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ROYAL AIRCRAFT ESTABLISHMENT
(FARNBOROUGH)

TECHNICAL NOTE No. WE. 15

A NOTE ON CONFIDENCE AND RELIABILITY IN GO-ON GO TRIALS [U]

by

J. W. Frame

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A NOTE ON CONFIDENCE AND RELIABILITY IN GO-NO GO TRIALS

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SUMMARY

A method and brief numerical tables are given for ascribing confidence in a given level of reliability after a series of go-no go tests have been done. The conditions necessary for success in planning a trial intended to establish a given level of confidence in a given reliability are also considered. Finally the validity of the theory for application under the circumstances to be expected in weapon proving is discussed.

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1 INTRODUCTION

1.1 This note is concerned with the type of trial in which the result of each individual test is either a success or a failure and with the statements about reliability which can reasonably be made on the basis of a number of such tests. The application in mind is to trials of a small number of articles, such as are usually undertaken in the initial proving of a new weapon, and not to a continuous inspection process. The theory assumes that the individual tests are independent and random with respect to the articles tested; the practical implications of this are discussed later. The two main questions considered are:-

(A) Given that a trial has been done yielding f failures in n tests, what statement of the form "The trial shows that the reliability is greater than R with confidence C" is justified?

(B) If a trial is to be done with the object of demonstrating reliability greater than R with confidence C, how should it be planned and what conditions must be satisfied if there is to be a good chance of a successful demonstration?

2 QUESTION A

2.1 Answering question A demands that the variables R, and C should be replaced by numerical values and before this can be done a rule for the numerical evaluation of confidence is necessary. Such a rule is bound to be a restriction on the most general idea of confidence and the numerical measure of confidence chosen may not therefore enjoy all those properties which might intuitively be expected of it. After f failures have occurred in n trials having confidence that the reliability is greater than R must depend on there being a high probability that less reliability would have resulted in more failures. The chance of more than a given number of failures could easily be evaluated if the true reliability were known, but it is not. This chance evidently increases as true reliability decreases and so would have its smallest value if the true reliability were R. This value, therefore, gives a lower limit to the true confidence and it will be referred to as the confidence that the reliability is greater than R. The rule for evaluating the confidence is then,

<u>Rule</u>. The confidence that reliability is greater than R may be computed as the probability that, if the true reliability were R more failures would occur in the tests than those actually occurring.

2.2 Let the true reliability be q; then the probability of any given number of failures in n tests of articles selected at random from a constant population is the corresponding term of the binomial expansion

$$(q + p)^n = \sum_{s=0}^{n} C_s^n \, q^{n-s} \, p^s \qquad (1)$$

where

$$q + p = 1. \qquad (2)$$

The definition of confidence then gives

$$C = \sum_{s=f+1}^{n} C_s^n R^{n-s} p^s . \tag{3}$$

The values of these sums of binomial terms have been tabulated[1] for

$$n = 1(1)50(2)100(10)200(20)500(50)1000$$

$$p = 0(0{\cdot}01)0{\cdot}50$$

and using the notation of these tables we have

$$C = \sum_{s=f+1}^{n} e(n,\ s,\ 1-R) = E(n,\ f+1,\ 1-R) \tag{4}$$

where $$e(n,\ s,\ p) = C_s^n q^{n-s} p^s . \tag{5}$$

The relationship between C and R derived in this way is illustrated in Tables 1-3 for values of f of 0, 1 and 2.

3 QUESTION B

3.1 In developing equipment it is necessary to decide at an early stage how many articles will be needed for testing so that timely supply can be ensured. If the reliability and confidence required are specified then the method given above determines the number of tests needed for any allowed number of failures. For example, approximately 80% confidence in an 80% reliability is provided by a 0/7, or 1/14, or 2/20 ratio of failures to tests. However, this information is of little practical value unless there are good prospects that a trial based on it will lead to the desired result. Now it follows at once from the rule given in 2.1 that if the actual reliability is only very little better than the desired value, then the chance of a successful trial can be but little better than 1-C. Hence for a successful outcome it is essential that the reliability aimed for in design should be considerably in excess of that which it is desired to demonstrate. This situation is a direct consequence of the need to base confidence on a high chance of excluding samples of reliability less than the critical value and cannot be evaded by any manoeuvring with the trial plan. The effect of actual reliability on chance of success of the trial is illustrated in Table 4 which refers to trials intended to demonstrate at least 80% confidence of 80% reliability. These chances have been derived from Tables 1-3 by using the fact noted above that chance of success in a trial is 1-C. For use in this way the tables have been extended to low confidence levels which are not of direct interest.

