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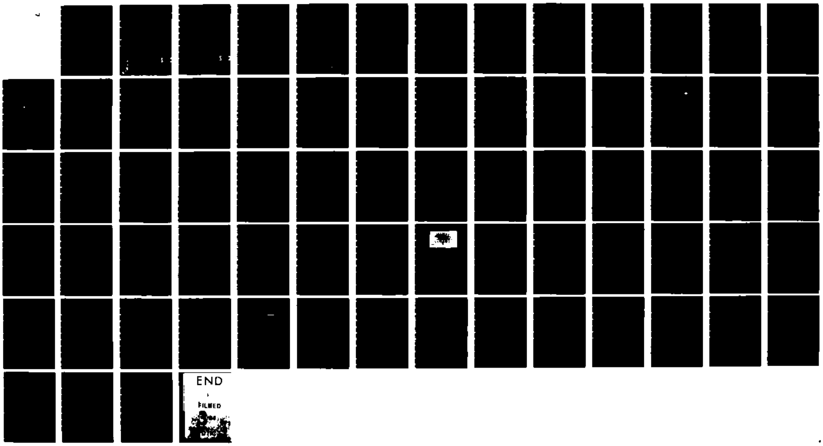

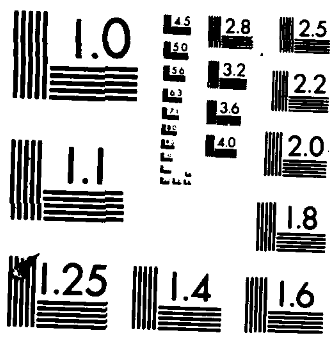

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SERIES DETONATOR INITIATION SYSTEM

THESIS

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THESIS

Presented to the Faculty of the School of Engineering

of the Air Force Institute of Technology

Air University

in Partial Fulfillment of the

Requirements for the Degree of

Master of Science

by

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Graduate Electro-Optics

December 1983

<u>Preface</u>

This thesis was proposed by the Air Force Weapons Lab and is to be used in their present studies of magnetic flux compression generators. They have developed a series modular detonator system and needed a detonator initiation system to fire it reliably and reproducibly. This detonator initiation system meets those needs. Although circumstances prevented this system from being extensively tested, the results that I obtained indicate that this detonator initiation system will meet the needs of the Air Force Weapons Lab.

I would like to thank the people working at the Advanced Concepts Branch of the Air Force Weapons Lab for their help during my stay there, especially the Maxwell employees for their insight and suggestions regarding the design and building of this initiation system.

Funding for this project was provided by the Air Force Weapons Laboratory and the Defense Nuclear Agency.

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Notation

I_b - burst current, current through firing circuit at time of bridgwire burst

I_{bth} - threshold burst current, burst current that will fire 1/2 the detonators in a given lot

T_b - time of burst, time between application of voltage across the bridgewire and when the bridgewire bursts

T - initiation circuit current period

V_o - initial firing set capacitor voltage

$\dot{I}$ - initial current rate of rise

G - action, integral of current squared from time equal zero to time of burst

E_w - energy required to vaporize the bridgewires

Te - firing temperature

N - number of detonators in the array

C - main firing set capacitance

L_d - detonator array/return conductor combination inductance

L_c - connector cable inductance

L - total initiation system inductance

R_w - total bridgewire resistance

R_{cw} - total cold bridgewire resistance

R_b - individual bridgewire resistance at time of burst

R_d - detonator array/return conductor combination resistance, excluding bridgewires

R_c - connector cable resistance

R_{fs} - firing set resistance

R - total initiation system resistance, excluding bridgewires

Abstract

The purpose of this thesis was to design, build, and test a high voltage detonator initiation system capable of firing a series modular detonator array. This initiation system was designed to optimally fire a detonator array of 25 detonators, but is capable of firing detonator arrays of different lengths.

The procedures used to develop this initiation system included four steps. First, the minimum burst current and the maximum current frequency required for successful detonator initiation were determined. Second, the equivalent circuits of the detonator array/return conductor combination and connector cable were derived. Third, the design of the initiation system was made. Fourth, the initiation system was built and tested.

The testing of the initiation system using array sizes of 3 and 25 detonator models was limited. These tests showed that the firing switch had an average delay time of 733 and 725 nsec respectively for the small and large arrays. The maximum firing switch jitter was 50 nsec, which was measurement limited, for both array sizes. The maximum jitter of the bridgewire bursts in the individual array elements was 20 and 40 nsec respectively for the small and large array.

I Introduction

This thesis deals with the problem of how to successfully initiate a series modular array of exploding bridgewire (EBW) detonators. In this chapter, the material necessary for the reader to understand this problem and the approach used to solve it will be presented. In particular, the background, the exact problem, the scope and assumptions, the review of pertinent literature, and how this problem was solved will be presented.

Background

The origin of this problem on how to successfully initiate a series of modular array of EBW detonators comes from present studies of magnetic flux compression generators. Explosively driven magnetic flux compression generators are very compact sources of large amounts of energy suitable for powering a number of advanced weapons concepts currently under consideration at the Air Force Weapons Lab (AFWL) and in other Department of Defense and Department of Energy laboratories. The peak power and peak current produced by a generator are functions of the rate of consumption of the explosive charge in it for a given size and geometry. Hence, a key element in the development of these generators is the successful simultaneous initiation of large areas of the explosive charge.

