ALLIED ORDNANCE PUBLICATION

AOP-43 (Edition 3)

ELECTRO-EXPLOSIVE DEVICES, ASSESSMENT AND TEST METHODS FOR CHARACTERIZATION

GUIDELINES FOR STANAG 4560

AOP-43

NOVEMBER 2016

ALLIED

ORDNANCE

PUBLICATION

ELECTRO-EXPLOSIVE DEVICES,
ASSESSMENT AND TEST METHODS FOR CHARACTERIZATION
GUIDELINES FOR STANAG 4560

AOP-43

NORTH ATLANTIC TREATY ORGANIZATION (NATO)

NATO STANDARDIZATION OFFICE (NSO)

NATO LETTER OF PROMULGATION

21 November 2016

1. The enclosed Allied Ordnance Publication AOP-43, Edition 3, ELECTRO-EXPLOSIVE DEVICES, ASSESSMENT AND TEST METHODS FOR CHARACTERIZATION – GUIDELINES FOR STANAG 4560, which has been approved by the nations in the CNAD Ammunition Safety Group, is promulgated herewith. The agreement of nations to use this publication is recorded in STANAG 4560.

2. AOP-43, Edition 3, is effective upon receipt and and supersedes AOP-43, Edition 2 which shall be destroyed in accordance with the local procedure for the destruction of documents.

3. No part of this publication may be reproduced, stored in a retrieval system, used commercially, adapted, or transmitted in any form or by any means, electronic, mechanical, photo-copying, recording or otherwise, without the prior permission of the publisher. With the exception of commercial sales, this does not apply to member or partner nations, or NATO commands and bodies.

4. This publication shall be handled in accordance with C-M(2002)60.

Edvardas MAŽEIKIS
Major General, LTUAF
Director, NATO Standardization Office

RESERVATIONS

NATION	SPECIFIC RESERVATIONS

TABLE OF CONTENTS

ELECTRO-EXPLOSIVE DEVICES, ASSESSMENT AND TEST METHODS FOR CHARACTERIZATION - GUIDELINES FOR STANAG 4560

AIM

1. The aim of this AOP is to guide engineers in the methods of characterization of Electro-Explosive Devices (EED) given in STANAG 4560.

INTRODUCTION

2. Comments listed follow the order in which they appear in STANAG 4560. Where given, the paragraph numbers shown in brackets indicate the relevant paragraph in STANAG 4560.

RELATED DOCUMENTS

3. The list is not exhaustive and test engineers should be aware that other relevant STANAGs may be in the course of development. Users should be aware that STANAGs 4234, 4235 and 4236 have been replaced by leaflets in AECTP 200 and STANAGs 4239, 4324, 4327 and 4416 replaced by leaflets in AECTP 500.

DEFINITIONS

4. It is emphasised that STANAG 4560 is for Characterization not Qualification and attention is drawn to these definitions at Para 2 of the STANAG. Definitions of terms specific to STANAG 4560 are to be found in the main body of the STANAG and AOP 38.

GENERAL

5. The STANAG furnishes general requirements for establishing a uniform method for testing EED. The purpose of the testing program is to determine the electric characteristics, soundness of mechanical design, output, and resistance to deleterious service environments.

6. Assessment and characterization of the EED is required in support of National Authorities, tasked to provide an impartial appraisal of the safety and suitability for service of weapons and those parts of weapon systems, stores and other devices, in which EED are used.

7. EED are a sub-set of Electro-Initiated Devices (EID). This document does not address the characterization of all EID but could be used as guidance to their characterization. Examples of EID not covered are: laser initiators, fusible links, and burn wires.

8. An EED is a one shot explosive or pyrotechnic device used as the initiating element in an explosive or mechanical train and which is activated by the application of electrical energy. An explosive reaction process occurs in an EED when the temperature of a small amount of explosive is raised beyond its ignition temperature due to the heat, generated by the input of electrical energy or by detonation when struck by a flyer released, due to that increase in temperature.

9. For the purposes of this agreement the term includes, but is not limited to, fuzeheads, caps, detonators igniters and initiators. Those EED in current and envisaged service use are Bridge-Wire (BW), Film Bridge (FB), Conducting Composition (CC), Semi-conductor Bridge (SCB), Exploding Bridge-Wire (EBW) and Exploding Foil Initiators (EFI).

10. EED are used widely within military systems to perform a variety of tasks, such as the initiating component in explosive trains, as gas generators, in heat or mechanical energy sources and to perform munition/system functions.

11. EED can form a component part of a munition system or subsystem having no separate existence, save during manufacture, refurbishment or disposal, in the munition life cycle. Alternatively they may be fitted into a munition system late in the deployment phase such as when used for demolition purposes. In the latter case, the EED will usually experience a more severe overall environment than those that are installed within munitions.

12. EED Categories. Historically, EED have been divided into 2 categories based on their electrical characteristics. Those that are initiated by voltages in the order of 10s of volts (termed low voltage devices) and those that require a no-fire of greater than 500 V (termed high voltage devices). Generally, only high voltage devices are permitted to be used in non-interrupted explosive trains.

13. The electrical input needed to initiate the EED can be obtained from sources installed within the system (weapon/store) or from external sources in, say a demolition firing unit or a launch platform connected to the weapon/store through an umbilical cable.

14. The output from an EED lags the input by a time dependent upon the physical and chemical properties of the active components of the device. This is often called the reaction time, which is the time taken from application of the stimulus to the measurable output.

15. The method by which the EED will be assessed as safe and suitable for use will involve:

a. A design assessment including a hazard assessment.

b. The formal qualification of the explosives used in the EED.

c. Tests to ensure the compatibility of explosives and materials used.

d. Characterization of the EED including:

(1) Electrical characterization.

(2) Environmental tests to show general robustness.

(3) Performance tests.

16. Design Assessment. The design assessment of an EED will be based upon documented evidence, which will assist verification against the needs given in Paragraph 6.

a. The following information will assist in the assessment process:

(1) Production standard drawings.

(2) Specifications of the materials used including physical and chemical properties likely to be relevant; such as strength, stability, compatibility etc.

(3) Manufacturing processes.

(4) Quality plan.

b. Hazard Assessment. A hazard assessment should be conducted for the EED as an independent item. Design shortcomings and random failure of components in the EED should be considered. The measures taken to reduce the risk of inadvertent initiation should be stated, where appropriate.

c. Environmental Assessment. The range and effect of environments to which the EED is likely to be exposed needs to be determined by assessment of its proposed life cycle. Generally the minimum tests that are required are in accordance with Annexes C and D of STANAG 4560 but the limits and temperatures should be assessed for its proposed life cycle.

17. Qualification of Explosives for use within an EED. Qualification, as opposed to Characterization, is the assessment of an explosive by the National Safety Approving Authority (NSAA) or other appropriate authority to determine if the explosive possesses properties that make it safe and suitable for consideration for use in the intended role. It is a risk reduction exercise and is an intermediate stage leading to Type Qualification. Explosive materials proposed for military use should be assessed in accordance with the principles and methodology given in STANAG 4170 (AOP 7).

18. Compatibility. Within an EED, explosive compounds need to be compatible with metals and non-metallic materials with which they are in intimate contact. Compatibility can be assessed either from a programme of testing (see STANAG 4147) or by read-across from previous tests.

STANAG 4560 ANNEX A - NATIONAL POINTS OF CONTACT

19. Annex A provides addresses of the National POC, where guidance may be sought on where characterization data, when formally requested, is possibly held.

20. Where appropriate the national authority should be able to offer to other NATO users the data and results on some if not all the tests listed in Annex B. As a number of tests, especially environmental, are carried out during type qualification of a specific system care should be taken when using test results based on similarity, even on comparable systems.

STANAG 4560 ANNEX B - CHARACTERIZATION OF ELECTRO-EXPLOSIVE DEVICES

21. Annex B identifies the EED characterization tests needed to provide the foundation data used in this appraisal.

22. This characterization is generic to the EED and the resulting data can be used to assess the electrical safety and to give a degree of confidence that when installed in a system the EED will meet the system environmental technical requirements. It is emphasised that characterisation is not qualification or full appraisal but only the data to assist in the overall qualification assessment. This needs to cover design and manufacture, including explosive content, initiation and output over a variety of general conditions of use.

23. Where the EED cannot be characterized in isolation the smallest testable item containing one of the above components shall be used with the approval of the NSAA or appropriate national authority. When characterizing an EED as the smallest testable component, the inherent safety characteristic must be agreed by the NSAA before the data will be accepted.

24. In assessing the suitability of an EED after characterization, the following will need to be addressed:

a. The EED should provide the desired response when supplied with the specified electrical input.

b. The EED should not function inadvertently under any natural or induced conditions likely to be encountered throughout its Life Cycle.

c. The output from the EED should not be degraded unacceptably by internal change caused by exposure to the external environments it is likely to experience over its intended life cycle.

d. The EED should be reliable and safe to assemble and handle.

25. The tests identified in this Annex are not exhaustive and should be considered as a minimum requirement in the characterization of an EED.

a. <u>Electrical Characterization</u>. It is important for safety and suitability for service reasons to know the level of energy and/or power at which an EED will be initiated or to be able to calculate the probability of firing if the EED is exposed to any input level.

(1) <u>EED resistance</u> (To include range and geometric and arithmetic mean with standard deviation of the sample tested).

(2) <u>All-fire and No-fire Thresholds</u> (Power or Current and Energy). These thresholds are predictions obtained from statistical test data and are usually given at a specified confidence level. Nevertheless, in order to allow the predicted input level corresponding to any probability (or vice versa) to be determined by the individual nation, all details of the tests should be provided. These details include test method, number of samples and shot results with, as a minimum, the mean value and the standard deviation.

(a) <u>No-Fire Threshold Power/Current (for BW, FB, CC, SCB only).</u> The no-fire threshold power/current of an EED is defined as the power/current required to produce a 0.001 probability of fire at the 95% single-sided lower confidence level when applied to the EED for a time which is significantly greater than the thermal time constant of the device, (e.g. >10 τ).

(b) No-Fire Threshold Energy (all EED). The no-fire threshold energy is defined as the energy which would produce a 0.001 probability of fire at the 95% single-sided lower confidence level if applied to the EED for a time which is significantly less than the thermal time constant of the device, (e.g. $<0.1\ \tau$).

(c) All-Fire Threshold Energy (all EED). The all-fire threshold energy is defined as the energy which would produce a 0.999 probability of fire at the 95% single-sided upper confidence level if applied to the EED.

(d) Maximum Allowable Safe Stimulus (MASS) (all EED). The MASS is the projected voltage at which an EED has a 10^{-6} probability to fire with ideal confidence. This is a value that typically is calculated from the same data as the No-Fire Threshold.

(3) Malfunction Threshold. (also known as Maximum No Damage Current). Unlike BW, FBW and CC devices, where the AFT is not very different from the NFT, an EFI has a more discernible transition between visible or measurable damage of the bridge and detonation of the pellet. The electrical pulse having a well-defined characteristic to produce a flyer with the correct velocity and size to cause detonation is unlikely to be generated by external influences. However, sufficient electrical energy could be generated within the system to cause damage to the bridge, which may or may not cause film shear to occur, which does not result in initiation of the explosive. Although such a situation would not lead to inadvertent initiation, the system may be incapable of correct operation, when a valid firing pulse is received. Therefore it is more relevant to define a malfunction threshold (MFT).

(4) Thermal Time Constant. In order to determine whether an EED will be susceptible to the energy of a pulsed environment the thermal time constant is required to be assessed.

(5) Electrostatic Discharge (ESD). This test confirms minimum acceptable design safety and reliability characteristics of the EED with respect to inadvertent ESD inputs.

(a) There are two ways an EED can be damaged by ESD, each case could influence device reliability and safety.

