FRANKLIN APPLIED PHYSICS

explosives and pyrotechnics

The Newsletter of explosives, pyrotechnics and their devices

Volume 47 ~ Number 11 **November 2014**

EED SENSITIVITY TESTING

The only way to test the sensitivity of an EED is to apply a stimulus, and see whether it fires. It seems reasonable to assume that if the stimulus level is greater than some critical value called the "all-fire," then the EED will fire; and conversely if the applied stimulus level is very low, i.e., lower than a critical value called the "no-fire," then the EED will not fire.

We can never directly measure these critical values. We would need "all EEDs," to test a value at which "all EEDs" fire, i.e., the all-fire value. But we don't have "all EEDs." We have just a few test items. Instead, we must estimate values for no-fire and all-fire stimulus levels.

These are always estimates, never measurements. Thus, it doesn't make sense to talk about the accuracy of a no-fire value.

We follow tradition in making these estimates. Since accuracy cannot be our guide, we follow in the footsteps of explosive testers over the years. There are various traditions – we will be discussing them in more detail later. Some people estimate all-fire and no-fire values using the "Bruceton" protocol. Others use the "Langlie" or the "Neyer" protocol, and so forth. Of course, every person has a favorite protocol. Often we hear voices saying that one protocol gives "more accurate" results than another. However, we should not listen to these voices. The question of accuracy has no answer, as we discussed above. All these traditional methods of estimating all-fire and no-fire levels give reliable, practical results. That is the valuable point to remember.

When one applies a stimulus to an electro explosive device, either it fires or it doesn't. Firing is the only response that interests us at present. Common sense tells us that, generally speaking, the stronger the stimulus we apply, the greater will be the probability that the electro explosive device will fire.

The quantitative nature of data from an EED sensitivity test does not depend on what type of stimulus was used. For example, at one stimulus level five EEDS were exposed, of which three fired and two did not. At another level four EEDS were exposed, of which two fired and two did not; and so on. This is the form that the data will take. The application of the method is the same regardless whether the stimulus is RF power, DC current, or anything else.

There must be a cause-and-effect type relation between the two parameters, "strength of stimulus" and "probability of firing." It makes sense to think that there is a one-to-one correspondence between the parameters. Thus, to every stimulus strength there corresponds a firing probability. If we knew exactly what that correspondence was, we could make a graph, which would probably look something like Figure 1. Note that the firing probability trails up towards 100 percent for very strong

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Email: info@FranklinPhysics.com

Edited by James G. Stuart, Ph.D.
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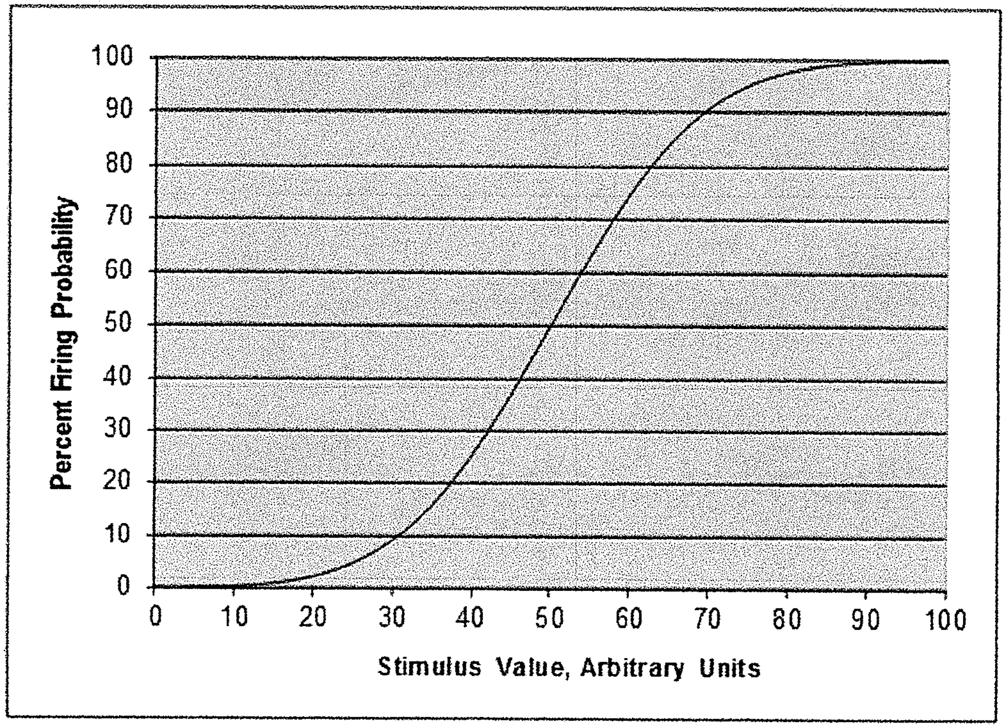
stimuli, and trails off towards zero for very weak stimuli. This behavior of the response curve agrees with our practical experience in working with EEDs.

Figure 1: Cumulative Firing Probability



It is important to remember, so we shall say it again, that the probability parameter graphed in Figure 1 cannot be measured at all points by any practical means. Figure 1 is a theoretical relationship that agrees with our intuitive understanding of how EEDS work, not a compilation of test data. Therefore if later on we want to make up a mathematical formula that has roughly the same shape as Figure 1, giving "probability of firing" as a function of "stimulus strength" for a certain type of EED, it will behoove us to keep that mathematical function as simple as possible, and to acknowledge at every step of the way that we don't really know what the curve looks like.

Users and designers of electro explosive device systems always want to know something about firing probability as a function of input stimulus strength, because they are interested in safety and in reliability of their systems. The only way this information can be obtained for a given type of EED is to take a number of devices and expose them to a certain stimulus level, noting how many of them fire. Thus, the firing probability at that stimulus level may be estimated. This procedure is followed at several different stimulus levels, until the person in charge of the test feels he has sufficient probability data.

We will first discuss a "distribution-free" approach to characterizing the firing probability of electro explosive devices. In this approach, we assume it is not possible to know the form of the probability distribution function. It is a safe approach because it involves no questionable assumptions, but it is unwieldy as will be seen below. In this approach, interpolation between data points is allowed if they are close together, but extrapolation into a region where no experimental data exists is prohibited.

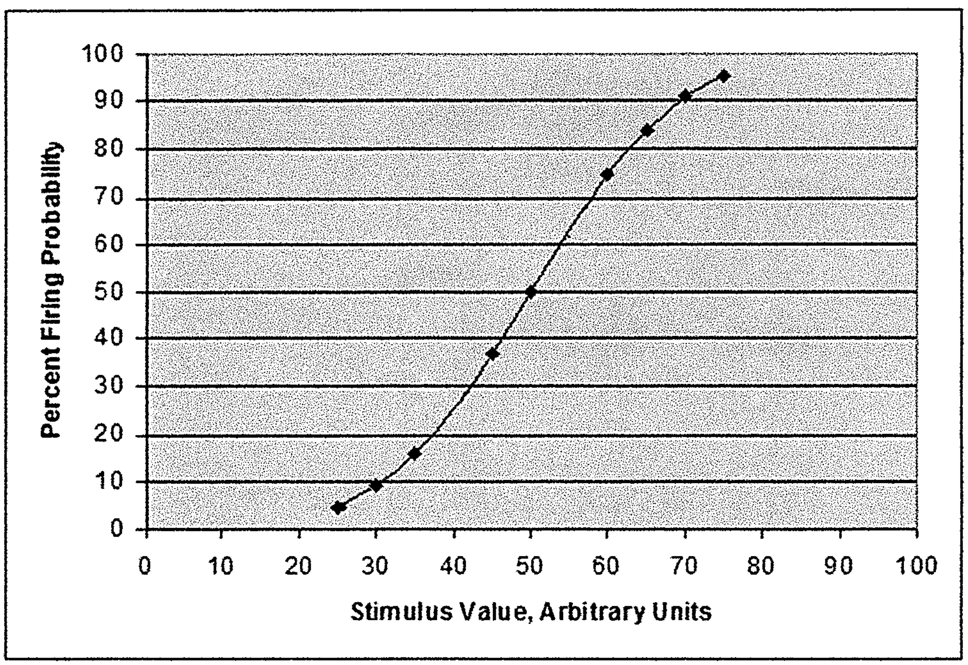
The distribution-free approach may be exemplified as follows. Suppose we have some electro explosive devices of type X. We wish to find out what stimulus strength corresponds to 80 percent probability of firing. We arbitrarily pick stimulus strength 4. We expose a number of items. We note that the fire probability seems to be about 70 percent, at stimulus strength 4. Then we expose some items to stimulus strength 6. We note that the fire probability now is about 90 percent. We then interpolate on a straight line between our two data points. We say that stimulus level 5 will correspond to 80 percent probability of firing.