One style of generator described as a coaxial generator has the potential of being both particularly fast and capable of delivering very high output currents. In the past, such generators were operated by initiating a long cylindrical explosive charge, placed along the axis of the generator, at one of its ends. This caused the armature to expand in a conical shape that traveled down the length of the generator tube trapping the magnetic flux before it. However, it has been proposed that the explosive charge be initiated simultaneously along its entire axis. This would cause the armature to expand in cylindrical shape with its radius being relatively constant along the entire axis of the generator at any point in time.

At the Air Force Weapons Lab, a detonator system has been developed to perform this function. The detonator system, shown in Figure 1, consists of individual modular EBW detonators connected end to end to form a series array that can be placed along the axis of a cylindrical explosive charge. The number of modular elements used can be varied to match the length of the explosive charge. The detonator array is initiated by connecting a high voltage firing circuit across its ends.

Problem

The purpose of this thesis is to design, build, and test such a high voltage detonator initiation system.

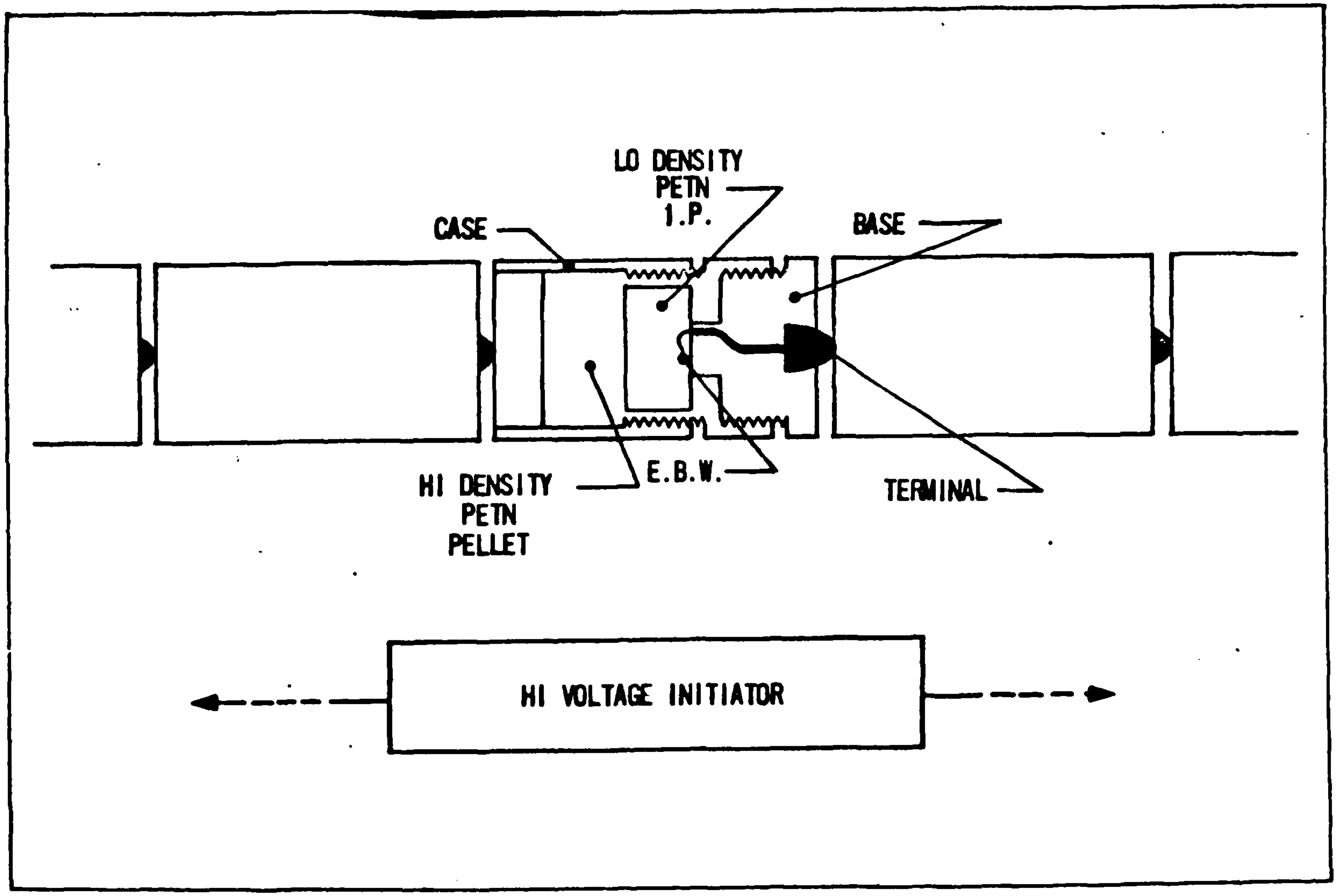

Fig 1. Modular EBW Detonator System

The detonator initiation system consists of a return conductor for the detonator array, a connector cable, and the actual firing set. The performance criteria used to judge it is its ability to fire the series modular array of detonators with low jitter, high reliability, and high reproducibility.