(b) The first way an EED can be damaged by ESD is when the damage occurs by a breakdown of the EED insulation when potential is developed between the pin and case of the EED. The pin to case test with the 5000 ohm resistor in series with the EED may be more severe than when the 500 ohm is in series because the length of time the potential is maintained increases the probability of a breakdown even though less potential is developed. Therefore, pin to case tests with each resistor in series with the EED are required.

(c) The second way an EED can be damaged by ESD is when the bridge is heated by potential between the EED pins. The energy delivered through a 500 ohm resistor to the EED is greater than that delivered through a 5000 ohm resistor. If the device passes the test with a 500 ohm resistor, it will also pass with a 5000 ohm resistor. Therefore, pin-to-pin tests with the 500 ohm resistor only in series with the EED are required. It is unlikely to expect any damage, much less a reaction in the pin to pin mode for EFIs.

(d) Simple calculation shows that the maximum current into a detonator from a capacitor charged to 25,000 Volts through a 500 ohm resistor is 50 Amps, or almost 2 orders of magnitude less than a typical EFI burst current. Since the RC time constant is around 0.25 microseconds, the current drops off to nothing in a few hundred microseconds. The total energy in the capacitor is 156 millijoules. For a typical EFI bridge of 50 milliohm resistance, only 1/10,000 of the energy is deposited in the bridge because the 500 ohm resistor in series absorbs most of the energy. Thus, the total energy that can ever be deposited in the bridge is on the order of 16 microjoules. (Note that for a typical low voltage EED with a bridge resistance of 1 ohm the energy deposited in the bridge is of the order of 0.3 mJ which may be enough to initiate some devices). Over time, as EFI are tested pin to pin without damage, the pin to pin testing requirement may be eliminated, once enough confidence is developed that EFI are immune pin to pin ESD.

(6) Low Power Non-Functioning Test. This test is required for EBW. Since the explosive is in direct contact with the bridgewire it is necessary to ensure that the device cannot function as a low voltage device when currents slightly below the Maximum No Damage Current are applied.

b. Robustness of Design. Often the range and effect of environments to which the EED is likely to be exposed will be determined by assessment of its proposed life cycle. Where a general understanding of the reliability of an EED is required the national documents give guidance to the levels of test severity that should be applied. The effect of these environments upon a particular EED may be assessed by analogy to previous data on the safety and suitability of another EED of a similar design. Generally, however, tests are required to show the robustness of design of an EED and typical tests cover:

(1) Vibration

(2) Thermal shock

(3) Temperature-Humidity

(4) Leakage

(5) 1.5 m Drop

(6) Mechanical Shock

(7) Thermal Cook-off

(8) High Temperature

26. Sequential Environmental Tests. A sequential environmental tests programme should be designed to cover the relevant tests listed in Annex B of STANAG 4560. Where appropriate, these tests should be in accordance with STANAG 4370, STANAG 4157 or national standards and should reflect the Life Cycle for the EED as a separate item.

a. Two modes of EED application can be considered in the assessment:

(1) Where the EED is installed early in the life of a munition

(2) Where the EED exists as an independent item for most of its life, such as when fitted to a demolition charge prior to firing.

27. Performance Characteristics. The type of explosive compositions used, their quantity, degree of confinement and temperature will determine the output. The tests may need to cover a variety of applications to measure the amplitude and duration of the particular events, such as shock.

28. Thermal Time Constant Background Information. The majority of experience to date on EED electrical sensitivity behaviour is related to that described in the following section, where energy and power are the controlling parameters. Detailed analytical studies have been carried out to determine the nature of the bridge heating phenomena in conventional types of BW and FB EED. This work has been extended to cover electrical heating effects in the explosive components of both CC and metal cased BW devices. Over the frequency range dc to over 10 GHz CW, it has been demonstrated by the use of experimentation and theoretical modelling that, for a normal mode of initiation (pin to pin), sensitivity is a decreasing function of frequency.

29. When electrical power is dissipated in a resistive wire the temperature distribution in the wire and surrounding explosive will depend on a number of electrical and thermal parameters which are difficult to quantify. These parameters control the rate at which the BW responds thermally to the applied power. On the application of a step function of power the BW temperature approaches an equilibrium value almost exponentially. This rise may be characterised by a parameter called the thermal time constant (τ), which is related to the thermal response time of the EED not the reaction (or functioning) time.

$$T_{(t)}=T_{max}(1-e^{(-t/\tau)})$$

where:

T_t = Temperature rise after time t

T_{max} = Maximum temperature at equilibrium, when dT/dt tends to zero, heat lost will equal heat input and the temperature will reach its maximum value.

τ = Thermal Time Constant.

30. For a wire heated electrically, its final maximum temperature rise after time t will be proportional to the input power level, therefore:

$$T_t = kP(1-e^{(-t/\tau)})$$ where k is the constant of proportionality.

31. However, in an rf pulsed environment, susceptibility levels change significantly depending on radar pulse parameters and EED time constants can be of major importance. When power is applied for a time shorter than τ as a result of reducing the pulse width, heating becomes increasingly adiabatic, that is electrical energy is employed

more effectively as heat losses reduce. At a pulse width of approximately 0.1 τ a constant energy region is approached where the energy required for ignition approaches a constant value as pulse width (with increasing power levels) approaches zero. This is illustrated in the graph in Figure 1 below. Peak powers in a pulsed radar environment could be more than 1000 times the equivalent mean power and knowledge of the response to the short duration peaks is essential. This is also applicable to lightning, Electromagnetic Pulse (EMP) and Electrostatic Discharge (ESD). A basic disadvantage of EED is that as they function as a direct result of heating some part of the initiating material by an input of electrical energy, in addition to the need to prevent inadvertent initiation by the intended source of firing power or associated test equipment, it is necessary to provide protection against conducted and radiated electromagnetic interference (EMI) which may be induced by the electromagnetic (EM) environment. EMI could initiate an EED directly or indirectly by causing the firing circuit switches to operate prematurely.

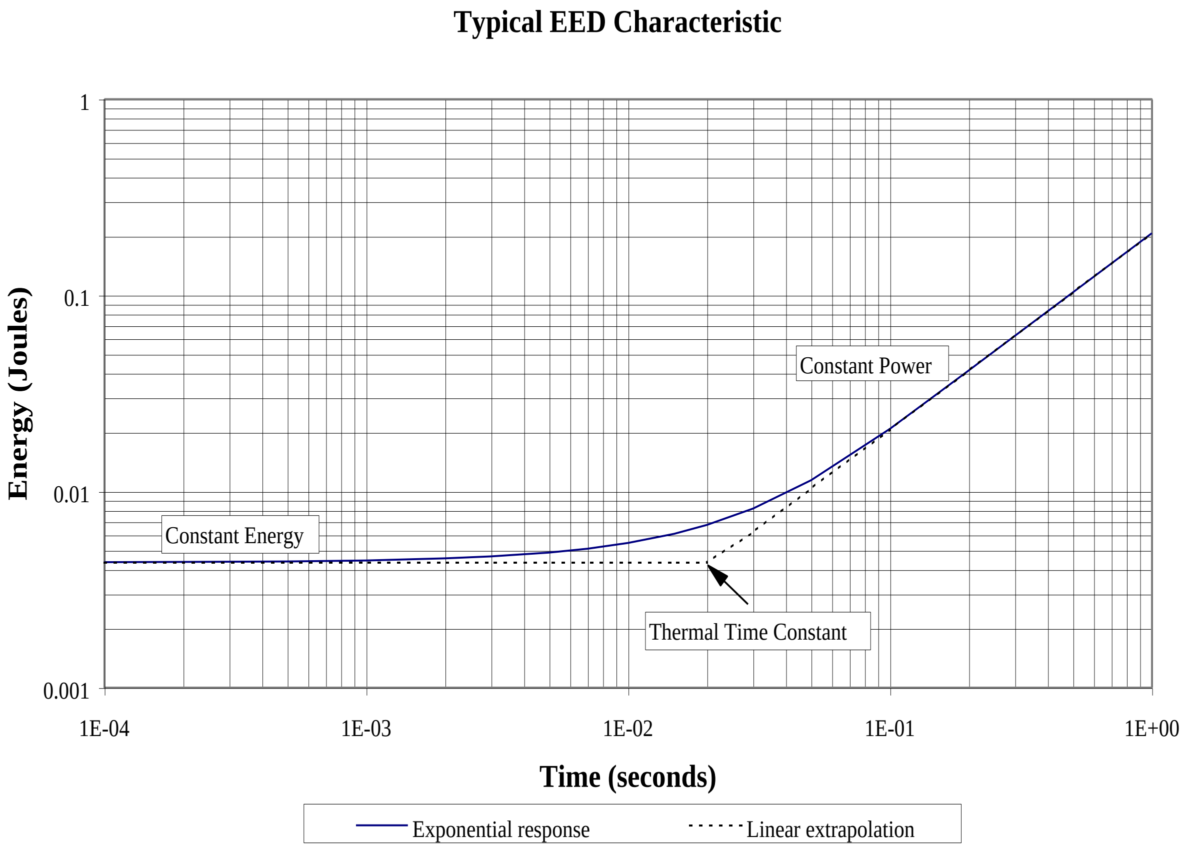

FIGURE 1. TYPICAL EED CHARACTERISTIC

32. The electric field intensities (V m^{-1}) are expressed in rms values and the power intensities (W m^{-2}) in mean values. (CW mean power = V_{rms} x I_{rms} ; mean pulsed power = peak power x duty ratio.) This information is sufficient to assess the potential susceptibility of those EED which respond to mean power. Energy sensitive EED may however, be susceptible to the energy content of a single radar pulse so knowledge of the peak pulse power level is important.

33. Some munitions and weapon systems, when in an operational mode, generate their own rf environment. EED firing systems employed in such munitions and weapon systems

should be designed and proved to remain safe and serviceable, in each operational configuration of their life cycle, when subjected to self-generated rf fields and those which might be generated by the weapon platform (e.g. vehicle, ship or aircraft in which the munition or weapon system is required to be stored, handled and operated).

34. These rf environments have in some cases been enhanced by individual national requirements dependent on specific operational scenarios and conditions in which the system shall remain either safe and/or suitable for service, or must function for safety. From this information it is possible to derive the EM environment levels which will apply to the system.

35. When assessing the susceptibility of an EED in this environment it is impractical to attempt to define uniquely the stimulus level at which none of a particular batch of EED will fire. The threshold sensitivity of the EED is usually derived from statistical measurements, an assumption being made that the probability distribution of sensitivity obeys a normal law, when the logarithm of the applied stimulus is taken as the independent variable. The NFT is defined in terms of the level at which 0.1% of the devices will fire. Due allowance is made for sampling errors by using the single-sided lower 95% confidence level for the 0.1% probability of firing.

36. There is a general trend towards achieving power thresholds in excess of 1 W although some EED in present use have power thresholds quoted below 10 mW. In some devices, low power and energy sensitivity are not always linked, for example some CC and FB EED have power thresholds in excess of 1 W yet energy threshold less than 50 μJ (due to the τ). This feature has definite advantages in particular designs for system applications where energy sensitivity is a design requirement, but such devices are to be avoided where rf or transient susceptibility is likely to be a relevant factor.

37. Power/current thresholds are used to assess the behaviour of EED in Continuous Wave (CW) rf environments where EED time constants are of little consequence. When power is applied for a time significantly longer than τ, the power required to raise the BW to an initiation temperature is independent of pulse width.

38. AECTP 500 leaflet 508-3 defines the assessment procedures and test methods to be used in determining the safety and suitability for service of munitions containing EED and associated electrical/electronic subsystems, exposed to the Electromagnetic Radiation Environment (EMRE) for NATO Forces.