3.2 Table 4 makes it clear that there is an advantage in increasing the number of tests but only if the actual reliability is well above that which it is desired to establish. There is also a possible bonus in that if less than the allowed maximum number of failures occur a higher level of confidence or reliability than that specified will have been established. The choice of the reliability to aim at in design and of the number of tests to plan for, are matters which must be settled on practical considerations, such as the cost of the items for test, the time taken by and cost of the tests themselves, and the penalties of failure. The preparation of a table, similar to Table 4, for the particular circumstances will provide a guide to the gains and losses incurred by the various possible plans.

4 SEQUENTIAL TESTS

4.1 The type of sequential test mentioned here may be regarded as an attempt to obtain the advantage in prospect of success offered by large numbers of tests without losing the opportunity to stop at a smaller number if failures are sufficiently infrequent. As an illustration let us take the conditions of Table 4. Suppose first that seven tests are done; if no failures occur then the desired confidence is established and the trial stops; if there are several failures then reliability is unlikely to be as good as required and there is no point in continuing to test; if, however, only one failure occurs the situation looks quite promising although the corresponding confidence level of 42% (see Table 2) is too low to be acceptable. This confidence level can be raised by doing further tests, provided of course that no further failures occur, and then we have a sequential testing system. It is clear at once, that however many further tests are done without a failure, the confidence attained will always be less than that corresponding to a successful first series. In fact, in continuing tests after a failure we are admitting samples which would otherwise have been rejected and so the confidence given by the rule in 2.1 must be less.

4.2 Suppose now seven more tests are done without failure, giving a final result of 1 in 14. The confidence engendered by this result is found by applying the rule, and is the sum of two terms; the chance of two or more failures in the first series of tests; and the chance of just one failure in the first series combined with one or more failures in the second. Hence at 80% reliability,

$$\text{Confidence} = E(7, 2, 0{\cdot}2) + e(7, 1, 0{\cdot}2)\,E(7, 1, 0{\cdot}2) \qquad (6)$$

$$= 71\%.$$

This may be compared with the 80% confidence given by success in the first series of seven tests and also with the 80% confidence given by one failure in 14 in a simple trial of 14 tests. The loss of confidence compared with the simple 14 test series represents the trade off for the right to stop the trial after 7 tests if no failures occur. By doing this samples are accepted which, although giving no failures in the first seven tests, might have given two or more failures in the second seven if testing had been continued; such samples would be excluded by the simple 14 test procedure.

The chance of such an event is

$$e(7, 0, 0{\cdot}2)\, E(7, 2, 0{\cdot}2) = 9\% . \qquad (7)$$

4.3 The choice of procedure in planning a trial using sequential tests is a very wide one and no concise tables of confidence values, similar to Tables 1-3 for simple trials, can be given. All that will be done here is to give a formula for the confidence in a general double sampling trial, similar to the particular example discussed in 4.2. Let n tests be done first; let the result be considered satisfactory if the number of failures is not more than a and unsatisfactory if there are r or more failures. Suppose the actual number of failures is between a and r and let a further m trials be done giving a total of f failures. Then the confidence is the sum of two parts; the chance of r or more failures in the first n tests; and the chance of failures between a and r in the first n tests followed by sufficient failures in the second series of m tests to make the total greater than f. Hence

$$C = E(n, r, 1-R) + \sum_{x=a+1}^{r-1} e(n, x, 1-R)\, E(m, f-x+1, 1-R). \qquad (8)$$

Equation (6) is a particular case of this with $a = 0$, $r = 2$, $f = 1$.