In designing this detonator initiation system, previously derived relationships (Ref 2,6,7,8,9,10,11,12) between the burst current and the detonator parameters; the burst current and the initiation system circuit parameters; and the time of burst and the initiation system circuit parameters were used or extrapolated as the case required. The burst current is defined as the current flowing through the bridgewires at the time of bridgewire burst. The time of burst is defined as the time between the application of voltage and when the bridgewires burst. These parameters and relationships will be covered in more detail in the subsection on the review of pertinent literature. The optimum combination of detonator array/return conductor, connector cable, and firing set components was chosen based on these relationships. The initiation system designed is an approximation of the actual initiation system, using several simplifications.

Scope

The detonator initiation system designed in this thesis was designed to optimumly fire 25 modular EBW detonators in the series detonator array. For a different number of modular elements, the initiation system characteristics (burst current, initial current rate of rise, initial firing set capacitor voltage, time of burst, system parameters) are different and need to be measured or calculated. The development of this thesis assumes the detonator initiation system will be used with the series modular detonator system developed at the AFWL. While the proposed use of this detonator initiation system is for operating coaxial magnetic flux compression generators, it can be used in any application where a cylindrically expanding shock wave is desired.

Assumptions

The approach used to design the detonator initiation system parallels the work previously done on EBW detonators. Most of the previous work dealt with initiating a single detonator at a time. It is assumed that this previous work is applicable to the series detonator array. Some simplifying assumptions were also made in the derivation of the equivalent circuit of the initiation system. First, the capacitance of the detonator array/return conductor combination was assumed to be negligible compared to the storage capacitance of the firing set. Second, the resistance of the modular detonators and the contact resistances in the detonator array were assumed to be negligible. Third, the inductance of the firing set was neglected. The effects of these assumptions on the performance of the initiation system were not noticeable.

Review of Pertinent Literature

EBW detonators operate by having the firing circuit current rapidly heat the bridgewire while inertia maintains the wire's shape. When the bridgewire finally starts to expand, it is superheated. The kinetic and thermal energy in the expanding bridgewire detonates the high explosive in the detonator. The current flowing in the firing circuit at the time of bridgewire burst is defined as the burst current (I_b) while the time of burst is defined as the time between the application of voltage across the bridgewires and when they burst. Previous work on EBW detonators has established a correlation between the detonator performance, the burst current, and the time of burst. These in turn have been related to the detonator parameters and firing circuit parameters. The following are the three main relationships used in the development of this thesis.

Threshold Burst Current - Detonator Parameters. The first major relationship that is used is between the threshold burst current and the detonator parameters. The threshold burst current (I_{bth}) is defined as that burst current that will cause one-half of the detonators in a given lot to detonate. Equation (1), derived by Tucker (Ref 12:211-232), shows this relationship for detonators with gold bridgewires and PETN explosive

$$I_{bth} = \frac{d}{\sqrt{\ell}} \left[850 + 35.5 \frac{(\ell d s_o^P \times 10^{-3} - 120)^2}{(\ell d s_o^P \times 10^{-3})^{3/2}} \right] \left[\frac{1}{(1.88-\delta)^3} \right] \times \left[1 - \frac{2 \times 10^{-2}(Te - 24)}{\sqrt{\ell}} \right] \quad (1)$$

where

I_{bth} - threshold burst current in Amps

d - bridgewire diameter in mils

l - bridgewire length in mils

s_o^P - explosive specific surface in cm^2/g

δ - explosive density in g/cm^3

Te - firing temperature in °C

The bridgewire length that is used in this equation is the individual detonator bridgewire length. Commercial EBW detonators have an all-fire burst current that is approximately 120 Amps larger than the threshold burst current (Ref 4:9-12). This convention was used in this thesis for calculating the required burst current needed to successfully detonate the detonator array.

Burst Current - Initiation System Circuit Parameters. The second major relationship that is used is between the burst current and the initiation system circuit parameters.

This relationship, derived from energy conservation by Cnare (Ref 2:188), is given by Eq. (2)

$$I_b = \left[\left(\frac{3GV_0}{L}\right)^{2/3} - \frac{2.25\ G^2}{C(3GL^{1/2}V_o)^{2/3}} - \frac{2RG}{L} - \frac{2E_w}{L}\right]^{1/2} \qquad (2)$$

where

I_b - burst current in Amps

V_o - initial firing set capacitor voltage in volts

C - total firing circuit capacitance in farads

L - total firing circuit inductance in henries

R - total firing circuit resistance, excluding bridgewires, in ohms

G - action integral in amp^2-sec

E_w - total energy needed to vaporize the bridgewires in joules

The values of G and E_w for gold bridgewires are determined by the equations

$$G = \left(.021\ \frac{A^2\text{-sec}}{(\text{cir-mil})^2}\right) A^2 \qquad (3)$$

and

$$E'_w = (8 \times 10^{-4}\ \text{J/cir-mil-mil})Al \qquad (4)$$

(Ref 2:190-191) where A is the cross-sectional area of the bridgewire in cir-mils and l is the length of the bridgewire in mils. Equation (4) gives the amount of energy dissipated in a single detonator bridgewire and hence must be multiplied by the number of detonators in the array before it is used in Eq. (2). Since the burst current is determined before the initial capacitor voltage, a more useful form of Eq. (2) is

$$V_0 = \frac{\left[(1/2LI_b^2+RG+E_w)+((1/2LI_b^2+RG+E_w)^2+2.25G^2L/C)^{1/2}\right]^{3/2}}{3GL^{1/2}} \quad (5)$$

which is the form used in this thesis. The initial current rate of rise also affects the performance of a detonator initiation system (Ref 6:284). Its value is normally approximated by V_o/L. A typical value for the initial current rate of rise is 1-2 KA/usec (Ref. 4:4).

