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# A NEW APPROACH TO ELECTRICAL CHARACTERIZATION OF EXPLODING FOIL INITIATORS

by

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December/décembre 1998

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2 Dec. 98
Date

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## ABSTRACT

In a previous study on electrical characterization of Exploding Foil Initiators (EFIs), a general statistical model that expresses the probability of detonation of EFIs as a function of the power delivered to the bridgefoil at burst and the rate of current rise was developed. This memorandum presents the statistical procedure applicable to EFI electrical characterization and describes the proper experimental methodology. Experimental results are given and processed to illustrate the methodology.

## RÉSUMÉ

Dans une étude précédente de la caractérisation électrique des détonateurs à élément projeté (DEP), on a développé un modèle statistique général qui exprime la probabilité de détonation des DEP en fonction de la puissance électrique qui traverse le film métallique à l'instant de son explosion et du taux de croissance du courant qui circule dans le film. Ce mémorandum présente la procédure statistique applicable à la caractérisation électrique des DEP et décrit la méthodologie expérimentale adéquate. Cette méthodologie est illustrée par la présentation et le traitement de résultats expérimentaux.

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## EXECUTIVE SUMMARY

The Smart Armour Protection System (SAPROS) is a concept of active protection of armoured vehicles against attacks of missiles, particularly those of the type that flies over the target and attacks it from the top. SAPROS uses electro-optic and radar sensors to detect and locate an incoming threat and uses an array of shaped charges mounted on the vehicle to defeat it. The shaped charges are selectively fired at the threat in clusters of three.

It is expected that the SAPROS fuzing system will employ an Electronic Safety and Arming Device (ESAD) using Exploding Foil Initiators (EFIs) in order to meet the system requirements for safety and suitability for service. Since the use of in-line all-electronic fuze technology is recent in weapon systems, the procedures available to evaluate design options and eventually assess SAPROS fuze safety and suitability for service are inadequate in several key areas. These include test procedures by which EFIs electrical sensitivity is characterized and ESAD test procedures for ensuring that the maximum allowable safe stimuli is not exceeded in service electromagnetic environments.

In this context, a study was conducted at DREV on electrical characterization of EFIs. The study, based on rigorous and efficient statistical procedures and EFI operating principles, resulted in a new approach to characterize EFI electrical sensitivity. This approach uses statistical modeling to link the probability of detonation of EFIs to two electrical parameters related to their functioning physics. The present memorandum describes the statistical procedure and proper experimental methodology associated with this new approach.

This work increases the DREV expertise in the EFI operation and will help to plan future EFI development programs and ensure that the Canadian Forces can be provided with timely advice. This expertise is also shared with NATO countries as part of a cooperative work to create a STANAG which will provide the methodology and procedures by which electro-explosive devices will be characterized to assess their safety and suitability for general and specific use.

## NOMENCLATURE

| | |
|---|---|
| $A$ | cross-sectional area of bridgefoil |
| $A_1,\ldots,A_n$ | EFI electrical parameters |
| $C_1,\ldots,C_k$ | elements parameterizing the family of possible models |
| $C_d$ | firing capacitance |
| $E_b$ | energy deposited into bridgefoil up to burst time |
| $F_i$ | function of electrical parameters |
| $G_b$ | specific action up to burst time |
| $I_b$ | current at bridgefoil burst time |
| $I_{\max}$ | peak current in bridgefoil |
| $I(t)$ | bridgefoil current at time $t$ |
| $\dot{I}(t)$ | rate of rise of current |
| $J_b$ | current density at bridgefoil burst time |
| $l$ | Gurney exponent |
| $L$ | EFI system inductance |
| $L_c$ | coupling inductance of the voltage probe |
| $p$ | probability of detonation |
| $P_1$ | response function |
| $P_b$ | power delivered to bridgefoil at burst time |
| $Q_0$ | initial charge on firing capacitor |
| $R$ | EFI system resistance |
| $r_b(t)$ | bridgefoil resistance at time $t$ |
| $t$ | time |
| $t_b$ | burst time |
| $V_0$ | initial voltage on firing capacitor |
| $V(t)$ | bridgefoil voltage at time $t$ |
| $V_c(t)$ | induced voltage at time $t$ |
| $\gamma$ | percent confidence interval |
| $\omega$ | angular frequency |

## 1.0 INTRODUCTION

Electro-explosive devices (EEDs) are electrically fired explosive initiators used in a wide range of applications. The exploding foil initiator (EFI) is a relatively new type of EED and an international agreement on a method of reporting EFI firing data has not been reached so far. At present, the voltage on the firing capacitor is the preferred characterization attribute, but it has several drawbacks being not related directly to EFI functioning physics (Ref. 1). The necessity of having appropriate methods for electrical characterization of EFIs justified the work described in Refs. 2-3 which investigated improvements to EFI statistical firing properties. This work used statistical modeling to identify the independent electrical parameters acting upon EFI probability of detonation and resulted in a new approach to characterize EFI electrical sensitivity.

This memorandum presents a general statistical procedure that can be used for characterizing EFIs and it describes the proper experimental methodology. Chapter 2.0 is a short summary of the main conclusions from Ref. 2 to introduce the general statistical model applicable to EFI characterization. Chapter 3.0 describes in three stages the design of the experiment stemming directly from the statistical model. The first stage concerns the measurement of the required electrical parameters and the instrumentation to make these measurements. The second stage is about the determination of the experimental domain and is based largely on physical considerations. The last stage is the statistical design of the experiment within the experimental domain. Chapter 4.0 presents the statistical analysis performed on the data gathered in the statistical experiment and, finally, chapter 5.0 describes a method to graphically summarize relevant information from the statistical analysis.

This work was carried out at DREV between February and June 1997 under Thrust 3e, “Air Weapon Systems”.

## 2.0 BACKGROUND

As mentioned in the introduction, the work described in Refs. 2-3 used statistical modeling to identify the independent electrical parameters or variables acting upon the EFI probability of detonation. The statistical modeling was based on the logit response model which is a natural choice for the EFI characterization problem addressed here. The general logit model is

$$P_1 = \frac{\exp\left(C_0 + \sum_1^k C_i F_i(A_1, A_2, \ldots, A_n)\right)}{1 + \exp\left(C_0 + \sum_1^k C_i F_i(A_1, A_2, \ldots, A_n)\right)} \qquad [1]$$

where $P_1$ is the response function, the $F_i$'s are functions of the EFI electrical parameters $A_1, A_2, \ldots, A_n$, and the $C_i$'s are the elements of a vector parameterizing the family of possible models. The modeling choice is done via the number and definition of the functions $F_i$ appearing in the above expression. In a classical logit model, the $F_i$'s are monomials in $A_1, A_2, \ldots, A_n$ so that the summation appearing in the above exponential function are indeed polynomials.

