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PROJECT CENTAUR

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Introduction

Project Centaur began as a low-priority, financially austere feasibility study, and ended up as the nation's first liquid hydrogen-fueled space booster under the direction of the National Aeronautical Space Administration. This was successfully demonstrated when AC-2 was launched from the Cape on November 27, 1963 and met all primary and secondary mission objectives. The present objective of the Centaur Project is to inject a Surveyor into a trajectory suitable for a "soft" lunar landing.

The structural system was designed to provide a lightweight structural arrangement with an aerodynamic shape consistent with the overall design of the vehicle, and to contain propellant (liquid oxygen and liquid hydrogen) in sufficient quantities to meet the mission objective. In addition, the structural arrangement had to support and protect the payload, as well as the vehicle systems and components from the extreme environments of both launch and outer space.

The tank structure is a thin-walled 301 stainless steel vessel of monocoque cylindrical section, pressurized to provide structural stability. Since propellant boiloff would provide a substantial loss, the tank had to be insulated. It was decided by the design groups to use jettisonable insulation for the tanks and for the payload. Since the jettisonable structures would be jettisoned during the booster phase of flight, additional performance would be available to the Centaur vehicle during the lunar injection phase of the flight.

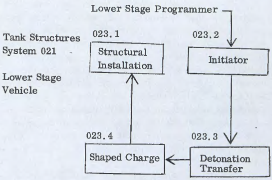
The first design concept for a system to separate the insulation structures consisted of pneumatic latches similar to those used in the first stage separation system of the Atlas. In the meantime interest had been revived in an adaptation of the old "primacord" of World War II as a shaped charge. Some tests were successfully concluded in the fall of 1963 at the Lewis Research Center Space Chamber, using shaped charges to separate the Atlas booster from the Centaur vehicle. These tests conclusively proved the feasibility of the design concept of using shaped charges as structural separation devices, but also demonstrated a substantial gain in the assessed reliability of the system as well as in the savings of weight.

The present insulation design consists of four lightweight insulation panels and a nose fairing. The nose fairing consists of a barrel section and a nose cone of the same type of construction. The insulation panels are separated from each other by flexible linear shaped charges (FLSC) and also from the vehicle. The nose fairing, which is split into two symmetrical halves, is separated from the vehicle with FLSC; and the two halves are separated from each other by the use of explosive latches. A jettison trajectory for the nose fairing halves is provided by the firing of two explosive valves attached to pressure bottles. The separation of the Centaur vehicle from the Atlas booster is accomplished with a shaped charge. The Surveyor is released by explosive latches similar in design to those used on the nose fairing.

The review I have just presented of the Centaur Separation System was given to acquaint you with the background against which I will give the remainder of the paper. Since the project was from its inception a Research and Development program the normal flow of failure reports and malfunction data would be of questionable value in the assessment of part, subsystem, and system reliability. Could a failure of a component in a bench test in the engineering test laboratory be considered a failure, or a need to improve the design? By contract agreement with the National Aeronautical Space Administration it was arranged that the reliability function would provide reliability assist in the design testing phase. With the completion of design evaluation testing, the normal functions of problem reporting take over and all discrepancies and failures are reported and assessed.

Reliability Assessment

The first step in the assessment task was to make up functional block diagrams of the various systems. A typical example is shown below,



The mathematical model was developed as shown below:

Evaluation. From the system logic it can be shown that the reliability of the pyrotechnic portion of this system is:

$$R_{023} = R_1^2 \left[1 - (1-R_2R_3)^2 \right]$$

where

R_1 = Reliability of the shaped charges which cut the interstage adapter from the Centaur vehicle

R_2 = Reliability of the dual detonator assembly

R_2 = Reliability of the dual detonator assembly

R_3 = Reliability of the detonation transfer assemblies

Component	No. of Tests* (No. failures allowed)	Reliability (90-percent Lower Confidence Bound)	Mission Equivalent Failures
Shaped Charge Assembly			
Dual detonator Assembly			
Detonator Transfer Assembly			

Development Testing

"Development testing can be defined generally as an empirical technique used to generate information that is not otherwise readily obtainable because of the inadequacy of applicable theory or the relative difficulty of achieving a theoretical solution." [1.] So states the Navy Reliability Handbook which is a useful guide in the incorporation of reliability requirements into development testing. It divides development testing into two broad catagories in which the reliability design test criteria are incorporated into the tests. The first type is an investigative or exploratory test (test of inquiry). The second type is a verification or comparison test (test of hypothesis).