Time of Burst - Initiation System Circuit Parameters. The last major relationship that is used is between the time of burst and the initiation system circuit parameters. Leopold (Ref 8:138) has related the time of bridgewire burst on the current waveform to different performance characteristics of detonators. For reliable and reproducible results, the bridgewires should burst during the first one-fourth period of the current waveform. The time of burst can be approximated from the burst current and the initial current rate of rise. The maximum firing circuit current frequency can then be found for this time of burst. This is done by setting the time of burst equal to 1/4 the current period.

The frequency and period of the firing circuit current can be found from

$$f = \frac{1}{T} = \frac{1}{2\pi} \left[\frac{1}{LC} - \frac{(R+R_{cw})^2}{4L^2} \right]^{1/2} \qquad (6)$$

where

C - total circuit capacitance

L - total circuit inductance

R - total circuit resistance, excluding bridgewires

R_{cw} - total cold bridgewire resistance

By varying the circuit parameters, the current frequency can be made less than the previously determined maximum current frequency.

Approach and Presentation

The approach used for this study and the order it will be presented in the rest of this thesis is:

(1) - the determination of the burst current and time of burst

(2) - the derivation of equivalent circuits for the detonator array/return conductor combination and connector cable

(3) - the design of the detonator initiation system

(4) - the construction and testing of the detonator initiation system

Burst Current and Time of Burst. In the first step, the detonator parameters of the modular EBW detonators were used to calculate a minimum burst current. This burst current in turn allowed the time of burst and the maximum firing circuit current frequency to be determined. These results are presented in Chapter 2.

Equivalent Circuits. In the second step, the equivalent circuits for the detonator array/return conductor combination and the connector cable were determined. This step was done for several return conductor configurations and several types of connector cables. The equivalent circuits consist of series connected inductances and resistances. These results are presented in Chapter 3.

Design of Firing Set. In the third step, the capacitance and initial capacitor voltage of the firing set were chosen to achieve the previously determined burst current and an acceptable firing circuit current frequency. In practice, the burst current was only closely approximated. The final design of the firing set has the capacitor connected in series with the firing switch. The firing set also includes a charge/dump switch and the necessary control circuitry. This design and the calculations leading to it are presented in Chapter 4.

Build and Test. The last step of this project involved the building and testing of the detonator initiation system. The testing consisted of two phases using dummy loads and detonator models. The dummy loads were shorting wires with the same resistance and inductance as the arrays of detonator models. The detonator models were the same shape as the actual detonators except that no explosives were used. The first testing phase used the dummy loads to test the delay and jitter of the firing switch. The second testing phase determined the average time of bridgewire burst for the detonator model array, and the jitter in the time of burst of the individual array elements. These results and the analysis of them is presented in Chapter 5.

From this data, conclusions about the effectiveness of the design procedure and the series detonator initiation system were drawn. These conclusions and recommendations for further research are presented in Chapter 6.

II Burst Current and Maximum Current Frequency

In designing the series detonator initiation system, the first step was to determine the minimum burst current and the maximum firing circuit current frequency required for successful detonation of the series detonator array. This step includes the following four parts. The calculation of the threshold burst current from the parameters of the modular detonator used in this project and Eq. (1). The determination of the minimum all-fire burst current using a commercial EBW detonator convention. The calculation of the time of burst from the initial current rate of rise and the minimum burst current. And the calculation of the maximum firing circuit current frequency from the time of burst.

Detonator Parameters

In order to calculate the threshold burst current, it is necessary to know the detonator parameters. The modular detonator, shown in Figure 2, for which this initiation system was designed has the following dimensions and parameters:

length	-	2.06 cm (.8125 in)
outer diameter	-	.56 cm (.2188 in)
inner case diameter	-	.42 cm (.1663 in)
bridgewire length	-	30 mil
bridgewire diameter	-	2 mil
bridgewire material	-	gold