The EFI electrical parameters $A_1, A_2, \ldots, A_n$ considered in Ref. 2 are determined from bridgefoil current and voltage data recorded simultaneously during EFI detonation experiments. The main electrical parameters examined are:

$I_{\max}$ = peak current in bridgefoil
$I_b$ = current at bridgefoil burst time
$J_b$ = current density at bridgefoil burst time
$\dot{I}(t)$ = rate of current rise
$P_b$ = power delivered to bridgefoil at burst time
$E_b$ = energy deposited into bridgefoil up to burst time
$G_b$ = specific action up to burst time

As reported in Ref. 2, a large set of complete or incomplete polynomials of degrees ranging from 1 to 3 featuring pairs and triples of the electrical parameters has been fitted to the experimental data. Based on goodness of fit of the estimates, the conclusions were that two parameters, $\dot{I}(t)$ and $P_b$, are sufficient and that the best polynomial type within the range of experimentation was simply the complete polynomial of order 1

$$C_0 + C_1\dot{I}(t) + C_2 P_b \qquad [2]$$

such that the response function $P_1$ is given by

$$P_1 = \frac{\exp\left(C_0 + C_1\dot{I}(t) + C_2P_b\right)}{1 + \exp\left(C_0 + C_1\dot{I}(t) + C_2P_b\right)} \qquad [3]$$

Equation 3 is a general statistical model applicable to EFI electrical characterization. A specific model is obtained by finding with an appropriate algorithm the optimum values of the model parameters using the data gathered from the statistical experiment performed on the test EFI. For the particular EFI configuration used in Ref. 2 (which is described in Appendix A of the present document), the optimum values of the parameters $C_0$, $C_1$, and $C_2$ were determined and the resulting response function or probability of detonation within the range of experimentation is illustrated in Fig. 1. A cut in each of the canonical planes of Fig. 1 would produce an ordinary logistic distribution. This is illustrated in Figs. 2 and 3 where one of the two variables is held fixed and the other varied.

## 3.0 DESIGN OF THE EXPERIMENT

This chapter describes the physical experiment and its statistical design. It is assumed that the EFIs used will be suitably controlled prior to testing (batches, lots, storage time and conditions, etc.) such that the effects of any outside influences are eliminated or reduced.

### 3.1 Instrumentation and Measurements

The characterization method requires the determination of $\dot{I}(t)$, the rate of rise of current through the bridgefoil, and $P_b$, the power delivered to bridgefoil at burst. It entails that accurate simultaneous measurements of the current $I(t)$ through and the voltage $V(t)$ at the bridgefoil are mandatory because $P(t)$, the power delivered to bridgefoil at time $t$, is calculated using the relation

$$P(t) = V(t)I(t) \qquad [4]$$

and $P_b = P(t_b)$ where $t_b$ is the time at bridgefoil burst.

For current measurements, it is usual to use low-inductance current viewing resistors (CVRs) of the clamping type for flat cables. Inductance of these CVRs is a few nH and resistance range from 0.001 Ω to 0.01 Ω, depending on the application. A typical current waveform monitored via a CVR whose nominal resistance was 0.005 Ω with output fed into a 50 Ω termination impedance is given in Fig. 4. The CVR bandwidth is rated at 200 MHz with a corresponding rise time of approximately 2 ns. The example refers to the EFI system described in Appendix A.

Current data such as those given in Fig. 4 are employed to calculate the rate of current rise. There is evidence of a linear relationship on the rising part of the current waveform which is shown in greater details in Fig. 5. The method of least squares is applied on the data inside the interval delimited by the two symbols shown on the current waveform to estimate the parameters of the linear equation. The estimated value of the rate of current rise is 69.6 A/ns. The theoretical initial rate of current rise which is the maximum $\dot{I}(t)$ allowed by an EFI system is given by $V_0/L$ where $V_0$ is the initial voltage on the capacitor and $L$ the total system inductance. For the circuit inductance of approximately 30 nH and a capacitor voltage of 2500 V of the EFI system described in Appendix A, a maximum $\dot{I}(t) =$ 83.3 A/ns is computed.

Voltage measurements are obtained by employing a two-pin differential voltage probe whose schematic is shown in Fig. 6. The voltage probe uses a Tektronix CT-2 current transformer and a P6041 probe cable terminated in a 50 Ω load. The two-pin probe is a low impedance, high voltage, and relatively high bandwidth probe (> 200 MHz). Although the probe provides an essentially resistive load across the bridgefoil, some inductive coupling exists between the probe and the circuit. Depending on the geometry of the probe connection across the bridgefoil, this inductive coupling results in a more or less significant initial step on the voltage trace proportional to the rate of current rise. A typical example of a raw voltage measurement is given in Fig. 7. This measurement was done simultaneously with the current measurement of Fig. 4.

The induced voltage $V_c(t)$ must be removed from the measured voltage because it does not contribute to EFI performance. The initial step and other induced reactive voltage can be removed from the voltage trace using the relationship

$$V_c(t) = L_c\dot{I}(t) \qquad [5]$$

where $V_c(t)$ is the induced voltage at time $t$ and $L_c$ is the inductance of the probe. By employing the estimated value of the rate of current rise from the current record and the initial voltage step, an estimate of $L_c$ (normally of the order of a few nH) can be made and the measured voltage corrected according to

$$V_{corrected}(t) = V_{measured}(t) - L_c\dot{I}(t) \qquad [6]$$

The corrected voltage data resulting from these calculations performed on the measured voltage data of Fig. 7 are given in this Figure.

The time at bridgefoil burst is defined as the time at which the voltage across the bridgefoil reaches a maximum (Ref. 4). Therefore the corrected voltage data of Fig. 7 are used to determine $t_b$ ($t_b = 156$ ns). Finally, the current and corrected voltage waveforms are multiplied together (Eq. 4) to obtain $P(t)$, the power delivered to the bridgefoil as a function of time. The result is given in Fig. 8; the power at burst, $P_b$, is equal to 3.16 MW in this case.

A block diagram of a suggested equipment setup is presented in Fig. 9. Electrical data must be recorded on an oscilloscope with a time resolution that is adequate to record the signals without distortion. Digital recording is more convenient for purposes of data reduction. The outcome of an experiment (detonation/no detonation) is best determined by using an aluminum or steel witness plate placed in intimate contact with the acceptor explosive.

### 3.2 Experimental Domain

The experimental domain is defined by a range of $\dot{I}(t)$'s and $P_b$'s within which it is desirable and possible to perform the experiment. An insight into the details for determining the feasible regions of $\dot{I}(t)$ and $P_b$ is given below by considering the relationship of these two parameters to circuit parameters, i.e., inductance, capacitance, etc.

A schematic diagram of the electrical circuit of an EFI system is shown in Fig. 10. The circuit is basically a simple series RLC design, with a time dependent resistive element, $r_b(t)$, representing the bridgefoil as it bursts. For this equivalent circuit, Kirchhoff's rule gives the equation (an ideal switch is assumed):

$$L\frac{dI(t)}{dt}+RI(t)+r_b(t)I(t)-\frac{1}{C_d}\left(Q_0-\int_0^t I(\lambda)d\lambda\right)=0 \qquad [7]$$

where $Q_0$ is the initial charge on the capacitor $(Q_0 = V_0 C_d)$. No analytic expression exits for the current waveform because of the nonlinear resistivity of the bridgefoil during its burst process. The copper resistivity undergoes large changes as the copper material passes from a solid, to a liquid, to a vapor, and finally to a plasma. Rather than perform a detailed analysis it is more informative to consider simple circuit approximations to provide insight into the importance of various circuit parameters in determining the experimental domain.