The advantage of the distribution-free approach to EED testing is that when a percentage point has been determined, it can be considered very reliable because only straight-line interpolation was involved. The disadvantage is that a whole separate test must be conducted for each percentage point desired. Moreover, extremely large test lots of EEDs must be used to determine points far from the mean like 90%, 95%, and so on. These points are important for no-fire and all-fire values.

The example given above also shows how unwieldy the distribution-free approach can be. Enough EEDs had to be exposed to a stimulus with strength 6 to determine that nine out of ten devices would fire there, on the average. Just making that determination will take twenty or thirty EEDs at the minimum, and several hours of laboratory time. All that effort produces just one point on the graph, i.e., the 90-percent probability point. And it must be remembered that this is not the point we wanted; we still have to take more data, determine at least one more probability point, and interpolate. Then we find out that the stimulus strength corresponding to 80% probability of firing is 5, which is what we wanted to know. But what stimulus would produce 50% probability? or 99% probability? There is no way to tell from the data that has been taken so far. We would have to start all over again, for each probability point desired.

Now let us consider another approach, developing a distribution curve. Here is the procedure: by trial and error, we estimate probabilities at enough stimulus levels to characterize a curve. That is, we find stimulus levels corresponding to the lower knee of the curve, the mean or 50 percent probability point, and the upper knee of the curve. These can be pretty well established by ad-hoc tests. Then we sketch a smooth curve through our data points, and we assume that the curve is accurate everywhere, even in regions where no test data exists.

Figure 2: Fitting Data



This whole procedure is shown in Figure 2. The dark points are stimulus values where enough data was taken to estimate the firing probability pretty well. The smooth curve was drawn by eye through these points. The curve can be extrapolated into regions where there are no data points, at the two ends of the curve.

The procedure described above and illustrated in Figure 2 is called "fitting data points to an assumed form of distribution curve." When we have a spread of data points, we draw a curve through them, and the result looks like Figure 2. We have not proven that the real distribution curve looks like this; we just assume that it does.

There are various ways to take the data-points and draw a "best-fit," smooth curve through them. Usually the curve isn't really drawn "by eye," but by a mathematical fitting procedure. For purposes of this discussion it doesn't matter. The important thing to remember is that enough data points are taken to define the shape of the curve pretty well - that is, lower knee, mean and upper knee locations - and then a smooth curve is drawn through the data points.

In sum, the advantages of the approach illustrated in Figure 2 are that only limited testing (enough to locate the knees and mean of the curve) is required, and answers are produced everywhere. That is, the curve can be extrapolated and used to predict probability of firing at any stimulus strength. The disadvantage of this procedure is that you don't know how accurate those predictions are, out beyond the region where the experimental data points were taken.

In our next issues, we will discuss more methods of determining firing probabilities, and the advantages and disadvantages of each.

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Volume 47 ~ Number 12 **December 2014**

EED SENSITIVITY TESTING, continued

In the November issue we discussed sensitivity testing and the fact that the all-fire and no-fire levels are just estimates. The closest we got to a probability distribution function was an estimate drawn "by eye." In this issue we will begin to discuss some statistical methods.

The quantitative nature of data from an EED sensitivity test does not depend on what type of stimulus was used. For instance, at one stimulus level five EEDS were exposed, of which three fired and two did not. At another level four EEDS were exposed, of which two fired and two did not; and so on. This is the form that the data will take. Statisticians have developed powerful methods to analyze this kind of data. The goal of any one of those methods is to predict firing probability at any given stimulus level. The application of the method is the same regardless whether the stimulus is RF power, DC current, or anything else. Of course, we only change one variable during any test, so that we can determine the effect of that variable alone.

No-fire and all-fire levels are critical values that can never be measured directly. It's not a new problem, nor is it insoluble. Over the years a number of mathematicians have devised workable schemes for estimating all-fire and no-fire levels for EEDs. Most of these schemes also estimate other levels, e.g., the mean, that is, the stimulus level corresponding to fifty-percent probability of firing.

The Reverend Thomas Bayes (1702-1761), an English Presbyterian minister and mathematician, considered the question of how one might make inductive inferences from observed sample data about the populations that gave rise to these data.[1] He was interested in making statements about hypotheses from observations of consequences. He developed a theorem which calculated probabilities of "causes" based on the observed "effects." The theorem concerns computing conditional probabilities *after* the observation of sample evidence; for that reason it is often called "a posteriori probability" or "posterior probability." When we test a sample of EEDs, and we fit the test data to an assumed distribution of firing probability, we are applying the Bayes principle.[2]

The analytical procedures for most of the test schemes are based upon the assumption that the response of the initiators being tested is normally distributed (Gaussian) with respect to the stimulus strength. In cases where this assumption is not valid, a normalizing transformation is required. For example, for conventional hot-wire initiators, a better fit to the normal distribution curve is often obtained by using the logarithm of the stimulus.

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1 Hamburg, Morris. 1970. Statistical Analysis for Decision Making. Harcourt, Brace & World, New York.

2 Brunk, H.D. 1960. An Introduction to Mathematical Statistics. Ginn and Company, Boston.

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Figure 1 depicts the normal (Gaussian) distribution function with the standard deviation σ shown graphically. Several probability points are also labeled.

Figure 1: Normal Distribution with Standard Deviation

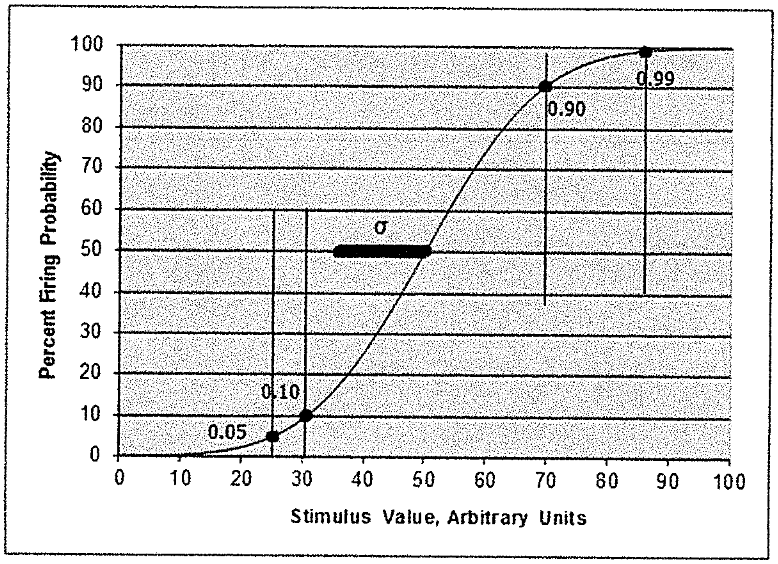

Table 1 gives some of the "percentage points" of the normal distribution. The z_α are mathematical values which indicate how far from the mean (50% probability) each probability point is, in this distribution function. As we can see in Figure 1, the 10% point (α = 0.10) is a little more than one σ from the mean; the 5% point is just over 1½ σ away. The same numerical values apply for 90%, 95%, 99%, etc. because of the symmetry of this distribution function.

Table 1: Some Percentage Points of a Normal Distribution

α	0.50	0.10	0.05	0.02	0.01	0.005
z_α	0	1.282	1.645	1.960	2.326	2.576

When we assume a normal distribution for firing probability, the notion of accuracy itself does not apply to these extreme percentage points because they can never be measured, only extrapolated to or, in other words, guessed at. At the extremes of the data range, where we don't have much data, we're not really sure that our distribution is normal. In fact, it probably isn't. But the mathematical analyses we can do with a normal distribution gives us reasonable estimates which are very useful.