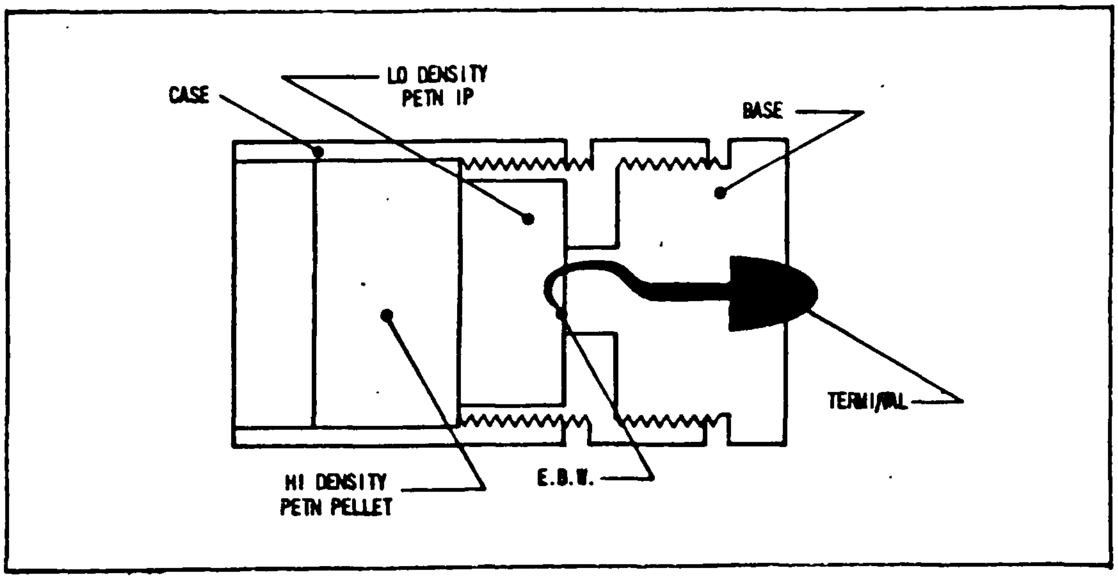

Fig 2. Modular EBW Detonator

The explosive density and specific surface of the initial pressing of PETN is not specified for this detonator. However, a typical value of the initial pressing density is .88 g/cm^3 (Ref 4:4-5) and a typical value of the explosive specific surface for detonators with these bridgewire parameters is 4000 cm^2/g (Ref 12:215-223).

Threshold Burst Current

To calculate the threshold burst current, the firing temperature is assumed to be 24°C since the threshold burst current will decrease for any higher temperature. Using this firing temperature, the given detonator parameters, and Eq. (1); the threshold burst current was calculated to be 361 Amp.

Minimum All-Fire Burst Current

Using the commercial EBW detonator convention that the all-fire burst current is 120 Amp larger than the threshold burst current (Ref 4:9-12), the minimum all-fire burst current for the modular detonator used in this thesis is 481 Amp. To account for possible variations in the explosive density and the explosive specific surface of the initial pressing of PETN in the detonator, a burst current of 750-850 Amp (nominal value of 800 Amp) was used in the design of the detonator initiation system. The range in the specified burst current accounts for the fact that readily available components were used in the initiation system and a specific predetermined burst current may not be achievable.

Time of Burst

The time of burst is approximated from the specified burst current and initial current rate of rise ($\dot{I}$). Table 1 gives the times of burst for a burst current of 800 Amp and initial current rates of rise between 1.1 - 1.8 KA/usec.

Maximum Firing Circuit Current Frequency

For this project, the operating region was chosen to be the first 1/4 period of the current waveform. The maximum firing circuit current frequency was calculated by setting

Table 1

Times of Burst for Different Initial Current Rates of Rise and Specified Burst Current

$\dot{I}$	time of burst
1.1 KA/usec	727 nsec
1.2 KA/usec	667 nsec
1.3 KA/usec	615 nsec
1.4 KA/usec	571 nsec
1.5 KA/usec	533 nsec
1.6 KA/usec	500 nsec
1.7 KA/usec	471 nsec
1.8 KA/usec	444 nsec

Table 2

Maximum Current Frequency for Different Initial Current Rates of Rise

$\dot{I}$	maximum current frequency
1.1 KA/usec	343.9 KHz
1.2 KA/usec	374.8 KHz
1.3 KA/usec	406.5 KHz
1.4 KA/usec	437.8 KHz
1.5 KA/usec	469.0 KHz
1.6 KA/usec	500.0 KHz
1.7 KA/usec	530.8 KHz
1.8 KA/usec	563.0 KHz

the time of burst equal to 1/4 the current period. Table 2 gives these maximum frequencies for initial current rates of rise between 1.1 - 1.8 KA/usec. The initiation system components were chosen to produce an initial current rate of rise and a current frequency less than the corresponding maximum frequency.

III Detonator Array/Return Conductor Combination and Connector Cable Equivalent Circuits

The second step in designing the series detonator initiation system was the derivation of the equivalent circuits for different detonator array/return conductor combinations and connector cables. The detonator array consists of 25 modular detonators with a total length of 51.5 cm. A return conductor provides the return path for the current back to connector cable. The connector cable is a 30.5 m (100 ft) section of coaxial cable that connects the firing set to the detonator array. Since the capacitances of the detonator array/return conductor combination and connector cable are neglected, the equivalent circuits consist of series connected inductances and resistances.

Detonator Array/Return Conductor Combination

The derivation of the equivalent circuit for the detonator array/return conductor combination involves three parts; the calculation of the required insulation between the detonator array and return conductor, the choice of type and placement of the return conductor, and the calculation of the inductances and resistances of the equivalent circuit for different detonator array/return conductor combinations.