39. Knowledge of the pulse response is important in rf trials where a distinction is required between the responses to Pulse and Continuous Wave (CW) excitation. From analysis of EED sensitivity results, the constant energy and the constant power lines obtained from a graph similar to Figure 1 are extrapolated linearly until they intercept. This occurs at a point on the pulse width axis equivalent to the ratio of the no-fire threshold energy and no-fire threshold power, and defines the thermal time constant, (τ).

40. In the transition region between constant power and constant energy behaviour, the extrapolation gives poor correlation with empirical data. For a typical BW device, assuming the temperature build-up to be exponential, the following relationship may be obtained:

$$E(t_1) = \frac{P_{TH}\, t_1}{1 - \exp(-t_1/\tau)} \qquad (1)$$

where: $E(t_1)$ = energy to give 0.1% functioning at 95% single sided lower confidence limit when applied in time t_1.

P_{TH} = NFT power.

t_1 = pulse width.

τ = thermal time constant.

a. This relationship gives better agreement with empirical data than does simple extrapolation as shown by the chain-dotted line in Figure 1.

b. Equation (1) can be written in terms of a power threshold for a single pulse:

$$\hat{P} = \frac{P_{TH}}{1 - e^{(\frac{-t_1}{\tau})}} \qquad (2)$$

or in terms of repetitive pulses:

$$\hat{P}(t_1, t_2) = \frac{P_{TH}(1 - e^{(\frac{-t_2}{\tau})})}{1 - e^{(\frac{-t_1}{\tau})}} \qquad (3)$$

or in terms of the mean power in the repetitive pulsed waveform:

$$P(t_1, t_2) = \frac{P_{TH}(1 - e^{(\frac{-t_2}{\tau})})t_1}{(1 - e^{(\frac{-t_1}{\tau})})t_2} \qquad (4)$$

Where: $\hat{P}(t_1)$ = pulse power threshold for single pulse.

t_1 = pulse width.

t_2 = pulse repetition period.

$\hat{P}(t_1, t_2)$ = peak power threshold for repetitive pulse stimulus.

$P(t_1,t_2)$ = mean power threshold for repetitive pulse stimulus.

c. This general treatment has been tested against the measured performance of EED other than BW types. Its application is appropriate to devices that have thermal time constants comparable with radar pulse durations. Typical of these devices are the range of CC, some FB and EFI EED, with τ in the range 0.1 to 200 µs.

d. The physical interpretation of the heating phenomena associated with FB and CC devices is not as straightforward as for BW EED. Nevertheless in the limit both energy and power zones would be expected to apply. Measurements have shown that to a first approximation the behaviour of these devices agrees with the law described by Equation (1) and as with BW devices differences between experimental results and the single exponential law exist around the transition region. Also, in the case of FB devices the extremely good thermal contact between film bridge and substrate modifies heat transport to the extent that, even under extremely short pulse conditions the characteristic constant energy behaviour is not well defined. A slight positive slope in the energy vs. pulse width relationship exists even for sub-microsecond pulse duration. For practical trials use, these differences are sufficiently small to be neglected and the behaviour described by Equations (3) and (4) is regarded as acceptable.

STANAG 4560 ANNEX C - BW, FB, SCB and CC CHARACTERIZATION TESTS

41. BW, FB and CC have been characterised over the past 35+ years using national test procedures. These procedures, though different, are normally considered adequate tests providing the NSAA or other appropriate authority has monitored them. The latest issues of the national accepted test procedures are listed below:

a. France:

(1) Measurements of the Characteristics of Explosive Components - Test Procedures G.T.P.S. No 12 May 1987

GTPS :

- N° 11A: Probit statistical method
- N° 11B: One-Shot statistical method
- N° 11C: Bruceton statistical method
- N° 11F: Severe test method

(2) GAM DRAM 01

b. Germany:

(1) TL 1375- 1000, Initiating and Igniting Devices - General Requirements.

(2) VG 95 378 (Part 11) - EMC of Electro-Explosive Devices (EED): Test Method for Proof of Immunity to Disturbance of EED Towards Pulses of Electrostatic Discharge.

c. GBR:

Defence Standard 59-114 Part, 2: Principles for the Design and Assessment of Electrical Circuits Incorporating Explosive Components

d. USA:

(1) MIL- DTL-23659 Initiators, Electric, General Design Specification For.

(2) MIL-HDBK-1512 Electro-explosive Subsystems, Electrically Initiated, Design Requirements and Test Methods.

42. Though characterization of SCB is in its infancy in military application the initial research indicates that the methods of characterization listed in Annex C are presently appropriate.

43. With more reliance on manufacturers providing characteristic test data to NSAA and other national authorities when considering overseas sales, it has been seen appropriate to consolidate these tests to provide a single guidance for national defence

agencies and contractors.

44. The sensitivity of an EED is established from three basic parameters, the threshold power (P_{th}), energy (E_{th}) and the thermal time constant (τ) where the latter is defined as the ratio of threshold energy to threshold power.

$$\tau = E_{th} / P_{th}$$

45. If two of the parameters are known the third parameter can be calculated. Where the energy threshold has not been measured, the thermal time constant (τ) can also be derived from the ratio of the 50% power level and the 50% energy level obtained in other tests.

46. In the past a number of nations have determined the no-fire threshold (NFT) current. When the NFT is determined in this manner the P_{th} can be calculated using the square of the NFT current and the geometric mean of the resistance of those EED tested.

47. EED used in a system shall have as high a no-fire threshold (NFT) as possible whilst meeting the system requirements and shall have well characterised NFT parameters for both normal and abnormal firing modes as appropriate.

48. One Watt/One Ampere. The one watt and one ampere test should not be confused with the no-fire threshold test. While the one Watt/one Amp test, identified in MIL-DTL 23659, provides a method to determine that the device will not fire or dud when subjected to such parameters, wherever possible RADHAZ (HERO) tests should use the no-fire threshold determined during the firing properties test. This one watt and one ampere requirement in conjunction with other design requirements serves as a means of reducing hazards from spurious electric sources including electromagnetic radiation but does not solve radio frequency (rf) susceptibility problems.

49. Some nations classify EED into 2 categories:

a. Class A. EED that are capable of being actuated within one second from a 28 ±2 V source capable of delivering not less than 10 Amperes.

b. Class B. EED that are not capable of being actuated within one second from a 28 ±2 V source capable of delivering not less than 10 Amperes.

50. The electrical characterisation tests provide the foundation for Hazard of Electromagnetic Radiation to Ordnance (HERO) (USA), Dommages dus aux Rayonnements électromagnétiques sur les Armes et les Munitions (DRAM) (France), and Radio Hazard (RADHAZ) (UK) trials.

51. Resistance (Annex C Para. 6). These tests are to be conducted in accordance with national procedure, e.g. MIL-STD-202, Method 303.

a. 2-Wire Measurement. A conventional multimeter measures resistance by passing a known current through the item under test (IUT) and measuring the voltage produced by this current. Measurements of resistance in this manner are subject to 3 sources of error, which are more significant when measuring lower values (<1Ω). These are:

(1) Resistance of test leads. If the measurement is made on the resistance range of a multimeter, the result will include the resistance of the test leads. A correction can be made for this resistance but there will be a loss of accuracy.

(2) Contact Resistance of Test Probes. Connection of the measuring instrument to the IUT (Item Under Test) will introduce contact resistance at each end of both of the test leads. These resistances are random, variable and difficult to control. As they cannot be quantified, corrections for them cannot be made.

(3) Thermo-electric Potentials. The test circuit is likely to include contact between dissimilar metals. If these contacts are at different temperatures, thermo-electric voltages will be generated. These may be large enough to cause significant errors, particularly if the measuring instrument is passing a current of 1 mA or less through the IUT.

b. 4-Wire Measurements. Errors from the above sources can be minimised by correct use of a four terminal measuring instrument. This will have separate terminals for its current source and voltmeter. The current source drives the correct value of current through the IUT regardless of stray resistance in test leads or connections. The voltage terminals of the instrument must be connected separately to the IUT. The voltage reading will then not be affected by any reasonable value of resistance in the test leads or contacts. Errors from effects a. (1) and (2) are thus kept to a minimum. To reduce possible errors from source (3), higher values of test current should be used, e.g. 10 mA to 100 mA, (with due consideration of inadvertent initiation or damage to the EED) so that the voltage produced across the IUT is large compared with any thermo-electric potentials (usually 10’s of microvolts). To check whether there are still errors from this source, the connections of the voltage measuring probes to the IUT should be interchanged. If the positive and negative voltage readings are different, an average of the two magnitudes will give a more accurate result, e.g. if a 10 mA current source produces readings of +190 μV and –210 μV across the IUT, its resistance should be taken as (190 μV + 210 μV)/(2 x 10 mA) = 20 mΩ. The test current used should be typically 10% of the designed/estimated NFT current and can be determined using manufacturers figures or the experience of the operator from similar devices. When it is important that the temperature of the specimen shall not rise appreciably during the measurement, the test voltage shall be applied uninterruptedly for as short a time as practicable, but in no case for more than 5 seconds, unless otherwise specified.

52. Insulation Resistance (Annex C para 7). For devices that are housed in an insulated package an impressed direct voltage tends to produce a leakage of current through or on the surface of this insulation. This could be caused by either accidental discharge through the bridge of the device, or from an external source contacting any part of the initiator and for example creating an explosive reaction by current conducted through the explosive itself. Knowledge of insulation resistance is important, even when the values are comparatively high, as these values may be limiting factors in the design of high-impedance circuits. Low insulation resistance, by permitting the flow of large leakage currents, can disturb the operation of circuits intended to be isolated, for example, by forming feedback loops. Excessive leakage currents can eventually lead to deterioration of the insulation by heating or by direct current electrolysis. Insulation resistance measurements should not be considered the equivalent of dielectric withstanding voltage or electric breakdown tests. A clean, dry insulation may have a high insulation resistance, and yet possess a mechanical fault that would cause failure in the dielectric withstanding voltage test. Conversely, a dirty, deteriorated insulation with a low insulation resistance

might not break down under a high potential. Since insulating members composed of different materials or combinations of materials may have inherently different insulation resistances, the numerical value of measured insulation resistance cannot properly be taken as a direct measure of the degree of cleanliness or absence of deterioration. The test is especially helpful in determining the extent to which insulating properties are affected by external influences, such as heat, moisture, dirt, oxidation, or loss of volatile materials.

53. Electrical Characterization (Firing Properties Test of Annex C Para. 8). From the firing properties test, two thresholds can be derived. These are:

a. The no-fire threshold, (defined in Para 2.m. of STANAG 4560).

b. The all-fire threshold, (defined in Para 2.a. of STANAG 4560).

54. These thresholds are typically obtained from statistical test data and are usually given at a specified confidence level. Nevertheless, in order to allow the predicted input level corresponding to any probability (or vice versa) to be determined, all details of the tests should be provided as required by the NSAA or other appropriated authority. These details include test method, number of samples and shot results with, as a minimum, the mean value and the standard deviation.

55. Sensitivity Test Methods. There are presently five test methods generally accepted for sensitivity testing of one shot devices: Probit, Langlie, Weibull One-Shot Transformed Response (OSTR), Bruceton, and Neyer D-Optimal. Each of these tests has a degree of limitation dependent on the information known on similar devices. For details see Annex B to this document.

56. Thermal Time Constant Computation (Annex C para 10). A typical flow chart which combines Bruceton with Probit to determine the power and energy thresholds required for the determination of the Thermal Time Constant is shown in Annex A of this AOP.