The Bruceton Test

Let us first consider the well-known and often-used Bruceton protocol.[3] Developed in Bruceton, Pennsylvania USA in 1948 to characterize one-shot type of behavior such as the functioning of an explosive device, this method for sensitivity analysis is most commonly used nowadays, by international[4]

[3] W. J. Dixon & A. M. Mood, "A Method for Obtaining and Analyzing Sensitivity Data," Journal of the American Statistical Association, March 1948, pp. 109-126; also see "Introduction to Statistical Analysis" by Wilfred J. Dixon and Frank J. Massey, Jr. (McGraw-Hill Book Co., Inc., New York, 1957).

[4] Recommendations on the Transport of Dangerous Goods. Manual of Tests and Criteria. Third revised edition. United Nations. ST/SG/AC.10/11/Rev.3. Sales No. E99.VIII.2. Appendix 2: Bruceton and Sample Comparison Methods.

agreement. The most recent version of MIL STD 1576 defines all-fire and no-fire levels for EEDs as percentage points predicted by a Bruceton test. That is a good, practical definition based on years of experience.

The Bruceton method is one of the favorites for determining all-fire and no-fire levels. With this procedure we can estimate the mean, i.e. the level of stimulus at which there is a 50% probability of obtaining a positive result, as well as the standard deviation. From those values, we can estimate device firing probability as a function of stimulus level, with any chosen confidence interval.

Computer programs are available which will make the calculations when we input test data. One may be downloaded from our website, FranklinPhysics.com.

The Bruceton method involves applying different levels of stimulus and determining whether a positive reaction (i.e. the EED fires) occurs. Performance of the trials is concentrated around the critical region by decreasing the stimulus by one level in the next trial if a positive result is obtained and increasing the stimulus by one level if a negative result is obtained. Usually about 5 preliminary trials are performed to find a starting level in approximately the right region and then at least 25 trials are performed to provide the data for the calculations. The protocol proceeds as follows:

Depending on what is desired, the input stimulus can be measured in amperes, kilovolts, milliwatts, or any other unit. The duration of the stimulus is fixed and its magnitude is either raised or lowered before each individual test by a fixed increment (d), depending upon whether the preceding observation was a misfire (non-fire) or a fire. For hot-wire devices a logarithmic increment is generally used since by this transformation a normally-distributed sample is obtained. Where the normality of the sample is questionable it should be first tested and then, if possible, corrected by an appropriate normalizing transformation. The testing procedure consists of the following steps:

We first choose about six stimulus levels. Using the results of a few preliminary exposures, we estimate the lowest stimulus value for which we always obtain a fire and the highest value for which we always get a misfire. For example, these preliminary values might be 180 and 100 milliwatts. Assuming a log-normal distribution function as mentioned above, we take the (base 10) logarithm of these two stimulus values. Then we divide the range into about six evenly spaced values (logarithms) - call them S1 (lowest strength) through S6 (highest strength). The difference between any two adjacent numbers we call "d," the test increment. To find the actual stimulus levels, take the antilogarithm of each number Si; note that these actual levels will not be evenly spaced. For our example, Table 2 shows the linear (logarithmic) test levels on the left – these are the ones used in the Bruceton calculations; on the right are the transformed levels that are used for test exposures.

Table 2: Logarithmic and Actual Stimulus Values

	Linear Level	Transformed Level
S6	2.25	180
S5	2.20	158
S4	2.15	141
S3	2.10	126
S2	2.05	112
S1	2.00	100

interval d = 0.05

The test procedure is simple: expose an EED at one of the levels; if it fires, expose the next EED at the next lower level; if it does not fire, expose the next EED at the next higher level. Use this same criterion for each new EED in the test.

We record our data in a typical Bruceton chart. This chart may be either horizontal or vertical. The rows (or columns) are labeled with the various values of the stimulus. Then the data is entered as F's and M's, one per column (or row); F represents a fire and M stands for misfire (no-fire). Because of the way the test was performed, the chart will have a zigzag appearance, like Figure 2.

Figure 2: Bruceton Data Chart

```
S6 . F
S5 .   F                       F
S4 .     F   F       F      M    F   F       F
S3 .       M   F   M    M          M   F   M
S2 .             M                       M
```

We generally continue testing EEDs until we have done forty or fifty of them. The exact number is not important. We must have at least four, and no more than seven, different levels at which an EED was tested (three to six of these will include "fires"). If we have more or fewer, the approximations in the analysis break down and the results are not reliable.

We can input the data into a Bruceton computer program to get the results. Or we can do the calculations, which are fairly simple for the Bruceton protocol. We use the logarithmic values for all calculations and then convert the final results by taking the antilogarithms. We use the following method:

If there are any levels with only one entry *at the beginning of the test*, such as S6 in Figure 2, we do not use them. Count the total remaining numbers of F's and M's; we will use the ones there are fewer of. If the numbers are equal, we may use either F's or M's. In our example of Figure 2, there are fewer M's so we use them. Count the number of the chosen result for each stimulus level; we will use these values in our calculations.

Make another table with the following columns:

- Logarithmic stimulus level
- Number of increments (d) above lowest stimulus used for your chosen result – call it i (i is 0 for the lowest level at which chosen result occurs)
- Number of times chosen result occurred at this level – call it n_i
- The product of columns two and three – $i \times n_i$
- The product of columns two and four – $i^2 \times n_i$

Figure 3: Bruceton Test Data Analysis

Stimulus (log)	i	n_i	in_i	i^2n_i
S4	2	1	2	4
S3	1	5	5	5
S2	0	2	0	0

Now calculate the sums of the entries in columns three, four, and five:

$N = \Sigma n_i$ (i starts at 0)
$A = \Sigma (i n_i)$
$B = \Sigma (i^2 n_i)$

In our example, N = 8, A = 7, and B = 9.

We let y = lowest stimulus value for the chosen result (F or M) and d = interval between levels. In our example, y = S2 =2.05 and d = 0.05. Remember, we do all the calculations with logarithmic values.

We determine the estimated mean firing level μ by calculating

$$\mu = y + d\left\{\frac{A}{N} \pm 0.5\right\}$$

where we use +0.5 if M's are being used and -0.5 if F's are used.

We calculate the standard deviation σ using

$$\sigma = 1.62d\left\{\left[\frac{NB - A^2}{N^2}\right] + 0.029\right\}$$

Note that this method produces an estimate for the standard deviation, not its square as in other methods.

For our example, μ = 2.119 and σ = 0.0315.

Percentage points are estimated by $\mu \pm z_\alpha \sigma$, where z_α are the percentage points of a normal distribution given in Table 1. Thus, if we want the 99% reliability all-fire, we use z_α= 2.326 and get 2.19. Similarly, the 1% no-fire would be 2.05. Remember, these are logarithmic values. Now at the end we take the antilogs to get all-fire = 155 mW and no-fire = 111 mW. The 50% firing probability level is 10^μ = 132mW.

We usually do separate tests for the all-fire and no-fire values. For the all-fire test, we use a short-duration stimulus because we want our EED to fire quickly upon receiving the proper firing signal. On the other hand, we use long exposures (such as 5 minutes) for the no-fire test, to make sure that the devices that do not fire have instead reached thermal equilibrium and will not be heated any further by the input stimulus.

We can also calculate confidence intervals from the Bruceton data, but the procedure is fairly complicated because it depends on a multiplicative factor which itself depends on data values. Such calculations are included in most Bruceton computer programs.

The Bruceton method is a fairly simple way to estimate firing probabilities for EEDs. It uses a limited number of stimulus values and most of the calculations are not very difficult. It is a very effective and often-used method for determining all-fire and no-fire levels.

We will discuss other statistical test protocols in the next issue.

UPCOMING MEETINGS

The dates for the **41st IPS / EUROPYRO 2015** symposium in Toulouse, France, have been changed to 4-7 May 2015. Please note the update on our calendar.

FRANKLIN APPLIED PHYSICS COURSE OFFERED

This summer we will again present the Franklin explosives training course here in Oaks, Pennsylvania. We can also present this course, or shorter courses in Electroexplosive Safety tailored to your particular needs, at your location. We have made such presentations for more than 60 governmental and industrial sponsors.

Unlike most other explosives safety courses, ours concentrates specifically on EEDs.