In tests of inquiry applied to reliability problems, these are divided into two broad areas: 1) Measurement tests to measure the reliability of an item and 2) Evaluation relationships between environments or parameters which influence reliability. It is at this level that the reliability function analyze the test data and establishes confidence limits on the failure data. This is the first level of reliability input to the assessment model discussed earlier.

Tests of hypothesis are used as verification that the item meets its prescribed reliability (i.e., design proof tests). The selection of alternatives is a form of hypothesis testing. It is interesting to note that while the primary object of the test is to verify the design prediction, a secondary objective is to estimate the actual reliability observed during the test. Design proof tests offer excellent opportunities to test the validity of the reliability assessment.

Direct Multiple Sampling

Direct Reliability Demonstration

One-shot devices do not lend themselves to an evaluation through the simple methods of a reliability figure of merit analysis, using exponentially destributed reliabilities. [2] The G.E. handbook points out that one-shot devices have singular characteristics and any purchased lot may have wide variability peculiar to the manufacturing process. The reliability of this device can only be determined by direct demonstration firing of multiple samples. The reliability value obtained by this method is only applicable to the lot from which the samples were taken.

The method of determining the required number of test units to meet a specified reliability at a certain confidence level is the chi-squared (x^2) approximation of the bionomial. The level that is specified by the range safety requirements is the one that is usually used. This is the demonstrated 99.9% reliability at a confident level of 90%. A check of the tables in the handbook indicates that three thousand units are to be tested without a failure. If the item is to be used redundantly, a total of 70 dual units or 140 single units must be tested without a failure. If a failure occurs the following approximation of units to be tested is used:

$$N^* = \frac{5}{2} N \qquad (1)$$

N - number of original units undergoing test

N* - number of units to be tested when one failure is observed in the original sample N.

The handbook points out there is no substitute for direct reliability testing. If the item is used redundantly, the reliability figure for the single unit still has to be demonstrated. If this can not be done due to a limited number of units, then testing will have to be done to meet a reduced value by the use of redundancy, or isolation in the design application to assure the original reliability value.

With the increasing use of one-shot devices for critical applications the number of units that can be tested by this method begins to be one of economics. With the cost of such devices ranging from $10 to $100 it can be seen that to test several different configurations of these devices the program will be prohibitive. Other methods have taken the place of the massive testing of the no fire - all fire attribute.

Acceptance Testing

For non-electric detonators the design called for a destructive sample to consist of ten percent of each lot. The detonators were placed one-quarter of an inch apart, with loaded ends of the shells facing each other.

One was fired - acting as a donar, and the other was detonated - acting as a receiver. The acceptance requirement was that all units in the sample would detonate (i.e., no failures allowed). Failure of any unit would be cause for rejection of the entire lot. The spacing of the detonators was determined from a Bruceton test to be an all-fire distance at which 99.99% of all units would detonate, with a confidence of 97%. Since spacing between the detonators was a part of the design, not only was a design parameter confirmed by acceptance testing, but the sample being selected at random tended to be representative of the lot.

A review of the ten percent sampling plan (with no failures) by a statistician disclosed that with this plan the probability of acceptance of lots which 1% defective ranged from .90 for lots of one hundred, to .58 for lots of 500. Grant has shown that the level of protection is not given by the percent of the lot but by the size of the sample taken from the lot.[3] The sampling plan was revised to conform the MIL-STD 105.[4] The revised plan calls for an Acceptable Quality Level of 0.25 in lots of 266 to 459 units with a sample size of fifty.