57. When assessing the susceptibility of an EED for use in a pulsed rf environment it is impractical to attempt to radiate with all combinations of pulsed characteristics. The rf environment measured is also the average power density. The susceptibility in a pulsed environment, not used during the trials, can be determined by adjusting average susceptibility by a multiplying factor (MF) dependent on the pulse characteristics of the radiating source and the time constant of the device and is determined by:

$$MF = \frac{(1 - \exp^{(-t_2/\tau)})\, t_1}{(1 - \exp^{(-t_1/\tau)})\, t_2}$$

$\hat{A}PS$ = APS x MF

Where:

APS = Average Power Susceptibility.

$\hat{A}PS$ = Average Power Susceptibility in a pulsed environment.

t_1 = Pulse width.

t_2 = Pulse repetition period.

τ = Time constant

a. To determine the thermal time constant a further statistical analysis is required at a pulse width significantly shorter (typically 10 μs) than the τ. A wind-up test will indicate the starting level for the Bruceton test. Annex A to the AOP includes an example of this approach.

58. Electrostatic Discharge. (Annex C Para 11) Through a normal logistic cycle, weapons may undergo various phases of handling, such as packing, unpacking, wrapping in protective plastics or other coverings, assembling, transporting, loading and unloading etc. These processes may result in the development of an electrostatic charge on the handlers, transfer equipment, shipping container, munition weapon system or any ungrounded object. This charge, if transferred or discharged through the EED, munition or weapon system, may be sufficient to produce a dud or even exceed the threshold level for firing the EED. This may result in a catastrophic ignition of the propellant or explosive, depending on the design of the system.

a. AECTP 508-2 was written to describe ESD tests for munitions. The test for EED is the same, except for the following deviation:

(1) The test on EED uses the contact discharge only.

(2) Selection of discharge locations should include points assessed potentially to allow transfer of the energy to the bridge or directly to energetic material.

(3) For EED with a single firing lead the test shall include testing “pin-to-case”, with the EED housing being connected to ground and the ESD pulse being applied to the firing lead.

(4) For EED with two firing leads the test shall include testing

(a) “pin-to-case” (see (3) and

(b) “pin-to-pin” with the EED housing and one firing lead being connected to ground and the ESD pulse being applied to the other firing lead.

b. Where the EED may be directly exposed to Helicopter ESD (HESD), the NSAA may request a 300 kV HESD test during qualification.

59. Environmental Tests. Where a general understanding of the reliability of an EED is required the effect of these environments upon a particular EED may be assessed by analogy to previous data on the safety and suitability of another EED of a similar design or by the following tests.

60. Vibration (Annex C para 13). This test is applicable in order to obtain characterisation data about EED to adequately demonstrate their ability to resist a typical environment without unacceptable degradation of their characteristics. Following completion of the test the performance of the EED shall be checked for changes in the physical condition and electrical parameters (e.g. bridge resistance, insulation resistance).

61. Thermal Shock and Temperature-Humidity (Annex C paras 14 & 15). General tests for energetics have been agreed in accordance with STANAG 4157. Instead of the agreed STANAG tests the US have determined a consecutive programme for the thermal shock/humidity and altitude test. Where appropriate this may be called up by the NSAA and is outlined below:

a. The schedule has been arranged in such a manner that operations are not required outside normal working hours except for such supervision as may be necessary to insure proper operation of the test equipment.

b. It is not mandatory that the day/clock time schedule given below be followed: however, it is mandatory that the time, environmental, and sequence requirements be adhered to. It is also noted that only two conditioning chambers are required to accomplish this test. No less than two chambers may be used and still accomplish the temperature shock portion of this test. If it is desired to use three chambers, it is permissible provided the time, environmental, and sequence requirements are met. The fluctuations from the specified temperatures shall not exceed 2°C (5°F). When the temperature/altitude chamber door is opened to place test items inside, the chamber pressure will become atmospheric. The time required to return the chamber pressure to 4482 Pascal (0.65 psi or 33.6 torr) shall not exceed 1 hour.

c. Test specimens shall be supported on screen trays or racks so that all areas are exposed to the prescribed atmospheric conditions at all times throughout the test.

Procedure

Day 1.	0800	Place test items in a chamber maintained at +21° ±2°C (+70° ±4°F) at 50% relative humidity (RH).
	1200	Raise chamber temperature to a minimum of +71°C (+160°F) and the RH to 95%. The chamber temperature shall reach +71°C (+160°F) at 95% RH no later than 1300.
	1600	Remove test items from above chamber and immediately place in a chamber maintained at a maximum of –54°C (-65°F) at a pressure simulating a minimum altitude of 21,336 meters (70,000 feet) or a pressure less than 4482 pascal (0.65 psi or 33.6 torr).
Day 2.	0800	Remove test items from above chamber and immediately place in a chamber maintained at +21° ±2° C (+70° ±4°F) at 50% RH.
	1200	Remove test items from above chamber and immediately place in a chamber maintained at a maximum of -54°C (-65°F) at a pressure simulating a minimum altitude of 21,336 meters (70,000 feet) or a pressure less than 4482 pascal (0.65 psi or 33.6 torr).
	1600	Remove test items from above chamber and immediately place in a chamber maintained at a minimum of +71°C (+160°F) at 95% RH.
Day 3.	0800	Reduce chamber temperature to +21°±2°C (+70°±4°F) at 50% RH. The chamber temperature shall reach +21°C (70°F) at 50% RH not later than 0900.
	1200	Raise chamber temperature to a minimum of +71°C (+160°F) at 95% RH. The chamber temperature shall reach +71°C (+160°F) at 95% RH not later than 1300.
	1600	Remove test items from above chamber and immediately place in a chamber maintained at a maximum of -54°C (-65°F) at a pressure simulating a minimum altitude of 21,336 meters (70,000 feet) or a pressure less than 4482 pascal (0.65 psi or 33.6 torr).

Day 4.	0800	Remove test items from above chamber and immediately place in a chamber maintained at +21°±2° C (70°±4°F) at 50% RH.
	1200	Remove test items from above chamber and immediately place in a chamber maintained at a maximum of -54°C (-65°F) at a pressure simulating a minimum altitude of 21,336 meters (70,000 feet) or a pressure less than 4482 pascal (0.65 psi or 33.6 torr).
	1600	Remove test items from above chamber and immediately place in a chamber maintained at a minimum of +71°C (+160°F) at 95% RH.
Day 5.	0800	Reduce chamber temperature to +21°±2C (+70°±4°F) at 50% RH. The chamber temperature shall reach +21°C (+70°F) at 50% RH not later than 0900.
	1200	Raise chamber temperature to a minimum of +71°C (+160°F) at 95% RH. The chamber temperature shall reach +71°C (+160°F) at 95% RH not later than 1300.
	1600	Remove the items from above chamber and immediately place in a chamber maintained at a maximum of -54°C (-65°F) at standard ambient pressure.

d. This schedule shall be followed for a total of 4 weeks (28 days) except that on the second and fourth weekends the soak time shall be from 1200 on Friday until 0800 on Monday at a temperature of +71°C (+160°F) at 95% RH. At the conclusion of the temperature-shock/humidity/altitude test, the test items shall be allocated to the tests specified in STANAG 4560 Annex C Table 2.

STANAG 4560 ANNEX D - EBW AND EFI CHARACTERIZATION TESTS

62. High voltage devices in which the wire or film bridge is designed to explode are operated by the discharge of energy from a secondary store such as a capacitor. Correct functioning is only obtained if the energy is delivered to the bridge as a tailored pulse, with a rapid rise time, to a current peak of kA magnitude. The Fireset that was defined as the capacitor and trigger switch provides this energy.

63. Although it is unlikely that such a pulse can be generated in any way other than by the design source, it is still necessary to establish the level of power/energy that will affect the subsequent functioning of the device.

64. Though investigation of the parameters of such devices continues to be investigated, the presently accepted technique to identify the required parameters is given in Annex D.

65. Resistance (Annex D Para 5). This should be consistent with the method described in Paragraph 51 of this AOP.

66. The resistance shall be quoted as the range of the devices and the geometric and arithmetic mean with standard deviation of all devices measured during the test.

67. Firing Properties (Annex D Para 7). Reporting the electrical parameters of a system provides guidance to the designer on the voltage required at the source to provide reliable and safe detonation.

a. EFI/EBW operate on specific pulse characteristics and therefore the firing unit for the firing properties tests and the all-fire tests shall be as close as possible to the intended use firing unit configuration, preferably using the same components. Firing switches that will not operate in the same voltage range as the intended firing switch shall not be substituted. The test firing unit shall have transient firing properties that are within 25% of that of the intended firing properties - after modifications are made to measure the necessary data (such as the addition of a current viewing resistor).

b. Due to the possible degradation of the firing pulse the components shall not be used beyond their life ratings. Because of deterioration of the triggering device and/or firing capacitor, each Fire Set should be triggered no more than half its projected number of reliable firings. Normally this should not be more than 50 times.

c. Firing units should be calibrated before the first test to assure the discharge properties (ring downs) are acceptable, and the subsequent discharges monitored for changes, such as signs of component deterioration. Following any signs of deterioration, the fireset should be re-calibrated or if necessary changed.

d. When the Fire Set has been used at lower energy levels than its operational level, the fire set should be reset, with a full strength fire pulse, at least every 5 firings.

e. Statistical analysis of the firing properties data shall be used to predict the minimum All-Fire Threshold Voltage (AFTV), the maximum No-Fire Threshold Voltage (NFTV) and the Maximum Allowable Safe Stimulus (MASS) of the EFI/EBW using all 3 temperatures.

f. If the initiator cannot be fired within the temperature chamber, the initiator and the circuitry shall be inserted into an insulating container, temperature conditioned to a more extreme level, and transferred to the firing location so that the initiator is at the proper temperature when fired.

g. If the intended fireset produces a stimulus, that envelops or exceeds that of the Maximum Allowable Electrical Sensitivity Test (MAEST) fireset, the NSAA may consider the MAEST a redundant test and may allow the results of the firing properties tests to be sufficient to satisfy the MAEST requirement.

68. Malfunction Threshold (Annex D Para 8).

a. The MFT is defined as the stimulus, (voltage, current or power) when applied to the EED, that produces a 0.1% probability of damage at the 95% single-sided lower confidence level, such that the EED will not or may not fire when subsequently subjected to the operational firing pulse from the tactical fireset.

b. This is the parameter that should be used during HERO/RADHAZ trials when assessing the susceptibility of a system containing an EBW or EFI.

c. The requirement given in Annex D will require a minimum sample of 30 where the manufacturer has provided an acceptable malfunction threshold. Where this is not the case more will be required as advised by the NSAA or appropriate national authority.

69. With the use of the inspection approach, the MFT is determined by the minimum current that produces visible damage (physical) and/or measurable change in electrical (resistance) parameters. This approach prohibits the requirement for explosive but

provides a conservative value with respect to safety. Any discolouration or bubbling causing delamination should be considered as the onset of change.

70. Where inspection of the bridge, due to its design, is not practical then the EBW/EFI input leads shall be subjected to DC current levels in accordance with an accepted statistical method similar to that used for the firing properties test (Bruceton, Langlie, Neyer D-Optimal, etc.). The EBW/EFI shall be subject to DC current in a bare condition and conducted at a temperature of +23 +/- 10°C. The applied current shall not overshoot the intended test current level by more than 5%. The full test current shall be applied for a minimum of 1 minute. The period of time that the current is rising to the intended test current shall not apply to the 1 minute of test time. Assessment of damage or no-damage at each test level shall be made by the application of operational voltage from the intended fireset. If the operational voltage is unknown or undefined, the AFTV determined in the firing properties test shall be used. A detonation that meets the EBW/EFI's specified output criteria shall be considered evidence of no damage while failure to do so shall be assessed as a damaged result. Results shall be analyzed statistically and the mean and standard deviation of the no damage current shall be reported. The determination of damage or no-damage at each test level shall be determined by the application of operational voltage from the intended fireset. If the operational voltage is unknown or undefined, the AFTV determined in the firing properties test shall be used. Failure to detonate shall be considered evidence of damage and detonation shall be evidence of no damage. Results shall be analyzed statistically and the mean and standard deviation of the no damage current shall be reported.