Titled **Electro-Explosive Devices: Functioning, Reliability, and Hazards**, our five-day course will be offered again on 27-31 July 2015 by **Franklin Applied Physics**. Major topics to be covered include:

- Nature of explosions
- Chemistry and physics of explosives
- Gas expansion effects
- Detonation shock effects
- Types of pyrotechnics, explosives and propellants
- Initiation of explosives
- Output and applications
- Explosive trains and systems, fuzes, safe-arm devices
- Electroexplosive device (EED) principles, types of EEDs, uses and applications
- Static electricity (ESD) hazards to EEDs, hands-on ESD demonstrations
- Lightning hazards to EEDs
- Forensic investigation of EED accidents
- Radio frequency (RF) hazards to EEDs, demonstrations, proving RF safety, RF irradiation (field) tests, RF safe distance calculation
- RF ID-tag use with EEDs
- Other hazards: heat, flame, impact, vibration, friction, shock blast, and human error
- Precautions, safety practices, and Standard Operating Procedures
- Testing explosives: nondestructive tests on EEDs, need for tests, stimulus levels in EED tests, hands-on Bruceton-type and Langlie-type statistical firing tests, safety versus reliability
- Storage and shipment of explosives
- History of explosives
- Sources of information

Many of these subjects are in a state of maturing development; we present not only background, but also state-of-the-art developments.

The emphasis of this course is safety through understanding of the underlying physical phenomena. It is of particular benefit to EED handlers, their supervisors, safety engineers, instructors, designers, R&D personnel, quality control personnel, and inspectors.

The fee for the five-day course in July is $1519 (does not include food or lodging). For more information or to register contact Franklin Applied Physics, Inc., P.O. Box 313, Oaks, Pennsylvania 19456; Tel: (610) 666-6645; Fax: (610) 666-0173; E-mail: info@FranklinPhysics.com; Website: www.FranklinPhysics.com (you can register online).

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explosives and pyrotechnics

APPLIED PHYSICS

The Newsletter of explosives, pyrotechnics and their devices

Volume 48 ~ Number 1 **January 2015**

DANGEROUS USE OF TANNERITE

One of our colleagues recently told us about so-called exploding targets. These are intended for use by people who enjoy shooting a rifle at a target. In this case the target is a small plastic jar containing an impact-sensitive energetic material. When a high-energy rifle bullet hits this target, it explodes with a flash. This could be useful in training people to shoot accurately at a distance so great that it would be hard to tell, without a flash, whether the bullet hit the target. One brand of exploding target is called Tannerite, but there are other similar exploding targets with other names, e.g. Sure Shot.

The material used is a combination of ammonium nitrate powder and aluminum powder. The two powders are in separate containers for shipment and sale. This is what we call a binary explosive – neither component, by itself, is dangerous. The user mixes these two powders together, to make an exploding target. The manufacturer supplies a non-sparking plastic mixing container.

On the safety side, this kind of target will simply burn if touched with a flame. Shotgun pellets or pistol bullets will not do anything to this target. Only the impact of a high-velocity rifle bullet will make it explode.

The manufacturers of exploding target material give instructions on how to use this material safely. For instance, users should mix only a small quantity of the exploding material at any one time. Alas, some people have ignored those instructions, causing serious injury. We describe one example:

In Celina, Ohio, USA, in 2012, some people mixed a very large quantity of exploding target material. They bored a hole in the steel side of an old refrigerator. They put the energetic material inside the refrigerator, next to the hole. They secured the door of the refrigerator with metal screws. Then the people retreated about 50 yards (50 m) away. They shot rifles at the refrigerator, trying to shoot a bullet through the hole.

Eventually one rifle bullet went through the hole, and made the energetic material explode. Because of the large quantity, and because of the confinement with the fastened refrigerator door, the explosion was a very-high-energy detonation.

We regret to report that one person, who was watching this shooting contest at a distance of some 50 yards (50 m), received a terrible injury. A fragment from the steel refrigerator struck her arm, severing it. We are sorry for her.

In plain words, this particular target was a home-made bomb. Such things are dangerous and illegal. People should only use energetic materials as they are meant to be used. Improvised bombs like the one we describe here can only lead to trouble. We advise anyone near a home-made bomb to retreat rapidly to a great distance, and to alert the authorities.

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Oaks, Pennsylvania 19456-0313
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EED SENSITIVITY TESTING, continued

In the previous issue we described the Bruceton test, a very popular statistical firing test. In this issue we will describe another protocol, the Langlie type statistical firing test.

The Langlie Test

The main advantage of the Langlie approach[1] is that it yields valid statistical data but does not require any assumptions or guesses regarding the mean and standard deviation that are to be determined. The stimulus levels are not chosen in advance as in the Bruceton protocol.

The Langlie test procedure is unique in that we expose every EED to a different stimulus level. The scheme is as follows:

First, we choose an upper stimulus limit, one that will assuredly fire the EEDs. Then we choose a lower stimulus limit, one that certainly will not fire the EEDs. The region of stimuli between the lower limit and the upper limit is what we call the test interval.

The first stimulus value is the average of the upper and lower limits.

The general rule for calculating the $(n+l)^{th}$ stimulus level, having completed exposure of n EEDs, is to work backward in the test sequence, starting at the n^{th} exposure, until a previous exposure (call it the p^{th} exposure) is found, such that there are as many fires as misfires (no-fires) in the p^{th} through the n^{th} exposures. The $(n+l)^{th}$ level is then obtained by averaging the n^{th} level with the p^{th} level. If there exists no previous exposure level satisfying the requirement stated above, then the $(n+l)^{th}$ exposure level is obtained by averaging the n^{th} level with the lower or upper stimulus limit of the test interval according to whether the n^{th} result was a fire (F) or a misfire (M).

Table 1 on the next page shows a sample data sheet for a Langlie test. It includes the values that we averaged to calculate each required stimulus value, in the "average" columns. The column labeled "s" is the stimulus value. For instance, looking at the top line, in the first trial we averaged 15 and 1, the upper and lower limits, to get 8 volts. This is the value that we used for the first trial. The first device did not fire at that level, so we entered M in the result column. For the second trial, n+1 where n=1, there were no previous fires, so we averaged the first level (8) with the upper limit value. For the fifth trial, we averaged the stimulus values from the fourth and third trials, because counting back from the fifth row there is one misfire and one fire. For trial 7, when we counted back there were always more misfires than fires, so we averaged with the upper limit. For trial 19, we had to count back to trial 7 to get equal numbers of F's and M's – six of each – so we averaged the stimulus values of trial 18 and trial 7. In the table we find values of s_i, for required stimulus, which contain many decimal places, because of continued averaging. Our test equipment did not show that many decimal places, so we simply set the stimulus as close as possible to the required value. The column label "u" is the outcome of the trial: 0 means that it fired (F), 1 means that it did not fire (M). We will need these numerical values, 0 and 1, for the calculations in the analysis.

As in the Bruceton method, the Langlie test concentrates the data around the mean, because the protocol automatically raises the stimulus level after a device misfires, and lowers it after a fire. For the calculations in the Langlie procedure to work, we must have an "overlap" of fires and misfires, i.e., the lowest stimulus value which produced a fire must be less than the highest stimulus value which produced a misfire. In other words, there must be a region where fires and misfires are mixed together. If this condition is not met, the program will attempt, unsuccessfully, to divide by zero. In our example,

[1] Langlie, H.J. 1962. A Reliability Test Method for "One-Shot" Items. Aeronutronic division of Ford Motor Company, Publication No. U-1792. Work performed under U.S. Army Contract DA-04-495-ORD-1835.

the lowest fire occurred at stimulus level 8.95 (trial 15) and the highest misfire occurred at 9.53 (trial 6). Between these two stimulus values there are two more misfires and a fire, so we have a good overlap.

Table 1: Langlie Data Sheet

Upper limit 15 volts Lower limit 1 volt u=0 fire u=1 misfire

trial	average	average	s	result	u
1	15	1	8	M	1
2	8	15	11.5	F	0
3	11.5	8	9.75	F	0
4	9.75	1	5.375	M	1
5	5.375	9.75	7.5625	M	1
6	7.5625	11.5	9.53125	M	1
7	9.53125	15	12.26563	F	0
8	12.26563	9.53125	10.89844	F	0
9	10.89844	7.5625	9.230469	M	1
10	9.230469	10.89844	10.06445	F	0
11	10.06445	9.230469	9.647461	F	0
12	9.647461	5.375	7.51123	M	1
13	7.51123	9.647461	8.579346	M	1
14	8.579346	10.06445	9.321899	F	0
15	9.321899	8.579346	8.950623	F	0
16	8.950623	7.51123	8.230927	M	1
17	8.230927	8.950623	8.590775	M	1
18	8.590775	9.321899	8.956337	M	1
19	8.956337	12.26563	10.61098	F	0
20	10.61098	8.956337	9.783659	F	0

We begin the analysis by making estimates for the sample mean μ and standard deviation σ. We then calculate the values of the parameters in Equation 1, using our estimates of μ and σ.