If acceptance testing is the only testing accomplished on a lot of explosives prior to assembly into packages, a slight variation of MIL-STD 105D is suggested by Squeglia in which with and Acceptable Quality Level (AQL) of 0.1%, a single sample size of 125 units is sufficient for lots of 150 to 3200 items.[5]

With the addition of the range safety requirement of one ampere/one watt no-fire for five minutes, the previously used mechanical safe/arm mechanism was deleted from the design. The original mechanism was originally selected for the separation system based upon qualification testing plus about 250 tests (types not specified). The new design called for electrically initiated detonators which would be lightweight, would not depend on a mechanical linkage, would withstand more extreme environments, and would meet the range safety requirements. The acceptance testing was expanded to include resistance readings of the circuit, pin-to-case megohm checks, dimensional checks, and x-rays. Failure to pass any of the above requirements would be cause for rejection of the unit. A sample was selected and stabilized at high temperature, and a minimum of one ampere of direct current or one watt of direct power was applied for five minutes. If one or more of the units fired, this was cause for rejection of the lot. The same units were then placed into a steel holder against a target block. They were stabilized at low temperature and then had five amperes direct current applied. The requirement was that all should fire within a specified time interval and make a minimum indentation into the block. Failure of any item to perform the three requirements would be cause to reject the lot.

Direct reliability demonstration testing has an advantage of demonstrating reliability as a direct characteristic of the attribute (fire or no fire) and is based on the chi-squared approximation of the binomial. The economics of the electro-explosive devices (EED's) make this approach a costly route. On the other hand, the careful structuring of acceptance tests will yield almost the same information. If the time curves on firing tests are furnished by the vendor, this material can be analyzed both for distribution and for engineering data. There is much to be gained and little of the data of this type seems to be used.

Probability Estimates and Reliabilities

The estimates of reliability for the explosives are difficult to gather based on failure data. If the vendor has a failure of the part he replaces the part without any fuss to the customer. If the lot fails, again he replaces the lot. Hypergeometric calculations will verify the fact that a vendor can satisfactorily test a sample of fifty units out of a lot of 450 and pass the lot three out of five times while it is still one percent defective or more.

Acceptance testing can give a measure of estimated reliability with a degree of confidence. In the following example the only attribute tested by the vendor was that a sample of fifty units would fire a current of 5.0 amperes, with no failures. Since a failure rate is not spelled out by the specification, a method was developed to assess the reliability of the remaining lot in order to maintain the system assessment.

The reliability for each remaining lot was calculated by:

$$\text{Rel} = \frac{M - N - n}{M - N} \qquad (2)$$

N = lot or remaining lot

n = number of defects in that lot

M = total lot size

The probability of acceptance of the remainder of the lot was also calculated.

Probability of Acceptance of each lot with n defects is:

$$\Pr(A/n) = \frac{(M - n)!\ (M - N)!}{M!\ (M - N - n)} \qquad (3)$$

The Probability of Rejection of a lot of n defects is:

$$1 - \Pr(A/n) = \Pr(R/n) \qquad (4)$$

This equation was considered to be the confidence that the remainder of the lot had n or fewer defects.

TABLE 1

Predicted reliability of remainder of lot of 450 units - 50 having been tested with 0 failures

Remainder Lot Size N	Number of Defects n	Reliability $\frac{M - N - n}{M - n}$	Confidence 1 - Pr (A/n)
400	1	0.998	0.190
	2	0.995	0.210
	3	0.993	0.298
(60 were used for a sensitivity test - 0 failures)			
340	1	0.997	0.244
	2	0.994	0.430
	3	0.991	0.570
Another 60 were used on a sensitivity test - 0 failures)			
280	1	0.996	0.378
	2	0.993	0.613
	3	0.989	0.759
(128 units were used for production and special testing - 0 failures)			
52	1	0.981	0.884
	2	0.962	0.987
	3	0.942	0.999

NOTE: It is interesting to see that the remainder of the lot has diminished in reliability but confidence has increased.

Sensitivity Testing

There has been a rapid increase in sensitivity testing in the last few years. The reason is partly economic because, as was mentioned earlier, three thousand units are required to be tested to destruction to demonstrate a reliability of 0.999 at a 90% confidence level. A sample of sufficient size subjected to a suitable sensitivity test and utilizing standard statistical techniques will obtain almost the same information and to the same level of confidence. The two most popular tests are the Bruceton and the Probit methods.

Bruceton Method.