To simplify, we assume that circuit resistance and bridgefoil resistance may be neglected in Eq. 7 (Ref. 5). In this case the bridgefoil current, $I(t)$, is given as a function of time by the equation

$$I(t)=\frac{V_0}{\omega L}\sin(\omega t) \qquad [8]$$

where

$$\omega=\sqrt{\frac{1}{LC_d}} \qquad [9]$$

By definition the specific action up to burst time, $G_b$, is given by the equation

$$G_b=\frac{1}{A^2}\int_0^{t_b} I^2(t)dt \qquad [10]$$

where $A$ is the cross-sectional area of the bridgefoil. Substituting in the previous equation the expression for $I(t)$ from Eq. 8 and integrating yields

$$G_b = \frac{V_0^2}{A^2\omega^3L^2}\left[\frac{\omega t_b}{2} - \frac{1}{4}\sin(2\omega t_b)\right] \qquad [11]$$

A Taylor series expansion of the sine function in Eq. 11 about 0 yields

$$G_b = \frac{V_0^2 t_b^3}{3A^2L^2} \qquad [12]$$

and thus

$$t_b = \sqrt[3]{\frac{3A^2L^2G_b}{V_0^2}} \qquad [13]$$

From Eq. 8 it follows that the burst current density, $J_b$, is given by

$$J_b = \frac{V_0}{A\omega L}\sin(\omega t_b) \qquad [14]$$

and approximating the sine function with its argument and substituting the estimate of $t_b$ from Eq. 13 yields

$$J_b = \sqrt[3]{\frac{3V_0G_b}{AL}} \qquad [15]$$

From the electrical Gurney theory (Ref. 5), the power at burst (per unit mass) is proportional to the burst current density according to

$$P_b \propto J_b^{2-l} \qquad [16]$$

and thus

$$P_b \propto \left(\frac{3V_0G_b}{AL}\right)^{\frac{2-l}{3}} \qquad [17]$$

where $l$ is a Gurney exponent.

Equation 17 relates the maximum power at burst to be expected to circuit parameters and shows that this power increases with an increase in $V_0/L$, the theoretical initial rate of current rise in a capacitor discharge circuit. In an actual EFI system, this last parameter is bounded by the minimum circuit inductance $L$ attainable and the maximum rated voltage $V_0$ on the firing capacitor $C_d$. In a well design circuit, the value of $L$ is mostly fixed by the intrinsic inductance of the firing capacitor. Cable inductance, switch inductance and parasitic inductance will add to this value. Furthermore, the actual rate of current rise, $\dot{I}(t)$, is lower than the theoretical one resulting in lower values of $P_b$. Circuit resistance and bridgefoil resistance will also lower the values of $P_b$.

The EFI system of Appendix A is considered here as an example. For the EFI configuration of this system, the following relationship between $P_b$ and $J_b$ was established (Ref. 3)

$$P_b = \left(7.664\times10^{-6}\right)J_b^{1.6199} \qquad [18]$$

where $P_b$ is expressed in MW and $J_b$ in GA/m$^2$. Substituting in Eq. 18 the expression for $J_b$ from Eq. 15 yields

$$P_b = \left(7.664\times10^{-6}\right)\left(\frac{3V_0G_b}{AL}\right)^{0.5399} \qquad [19]$$

The expected maximum power that can be delivered to the bridgefoil at burst as a function of the theoretical initial rate of current rise is plotted in Fig. 11. In the calculations, $G_b = 2.4\times10^{17}$ A$^2$-s/m$^4$ and is assumed constant. This last assumption is not exactly true because it was observed experimentally that specific action to burst is only approximately constant and varies with the rate of deposition of electrical energy into bridgefoil (Ref. 6). From the characteristics of the capacitor discharge circuit, a value of

83.3 A/ns is calculated for the theoretical initial rate of current rise which corresponds to an estimated upper bound on $P_b$ equal to 5.53 MW.

There is a limitation on the minimum rate of current rise due to physical considerations. The expected maximum $P_b$ decreases with a decrease in $V_0/L$. Therefore at some point the rate of energy delivery to the bridgefoil will be sufficient to burst it but insufficient to impart a high enough velocity to the flyer plate to detonate the acceptor explosive. From preliminary experiments performed on the system described in Appendix A, it was concluded that there is little probability that a detonation of the acceptor explosive would be observed at a theoretical initial rate of current lower than about 10 A/ns. This corresponds to an estimated lower bound on $P_b$ equal to 1.76 MW.

The estimated feasible region within which $P_b$ and $\dot{I}(t)$ may be set is illustrated in Fig. 11. This region defines the experimental domain of the statistical experiment. The numerical value for the bounds are relevant only for the particular EFI and instrumentation used in the experiment reported at Ref. 2. However, the method described here may be used for obtaining the corresponding limits for any other EFI under characterization. The method given has useful physical interpretations, is simple to implement, and appears to work well with minimum preliminary experiments.

### 3.3 Statistical Experiment

Data collection methods can be separated into static and dynamic ones. Static methods fix once and for all the levels of the electrical parameters where the trials are to be done as well as the number of trials at each level. Dynamic methods use rules that fix the level of the next trial based on the output (detonation or not) of the current trial.

Dynamic or sequential methods, like the Langlie and Bruceton methods (Ref. 7), essentially consists in decreasing the selected electrical parameter when there is a detonation and increasing it when there is no detonation. The above dynamic methods use a fixed or quasi-fixed parameter increment, but the tendency is to use a systematically decreasing step length, like in the many variants of the Robbin-Monro method described in Ref. 8, in order to obtain a faster convergence.

However a distinction can be made between contexts that allow precise levels of testing and those where the value of the independent parameters at each level is more or less random around the intended value. This type may occur if, for example, the probability of detonation is extremely sensitive to the level of one of the independent parameters and the latter cannot be controlled with accuracy. In this case, it is not possible to base the fitting on the empirical proportions of detonation observed at each level divided by the number of trials at each corresponding level. The statistical input is then rather a list of "parameter level values, detonation/no-detonation" pairs where the level values of the parameters may vary widely.

The context described in the previous paragraph applies to the EFI characterization problem addressed here. In that case it is suggested to conduct experiment at different levels of the electrical parameters around the suspected median (where the probability of detonation is about 0.5). The median can be estimated by performing a few preliminary trials. This is not a mandatory requirement, it is simply likely to minimize the number of trials.

Programs exist for studying the power of different experimental designs (number of cells and number of observations per cell) in the context of 1D go/no-go fitting. In the 2D context, the problem is much more complicated and can be solved efficiently only through Monte-Carlo simulation.