Insulation Requirement. The amount of insulation required between the detonator array and return conductor is dependent on the maximum voltage that will be seen across it. This maximum voltage occurs between the case of the first detonator and the return conductor at the time of bridgewire burst. Since the connector cable inductance is an order of magnitude larger than the detonator array/return conductor combination inductance, this high voltage is generated primarily from the large negative dI/dt seen by the connector cable inductance at the time of burst. The maximum voltage is given by Eq. (7)

$$V_{max} \simeq R_b \, (N-1) \, I_b \tag{7}$$

where

- V_{max} - maximum voltage across insulation
- R_b - bridgewire resistance at time of burst
- I_b - burst current
- N - number of detonators in array

At the time of burst, the gold bridgewire is in the vapor phase and has a resistivity of approximately 10^{-3} ohm-cm. For the bridgewire used in the modular detonator, this corresponds to a bridgewire resistance at time of burst (R_b) of 3.76 ohm. The number of detonators in the array is 25, and for this calculation, a burst current of 1 KA, a value greater than the maximum of the design

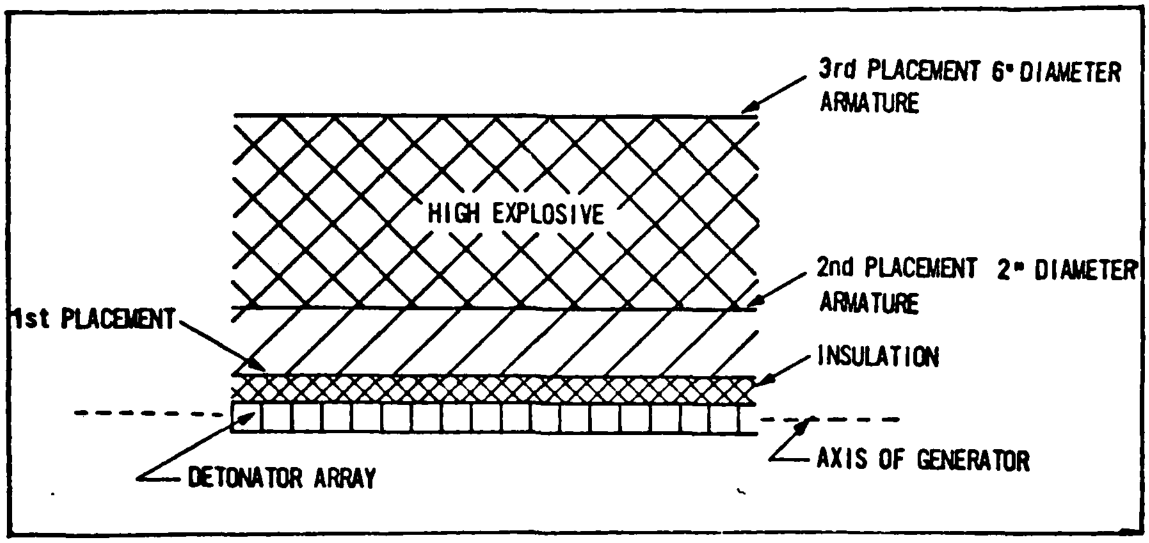

Fig 3. Three Placements of Return Conductor and Location of Detonator Array and Insulation

range, was used. Inserting these numbers into Eq. (7) gives a maximum voltage of 90 KV that will be impressed across the insulation.

For this project, the insulation that was used was acrylic tube with a breakdown strength greater than 2 KV/mil for pulsed operation. Therefore, the thickness of the insulation between the detonator array and the return conductor was greater than 45 mil.

<u>Type and Placement of Return Conductor</u>. In this thesis. only two different types of return conductors were considered. The first was gauge 24, 25, 26, or 27 copper wire. The second was a tube, 10 mil thick, made from Aluminum foil. These return conductors were chosen for their ability to handle the expected current flow and for their small cross-sectional area.

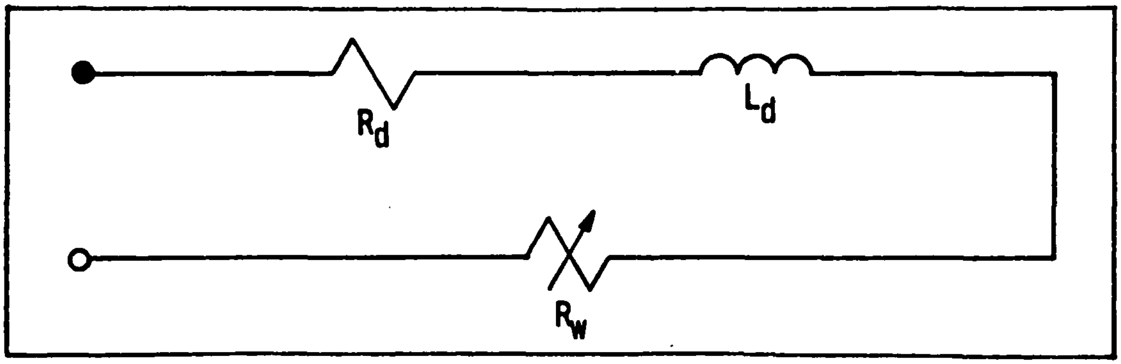

Fig 4. Equivalent Circuit of Detonator Array/Return Conductor Combination

Three different return conductor placements were considered for both types of return conductors. Figure 3 shows these three placements as well as the location of the detonator array and the insulation. The first placement is adjacent to the detonator array and insulation. The second and third are adjacent to the armature of the magnetic flux compression generator for diameters of 2 in. and 6 in.

Calculation of Resistances and Inductances. The equivalent circuit for the detonator array/return conductor combination used in this thesis is shown in Figure 4. It consists of a lumped total bridgewire resistance (R_w), the total array resistance (R_d), excluding bridgewires, and the total array inductance (L_d).

In calculating the values of these circuit elements, it was assumed the contact resistances and the resistance of the detonators, excluding bridgewires, was negligible. Hence, R_d is just the resistance of the return conductor.