4.4 It is still true in general that the confidence level given by (8) is always less than the confidence corresponding to the worst result acceptable in the first n tests, that is a failures. For, using (4),

$$\text{Confidence from } a \text{ failures in } n \text{ tests} = E(n, a+1, 1-R)$$

$$= E(n, r, 1-R) + \sum_{x=a+1}^{r-1} e(n, x, 1-R). \qquad \ldots (9)$$

Comparing with (8) we see that the summation part only differs in having added to each term factors in E which can never exceed unity. Hence the value given by (8) can never exceed (9). Furthermore, the first term, $x = a+1$, has the factor $E(m, f-a, 1-R)$ and, since $f>a$, this factor is always less than unity for any finite value of m. So the value given by (8) is always in practice less than that given by (9).

4.5 It is also true that the confidence given by (8) is less than that corresponding to f failures in m+n tests in a simple trial, but only provided that f is less than r. In a simple trial the confidence is given by

$$\begin{aligned} C &= E(m+n,\ f+1,\ 1-R) \\ &= E(n,\ f+1,\ 1-R) + \sum_{x=o}^{f} e(n,\ x,\ 1-R)\ E(m,\ f-x+1,\ 1-R) \\ &= E(n,\ f+1,\ 1-R) + \sum_{x=a+1}^{f} e(n,\ x,\ 1-R)\ E(m,\ f-x+1,\ 1-R) \\ &\qquad + \sum_{x=o}^{a} e(n,\ x,\ 1-R)\ E(m,\ f-x+1,\ 1-R). \end{aligned} \tag{10}$$

If $f = r-1$, then comparing with (8) we see that the first two terms are identical so that (10) is greater by an amount equal to its third term. If $f<r-1$ then we may write (8) as

$$E(n,\ r,\ 1-R) + \sum_{x=a+1}^{f} e(n,\ x,\ 1-R)\ E(m,\ f-x+1,\ 1-R) + \sum_{x=f+1}^{r-1} e(n,\ x,\ 1-R)$$

since in the summation form $x = f+1$ to $r-1$ the terms in E are all unity. This then gives for (8)

$$E(n,\ f+1,\ 1-R) + \sum_{x=a+1}^{f} e(n,\ x,\ 1-R)\ E(m,\ f-x+1,\ 1-R) \tag{11}$$

which again differs from (10) only by the third term in (10).

As remarked in 4.2 this difference arises from the chance of accepting samples which, although giving a or less failures in the first n tests, might, if tests had continued, have given sufficient failures in the second m tests to make the total failures more than f. The third term in (10) gives just this probability.

4.6 If f is equal to or greater than r then the confidence attained in the sequential trial may be the greater. As an example take

$$a = 0 \quad r = 2 \quad f = 2 \quad n = 10 \quad m = 5 \quad R = 80\%.$$

Then (8) gives

$$C = E(10, 2, 0{\cdot}2) + e(10, 1, 0{\cdot}2)\, E(5, 2, 0{\cdot}2) = 69\% \qquad (12)$$

whereas the confidence corresponding to 2 out of 15 in a straight trial is only 60%. This happens because samples which might have given only two failures in 15 tests have been rejected on giving two failures in the first 10 tests. The increase in confidence from this source has exceeded the loss due to the cause discussed in 4.5, which still operates here. In general under such circumstances the confidence in the sequential trial may sometimes be greater and sometimes less than in a straight trial.