## 4.0 STATISTICAL ANALYSIS

The statistical modeling is based on a logit response model featuring two independent variables (see Eq. 3). The fitting method is the algorithm to be used to find the optimal values of the model parameters, $C_0$, $C_1$, and $C_2$ in Eq. 3, from the data gathered in the statistical experiment. There are at least three popular methods: Maximum Likelihood Estimation (MLE), Non-Linear regression (NLR), and Linear Regression (LR). A description of these methods can be found in Ref. 9.

The use of a commercial statistical software package is recommended in the present context. SYSTAT$^{TM}$ for example is a well interfaced and well documented microcomputer program that allows General Linear Models (MGLH) and non-linear fitting (NLFIT) for any number of independent variables (Ref. 10). Optimizing parameters can be found for any fitness measure (MLE, Sum of Squares, etc.) using the non-linear fit. Error estimates on the parameters are provided.

Although SYSTAT™ itself can be used in the go/no-go context, there exists a more efficient specialized SYSTAT™ module. The LOGIT module allows very general logistic fitting since any polynomial transformation is allowed prior to fitting. It is not required to test at predetermined levels which is an important feature in the present context. Multiple independent variables and the use of a non-binary but discrete dependent variable are allowed. This approach, based on a MLE fit, has been used for the work reported in Ref. 2

## 5.0 CRITICAL CURVES

It is important for safety and suitability for service reasons to know the levels of the electrical parameters corresponding to a specified probability to fire an EFI at a given confidence interval. These levels are obtained by solving the equation

$$\text{probability of detonation } P_1 = p \qquad [20]$$

for the specified value of $p$. For the model considered here, the levels of the electrical parameters are straight lines given by the equation

$$\ln\left(p/(1-p)\right) = C_0 + C_1\dot{I}(t) + C_2P_b \qquad [21]$$

When $\dot{I}(t)$ is held fixed, the width of the $\gamma$ percent asymptotic symmetric two-sided confidence interval for the value of the $p$-quantile of $P_b$ is given by

$$W = \frac{2\ln(1+\gamma/1-\gamma)}{C_2} \qquad [22]$$

assuming that $C_2$ is positive. Note that $W$ is independent of $p$ and that asymptotic in this context means “if a sufficiently large number of observations has been taken”.

In practice $\gamma$ is generally equal to 0.95. For reference, at a given value of $\dot{I}(t)$, one is 95% sure that the value of $P_b$ is between:

$$\left[\ln\left(p/(1-p)\right) - C_0 - C_1\dot{I}(t) - \log(39)\right]/C_2 \qquad [23]$$

and

$$\left[\ln\left(p/(1-p)\right) - C_0 - C_1\dot{I}(t) + \log(39)\right]/C_2 \qquad [24]$$

when the probability of detonation is equal to $p$.

In EFI electrical characterization, the levels of the electrical parameters of particular significance are those corresponding to a probability to fire equal to 0.01 and 0.99 at a 95% confidence interval. These levels are defined as the maximum no-fire stimuli (MNFS) and the minimum all-fire stimuli (MAFS) respectively. The levels of the electrical parameters corresponding to a probability to fire equal to $10^{-6}$ are also of great interest and are defined as the maximum acceptable safe stimuli (MASS). As mentioned above, the MNFS, MAFS and MASS are straight lines called critical curves. As an example, the critical curves for the particular EFI used in Ref. 2 are illustrated in Fig. 12. As additional information, the critical curve corresponding to a probability to fire equal to 0.50 is also plotted (M). The dotted lines, corresponding to legend names followed by minus/plus sign, represent the lower/upper 95% confidence bound for each critical curve.

## 6.0 CONCLUSION

A new approach that integrates both statistical theory and methodology to EFI operating principles has been proposed to characterize EFI electrical firing properties. This approach uses a statistical model to provide a useful description of performance for EFI systems based on two parameters related to their functioning properties. The resulting firing characteristics provide information that was not previously available and that is particularly relevant to the assessment of EFI system.

It is believed that this work is only an important first step toward new and rigorous methods of characterizing EFI performance. With the increasing use of EFIs, the increasingly complex electromagnetic environment and the nature of many EFI applications, this issue becomes very important. The consequences of an inadvertent firing or a failure to fire could be extremely costly. Optimum statistical procedures for characterizing EFIs will help to minimize the likelihood of such events.

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# APPENDIX A

## Parameters of the EFI System of Ref. 2

### Capacitor discharge circuit

| | |
|---|---|
| capacitance | 0.15 μF |
| charge voltage | 2.5 kV |
| inductance $L$ (average) | 29.9 nH ($\sigma = 1.5$) |
| resistance $R$ (average) | 192.5 mΩ ($\sigma = 6.6$) |
| peak current $I_{\max}$ (average) | 3951.0 A ($\sigma = 44.8$) |
| current rise rate $\dot{I}(t)$ (average) | 73.6 A/ns ($\sigma = 2.6$) |

### EFI configuration

#### Bridgefoil

| | |
|---|---|
| material | copper (density = 8.930 g/cm$^3$) |
| thickness | 0.0044 mm |
| width | 0.193 mm |
| length | 0.193 mm |
| shape | square with rounded corners |

#### Tamper

| | |
|---|---|
| material | Kapton (density = 1.414 g/cm$^3$) |
| thickness | 0.0508 mm |

#### Flyer plate

| | |
|---|---|
| material | Kapton |
| thickness | 0.0254 mm |
| diameter | 0.193 mm |

#### Barrel

| | |
|---|---|
| material | Kapton |
| length | 0.125 mm |
| diameter | infinite barrel type |

#### Explosive

| | |
|---|---|
| name | hexanitrostilbene (HNS) |
| density | 1.57 g/cm$^3$ |
| specific surface area | 11-14 m$^2$/g |