Table 3

Inductances and Resistances of Detonator Array/Return Conductor Combination for Different Types and Placements of the Return Conductor

type of return conductor	placement of return conductor: first R_d (mΩ)	first L_d (uH)	second R_d (mΩ)	second L_d (uH)	third R_d (mΩ)	third L_d (uH)
24 gauge Cu wire	43	0.48	48	0.89	56	1.22
25 gauge Cu wire	55	0.49	60	0.90	71	1.23
26 gauge Cu wire	69	0.50	76	0.91	89	1.25
27 gauge Cu wire	87	0.51	96	0.93	113	1.26
10 mil thick Al tube	3	0.16	1	0.35	--	0.47

This resistance was calculated using standard wire tables for the copper wires (Ref 1:22) and $R=\rho l/A$ for the Aluminum foil tube. The array inductance was calculated using formulas given in Grover's book (Ref 5:31-47). A more thorough coverage of these inductance calculations and the simplifications that were made is given in Appendix A. Table 3 gives the calculated total detonator array/return conductor combination inductances and resistances, excluding bridgewires, for the different types and placements of the return conductors. The resistances are calculated to the nearest milli-ohm, and the inductances to the nearest 10nH. These values were used in the design of the initiation system.

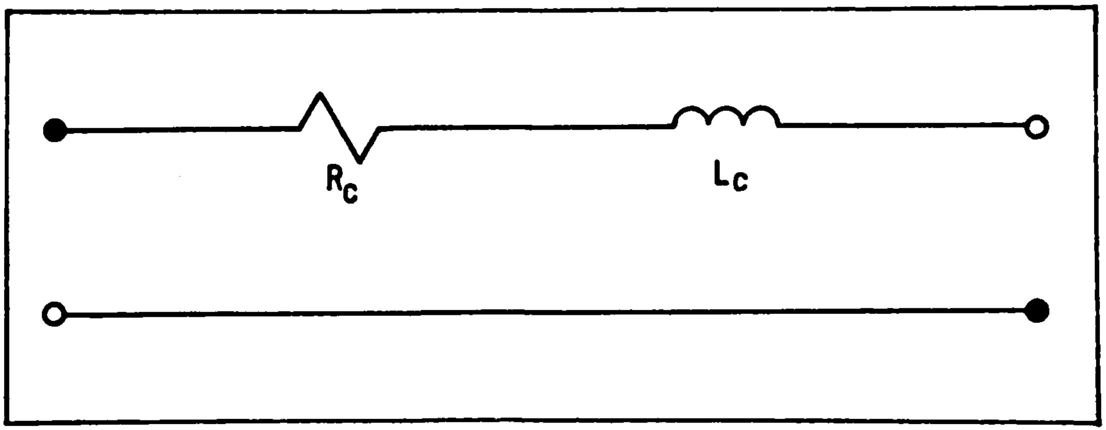

Fig 5. Equivalent Circuit of Connector Cable

The total bridgewire resistance (R_W) is variable during the operation of the detonator initiation system and will be treated as such in the equivalent circuit. The cold value of the total bridgewire resistance is 208 milli-ohm.

Connector Cable

After the equivalent circuits for the different detonator array/return conductor combinations were calculated, the equivalent circuits for the different connector cables were calculated. The equivalent circuit for the connector cable that was used in this project is shown in Figure 5. It consists of a total cable resistance (R_C) in series with the total cable inductance (L_C). The capacitances of the connector cables were calculated and found to be two orders of magnitude smaller than the firing set capacitance. Table 4 shows the cables that were selected, their

Table 4

Connector Cable Characteristics

cable (RG/U-)	Z_o (ohm)	$T_{1\text{-way}}$ (nsec)	R_c (mΩ)	L_c (uH)
34	71	153	481	10.84
35	71	153	322	10.84
73	25	314	1260	7.85
218	50	152	208	7.61

characteristic impedances, their one-way transit time, their resistance, and their inductance for a 100 ft long section.

The cables that were selected were coaxial cables chosen for their inductance values and/or availability at the AFWL. The inductances and resistances were calculated using the data given in the manufacturer's specification sheets (Ref 3:8-13) and equations applicable to coaxial cables given in most engineering handbooks. These values were also used in the design of the detonator initiation system.

IV Design of Firing Set

Having derived the equivalent circuits for the detonator array/return conductor combinations and connector cables, the last step in designing the series detonator initiation system was to design the actual firing set. This entailed choosing a firing set capacitance and its initial voltage such that the previously determined burst current and operating frequency were achieved. In particular, four procedures were required. The first procedure was to calculate the total inductance and resistance, excluding bridgewires, of the detonator initiation circuit. The second procedure was to compare the firing circuit current frequency with the previously specified maximum allowable frequencies. The first two procedures were repeated for all combinations of connector cables and return conductors at each of the three possible placements. The third procedure was to choose a combination of detonator array/return conductor, connector cable, and capacitor. The last procedure was to design the actual layout of the firing set.

Resistance and Inductance of Initiation System

In the first procedure, the total inductance and resistance, excluding bridgewires, of the detonator initiation circuit was calculated. These values were needed to calculate the firing circuit current frequency, the initial firing set capacitor voltage, and the initial current rate of rise. All of the resistance and inductance values necessary to calculate the total resistance (R), excluding bridgewires, and the total inductance (L) of the initiation system have been calculated except the resistance of the firing set (R_{fs}). This resistance includes a measured test resistance (33 mΩ), the parasitic resistance of the firing set leads, and the parasitic resistance of the closed firing switch (typically 20-30 mΩ). For simplicity, R_{fs} was assumed to be 100 mΩ.