Equation 1: Langlie Parameters

$$t_i = \frac{s_i - \mu}{\sigma}$$

$$g(t) = \frac{1}{\sqrt{2\pi}} e^{-\frac{t^2}{2}}$$

$$h_i = \frac{u_i}{1 - G_i} - \frac{1 - u_i}{G_i}$$

$$G_i = \int_{-\infty}^{t_i} g(t)\, dt$$

In Equation 1, the normalized stress deviate is t_i. The Gaussian ordinate for t is g(t). The "outcome" weighting parameter is h_i. The Gaussian area from negative infinity to t_i (cumulative probability) is G_i.

We use our estimated values of (μ, σ) to calculate t_i for each stimulus value s_i. Note that a computer is necessary for the Langlie analysis because of the complicated parameters which must be evaluated for each data pair, and for each iteration of the analysis. The Excel spreadsheet of Table 2 does these calculations for us.

Then we form the sums in Equation 2.

Equation 2: Langlie Sums

$$\sum_{i=1}^{N} g(t_i)\, h_i = 0$$

$$\sum_{i=1}^{N} t_i\, g(t_i)\, h_i = 0$$

If the sums are not zero, we make adjustments to the values of (μ, σ) until the equalities hold true. In our example we began with estimates μ= 9.3 and σ= 0.5, and the initial sums were -0.88 and -0.57. In practice, we adjust the values (μ, σ) at the bottom left of Table 2 until the sums at the bottom right of Table 2 are as close as possible to zero. Having done this with our data, we found that the maximum-likelihood estimated values are μ =9.22 volts and σ =0.42 volt.

Table 2: Langle Anaysis Sheet, Part A

trial	s	u	t	g	h	gh	tgh
1	8	1	-2.90476	0.00587	1.00184	0.005881	-0.017083
2	11.5	0	5.42857	1.6E-07	-1	-1.59E-07	-8.64E-07
3	9.75	0	1.2619	0.17992	-1.1154	-0.200689	-0.25325
4	5.4	1	-9.09524	4.3E-19	1	4.34E-19	-3.95E-18
5	7.6	1	-3.85714	0.00023	1.00006	0.000235	-0.000905
6	9.5	1	0.66667	0.31941	3.96051	1.265044	0.843363
7	12.3	0	7.33333	8.4E-13	-1	-8.38E-13	-6.14E-12
8	10.9	0	4	0.00013	-1	-0.000134	-0.000535
9	9.2	1	-0.04762	0.39845	1.92682	0.767737	-0.036559
10	10.1	0	2.09524	0.04442	-1.0184	-0.045238	-0.094785
11	9.6	0	0.90476	0.26492	-1.2237	-0.324174	-0.2933
12	7.5	1	-4.09524	9.1E-05	1.00002	9.1E-05	-0.000373
13	8.6	1	-1.47619	0.13417	1.07521	0.144265	-0.212963
14	9.3	0	0.19048	0.39173	-1.7375	-0.680638	-0.129645
15	8.9	0	-0.7619	0.29841	-4.4831	-1.337802	1.019277
16	8.2	1	-2.42857	0.0209	1.00764	0.021059	-0.051144
17	8.6	1	-1.47619	0.13417	1.07521	0.144265	-0.212963
18	8.9	1	-0.7619	0.29841	1.2871	0.38408	-0.292633
19	10.6	0	3.28571	0.00181	-1.0005	-0.001806	-0.005935
20	9.8	0	1.38095	0.15373	-1.0913	-0.167763	-0.231672
					sums	-0.025585	0.028894
	mu	sigma					
	9.22	0.42					

Following Langlie's work, we call our results (from the bottom of Table 2) μ_e (estimated mean, with value 9.22 in our example) and σ_e (estimated standard deviation, with value 0.42). We show the completion of the analysis, explained below, in Table 3.

First, we correct our estimated standard deviation for "bias" – σ_e is always too small. A graph defines the relation between bias β and the number of trials N. We have N= 20; the program gives β= 0.78. Equation 3 gives 0.536 as the unbiased estimated standard deviation for our example.

Equation 3: Unbiased Estimate

$$\hat{\sigma} = \frac{\sigma_e}{\beta}$$

Equation 4 gives the variance of the estimated mean and of the estimated standard deviation, and the results in our example.

Equation 4: Variance of Estimators

$$V(\mu_e) = \frac{2.5\,\hat{\sigma}^2}{N} = 0.036$$

$$V(\sigma_e) = \frac{3.2\,\hat{\sigma}^2}{N} = 0.046$$

Table 3: Langlie Analysis Sheet, Part B

estimated mean	9.2
estimated standard deviation, biased	0.42
N	20
bias	0.78
unbiased estimated standard deviation	0.535919
variance of estimated mean	0.035901
variance of unbiased estimated standard deviation	0.045954
all-fire confidence, percent	95
all-fire confidence, fraction	0.95
all-fire probability of firing, percent	99.9
all-fire probability of firing, fraction	0.999
all-fire k	3.090232
all-fire l	1.644854
All Fire Level	11.98944
no-fire confidence, percent	95
no-fire confidence, fraction	0.05
no-fire probability of firing, percent	0.1
no-fire probability of firing, fraction	0.001
no-fire k	-3.09023
no-fire l	-1.64485
No Fire Level	6.410563

We define the all-fire level by the following statement: we have 100α % confidence that the stimulus s, corresponding to 100θ % probability of firing, is less than or equal to the value of s calculated from Equation 5.

Equation 5: All-Fire Stimulus

$$s = \mu_e + k\hat{\sigma} + \ell\sqrt{V(\mu_e) + k^2 V(\sigma_e)}$$

$$\text{where} \quad \theta = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{k} e^{-x^2/2}\, dx$$

$$\text{and} \quad \alpha = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\ell} e^{-x^2/2}\, dx$$

For example, if we choose θ=0.999 and α=0.95, we follow Equation 5 to find that s = 11.99V. That is our all-fire level, with 99.9% reliability, and 95% confidence. Similarly, for the no-fire level, we use θ=0.001 and α=0.05 to get 6.41V.

If you have a computer, the Langlie method is not very difficult to use. It does not require choosing the stimulus levels in advance, as in the Bruceton method. Often fewer trials are needed than for the Bructeon test. However, care must be taken in following the protocol for determining stimulus levels in the Langlie method.

UPCOMING MEETINGS

The **8th World Conference on Explosives and Blasting** will be held 26-28 April 2015 at Lyon, France. This conference is presented by the European Federation of Explosives Engineers (**EFEE**), together with the French Group of Explosives Engineers (GFEE) and Syndicat National des Entrepreneurs de Travaux Publics spécialisés dans l'Utilisation d'Explosifs. More than 500 professionals from over 50 different countries are expected to attend. This will create a great opportunity to meet colleagues from the construction, demolition, quarrying and mining industry; to build networks and exchange information, news and techniques both for users and manufacturers of explosives and drilling operations as well as for consultants and clients. The conference will include a large exhibition area which will display and demonstrate the latest developments across the industry.

Papers have been submitted on a range of topics including:

- Health, safety, and environment
- Management covering blast design
- Blasting covering experience from projects
- Shot hole development
- Technical development
- EU directives and harmonization work

The conference language is English. Note that the conference begins on Sunday with registration and workshops plus a welcome reception. There is an "early bird" discount for registration online by 31 January 2015.