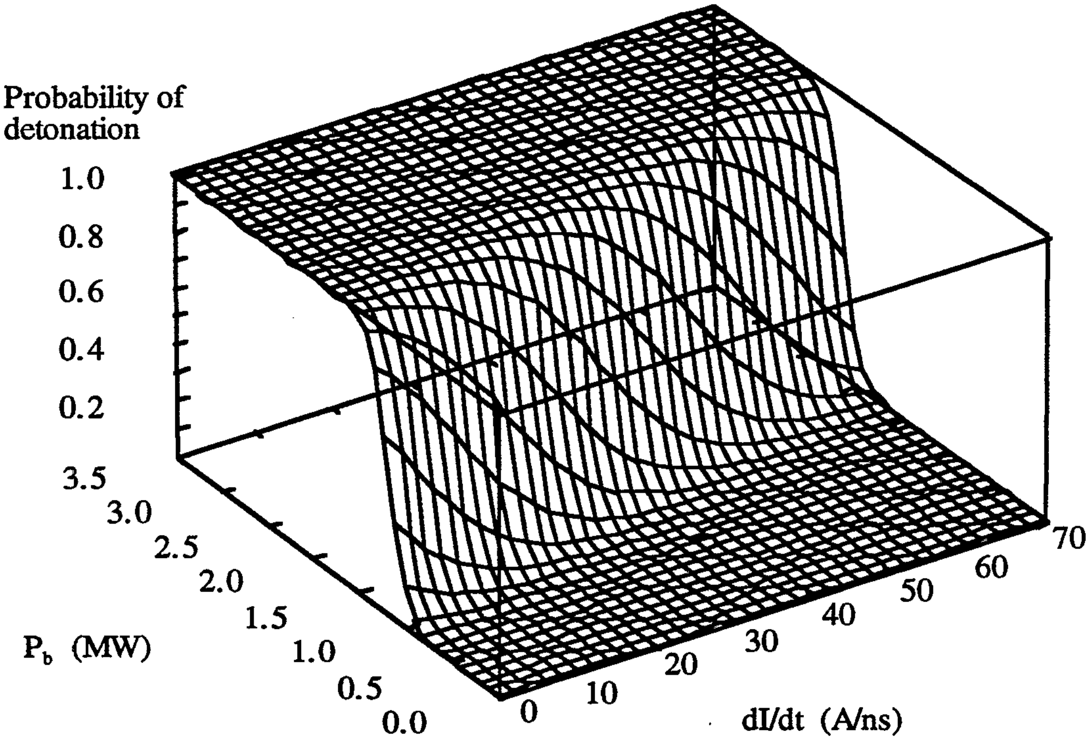

FIGURE 1 - Probability of detonation as a function of $P_b$ and $\dot{I}(t)$ of the EFI configuration of Appendix A

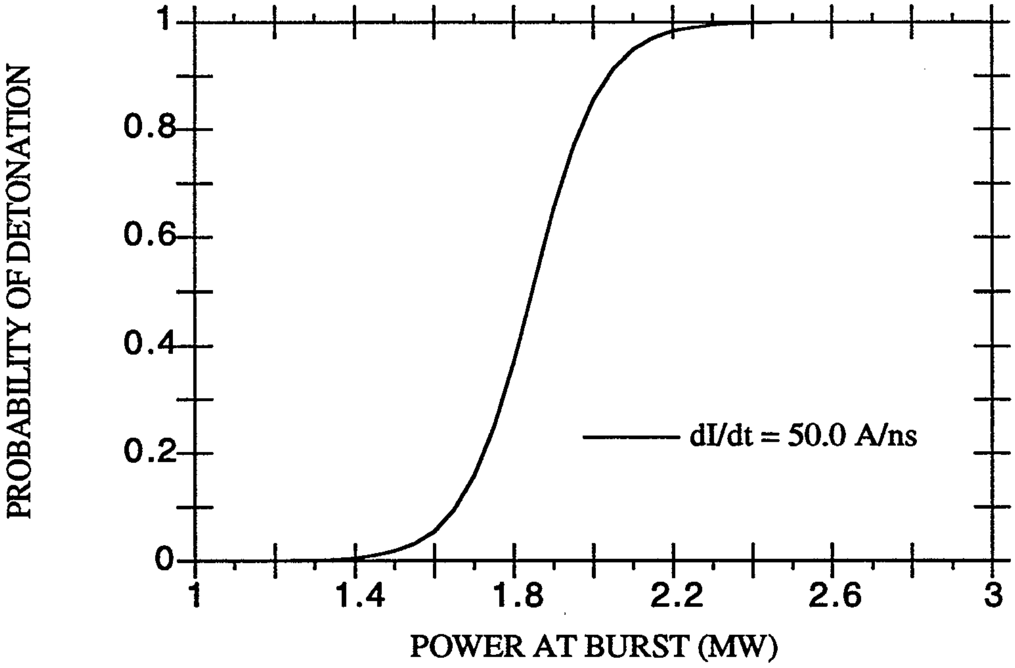

FIGURE 2 - Probability of detonation as a function of $P_b$ at a constant $\dot{I}(t)$ value of 50.0 A/ns

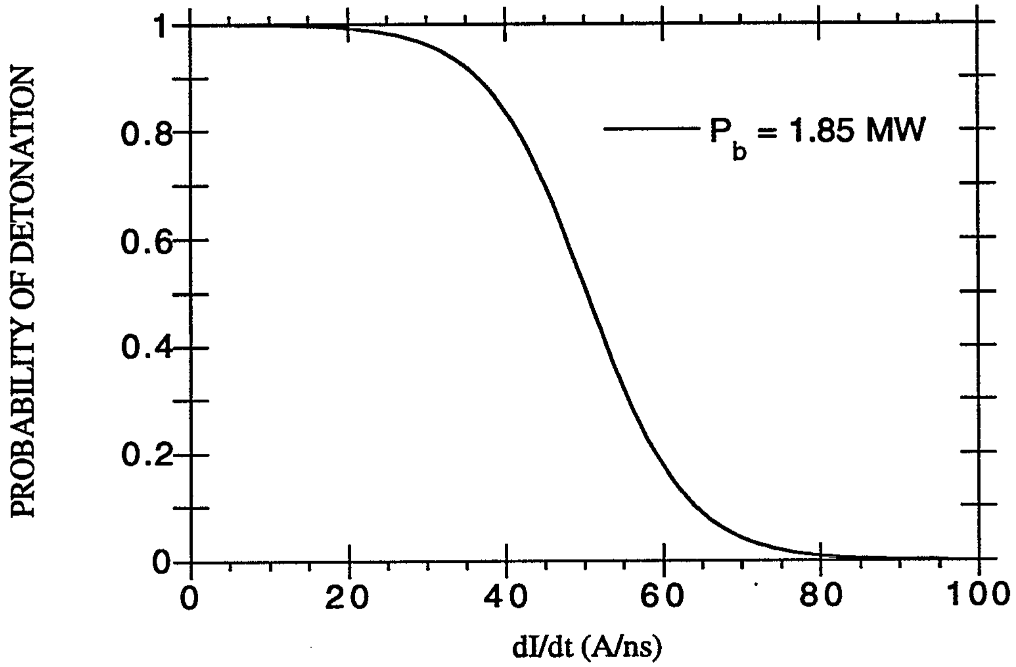

FIGURE 3 - Probability of detonation as a function of $\dot{I}(t)$ at a constant $P_b$ value of 1.85 MW