The Bruceton, or "up-and-down" method was developed at the Bruceton Laboratory at Princeton University by the Naval Bureau of Ordanance. Due its relative simplicity and more economical sample size, the Bruceton method has become the most popular choice among test groups to estivate the reliability and the safe functioning of explosive devices.

Testing of a Dimensional Variable.

A typical design problem was to decide what should be the standoff distance for some 15 grains per foot shaped charge to obtain the optimum cutting of a recessed aluminum flange 0.090 inch thick. The procedure was to fire the shaped charge at a predetermined distance and then to examine the flange for cutting. If the flange was completely cut the fixture was moved up a standard increment (in this case 0.004 inch). The process was repeated until a failure to cut was observed. Then the process was reversed. A part of the test is tabulated as follows:

TEST DATA

X = cut completely
O = failed to cut completely

Gap between S/C & FLG	31	32	33	34	35	36	37	38	39	40	41	42
.172		O										
.168	X		O		O		O					
.164				X		X		O		O		O
.160									X		X	

Calculation of the 50% reliable distance $(\bar{X}_R)$

The data is tabulated as follows:

Gap (d)	i	x	o	ix	i^2x
.172	5	0	1	0	0
.168	4	1	4	4	16
.164	3	4	5	12	36
.160	2	5	5	10	20
.156	1	4	5	4	4
.152	0	5	0	0	0

n = 19 0 = 20 A = 30 B = 76

1. The calculation of $\bar{X}_R$ is obtained from the following formula:

$$\bar{X}_R = c + d\,(A/n + 1/2) \qquad (5)$$

$$\bar{X}_R = .152 + .004\left(\frac{30}{19} + 1/2\right) = .152 + .004\,(2.08) = .160 \text{ inches}$$

2. Calculation of the standard deviation (σ_R)

1) Find $M = \left(nB - A^2\right) n^2$ (6)

$$M = \frac{19 \times 76 - 30^2}{19^2} = \frac{1444 - 900}{361} = 1.51$$

2) Find the value of s corresponding to the value of M from Table 1 of Nav Ord Report 2101.

s = 2.4839

3) Find $\sigma_R = s\,d$ (7)

$$\sigma_R = 2.4839 \times 0.004 = 0.010 \text{ inch}$$

3. Calculation of the percent reliable cutting distance versus the standoff curve on the test sample:

Percent	t	$t\sigma_R$	Standoff $X_R \pm t\sigma_R$
0.1	3.09	0.0309	0.191
1	2.326	0.0233	0.183
5	1.645	0.0165	0.176
10	1.282	0.0128	0.173
25	0.675	0.0068	0.167
50	0	0	0.160
75	-0.675	-0.0068	0.153
90	-1.282	-0.0128	0.147
95	-1.645	-0.0165	0.144
99	-2.326	-0.0233	0.136
99.9	-3.09	-0.0309	0.129

4. Calculation of the sampling error $(\sigma_{\bar{X}})$ for the test sample mean $\bar{X}_R$:

$$\sigma_{\bar{X}} = \sigma_R \, G/(n)^{1/2} \qquad (8)$$

G = 0.93 from Graph 3 of Nav Ord Report 2101

$$\sigma_{\bar{X}} = 0.010 \times \frac{0.93}{\sqrt{19}} = 0.010 \times 0.213$$

$$= 0.00213 \text{ inch.}$$

5. Calculation of the sampling error (σ_σ) of the standard deviation of the test sample (σ_R):

$$\sigma_\sigma = \sigma_R \, H/(n)^{1/2} \qquad (9)$$

H = 1.91 from Graph A of Nav Ord Report 2101

$$\sigma_\sigma = 0.010 \times \frac{191}{\sqrt{19}} = 0.0096 \times 0.438$$

$$= 0.0044 \text{ inch.}$$

6. Calculation of the confidence intervals for the mean $(\bar{X}_R)$ and the standard deviation (σ_R) for a 90% interval:

(Note: Since the mean and the standard deviation calculated above are only estimates, confidence limits can be obtained by the relationship of

$$y \pm t\,\sigma_y \qquad (10)$$

where y = estimate and σ_y = standard error. The constant t can be derived from Table 2 of Nav Ord Report 2101)