71. Thermal Time Constant (Annex D Para 10). Knowledge of the pulse response is important in rf trials where a distinction is required between the responses to Pulse and Continuous Wave (CW) excitation. For the analysis of EED susceptibility results the constant energy and the constant power lines obtained from a graph similar to Figure 1, are linearly extrapolated until they intercept (extrapolations cross). This occurs at a point of the pulse width axis equivalent to the ratio of the no-fire threshold energy and no-fire threshold power, and defines the thermal time constant, T_C or τ. The test is designed to identify a number of points on both the constant power and energy region to enable extrapolation.

72. Electrostatic Discharge (25 kV) (Annex D Para 11). see paragraph 58.

73. Non-Interrupted Explosive Train Requirement (Annex D Para. 12). If an EFI/EBW is to be considered for use in a non-interrupted explosive train there is a requirement to establish fundamental electrical sensitivity thresholds, below which an EFI/EBW must not detonate (e.g. STANAG 4187). The requirement in STANAG 4187 is that the electrical initiator:

a. Shall not be capable of being detonated by any electrical potential of less than 500V applied directly to the initiator.

b. Shall not be capable of being initiated by an electrical potential of less than 500 V when applied to any accessible part of the fuzing system during and after installation into the munition or any munition subsystem.

74. An EFI/EBW will not be considered for qualification for non-interrupted explosive train use if the reaction is a detonation. If the EFI/EBW is intended for use as a stand-alone configuration item, or an application in which the leads of the EBW/EFI may be externally exposed or accessible, the initiator shall not exhibit a functional explosive reaction (deflagration, explosion, or detonation) during this test. To meet this requirement

2 tests are proposed, though the NSAA may require further tests:

a. Electrical Cook-Off. This test is used to determine the sensitivity of a test sample to accidental exposure to AC and DC power sources up to 500V, for example from a ground loop.

b. Maximum Allowable Electrical Sensitivity Test (MAEST). This test is intended to serve as an implementation device for the current STANAG 4187 requirement that initiators used in non-interrupted explosive trains be incapable of being detonated by any electrical potential of less than 500 volts. The intent of this test is to establish the electrical sensitivity threshold of an EFI/EBW if it is to be considered for use in a non-interrupted explosive train. The approach taken to accomplish this is to define a "Standard" fireset, which would be used by all EFI/EBW to establish the NFT and the MASS for a standard fireset. When an EFI/EBW is capable of meeting the required threshold using this fireset, it would be considered that the EFI/EBW inherently had a sufficient degree of electrical insensitivity to be used in non-interrupted explosive train applications. The "Standard" fireset is not related to the intended-use fireset, and is to be used for this test only. The general idea is to have an adequately sized high voltage capacitor, coupled with a sufficiently efficient high voltage switch and associated circuitry, to ensure adequate electrical insensitivity is provided for in the EFI/EBW design. It is recognized that the details established for the "Standard" fireset are somewhat subjective. The goal in establishing the details is to strike an acceptable balance between ensuring an adequate degree of safety is provided for by the selected insensitivity threshold, and avoiding driving EFI/EBW/fireset designs to impractical design solutions. If the design fireset produces input stimulus, which envelops or exceeds that of the standard fireset, the maximum allowable electrical sensitivity test (MAEST) may not be required by the NSAA. The firing unit for the electrical sensitivity tests shall be defined by the following:

(1) The high voltage capacitor shall have a capacitance of 0.1 µF –0% +20%.

(2) The diagnostic component in the test set shall be calibrated and may be either a current viewing resistor (CVR) or a current viewing transformer (CVT) or both.

(3) The high voltage switch must demonstrate a wide dynamic range, be extremely efficient, and must be reproducible shot to shot. Additionally, the switch used should be linear to within 5% when peak current is plotted against charge voltage for ringdowns across the voltage range to be tested. The voltage range tested shall include a minimum of 5 ringdown levels equally spaced across the voltage range. High voltage vacuum relays, semiconductor switches, and shock switches are acceptable as long as they deliver a minimum of 90% of the capacitor energy into a 0.5Ω load consistently.

(4) Two loads shall be used to evaluate the test set. A short at the output connector and low inductance resistor of 0.5 Ω shall be used to represent the range of dynamic impedances of the EFI/EBW.

(5) A typical schematic of the Capacitor Discharge Unit (CDU) is shown in Figure 2.

(6) A minimum of three discharges of the firing unit (ringdowns) shall be performed at two voltages (500 and 1000 volts) using each of the loads and shall meet the requirements for the parameters listed in Table 1 as defined in Figures 3 and 4.

(7) The circuit inductance shall be no less than 20 nano Henries and no greater than 35 nano Henries.

(8) The performance of the test set when shorted at the output connector is illustrated in Figure 3. The parameters of interest are defined in the figure and their values are listed in Table 1.

(9) The amount of energy delivered to the load and the rate that it is delivered during the first half cycle of a capacitor discharge is a measure of importance for EFI/EBW response. A measure of the area under discharge curve and the rise time should be able to arbitrate the efficiency of the fireset, see Figure 4.

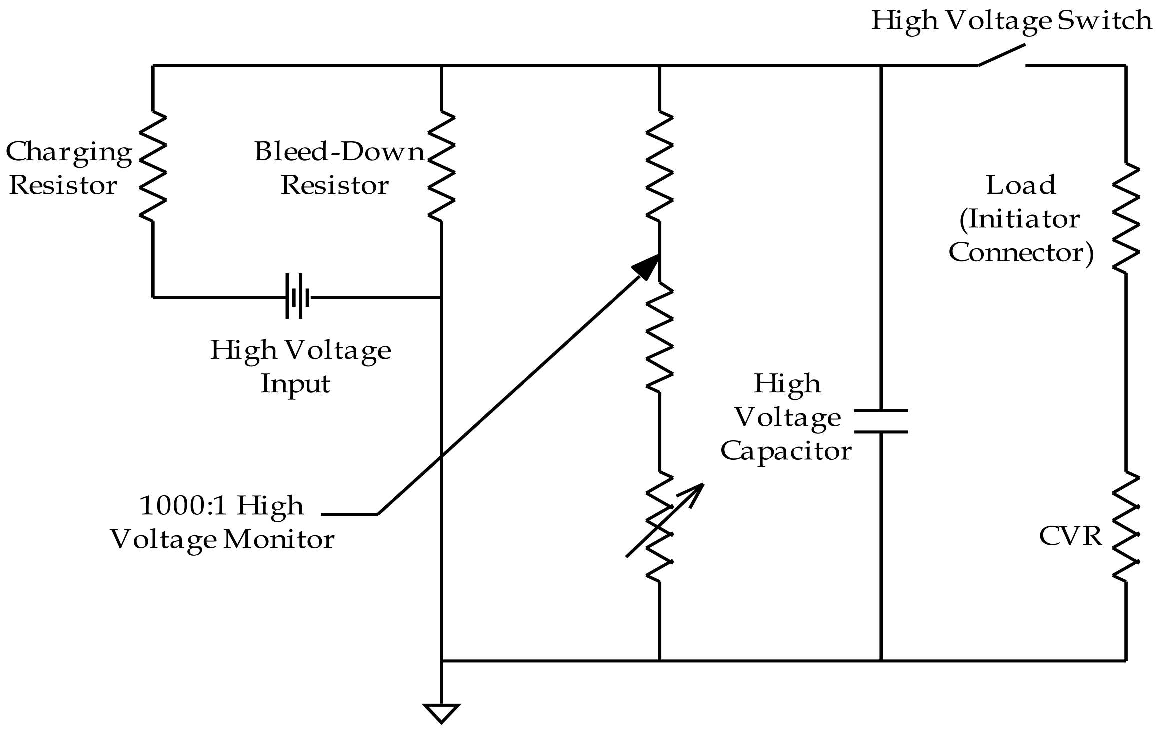

FIGURE 2. FIRESET SCHEMATIC

Load	Short at 500 Volts (Ringdown)	0.50 Ω load at 500 Volts	Short at 1000 Volts (Ringdown)	0.50 Ω load at 1000 Volts
10% to 90% Risetime (t_r)Time to first peak	65 ns max. 35 ns min.	75 ns max. 45 ns min.	65 ns max. 35 ns min.	75 ns max. 45 ns min.
First Peak Current (I_1)	800 Amps minimum	380 Amps minimum	1700 Amps minimum	780 Amps minimum
Second Peak Current (I_2)	490 Amps minimum	NA	1150 Amps minimum	NA
Period (Δt)	430 ns maximum	N/A	425 ns maximum	N/A
Delivered Energy (area under discharge curve* Load Resistance) $\int_0^{P/2} i^2 R dt$	N/A	9.5 mJ	N/A	40 mJ

TABLE 1. STANDARD FIRESET PARAMETER REQUIREMENTS AT 500 & 1000 VOLTS

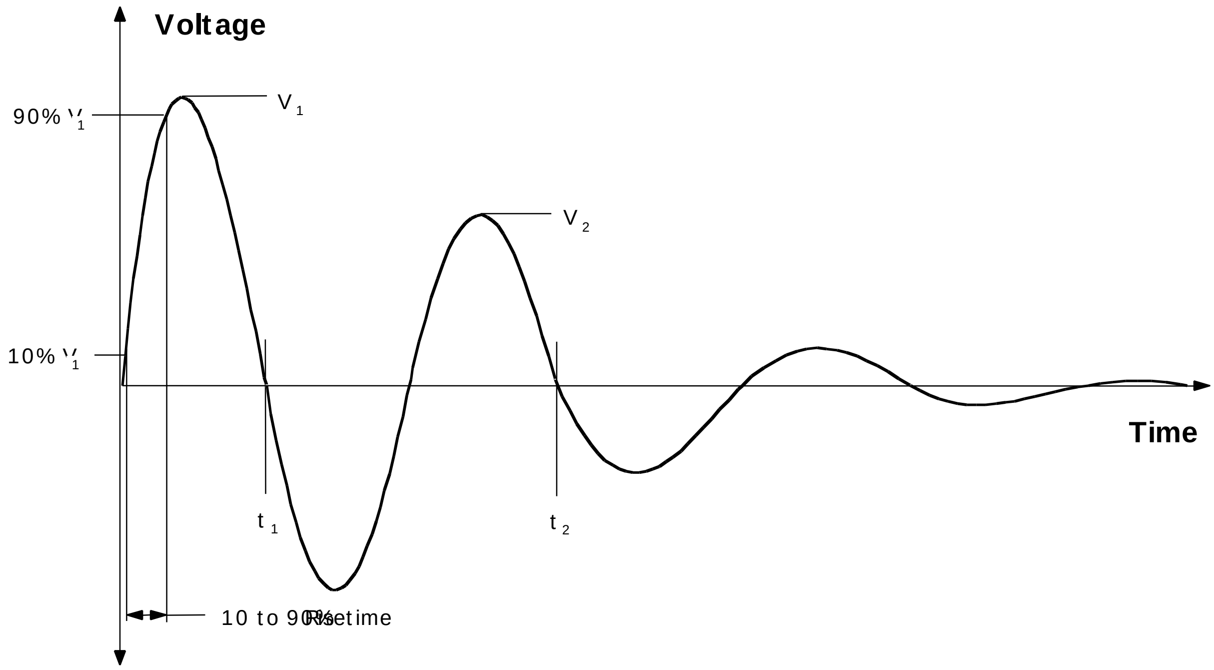

FIGURE 3. TYPICAL RINGDOWN INTO A SHORT CIRCUIT

Additional Information on Figure 3:

Measured Parameters:	First Peak (V_1)
	Second Peak (V_2)
	Period ($\Delta t = t_2 - t_1$)
	10% to 90% Rise time (t_r)
Derived Parameters:	First Peak Current $I_1 = \frac{V_1}{R_{CVR}}$
	Second Peak Current $I_2 = \frac{V_2}{R_{CVR}}$
	Steady State Resistance $R = \frac{(2\Delta t)\ln\frac{V_1}{V_2}}{C[4\pi^2 + (\ln\frac{V_1}{V_2})^2]}$
	Steady State Inductance $L = \frac{\Delta t}{C[4\pi^2 + (\ln\frac{V_1}{V_2})^2]}$

Where: R_{CVR} is the resistance of the Current Viewing Resistor (CVR) in Ohms;
C is the Capacitance of the capacitor in Farads.