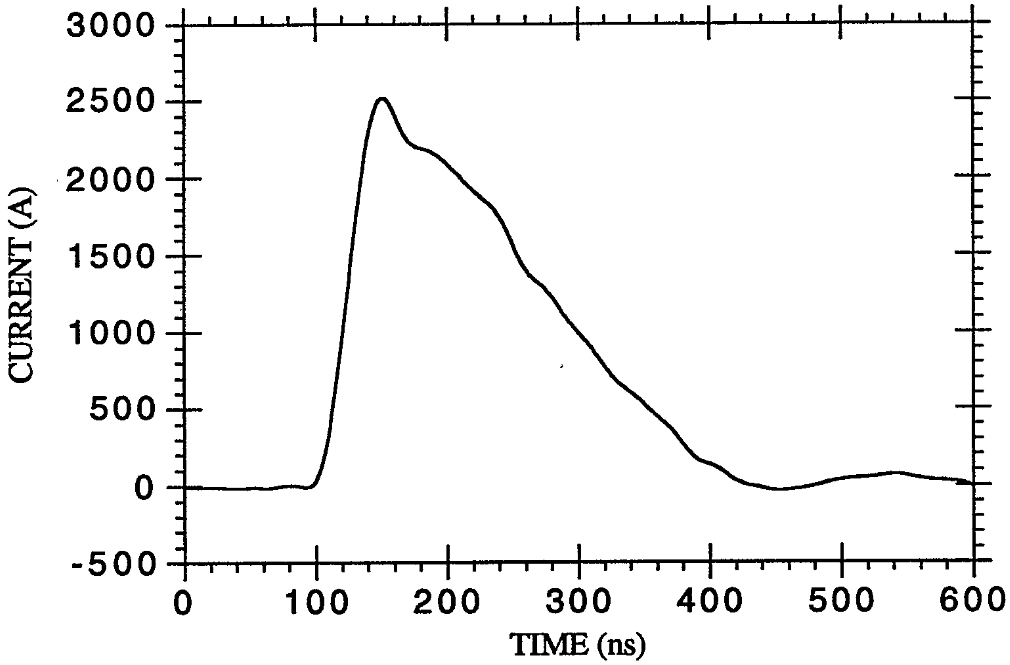

FIGURE 4 - Typical current waveform monitored via a CVR during a bridgefoil burst experiment on the EFI system of Appendix A

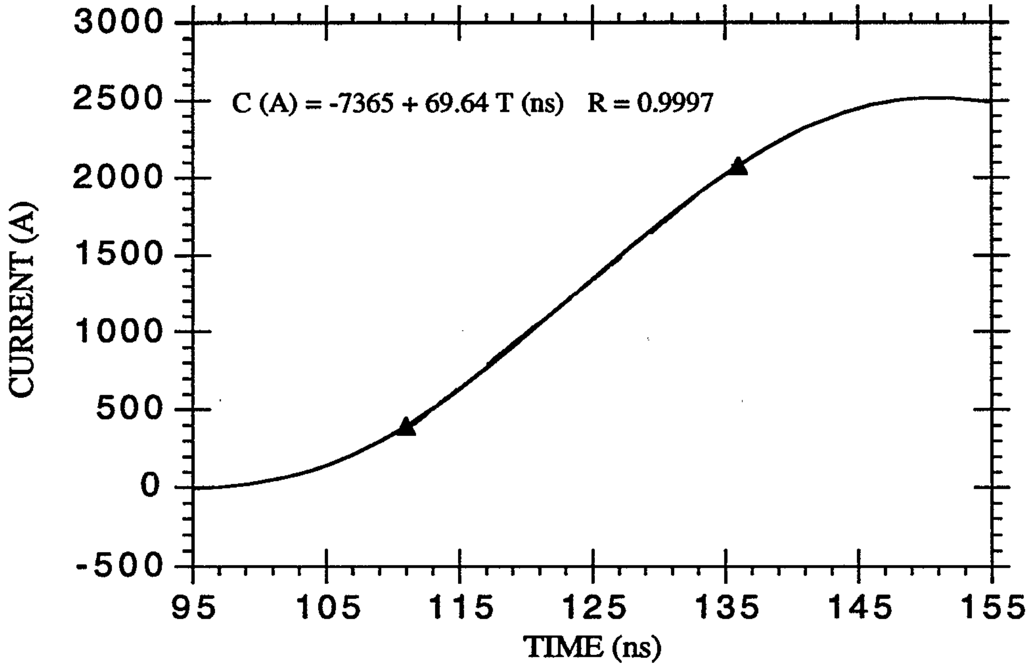

FIGURE 5 - Rate of current rise calculation performed on the current data of Fig. 4

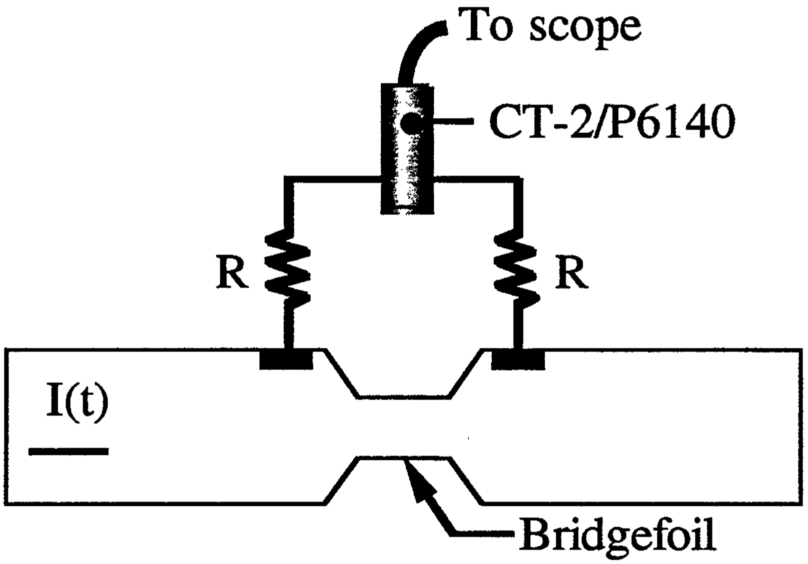

FIGURE 6 - Schematic of the two-pin differential voltage probe used to measure the voltage across the bridgefoil during bridgefoil burst experiment

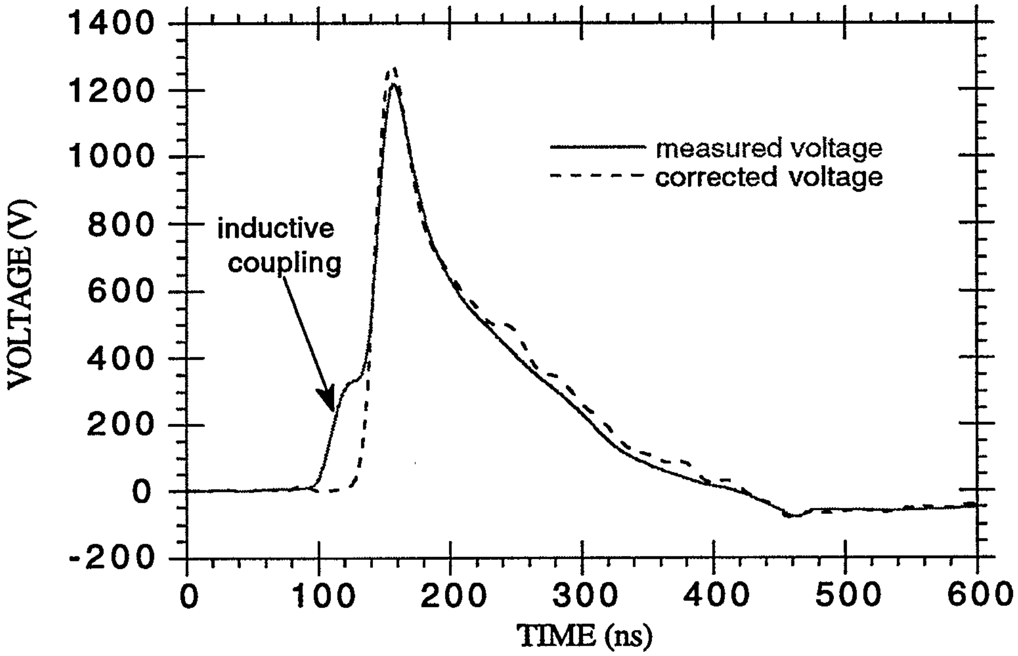

FIGURE 7 - Typical measured and corrected voltage waveforms. The measured voltage data were recorded simultaneously with the current data of Fig. 4