4.7 The preceding paragraphs have discussed some of the properties of double sampling plans without attempting to balance their advantages and disadvantages as compared with simple trials. The evident attraction is the saving which accrues if the first series of tests is successful. The real value of such a saving will depend partly on whether the articles saved are useful for other purposes, since it is unlikely in practice that the manufacture of those required for the second part of the trial could be delayed until the results of the first part were known. The value also depends on whether the tests themselves are expensive and time consuming to carry out. It has been shown that the confidence level established in the second part of a double sampling trial is necessarily lower than that given by a successful first part. Therefore, either a lower level of confidence than that desired must be accepted, if the trial goes its full length, or the confidence aimed for in the first part must be unnecessarily high. If the latter alternative is adopted then the chance of success in the first part will be correspondingly reduced. This suggests that a sequential trial plan is particularly appropriate where a certain desired level of reliability and confidence has been stated and is aimed at in the first part of the trial, but it is reasonable to expect that a lower level could be accepted rather than reject the equipment entirely. This situation is not uncommon in the weapon development field and each particular case must be treated on its merits. As a final illustration Table 5 compares three of the trials plans already discussed in respect of the probability of the various possible outcomes and of the expectation of the number of tests to be done; the notation follows that previously used.

5 APPLICABILITY OF THE THEORY

5.1 The formulae given above depend on the assumptions that a large population of the articles concerned is available; that a sample of size n, small in comparison with the total population, is drawn at random; and that each of these n articles is tested independently. If any of these conditions fail the theory is not strictly applicable but it may, nevertheless, remain approximately valid if the actual conditions are not too different from those assumed.

5.2 The size of the population is significant because the theory assumes that each test has the same chance of being a failure. Now if an article is picked from a small population the properties of the population itself are altered.

For example, if a population of ten contains two duds and if a dud is picked for the first test, then the population remaining has a quite different proportion of duds; the article for the second test has then to be picked from this different population. Of course, if the article first tested can be replaced unchanged before the second selection is made, a constant population can be maintained but in weapon testing the weapon is often damaged or destroyed in test and so replacement is not possible. An exact theory for small populations can be developed using the hypergeometric series and also approximations other than the simple binomial can be used; see Chapter IV, example 6 of the reference[1]. As a rule however the population for any weapon is at least 100 and often much greater; of these only a small proportion are used in proving trials so that the simple binomial theory should generally be adequate. If however only a few of some very specialised weapons are to be produced and an appreciable proportion are to be used in proving then the effect of the small population must be taken into account.

5.3 The second requirement, that the articles to be tested are picked at random from the population, is less easy to satisfy. In the type of trial under consideration it is inevitable that the tests should be done on some of the first articles to be made and the results be used to justify further production. This is certainly not random selection from the whole population. Any time dependent factor in manufacture, such as wear on tools, any change of machines or operatives in expanding production to its full scale, or any late modifications to the system, all militate against the randomness of the selection process. This difficulty is not one which can be overcome by resort to statistical theory. It demands rather a determined attempt by designer and production engineer to satisfy themselves that the articles to be tested are really representative of those to be produced subsequently. It would clearly be desirable to repeat the trial later with a more random selection of articles from normal production but this is only likely to be possible for simple weapons produced in large numbers and if the trial itself is not too time consuming and expensive. These considerations suggest that statements about confidence and reliability based on trials of early production articles should be treated with some caution.

5.4 The third requirement would be met if each article were tested separately but, for reasons of economy, this is not always done. For example when a duplicated system is tested the two halves of the system may be separately monitored and the results counted as two tests of the single system. There would be no objection to this if the conditions of the test were fully controlled, so that each article was always subjected to precisely the same conditions, but in most weapon trials there are uncontrolled characteristics of the environment which may vary from test to test. If this variability from the mean environment is capable of significantly affecting the result, tests done together cannot be regarded as independent. The variability of the environment is not then as fully explored as it would be in testing each article separately and there must therefore be less confidence in the reliable performance of the articles. To treat each multiple test as a single test only would however be unduly severe because the variable test conditions are not the only factor in causing failure. Where the confidence should be placed between these extremes depends on the importance, relative to other factors, of departures from the mean test conditions in causing failures and it is possible that other trials carried out in the course of development of the article may give some indication of this. Alternatively a statistical test could be made for correlation of failure with the grouping of articles in multiple tests but, since a successful trial implies very few failures, it is unlikely that the results of such a test would be significant.

REFERENCE

No.	Author	Title, etc.
1	Staff of the Computation Laboratory of Harvard University	Tables of the cumulative binomial probability distribution. Harvard University Press. 1955.