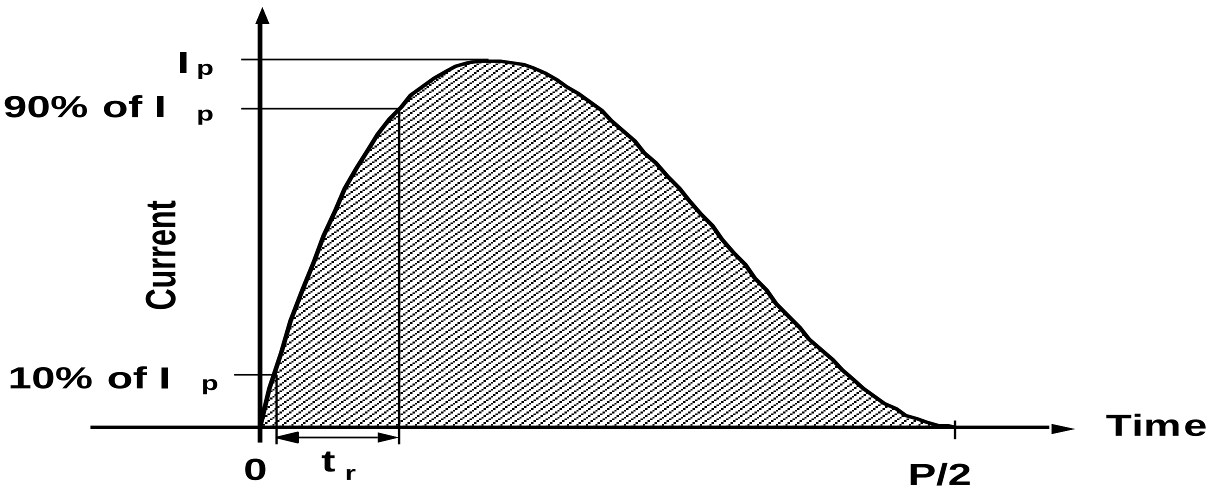

FIGURE 4. TYPICAL DISCHARGE INTO A 0.5 OHM LOAD FOR CALCULATION OF AREA UNDER THE CURVE ($\int_0^{P/2} i^2 R\,dt$) AND RISE TIME (t_r)

75. Statistics. All methods used are small sample based. Therefore error in the estimates will occur. Care must be exercised when choosing test stimulus levels during the tests. If empirical data on the specific design is not available to assist selection of test

levels before start of the test then additional samples should be allocated to perform pre-test evaluations. All of the methods used here assume the distribution of the threshold stimulus levels is normal. It is simple to generalize this assumption and require that some function, such as a logarithm, of the threshold levels is normally distributed. None of the test methods will be able to determine if even a relatively large percentage of the exploding foil initiators are duds, that is, those that will not function at any voltage. Thus, threshold tests must always be backed up with testing a sufficient quantity at an all-fire voltage.

a. Reliability and Confidence Levels. An example, for illustrative purposes, of an EFI that is required to have a reliability of 0.999 and 95% upper confidence limit is presented. This means that 95% of the time no more than 1 in 1,000 EFI will fail to function at the estimated all-fire rating. Explosive system reliability assessments should use the minimum stimulus values that the ignition system delivers to the EFI to assess realistic system level reliability. Figure 5 shows an example of a typical probability curve that is obtained from analysis of sensitivity test data. The y-axis is plotted using probability scaling. The solid straight line in the center gives the best guess for the probability of functioning at the given voltage. Also shown is the 95% upper side confidence curve for this data. To interpret the confidence curves a horizontal line at the 99.9% probability level intersects the most likely and 95% upper confidence curves at approximately 920 and 1004 volts respectively. Thus, 1004 volts is the 95% upper confidence limit for 99.9% probability of fire for this fireset and initiator.

b. Safety and Confidence Levels. Figure 5 shows an example of a typical probability curve that may be obtained from analysis of sensitivity test data being used to predict safety. This projected voltage at which the EFI has a 10^{-6} probability to fire point estimate is presented. This is the best guess that no more than 1 in 1,000,000 EFI will function at the estimated MASS rating. The horizontal line at the 0.000001 probability of fire level intersects the most likely line at approximately 700. For safety analysis the 700 volt level represents the MASS, with 500 volts representing the lowest allowable no-fire voltage at which 1 in 1,000,000 units would respond.

c. As NFT is defined as the threshold level determined by a statistical test using the intended fireset at which the probability of firing a high voltage device is 0.001 with a 95% single sided lower confidence it is necessary to conduct a series of test firings to allow the NFT to be derived. Figure 5 illustrates an example of a typical probability curve that may be obtained to predict safety. The projected voltage at which the EFI has a 10^{-3} probability to fire with 95% single sided lower confidence is presented. This means that there is a 95% confidence that no more than 1 in 1,000 EFI will function at the estimated NFT rating. The horizontal line at the 0.001 probability of fire level intersects the 95% lower confidence curve at approximately 660. For safety analysis the 660 volt level represents the NFT, with 500 volts representing the lowest allowable no-fire voltage at which 1 in 1,000 units would respond at the 95% lower confidence interval.

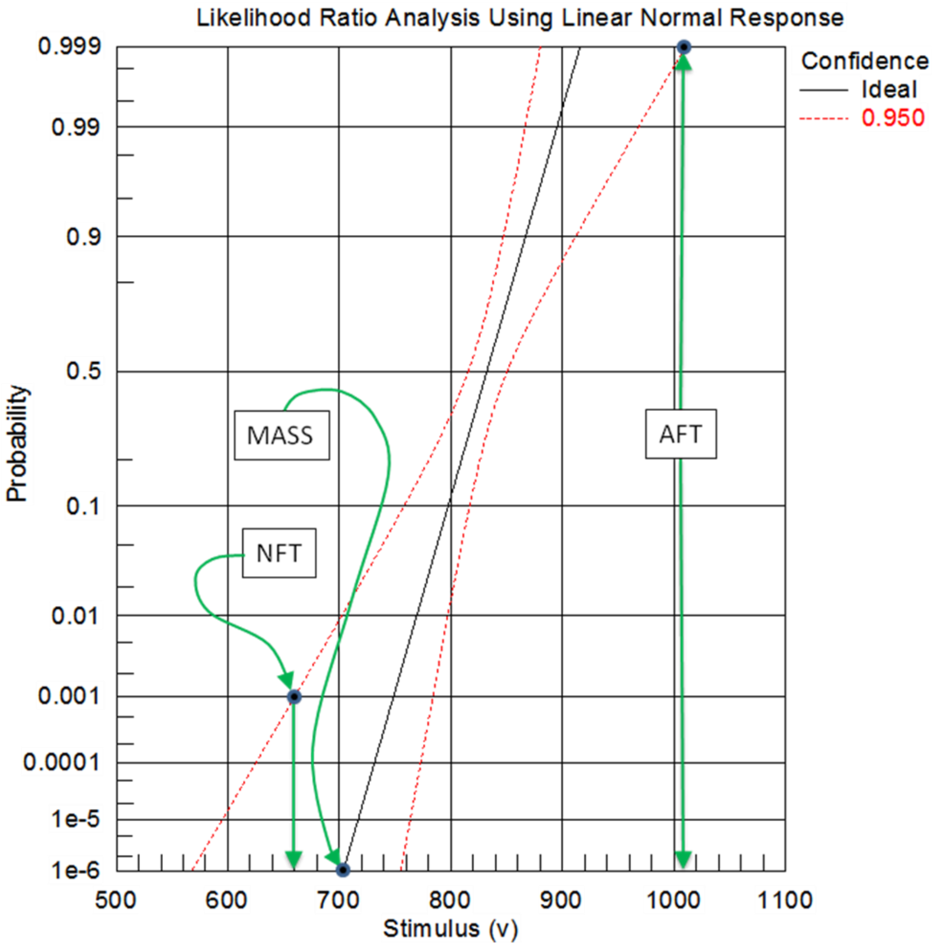

FIGURE 5. FIRING SAFETY AND RELIABILITY ESTIMATE

<u>Typical Example of the Determination of the Thermal Time Constant using Bruceton with Probit</u>

1. It is stressed that this is only one example of a statistical method and the method used has to be accepted by the NSAA. The example is used for obtaining the AFT and/or the NFT and can be divided into three stages (illustrated in Figures 6 and 7):

a. <u>Initial Assessment</u>. During this stage estimates of the mean and standard deviation of the EED power threshold are measured for a range of pulse widths, from which a working value of the τ can be derived. At each pulse a small sample, no more than 4 or 5 devices, will be selected at random and each one subjected to a gradually increasing stimulus until it fires (wind-up test). This may be done by repeated pulsing at increasing levels or by applying a ramp stimulus. (N.B. This is the only occasion when EED are subjected to more than one pulse at a time. As the basic sensitivity may be affected by repeated stimuli these results are not included in the final analysis). The mean of the wind-up test levels is used as the initial firing level for the subsequent Bruceton tests. This will be followed by a Bruceton test performed on a minimum of 20 devices. Where manufacturer's data and experience of device is available, it is usually possible to perform this procedure only twice:

(1) Once at a pulse width at least 10 times greater than τ (constant power region).

(2) Again at a pulse width at least 10 times less than τ (constant energy region).

Completing this procedure twice will require approximately 50 devices. Where this information is not available it will be necessary to perform the procedure up to a maximum of 5 times, aiming to determine pulse widths 10 times greater and 10 times less than τ. Here approximately 125 devices would be necessary for these tests. The ratio of the 50% firing level ($E_{50\%}$) measured at the pulse width much less than estimated τ to the 50% firing level ($P_{50\%}$) measured at the pulse width much greater than estimated τ is used as the working value of the thermal time constant for the subsequent tests. Occasionally some of this information can be deduced from manufacturer's data but it is usually necessary to conduct a series of wind-up and Bruceton tests.

b. <u>Power Threshold (P_{th}) Assessment</u>. During this stage the value of P_{th} is evaluated using the Probit Transformation technique. The test stimulus pulse duration is set to a value much greater than the initial estimate of τ. The test requires approximately 120 EED.

(1) If the estimate of τ from the Bruceton tests is much greater than the pulse width and interval of typical pulsed rf emitters, no further measurements are necessary. The energy threshold (E_{th}) can be estimated from the τ value obtained in the Bruceton tests.

(2) If the estimate of τ from the Bruceton tests is much less than the pulse width and interval of typical pulsed rf emitters, two further stages are necessary as outlined in subparagraph c.

c. Energy Threshold (E_{th}) Assessment for RADHAZ Trials. For accurate assessment of induced transients or where τ is comparable to, or less than, the pulse width and/or interval of radar emitters it is necessary to evaluate E_{th} with pulses much less than the estimate of τ. This will require about a further 200 devices. Where the NFT is quoted as a current value, and the NSAA requires using the power, the NFT parameter can be determined using the geometric mean resistance from the test sample multiplied by the NFT current squared.