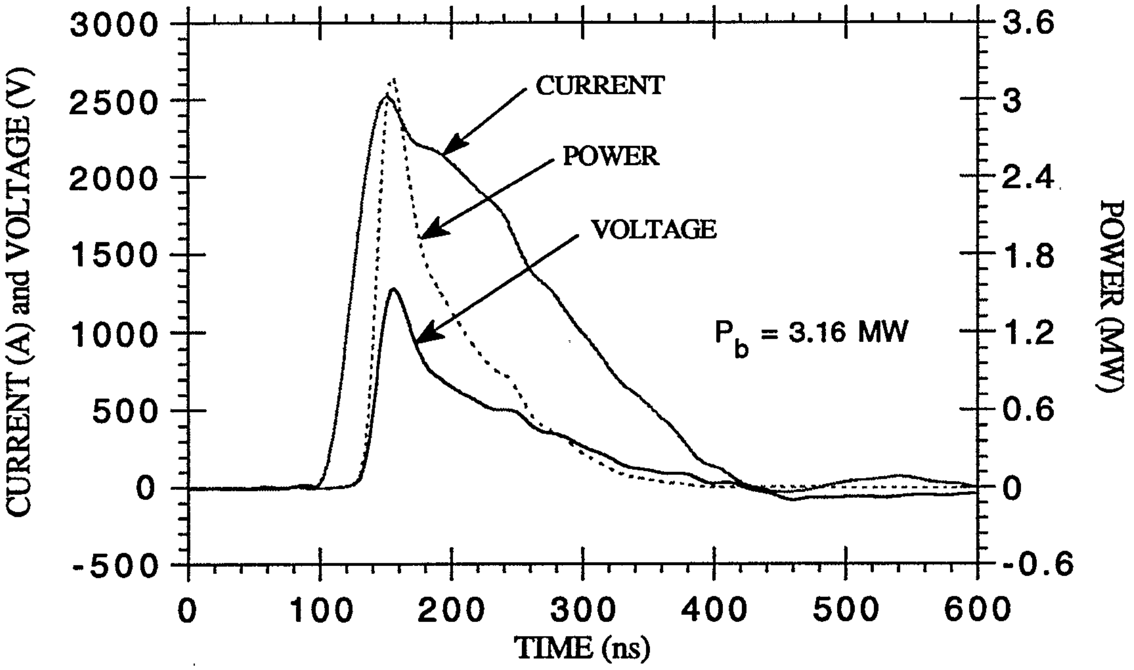

FIGURE 8 - Power delivered to bridgefoil as a function of time calculated from the current and corrected voltage data of Figs. 4 and 7 respectively