Attached: Tables 1-5
Detachable Abstract Cards

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TABLE 1

Confidence levels for no failure

The table shows the confidence (%) in the stated reliability if no failures occur in the stated number of tests.

Number of Tests	Reliability (%)									
	60	70	75	80	85	90	95	97	98	99
1	40	30	25	20	15	10	5	3	2	1
2	64	51	44	36	28	19	10	6	4	2
3	78	66	58	49	39	27	14	9	6	3
4	87	76	68	59	48	34	19	11	8	4
5	92	83	76	67	56	41	23	14	10	5
6	95	88	82	74	62	47	26	17	11	6
7	97	92	87	79	68	52	30	19	13	7
8	98	94	90	83	73	57	34	22	15	8
9	99	96	92	87	77	61	37	24	17	9
10		97	94	89	80	65	40	26	18	10
12		99	97	93	86	72	46	31	22	11
15			99	96	91	79	54	37	26	14
20				99	96	88	64	46	33	18
25					98	93	72	53	40	22
30					99	96	79	60	45	26
40						99	87	70	55	33
50							92	78	64	39
60							95	84	70	45
75							98	90	78	53
100							99	95	87	63

TABLE 2

Confidence levels for one failure

The table shows the confidence (%) in the stated reliability if one failure occurs in the stated number of tests.

Number of Tests	Reliability (%)									
	60	70	75	80	85	90	95	97	98	99
3	35	22	16	10	6	3	1			
4	52	35	26	18	11	5	1	1		
5	66	47	37	26	16	8	2	1		
6	77	58	47	34	22	11	3	1	1	
7	84	67	56	42	28	15	4	2	1	
8	89	74	63	50	34	19	6	2	1	
9	93	80	70	56	40	23	7	3	1	
10	95	85	76	62	46	26	9	3	2	
12	98	91	84	73	56	34	12	5	2	1
15	99	96	92	83	68	45	17	7	4	1
20		99	98	93	82	61	26	12	6	2
25			99	97	91	73	36	17	9	3
30				99	95	82	45	23	12	4
40					99	92	60	34	19	6
50						97	72	44	26	9
60						99	81	54	34	12
75							89	66	44	17
100							96	81	60	26

TABLE 3

Confidence levels for two failures

The table shows the confidence (%) in the stated reliability if two failures occur in the stated number of tests.

Number of Tests	Reliability (%)									
	60	70	75	80	85	90	95	97	98	99
6	46	26	17	10	5	2				
7	58	35	24	15	7	3				
8	68	45	32	20	11	4	1			
9	77	54	40	26	14	5	1			
10	83	62	47	32	18	7	1			
12	92	75	61	44	26	11	2			
15	97	87	76	60	40	18	4	1		
20	99	96	91	79	60	32	8	2	1	
25		99	97	90	75	46	13	4	1	
30			99	96	85	59	19	6	2	
35				98	91	69	25	9	3	1
40				99	95	78	32	12	5	1
45					97	84	39	15	6	1
50					99	89	46	19	8	1
55						92	54	24	10	2
60						95	58	27	12	2
70						98	69	35	17	3
80						99	77	43	22	5
90							83	51	27	6
100							88	58	32	8

TABLE 4

Dependence of success of trial on actual reliability

Proposed number of tests	7	14	20
Maximum number of failures allowed	0	1	2
Probability of success of the trial if the actual reliability is:-			
80%	0·20	0·20	0·20
85%	0·32	0·36	0·40
90%	0·48	0·58	0·68
95%	0·70	0·85	0·92

TABLE 5

Comparison of trial plans

Trial Specification				Failures	Confidence in 80% reliability	Chance of result if actual reliability is		Expectation of number of tests if actual reliability is	
n	a	r	m	f		90%	95%	90%	95%
7	0	2	7	0	80	48	70	10·6	9·1
				1	71	18	18		
14	1	2	-	0	96	23	49	14	14
				1	80	35	36		
10	0	2	5	0	89	35	60	13·3	12
				1	80	25	24		
				2	69	13	6		

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