For more information please email info@efee2015.com or visit the website www.efee2015.com

MEETINGS, COURSES, AND OTHER ACTIVITIES

Activity	Venue	Date(s)	E&P Issue
Blasters Weekend	New Orleans,Louisiana,USA	31 Jan.–1 Feb. 2014	Oct. 2014
41st Annual Conference on Explosives and Blasting Technique	New Orleans,Louisiana,USA	1-4 Feb. 2015	Apr. 2014
8th World Conference on Explosives and Blasting	Lyon, France	26-28 Apr. 2015	this issue
41st International Pyrotechnics Seminar	Toulouse, France	4-7 May 2015	May 2014
EUROPYRO 2015	Toulouse, France	4-7 May 2015	May 2014 and Dec. 2014
46th International Annual Conference of the Fraunhofer ICT	Karlsruhe, Germany	23-26 June 2015	Oct. 2014
Underwater Blasting		3-5 Mar. 2015	Nov. 2014
Rock Blasting and Overbreak Control		21-23 Apr. 2015	Nov. 2014
Blasting Geology		5-7 May 2015	Nov. 2014
Effective Quarry Blasting Methods		19-21 May 2015	Nov. 2014
Electro-Explosive Devices: Functioning, Reliability, and Hazards	Oaks, Pennsylvania USA	27-31 July 2015	Dec. 2014

FRANKLIN APPLIED PHYSICS

explosives and pyrotechnics

The Newsletter of explosives, pyrotechnics and their devices

Volume 48 ~ Number 2 **February 2015**

EED SENSITIVITY TESTING, continued

In previous issues we have discussed the distribution-free approach to determining EED sensitivity, such as all-fire and no-fire levels, as well as two popular statistical firing tests based on the normal distribution (the Bruceton and Langlie tests). In this issue we will briefly discuss other protocols which may be used to give equivalent results.

The Probit Test

The Probit technique[1] is ordinarily used where interest is in specific probability levels. By expending greater numbers of EEDs at or near the level of interest the estimate of the level is improved. If, for example, the 90 percent point is accurately required, then the majority of the lot could be tested around this point. By doing so, an accurate determination would be made at this level, at the expense of information at other levels.

In its application to EED testing, the Probit method is used infrequently, due to the limited size of test-lots usually available. Hence, this technique is used only as a substitute for the Bruceton when it is found that the latter procedure cannot be used conveniently. Probit analysis may be used for treating Bruceton data taken with a procedural error; for example, when a firing level has been omitted or an incorrect estimate required a subsequent change of the increment between test levels.

Basically, the Probit technique calls for firing groups of EEDs at several pre-assigned levels. As with the Bruceton technique, prior knowledge of the anticipated response greatly simplifies the choice of levels. A good first choice of levels for a five-level Probit test, for example, would be A, A ± ½ B, and A ± B, where A and B are the estimated mean firing level and the standard deviation. Note the similarity to the evenly-spaced levels of a Bruceton test. These levels correspond roughly to the 15%, 30%, 50%, 70% and 85% levels of the probability distribution.

Without any grounds for estimating the response, the levels must be guessed. A poor first guess will mean the test should be started over again from the beginning. If tests are planned for extreme levels (90%, 10%) it should be realized that many samples will be required. The actual number required to ensure that both fires and non-fires will be observed can be estimated by the binomial distribution.

In analyzing data by Probit techniques, the percentage of fires is determined at each testing level. These percentages are then converted to probit units and the data are plotted on linear graph paper using probits of fires as the ordinate, and as the abscissa, the logarithm of the testing levels. The reference gives complete instructions for determining the mean, standard deviation, all fire and no-fire levels.

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[1] Finney, D.J. 1952. Probit Analysis, 2nd edition. Cambridge University Press, England.

Published twelve times a year by FRANKLIN APPLIED PHYSICS, INC.
98 Highland Avenue, P.O. Box 313
Oaks, Pennsylvania 19456-0313
Tel.: (610) 666-6645, Fax: (610) 666-0173
Email: info@FranklinPhysics.com

Edited by James G. Stuart, Ph.D.
Subscription: $47.50 per year
$51.50 outside USA
$5 single copy

The Robbins-Monro Test

The Robbins-Monro method[2] when applied to electroexplosive devices may be used to find the stimulus level which corresponds to any desired probability of firing. The reference gives mathematical proofs. Another reference[3] contains a critical evaluation of the Robbins-Monro method, and a Monte Carlo type test of its ability.

The process may be described quite simply: Let x be a stimulus level, and y(x) is the result when an electroexplosive device is exposed to stimulus x. y(x)=1 means that it fired, and y(x)=0 means that it did not fire. (Note that this is opposite the system in the Langlie protocol.)

Equation 1: Robbins-Monro Test Levels

$$x_{r+1} = x_r - a_r[y_r(x_r) - p]$$
$$a_r = \frac{C}{r}$$

If an estimate is required for x_p, the stimulus level for which the chosen probability of firing is p, then a series of observations $y_r(x_r)$ is taken at levels x_r given by Equation 1. The value of p will be between 0 and 1; for instance, if we want the 80% firing level, then p=0.8.

The a_r are positive constants. After n observations, x_{n+1} is taken as the estimate of x_p. Equation 1 ensures that, if the r^{th} observation $y_r(x_r)$ is unity (a fire), the next observation is taken at a lower level; and if $y_r(x_r)$ is zero (a misfire), the next observation is taken at a higher level.

The factors a_r are chosen to depend on r so that successive changes of level become smaller and observations converge to the true value x_p. A good choice is given by Equation 1 where C is any positive number. The process described above is simple to do and does not make any assumption about the shape of the probability distribution function. It tends to concentrate the data points in the region of the probability level which is of interest.

The Neyer Test

The Neyer protocol[4,5,6] has similarities to the Langlie protocol. It purports to require fewer test items to obtain similar results, because the Neyer test has three separate parts, with different calculations for stimulus levels in each. The first part focuses in on the mean, the next section does a binary search to get unique estimates, and the final part chooses levels in a way to optimize the quantity of interest, e.g. the standard deviation, the mean, etc. The Neyer Test protocol is not in the public domain; you must purchase the program from Dr. Barry Neyer who created it.

The Einbinder or OSTR Test

The Einbinder or one-shot-transformed method (OSTR) of testing electroexplosive devices is a transformed-response version of the Langlie method (described in our January issue), with an extra

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[2] Robbins, Herbert; Monro, Sutton. 1951. A Stochastic Approximation Method. Annals of Mathematical Statistics, Volume 22, pp. 400-407.

[3] Wetherill, G.B. 1963. Sequential Estimation of Quantal Response Curves. Royal Statistical Society B, Volume 25, pp. 1-48.

[4] Neyer, Barry T. How to Learn More from Sensitivity Tests. Proceedings of the Fifteenth Symposium on Explosives and Pyrotechnics, April 19-21, 1994, Essington, Pennsylvania. Franklin Applied Physics, Inc.

[5] Neyer, Barry T. μ +/– $K\sigma$ Analysis of Various Threshold Tests. Proceedings of the Sixteenth Symposium on Explosives and Pyrotechnics, April 29 to May 1, 1997, Essington, Pennsylvania. Franklin Applied Physics, Inc.

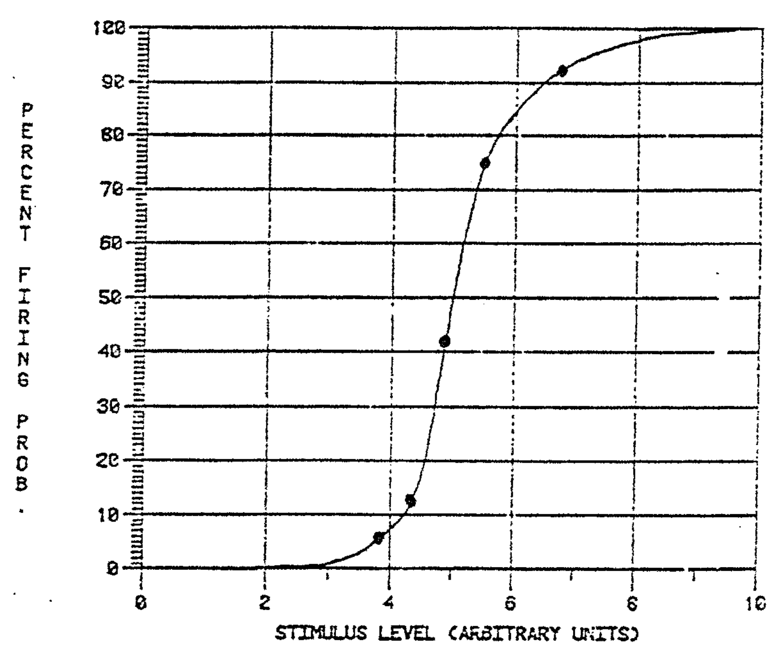
[6] Neyer, Barry T. ISO 14304 Annex B All Fire/No Fire Test and Analysis Methods. Proceedings of the 17th Symposium on Explosives and Pyrotechnics, 27-29 April 1999, Philadelphia, Pennsylvania. Franklin Applied Physics, Inc.