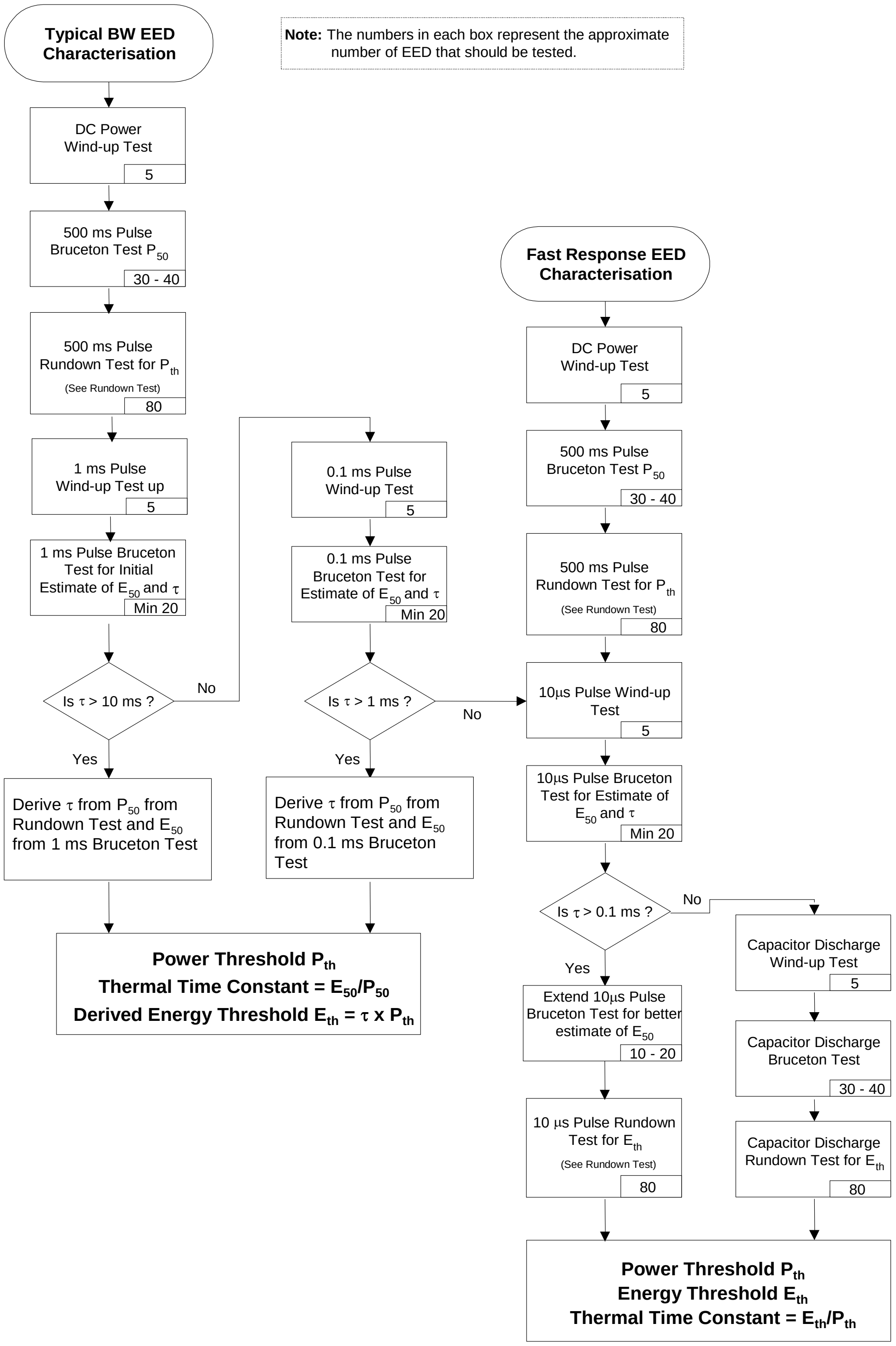

FIGURE 6: TYPICAL STRATEGY FOR EED NFT AND THERMAL TIME CONSTANT DETERMINATION

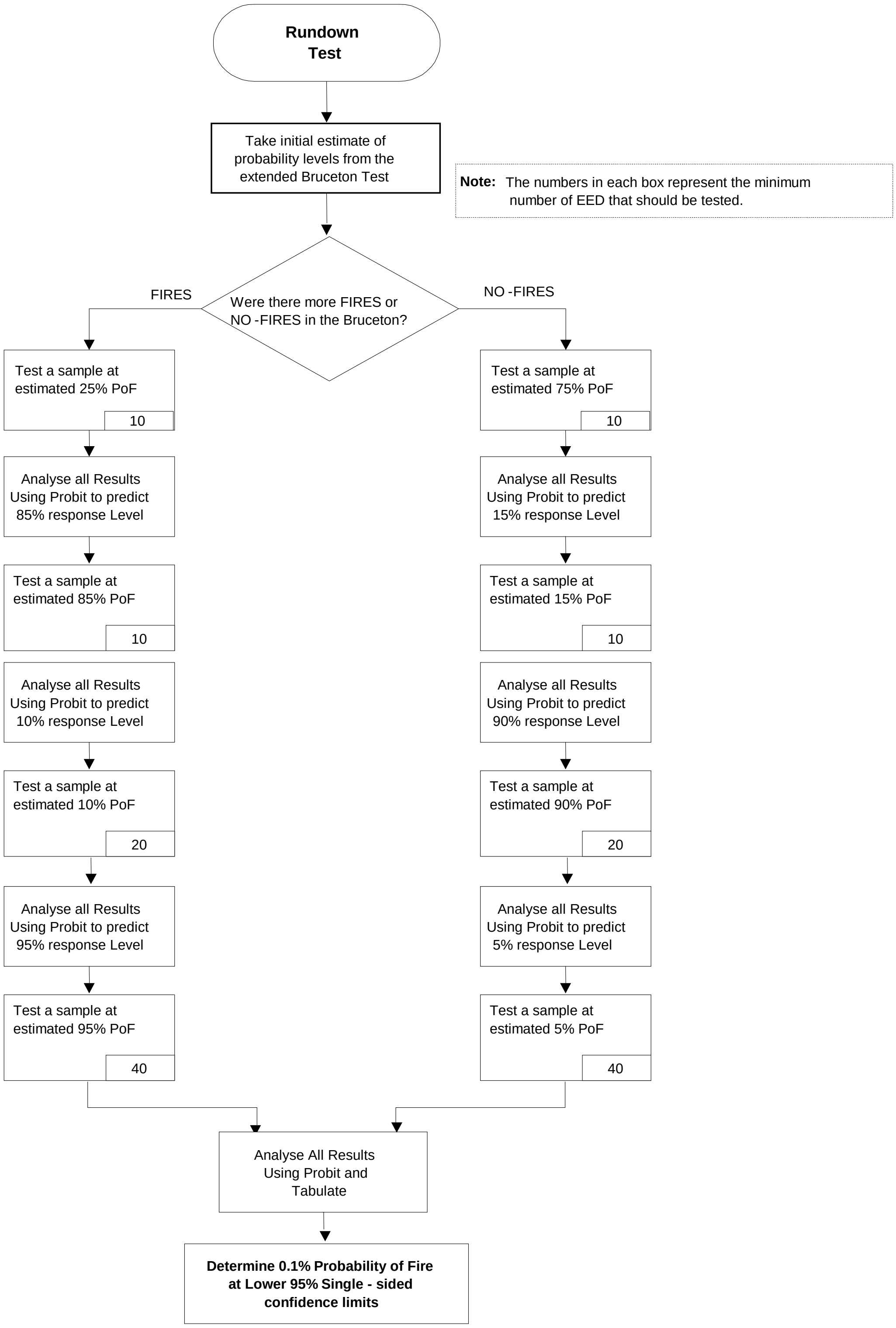

FIGURE 7: THE RUNDOWN TEST

SENSITIVITY TEST METHODS

1. There are presently five test methods generally accepted for sensitivity testing of one shot devices: Probit, Langlie, Weibull One-Shot Transformed Response (OSTR), Bruceton, and Neyer D-Optimal. Each of these tests has a degree of limitation dependent on the information known on similar devices

2. Probit Method.

a. Probit features.

(1) Designed to estimate the entire response curve or any portion thereof.

(2) It is assumed that the probability of a response versus stimulus level is described by a cumulative, normal distribution.

(3) Stimulus levels are normally chosen in advance. Therefore, subsequent trials do not depend on previous results, and no constant step size is required. Test levels can be added or deleted if previous results so indicate.

(4) Deviations about any given stimulus level must be held within a tight range.

(5) The number of trials required is usually larger than that of the other methods.

(6) The test method is less complex than other methods.

(7) The quality of the fit between the observed results and the assumed distribution can be readily illustrated in the vicinity of the mean.

(8) The estimate of the mean is unbiased for practical purposes.

(9) The estimate of the standard deviation is biased to the low side.

(10) The need to use a computer program to implement the analysis calculations will depend on the type of analysis procedure selected. If the commonly used maximum likelihood estimates, for example, are employed, a computer program would be necessary.

b. Probit procedure.

(1) Select the stimulus levels and the number of trials to be conducted at each stimulus level. The same number of trials at each stimulus level is not necessary. The stimulus levels chosen should concentrate about the percentile being estimated and cover the range of stimuli giving approximately 0 to 0.5 probability when estimating a low percentile, 0.5 to approximately 1.0 probability when estimating a high percentile, or approximately 0 to 1 probability when estimating the mean.

(2) At each stimulus level, conduct the required number of trials and record the results.

c. Probit analysis. The stimuli and results are used to calculate maximum likelihood estimates of the mean and standard deviation of a normal distribution. It is assumed that the probability of response versus stimulus is described by a cumulative, normal distribution. A computer program is necessary to implement the computations.

3. Langlie Method.

a. Langlie features.

(1) Designed to estimate the stimulus for which there is a 0.5 probability of response.

(2) It is assumed that the probability of a response versus stimulus level is described by a cumulative normal distribution.

(3) Subsequent stimulus levels depend on previous test results.

(4) Step sizes are variable.

(5) Number of trials required is usually smaller than that of Probit, OSTR, and Bruceton tests.

(6) Test method is more complex than Probit and Bruceton tests.

(7) The estimate of the mean is unbiased for practical purposes.

(8) The estimate of the standard deviation is biased, but a bias correction can be applied if the Langlie Method is rigorously followed.

(9) The need to use a computer program to implement the analysis calculations depends on the type of analysis procedure selected. If the commonly used maximum likelihood estimates, for example, are employed, a computer program would be necessary.

(10) The test equipment must be capable of covering the entire, continuous range of stimuli.

(11) Upper and lower test limits must be chosen prior to testing.

(12) If the time or effort required to obtain the information from the previous trial is excessive, this method may not be appropriate.

(13) Once the next stimulus level is determined, if the method requires too much time and difficulty to prepare the test item/apparatus for that trial, the method may not be appropriate.

(14) A stopping rule is required.

b. Langlie procedure.

(1) Setting the limits to be approximately 4 standard deviations from the mean produces the best results. Call these stimuli L and U.

(2) A stopping rule is selected. It is recommended that at least 20 trials or 5 reversals with a zone of mixed results be used unless an alternate stopping rule was previously agreed to by the sponsoring activity.

(3) The first trial is conducted at a stimulus equal to the average of U

and L.

(4) For the remaining trials the general rule is: The (K+1)th stimulus is equal to the average of the Kth stimulus and, counting backwards through the results, the stimulus whose result was such that there is an equal number of responses and non-responses over that interval of trials. If this is not possible, average the Kth stimulus and U or L, as appropriate. Use U if the Kth result was a non-response and L if the Kth result was a response.

(5) The remaining trials are determined in a similar manner.