N = 19 - 1 = 18 P = 1 - .90 = .10

t = 1.73

1) Limits of $\bar{X}_R = \bar{X}_R \pm t\,\sigma_{\bar{X}}$ (11)

$$= 0.160 \pm 1.73 \times 0.00213$$

$$= 0.160 \pm 0.0037$$

$$= 0.1563 \text{ to } 0.1637 \text{ inch.}$$

2) Limits of $\sigma_R = \sigma_R \pm t\,\sigma_\sigma$

$$= 0.010 \pm 1.73 \times 0.0044$$

$$= 0.010 \pm 0.0076$$

$$= 0.0176 \text{ to } 0.0024 \text{ inch.}$$

7. Calculation of the confidence intervals of the mean and standard deviation at the 99% confidence interval:

N = 19 - 1 = 18 P = 1 - .99 = .01

t = 2.88

Limits of $\bar{X}_R = 0.160 \pm 2.88 \times 0.00213$

$$= 0.160 \pm 0.0061$$

$$= 0.154 \text{ to } 0.166 \text{ inch.}$$

Limits of $\sigma_R = 0.010 \pm 2.88 \times 0.0044$

$$= 0.010 \pm 0.0126$$

$$= 0.0026 \text{ to } 0.0176 \text{ inch.}$$

8. Calculations of the percent cutting versus the standoff curve for the most pessimistic 99% confidence interval (the lower limit)

$\bar{X}_R = 0.154$ $\sigma_R = 0.0176$

Percent	t	$t\,\sigma_R$	Standoff $\bar{X}_R - t\,\sigma_R$
50	0	0	0.154
75	0.675	0.0152	0.139
90	1.282	0.0289	0.125
95	1.645	0.0371	0.117
99	2.326	0.0525	0.102
99.9	3.090	0.0698	0.084
99.99	3.719	0.0840	0.070
99.999	4.265	0.0964	0.058

Based on the above calculations the conclusion is is the 15 GPF shaped charge will cut 0.090 inch thick aluminum flange at least 99.999% of the time (with a probability of 99.5%) when the standoff does not exceed 0.058 inch.

Testing of a Current Variable.

When the range safety requirement of one amper/one watt no-fire was imposed, practically all electro-initiators were tested by the Bruceton method since AFMTCP 80-2 requires the no-fire level to be varified by a method of sensitivity testing, Bruceton or similar.

A sample of sixty squibs was selected from a lot and was tested by the Bruceton method. The first ten units were fired at random to establish a rough mean and standard deviation. After the first ten units were expended, the test proceded in the classic Bruceton method using amperage as the test variable. The calculations of the sample mean firing current ($\bar{X}_R$) and the standard deviation (o_R) were as follows:

$$\bar{X}_R = 2.838 \text{ amperes}$$

$$O_R = 0.0564 \text{ amperes}$$

These figures were corrected for sample error for 90% confidence level (i.e., 90% probability of including the true lot values).

The no-fire current level (o.001) reliability) was calculated by taking the lower 90% confidence level for the mean and subtracting 3.09 standard deviations, using the upper (i.e., largest) 90% confidence level of the standard deviation. The result was a no-fire current level (0.001 probability with a 95% confidence factor) of 2.581 amperes. The all-fire/current (0.999 probability) was 3.095 amperes.

Second Thoughts on the Bruceton Method.

The recent use of electro-initiators in space projects to perform functions requiring a high degree of reliability, makes reliability prediction from a small sample risky business. The Bruceton has become a popular test/method because the ease with which the test can be performed, the simplicity of the calculations, and the economy of the sample size.

Martin and Saunders performed a computer study to simulate the Bruceton method, using the Monte Carlo approach. The mean was found to be consistant regardless of sample size of 25 or 100 units but the estimates of themean with sample size of 100 closely corresponded with the theoretical mean. Confidence limits at 5% appeared reasonable, but below 5% the limits could be misleading. With samples of 25 items, the estimates of the mean were widely distributed and some occurred outside the expected distribution.

The test interval of one standard deviation or below showed little difference but a test interval of two standard deviations showed a more widely spaced interval with a near normal distribution. Sample size also had a definite effect upon the standard deviation. With small sample size (25) the correlation between the sample and the true standard deviation was .75. With samples of 100 the correlation is .98, using test intervals of two standard deviations.