parameter included for skewness in the curve-fitting section of the analysis. "Transformed-response" means that a procedure is followed which concentrates the testing in the region of the probability level of major interest.[7,8]

The way this is happens may be illustrated by the following example: a certain voltage is applied to an EED. If it does not fire, the voltage level is increased for the next device; if on the other hand it does fire, the next device is exposed to the same voltage. If this second device does not fire the voltage level is increased, but if it does fire the voltage level is decreased. In other words, the test engineer increases the voltage whenever there is a misfire, and decreases the voltage whenever there are two fires in succession. This two-to-one ratio forces the data to concentrate around the 66 percent point. Similarly, a four-to-one ratio would force the data to concentrate around the 80 percent point, and so on. The advantage of the Einbinder method is that it is guaranteed to be quite accurate in the neighborhood of the percentage point around which the data points were centered. One disadvantage that the Einbinder method shares with the distribution-free method described in the November issue, is that extremely large test lots of EEDs are required if the percentage point of interest is far from the mean, like 90% or 95%. For this reason most Einbinder tests will, as a practical matter, be run close to the mean or 50 percent point.

The Einbinder method of curve fitting allows for a skewed distribution of probability - a Weibull curve, with one shoulder steeper than the other. This is illustrated in Figure 1 which shows a distribution curve whose lower knee is steep while the upper knee is gradual. Bruceton and Langlie tests always force data points to fit a symmetrical curve, but the data points in Figure 1 would not fit very well on a symmetrical curve. Therefore for the group of data points pictured, the Einbinder method would give a better fit and more accurate results than the other methods. The Einbinder method yields a coefficient of skewness, a parameter in the Weibull distribution which best fits the data being analyzed.

Figure 1: Skewed Curve



The Bruceton and Langlie methods both tend to concentrate the data points around the mean or 50-percent point. The Einbinder method makes it possible to concentrate data around any percentage

[7] Einbinder, Seymour, "A Sequential Sensitivity Test for Extreme Percentage Points and Estimation Using a Weibull Response Model." Paper presented at 17th Army Operations Research Symposium, 7-9 November 1978, Fort Lee, Virginia.

[8] Wetherill, G.B. "Sequential Estimation of Quantal Response Curves." J. Royal Statistical Society "B," Volume 25, pp. 1-48 (1963).

point. Of course if the 50-percent point is selected then the Einbinder method should give the same results as the Bruceton or Langlie methods. One way of looking at this would be to say that the Einbinder method gives the test engineer a degree of freedom.

The ability of the Einbinder test to concentrate data around a percentage point other than the mean is not helpful in determining all-fire or no-fire levels. It is impossible to take any useful data at all near the no-fire point, much less to concentrate data around it. Therefore when extreme percentage points are desired the Einbinder test will be run centered around the mean, where it offers little advantage over the more common Bruceton and Langlie methods.

Similarly, the ability of the Einbinder test to measure the skewness of the probability distribution curve is not helpful in determining all-fire and no-fire levels. The fact that a skewed curve predicts firing probability more accurately than a symmetrical curve over the range of levels where firing tests were done has nothing to do with accuracy in determining extreme percentage points. Extrapolation of the curve is always just a guess, so the all-fire and no-fire levels are only estimates.

Protocol Equivalence

Technical people at Franklin Applied Physics, Inc. have compared[9] various types of statistical tests that can be used to evaluate EED sensitivity. They fired thousands of T18E3 detonators, following the Bruceton procedure and the Probit procedure, as well as other procedures.

Results of the Bruceton and Probit tests were in good agreement. The mean, standard deviation, all-fire, and no-fire levels predicted by the Bruceton test did not differ significantly from those predicted by the Probit test method.

The choice of protocol depends on the individual tester's comfort with the protocol, previous knowledge about the test items' sensitivity (for optimally choosing test parameters), the ease of changing the stimulus level, and the likely number of test items required to complete the test.

MEETINGS, COURSES, AND OTHER ACTIVITIES

Activity	Venue	Date(s)	E&P Issue
8th World Conference on Explosives and Blasting	Lyon, France	26-28 Apr. 2015	Jan. 2015
41st International Pyrotechnics Seminar	Toulouse, France	4-7 May 2015	May 2014
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46th International Annual Conference of the Fraunhofer ICT	Karlsruhe, Germany	23-26 June 2015	Oct. 2014
Underwater Blasting		3-5 Mar. 2015	Nov. 2014
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Blasting Geology		5-7 May 2015	Nov. 2014
Effective Quarry Blasting Methods		19-21 May 2015	Nov. 2014
Electro-Explosive Devices: Functioning, Reliability, and Hazards	Oaks, Pennsylvania USA	27-31 July 2015	Dec. 2014

[9] Hammer, Carl. May 1, 1955. Statistical Methods in Initiator Evaluation. Franklin Applied Physics, Inc. Report No. I-1804-1. Prepared for Picatinny Arsenal, Samuel Feltman Ammunition Laboratories.

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The Newsletter of explosives, pyrotechnics and their devices

Volume 48 ~ Number 3 **March 2015**

EED SENSITIVITY TESTING, concluded

In this issue we will wrap up our discussion of EED sensitivity testing by commenting further on some issues that have been mentioned in previous sections.

Confidence and Reliability

We often perform tests on explosive devices for the purpose of determining an all-fire or a no-fire stimulus value. Associated with such determination are the two concepts of confidence and reliability, which we will explain.

We always assume that there exists a large population of N items – this could, for instance, be a manufacturer's output over some period of time. From this population we randomly choose a small lot of n items, which we call our test lot. Note that $n<<N$.

We assume that the fraction of defective items in the large lot (size N) is θ, a number between zero and unity. For instance, if θ =0.02, then 2% of the items in the large lot are defective. This would mean that 98% of the items in the large lot are not defective. In other words, the reliability is 98%. Equation 1 gives the general expression.

Equation 1: Reliability Definition

$$Reliability = (1 - \theta)\cdot 100\%$$

Of course we cannot measure θ directly, because it is a characteristic of the large lot (size N). We do not have the large lot. All we have is our test lot (size n).

Suppose n=1. That means we choose just one item from our large lot (size N) and we examine this one item. We will try to estimate the defective fraction θ in the large lot. Suppose that we find our one item that we are examining is not defective. Then, our best estimate for θ would be zero, and our best estimate for reliability for the large lot would be 100%. However, we feel that sampling just one item from the large lot does not adequately represent the large lot. In other words, we have little confidence that the reliability is really 100%, based on a sample of one.

"Confidence," please note, depends upon the size n of our sample. "Confidence" depends upon whether we have a sufficient number n in our test lot to represent the large lot (size N) adequately. We will give a common-sense example:

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98 Highland Avenue, P.O. Box 313
Oaks, Pennsylvania 19456-0313
Tel.: (610) 666-6645, Fax: (610) 666-0173
Email: info@FranklinPhysics.com

Edited by James G. Stuart, Ph.D.
Subscription: $47.50 per year
$51.50 outside USA
$5 single copy

We do not know the defective fraction in the large lot; that is what we are attempting to determine. We test a small sample of 4 items. One is defective, and three are not. Clearly, at this point, our best estimate of the defective fraction is 0.25. However, we do not have much confidence in that value, because it is based upon finding just one defective item in our test lot. In order to increase our confidence, we sample and test some more items, until we have tested a total of 40 items; we find that 10 of them are defective. At this point, our best estimate of the defective fraction is still 0.25, but now we have more confidence in that estimate.

We have attempted here to explain the difference between "reliability" and "confidence," and how these two concepts relate to each other. There are statistical methods for determining both the reliability (or θ, the defective fraction of the large lot) and the numerical value of the confidence (such as 95% confidence), from a test of the small lot of n items. That discussion is beyond the scope of this article. However, the computer programs for the various protocols do make these calculations for us when we enter our test data.