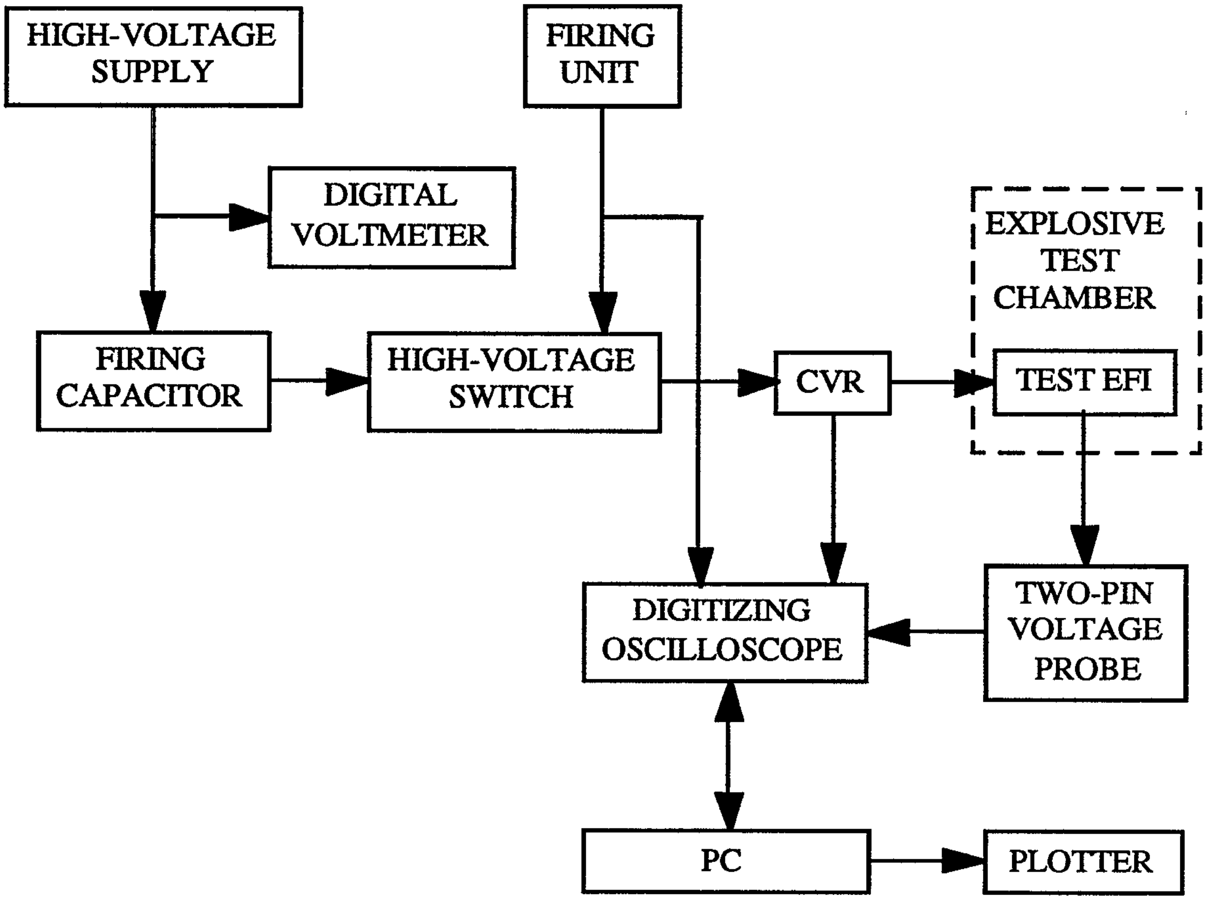

FIGURE 9 - Block diagram of suggested equipment setup

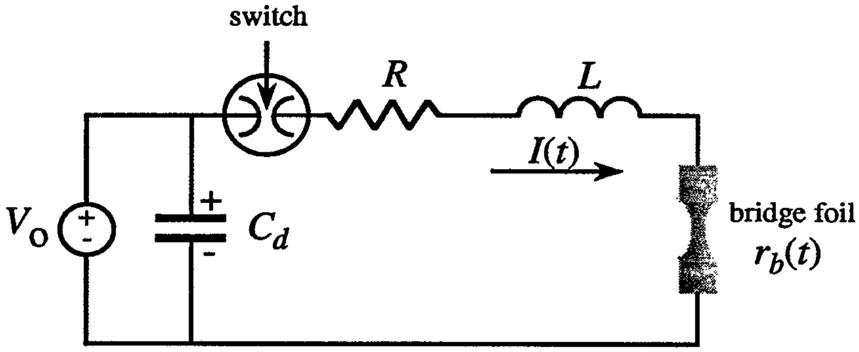

FIGURE 10 - Simple electrical equivalent circuit of EFI system

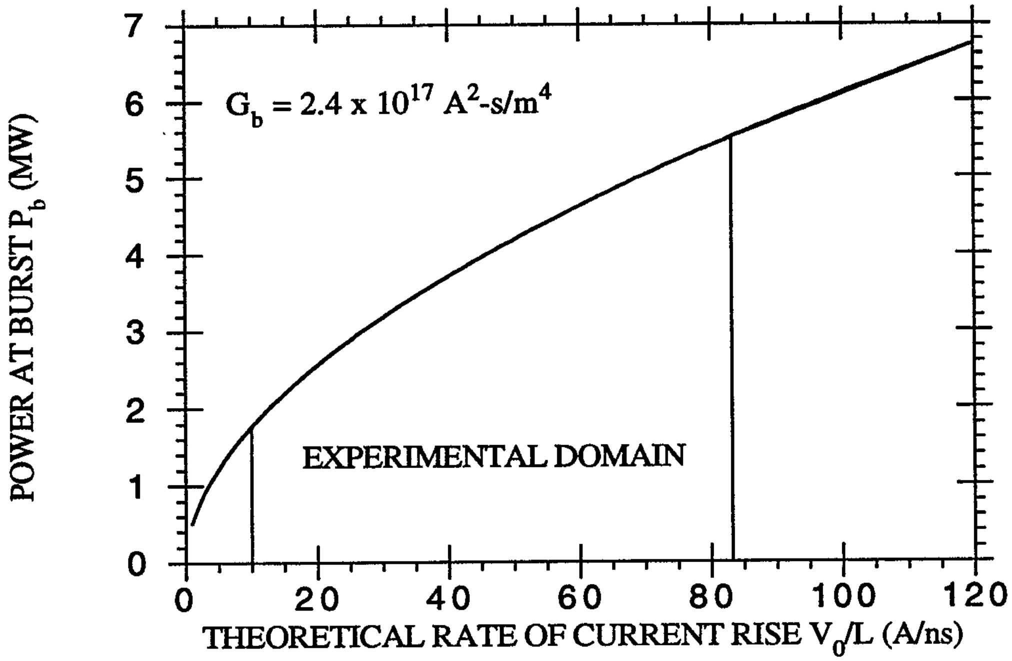

FIGURE 11 - Expected maximum burst power of the EFI configuration of Appendix A

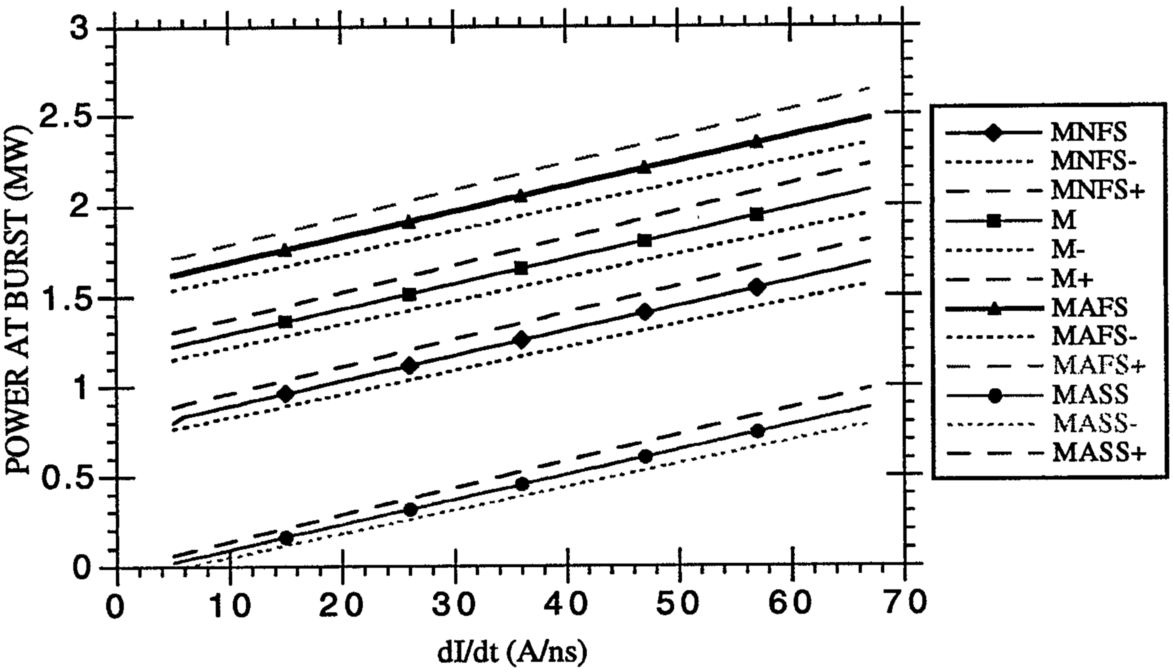

FIGURE 12 - Critical EFI electrical characteristics. The acronyms are defined in the text. In the above legend, the minus/plus sign is to be interpreted as the lower/upper bound associated with each critical curve

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2. SECURITY CLASSIFICATION
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3. TITLE (Its classification should be indicated by the appropriate abbreviation (S, C, R or U)
A New Approach to Electrical Characterization of Exploding Foil Initiators (U)

4. AUTHORS (Last name, first name, middle initial. If military, show rank, e.g. Doe, Maj. John E.)

Nappert, L., and Dr. Fortier, Claude

5. DATE OF PUBLICATION (month and year)

6a. NO. OF PAGES

6b. NO. OF REFERENCES
10

7. DESCRIPTIVE NOTES (the category of the document, e.g. technical report, technical note or memorandum. Give the inclusive dates when a specific reporting period is covered.)

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8. SPONSORING ACTIVITY (name and address)

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9a. PROJECT OR GRANT NO. (Please specify whether project or grant)

Thrust 3e Air Weapon Systems

9b. CONTRACT NO.

10a. ORIGINATOR'S DOCUMENT NUMBER

10b. OTHER DOCUMENT NOS
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In a previous study on electrical characterization of Exploding Foil Initiators (EFIs), a general statistical model was developed that expresses the probability of detonation of EFIs as a function of the power delivered to the bridgefoil at burst and the rate of current rise. This memorandum presents the statistical procedure applicable to EFI electrical characterization and describes the proper experimental methodology. Experimental results are given and processed to illustrate the methodology.

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