Recent work at the U.S. Naval Ordance Laboratory by Hampton, Ayres, and Kabik showed that bias is introduced into the Bruceton method in the estimation of the standard deviation, giving a value which was 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 percent point makes the predection of reliability or safety depend upon extreme extrapolation. Consideration of the Bruceton test shows that it is a good test for anyone who is interested in determining the 50% point but a poor test for determining high or low percent points.".

In summary, given a sufficient sample size and a ` proper test interval, the mean and the scatter about the mean are extablished with a reasonable degree of accuracy. As a verification of vendor quality it is an excellant tool. (Investigation of a sample that failed a Bruceton test disclosed the vendor was out of control. Investigation into unexplained variences in the test disclosed another vendor had a manufacturing problem.) The Bruceton test is very useful at temperature extremes to establish the mean and the scatter about the mean for operationsl requirements.

Probit Method

The English had been doing some research into the quantal response of insects to various concentrations of insecticides. The usual method was to plot the standard deviations vertically and the concentrations horizontally. Gaddum found that plotting the dosages in a linear fashion gave a skewed curve. He proceeded to plot the log dosages and found that the curve was now a normal curve and could be treated in a normal manner. Bliss in 1934 suggested the percentages as plotted vertically could be changed to standard deviations, and to eliminate negative values of the standard deviation, took the 50% value as being 5 probits or units of normal distribution. The work was picked up by the Bureau of Naval Ordnance in the evaluation of explosive trains and is incorporated into Navord Report 2101.

An attempt was made to evaluate the reliability of an explosive bolt. The bolts were machined with v-notches of thickness. The results were tabulated as follows:

X	n	%	y (empirical)	y(provisional)
68	9	100	8.7190	9.70
70	6	83.3	5.9661	8.42
72	6	100	8.7190	7.00
74	12	75	5.6745	5.67
76	9	22.2	4.2345	4.23
78	8	25	4.3255	2.82
80	8	0	1.9098	1.48

The empirical probits are derived from a table on the transformations of percentages to probits, and the provisional probits are derived from a line drawn by eye for the best fit. By graphing the results the x or x value corresponding to the probit was .749 inches. The standard deviation was found by measuring the x value of one probit increase. It can be seen that the short method of graphical presentation provides a quick estimate of the degree of breaking of the bolt. Since the problem was to calculate the design reliability, the mathmatical method was resorted to. It was proven that the design probability of having a failure was less than one to 10^{15}. For a further analysis of the mathematical method I will refer you to NAVORD REPORT 2101 or the U. S. Department of Commerce handbook 91.

The Probit method has several advantages. Since the method is to establish the quantal responses and measure them, standard test intervals are not required as they are in the Bruceton method. More test units are concentrated at the tails of the curve and give a better estimate of the extremes. If a distribution tends to be skewed, it can be plotted on log paper and treated as a normal curve by standard statistical methods. The graphical method is excellant for design estimates but confidence levels have to calculated.

The Probit method has a disadvantage that more units are required than in other tests and so is not as economical. The methods of calculation are a bit more cumbersome than in the Bruceton method. The Probit method does make the assumption that the distribution is a normal one.

Conclusion

Reliability assessment and demonstration continue at every phase of a space or military program. Much can be done to retrieve information during the development and acceptance testing phases. The monitoring of this effort is critical since varience on the part of the manufacturer can cause the design parameters to be altered, or cancelled entirely. The verification of design parameters use two/main methods of sensitivity testing, the Bruceton and the Probit. Each has its advantages and its disadvantages.

Based on the data presented in the paper, if the sample size is large (i.e., over one hundred) and the/test interval is large (i.e., two standard deviations) the Bruceton method gives results closely approaching the theoretical. In any event, sensitivity testing is required to verify the design reliability, and attribute testing (through well-structured tests) can establish system reliability.

Summary

With the development of the Centaur Project one of the earliest problems was to assess the reliability of explosive "one-shot" devices early in the program, and reassess the reliability estimates in the light of further testing. Three different methods of testing both by attributes and by variables are discussed along with the advantages and disadvantages of each.

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