Safety Margin

We were recently able to help a woman who was working on an automobile air-bag system. She was concerned about the safety margin. The airbag igniter was specified as having 1.0-ohm resistance, and no-fire current 0.45 ampere, so the no-fire or "safe" power level was 0.20 watt. As long as the electrical power dissipated in this igniter is less than 0.20 watt, it will not fire.

This engineer's problem was in computing the safety margin. Her employers require a safety margin of 10. Test data seemed to put this goal out of reach. During one test, a vehicle containing this airbag system had been driven very close to a powerful radio transmitter. A tiny sensor embedded for this test in the airbag igniter had indicated RF power pickup was 0.038 watt. This was greater than one-tenth of the safe level (one-tenth of the safe level would be 0.020 watt). Nevertheless, the engineer needed a safety margin of 10. She asked our advice.

A Bruceton-type statistical firing test had been carried out on this type of airbag igniter. We scrutinized the test data. The no-fire or "safe" level, i.e., 0.20 watt, corresponds to an acceptable, low value of risk. For a safety margin of 10, we want to be ten times safer. That means the risk should be smaller, by a factor of ten. If the 0.20 watt no-fire level was specified to have 99.9% reliability (or 0.1% chance of firing), then the 99.99% level would have only one-tenth the chance of firing, i.e. 0.01%. Analyzing the test data, we found this would correspond to a power level of 0.13-watt dissipated in the igniter.

In other words, if 0.13-watt electrical power is dissipated in this igniter, it is safe, it will not fire, and the safety margin is 10. The engineer was pleased to hear this. Her maximum RF pickup power was 0.038 watt. Therefore, her safety margin is greater than 10.

Final Comments

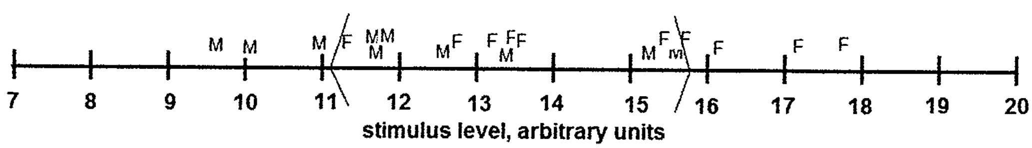
In performing a statistical firing test, we **never expose any test item more than once**. We know that the stimulus is in the range where the device might fire, and therefore it may be damaged in some way by the exposure, even if it does not fire. If it is damaged, it will no longer behave according to the same probability distribution and our statistical analysis will be corrupted.

We often assume a "log normal" probability distribution; that is, we assume that the logarithms of the stimulus values produce a normal (Gaussian) distribution function. The main reason for this assumption is to prevent negative values for no-fire levels. Sometimes the statistical calculations give rise to a fairly large value of standard deviation (σ), and when we calculate the no-fire level by subtracting standard deviations from the mean, as in the Bruceton test, we can get a negative number, which doesn't make much sense. If our calculations are all done on the logarithmic values, we can have a negative final result, but when we take the antilog the answer will always be positive. This "trick" is useful in protocols, like the Bruceton, where the stimulus values are chosen at the beginning of the test. It is not usually necessary in cases where the levels are determined as the test progresses.

In tests like the Langlie protocol, we can sometimes be led to a large standard deviation if we initially choose μ and σ such that the sums are near a local minimum that is larger than the true minimum. We will find that we can't get the sums to go as near to zero as we would like. The remedy is to begin the analysis again, with new estimates for μ and σ, leading to the true maximum likelihood values.

In some tests, the data indicate a large overlap of fires and misfires during the test. We give an example in Figure 1, where we have indicated fires (F) and misfires (M) along an axis of stimulus values that we used in a Langlie test. Here we see that the lowest stimulus for a fire was 11.3, while the highest stimulus for a misfire (no-fire) was 15.6, and there were thirteen results between these two stimulus values, enclosed by the brackets in the diagram. That is more than half the total trials in the test; we don't have enough data outside this region to characterize the distribution. In such cases the standard deviation will be too large for any of the protocols to give results that we can depend upon.

Figure 1: Chart of Data Overlap in a Langlie Test



Much of the statistical testing that is carried out on electroexplosive devices is for the purpose of establishing all-fire and no-fire levels. These are extreme percentage points (such as 99.9 and 0.1% probability of firing).They cannot be measured by the distribution-free method because to do so would take many thousands of EEDs and too much time and effort. It would not be practical. Therefore all-fire and no-fire levels must be determined by first assuming a distribution, or S-shaped curve, and then extrapolating out to the wings where the all-fire and no-fire points are. Enough data points must be taken to define the basic shape of the curve. Any of the statistical methods discussed will do. Our calculations will give us good estimates of the all-fire and no-fire levels, but we should remember that they are always only estimates. They are still very useful.

SINGLE-POINT FAILURE

When we think responsibly about a system, we try to identify any one component of the system which, if it fails, makes it possible for the entire system to fail catastrophically. From the reliability point of view, a catastrophic failure would be one that could render the system inoperable. From the safety point of view, a catastrophic failure would be one that could cause damage or bodily harm. If our system does contain such a component, then we say that the system is subject to single-point failure.

An example would be an electric initiator that starts the explosive train to separate the stages of a space rocket. If the initiator fails, the stages do not separate, and the rocket does not accomplish its mission – that would be a catastrophe.

One way to avoid a single-point failure of this rocket system is to have two initiators, both performing the same function. If one fails, the other will be adequate to initiate stage separation. That is good, but we must point out that duplicate initiators and firing systems add weight and cost.

In general, we can avoid the possibility of single-point failure by having two of everything. That approach, called "redundancy," is costly, but is sometimes necessary.

Another approach is to accept the fact that our system is susceptible to single-point failure, but to check that point before using the system.

As an example, we will discuss a special electric detonator intended for use at an oil or gas well. We will say that this detonator incorporates a radio frequency (RF) filter to protect against inadvertent firing caused by radio transmitters in the trucks at the well site. This is a good protection, because trucks at well sites often contain transmitters, sometimes quite powerful ones. If we think of this detonator as our "system," then the system is susceptible to two types of single-point failure. A reliability failure would ensue if the bridge wire of the detonator is not intact. A safety failure would ensue if the RF filter is missing.

Both these failure points can be checked during manufacture of the detonator. On the assembly line, an automatic ohmmeter can measure the resistance of the bridge wire, and flag any item whose bridge wire is not intact. Similarly, an automatic impedance meter can discern the presence or absence of the RF filter. These kinds of equipment are not complicated or expensive.

Moreover, both these failure points can be checked by the user of the detonator, at the well site. Before connecting the detonator to the explosive train, the user can attach the detonator briefly to a hand-held blasters' ohmmeter and measure the resistance. If the user wishes to confirm that the RF filter is present, a hand-held impedance meter can do that.

A third approach to the single-point-failure problem is to assume always that our system's single point might have failed. This would be a worst-case assumption. In the safety example that we discussed above, we assume that the RF filter might be missing – then we must take steps to bar any trucks (with radio transmitters) from coming near our detonator. In the reliability example that we discussed above, we assume that the bridge wire might be missing – then we must take steps to use a high-voltage fireset to make a high-energy electric arc inside the detonator to fire it. Certainly, using a system that we assume contains a failure entails extra work and extra cost.

Of these three methods that we have discussed for dealing with a system susceptible to single-point failure, we think that checking the point to make sure it has not failed is probably the easiest and cheapest. That is what we recommend in most cases.

MEETINGS, COURSES, AND OTHER ACTIVITIES

Activity	Venue	Date(s)	E&P Issue
8th World Conference on Explosives and Blasting	Lyon, France	26-28 Apr. 2015	Jan. 2015
41st International Pyrotechnics Seminar	Toulouse, France	4-7 May 2015	May 2014
EUROPYRO 2015	Toulouse, France	4-7 May 2015	May 2014 and Dec. 2014
46th International Annual Conference of the Fraunhofer ICT	Karlsruhe, Germany	23-26 June 2015	Oct. 2014
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Rock Blasting and Overbreak Control		21-23 Apr. 2015	Nov. 2014
Blasting Geology		5-7 May 2015	Nov. 2014
Effective Quarry Blasting Methods		19-21 May 2015	Nov. 2014
Electro-Explosive Devices: Functioning, Reliability, and Hazards	Oaks, Pennsylvania USA	27-31 July 2015	Dec. 2014