stated. All relevant background and previous knowledge should be considered. After an experimental program has been proposed, the interpretations of all foreseeable sets of results should be hypothesized before any firing is commenced. If the possible or likely outcomes are inconclusive, then the experimental program should be modified appropriately. The aid of a statistician throughout this planning stage is very necessary. It will reduce the probability of obtaining useless, errant or meaningless results.

And for results to be useful to those other than the experimenter, the background information, the assumptions and statistical procedures should be a part of the data. They should be given in enough detail to permit reconstruction of the logic used throughout the investigation.

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Response	RESP	Bruceton tests	BRUC
Probability	PRBA	Sensitivity	SENV
Communication	COMM	Detonators	DETN
Data	DATA	Explosives	EXPD
Extrapolation	EXTP	Initiators	INIT
Errors	ERRO	Components	COMO
Prediction	PRFD	Mathematics	MATH
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Statistics	STAT		
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