Note, at any stage, the most recent stimulus is always used in averaging. Finding the stimulus with which the most recent stimulus is averaged is the only tricky part of the strategy.

c. Langlie analysis. The stimuli and results are used to calculate the maximum likelihood estimates of the mean and standard deviation of a normal distribution. It is assumed that the probability of a response versus stimulus level is described by a cumulative normal distribution. A computer program is necessary to implement the computations.

4. <u>One Shot Transformed Response (OSTR) Method</u>.

a. OSTR features.

(1) Designed to estimate an extreme percentile of response stimulus.

(2) It is assumed that the probability of a response versus stimulus level is described by a cumulative, normal distribution.

(3) Subsequent stimulus levels depend on previous results.

(4) Step sizes are variable.

(5) Number of trials required is usually larger than that of Langlie and Bruceton tests.

(6) One or more trials are conducted at a stimulus level prior to changing. (If only one trial is used at each stimulus, this reduces to the Langlie Method.)

(7) The bias of the estimates of the mean and standard deviation has not been determined.

(8) Test method is more complex than the other methods.

(9) The need to use a computer program to implement the analysis calculations depends on the type of analysis procedure selected. If the commonly used maximum likelihood estimates are employed, for example, a computer program would be necessary.

(10) If obtaining the information from the previous trial requires too much effort and cost in order to determine the next stimulus level, this method may not be appropriate.

(11) Once the next stimulus is determined, if the method requires too much time and difficulty to prepare the test item/apparatus for that trial, the

method may not be appropriate.

(12) Upper and lower test limits must be chosen prior to test.

(13) A stopping rule is required.

(14) The test equipment must be capable of covering the entire, continuous range of stimuli.

b. OSTR procedure.

(1) Setting the limits to be approximately 4 standard deviations from the mean produces the best results. Call these stimuli L and U.

(2) Select the percentage point to be estimated. Then use the corresponding maximum number of trials to be conducted at a given stimulus level prior to applying a change in stimulus level. The number of trials at a particular stimulus level depends upon the percentile estimated; further into the tail of the distribution will require more trials. For planning purposes, the expected number of total trials actually required is approximately three-fourths of the maximum number of trials at each stimulus level times the number of stimulus levels.

(3) Establish the rule for increasing or decreasing the stimulus level. For example, suppose a lower-tail percentile with a corresponding maximum of three trials per stimulus level is chosen. The rule would be: Increase stimulus level if all three result in non-functioning; otherwise, decrease the stimulus level.

(4) Select a stopping rule. At least 5 reversals with a zone of mixed results, or at least 10 levels of stimuli, shall be used unless an alternate stopping rule was previously approved by the sponsoring activity. Occasionally, peculiar sequences of outcomes occur, that is, no zone of mixed results, which provide little or no information about the response distribution. This condition is minimized by using the change of response stopping rule rather than a fixed number of levels of stimuli. If upon stopping on number of reversals, a zone of mixed results has not occurred, the test procedures and goals should be examined to determine the possible cause of this anomaly. Additional trials will be required until a zone of mixed results is obtained.

(5) The first trial is conducted at the stimulus level equal to the average of L and U.

(6) Now follow the Langlie Method of para 79, except that more than one trial (up to the number selected in b(2) above) will be conducted at a particular stimulus level. Note: When n = 1, the OSTR method becomes the Langlie.

c. OSTR analysis. The stimuli and results are used to calculate maximum likelihood estimates of the mean and standard deviation of a normal distribution. These estimates can be used to predict functioning probabilities at other parameter values. It is assumed that the probability of a response versus stimulus is described by a cumulative, normal distribution. A computer program is necessary to implement the computations.

5. Bruceton Method.

a. Bruceton features.

(1) Designed to estimate the stimulus at which there is a 0.5 probability of response.

(2) Because of concentration of testing at the mean, this technique is the least effective at estimating probabilities at either extreme of the stimulus/response curve and should not be used for that purpose if any of the other methods are useable.

(3) It is assumed that the probability of a response versus stimulus level is described by a cumulative, normal distribution.

(4) Step size is fixed and chosen in advance.

(5) Test method is more complex than that of Probit test and less complex than that of Langlie and OSTR tests.

(6) The estimate of the mean is unbiased for practical purposes.

(7) The estimate of the standard deviation is biased to the low side.

(8) A stopping rule is required.

(9) Computations are much simpler than for the other analyses and can be done by hand.

(10) The number of trials required is usually fewer than that of Probit test and more than that of Langlie and OSTR tests.

(11) If obtaining the information from the previous trial requires too much effort and cost in order to determine the next stimulus level, this method may not be appropriate.

(12) Once the next stimulus is determined, if the method requires too much time and difficulty to prepare the test item/apparatus for that trial, the method may not be appropriate.

b. Bruceton procedure.

(1) Choose the step size for the stimulus. Ideally, it should be equal to the standard deviation (often unknown) of the underlying, normal distribution; if within about 0.5 to 2.0 times the true value, it should be adequate. If the step size chosen is too large, analysis may not be possible; if too small, the analysis may look acceptable but yield a seriously inaccurate estimate of the response versus stimulus curve.

(2) Choose a stopping rule. At least 10 reversals with a zone of mixed results or the maximum number of trials (at least 45 is recommended) shall be used unless otherwise approved in the test plan.

(3) Select a starting point. The starting point should be close to the estimate of the mean value.

(4) Conduct the first trial at the starting point.

(5) Select subsequent stimulus levels one step size above or below the preceding level, depending on whether the last trial resulted in a non-function or a function, respectively. Decrease the stimulus level after a function, and increase the stimulus level after a non-function.

c. Bruceton analysis. The stimuli (step size) and results (function or non-function) are used to calculate the maximum likelihood estimates of the mean and standard deviation of a normal distribution. It is assumed that the probability of a response versus stimulus is described by a cumulative, normal distribution.

6. Neyer D-Optimal Method.

a. Neyer D-Optimal features.

(1) Designed to estimate both population parameters.

(2) Because of concentration of testing at the D-Optimal points, this technique is the most effective at estimating probabilities at the extreme of the stimulus/response curve and should only be used for that purpose.

(3) It is assumed that the probability of a response versus stimulus level is described by a cumulative, normal distribution.

(4) The stimulus levels vary depending of the initial test parameters as well as all previous test information.

(5) Deviations about any given stimulus level can vary without effecting the validity of the test.

(6) Test method is more complex than all other methods. A computer program is required to calculate the stimulus levels and to perform the analysis.

(7) The estimate of the mean is unbiased for practical purposes.

(8) The estimate of the standard deviation is biased to the low side, but a bias correction (small compared with the variation of the estimate) can be applied.

(9) A stopping rule is required.

(10) Computations are much more complex than for the other analyses methods and require a computer program.

(11) The number of trials required is fewer than for any of the other methods.

(12) Because the initial test parameters are only used for the first few tests, the dependence on the initial test parameters is less than for any of the other methods.

(13) If obtaining the information from the previous trial requires too much effort and cost in order to determine the next stimulus level, this method may not be appropriate.

(14) Once the next stimulus is determined, if the method requires too much time and difficulty to prepare the test item/apparatus for that trial, the

method may not be appropriate.

(15) The same software can be used to conduct a c-Optimal test that will concentrate the stimulus levels near any desired extreme probability level if concentrated knowledge of one extreme level is desired.

b. Neyer D-Optimal procedure.

(1) Provide a guess for upper and lower estimates of the mean, call these MuMin and MuMax. It is not required that all devices function at MuMax or that no devices function as MuMin. Rather these levels should be chosen based on engineering judgment of the mean. The method will test outside of the MuMin to MuMax range if the true mean lies outside of the range. Also provide a guess for the standard deviation, called SigmaGuess. If an inaccurate guess is chosen, the method will adapt to find a better guess. Start the computer program and enter these values as directed noting that the parameter used has to have a cumulative normal distribution.

(2) Conduct each trial at the stimulus level given by the program. Enter the test results (either a response or a no response) as directed. If the test was conducted at a different test level than specified, then enter the actual stimulus level. The program will calculate the next stimulus level.

(3) The Neyer D-Optimal method uses a multi phase approach when picking the test levels.

(a) The initial phase consists of finding the region of interest (i.e. a region where some devices respond and some do not.) The first level will be mid way between the upper and lower estimated MuMin and MuMax. The initial step size is the maximum of SigmaGuess and ¼ *(MuMax – MuMin). If the first device responds (does not respond), then conduct the next test at a level one step size below (above) the previous level. Double the step size after each test. The first phase ends when there is at least one device responding and one that does not respond. The first phase will usually end after 2 devices have been tested if the test parameters are optimized to the population.

(b) The second phase consists of a binary search to “home in” on the 50%. Test each device mid way between the highest level at which a device fails to respond and the lowest level at which a device responds. End this phase when the difference between these two levels is less than SigmaGuess.

(c) The final phase consists of determining the 2 D-Optimal points (roughly the 15% and 85% points of the distribution) assuming a normal distribution using the Maximum Likelihood Estimates for the mean and standard deviation. When there is no zone of mixed results (all the levels at which devices respond are above the levels at which devices do not respond) use the SigmaGuess estimate for the standard deviation. Decrement the SigmaGuess by multiplying by 0.8 each time.

(4) The test may be stopped when the sample of devices are tested, or when the analysis shows that the required precision has been achieved.

c. Neyer D-Optimal analysis. The stimuli and results are used to calculate the maximum likelihood estimates of the mean and standard deviation of a normal distribution. It is assumed that the probability of a response versus stimulus is described by a cumulative, normal distribution. Various probability estimates are computed using these population parameters. The Likelihood Ratio Test is used to compute confidence intervals for all of the population parameters.

7. Conducting sensitivity tests. Set the stimulus level (distance to the target, firing voltage, barrier thickness, etc.) selected by the test method. It is important to set the stimulus as close as possible to the value specified by the method for all methods except the Neyer D-Optimal method.

8. Suggestions for efficient use of samples:

a. Stimulus and response. The five test methods presented in this annex are “sensitivity tests,” a term used in statistical literature to denote an experiment from which quantal response data are observed as the intensity of a stimulus is varied. There are variations of the Probit which do not require stimulus levels fixed and selected in advance. The stimulus may be the voltage on a capacitive discharge unit and the response or non-response, or function or no function, and so on. All applications of these type tests are characterized by the quantal result of a go/no-go, yes/no, success/failure, and so forth. The probability of a response must monotonically increase with increasing stimulus level.

b. Choosing a test strategy. It is usually assumed that the probability of a response versus the stimulus level is described by a cumulative distribution function. The normal Gaussian distribution shall be used unless there is statistical evidence supporting the use of another distribution, and such use is agreed to by the NSAA. For all the test strategies presented herein (except for the Bruceton test), the analysis procedures require a computer program. Often the statistical estimates will be biased. Unbiasing correction factors can be obtained in some cases.

c. Zone of mixed results. Another important characteristic of all sensitivity tests is called a zone of mixed results. If this zone does not occur, the population parameter estimates will be degenerate. The Likelihood Ratio Analysis typically used to analyze the Neyer D-Optimal test is able to provide estimates of confidence regions in this case as well. A zone of mixed results occurs if the largest non-response stimulus level exceeds at least the minimum stimulus level for a response. The chance of a non-occurrence of a zone of mixed results increases with diminishing sample size.

d. Stopping rule. When conducting one of the test strategies of paragraph 75 or any sensitivity test, there must be a stopping rule. The most common is to fix the maximum number of trials in advance. Another strategy gaining favour is selecting in advance the number of reversals of response.

e. Reporting results. When reporting results, the raw test data (response or nor response) at each level must be reported in addition to the analyzed results such as the mean, standard deviation, no-fire and all-fire levels to allow the customer to verify the analysis.