Figure 6 shows the equivalent circuit of the detonator initiation system where:

- C - firing set capacitance
- R_{fs} - firing set resistance
- R_c - connector cable resistance
- R_d - detonator array/return conductor combination resistance, excluding bridgewires
- R_w - total bridgewire resistance
- R - total initiation system resistance, excluding bridgewires
- L_c - connector cable inductance
- L_d - detonator array/return conductor combination inductance
- L - total initiation system inductance

R and L were calculated for all combinations of connector cables and return conductors at each of the three possible

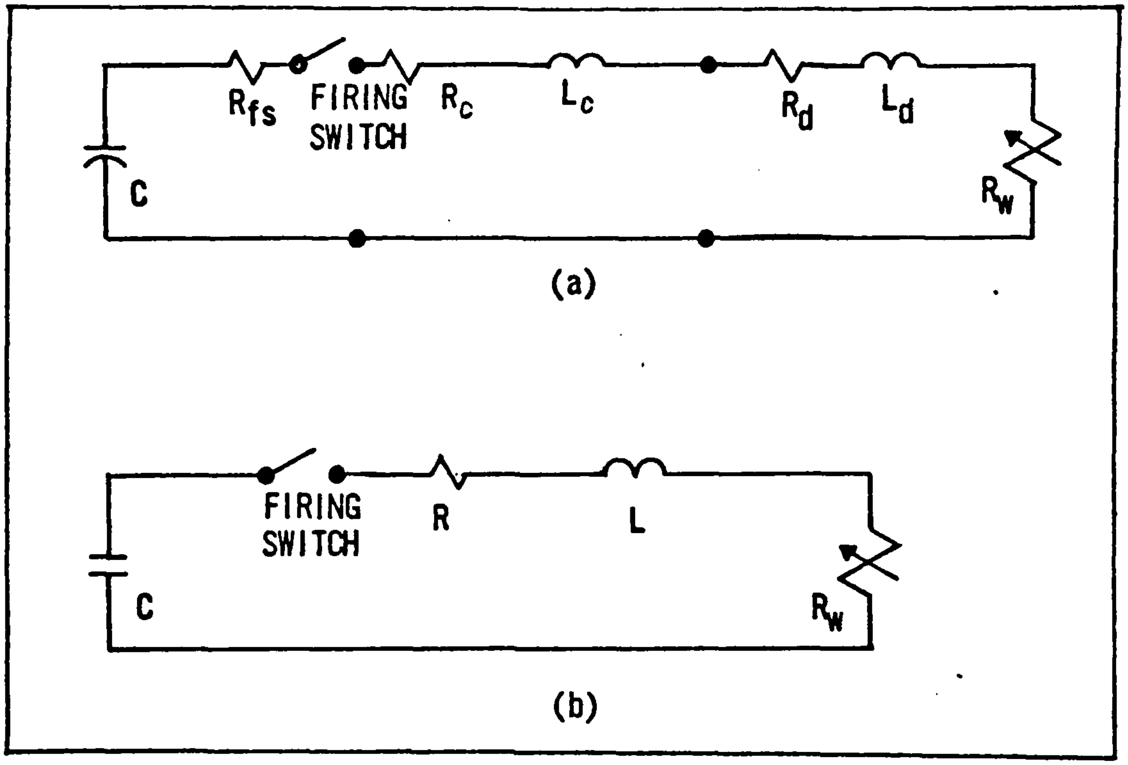

Fig 6. Equivalent Circuit of Detonator Initiation Circuit with: (a) Individual, and (b) Combined Elements

placements. These values in turn were used in the calculations of the firing circuit current frequency, the initial firing set capacitor voltage, and the initial current rate of rise. The tabulated values of R and L can be found in Appendix B.

Current Frequency vs Specified Maximum Frequency

The second procedure in the design of the firing set was to compare the firing circuit current frequency with the previously specified maximum frequencies. This included choosing a capacitance and calculating the corresponding current frequency, calculating the initial firing set capacitor voltage, calculating the initial current rate of rise, and comparing the current frequency with the specified maximum frequency for the calculated initial current rate of rise.

Capacitance and Current Frequency. The current in the firing circuit is a damped sinusoid with a frequency determined by Eq. (6). For an increase in the circuit capacitance, inductance, or resistance; the current frequency decreases. Therefore, a capacitance of .1-.5 uF is necessary to achieve the operating frequency regions given in Table 2. Because of their availability at the AFWL, capacitances of .25 uF and .5 uF were used in these calculations. The current frequency was calculated for every combination of capacitor, connector cable, and return conductor at the three possible placements.

Initial Firing Set Capacitor Voltage. The initial firing set capaciator voltage (V_o) is related to the initiation system circuit parameters and the burst current by Eq. (5). The values of G and E_w in Eq. (5) are .336 A^2-sec and 2.4 J respectively for the detonator array studied in this thesis. Using a burst current of 800 Amp, values of V_o were calculated for every combination of capacitor, connector cable, and return conductor at the three possible placements.

Initial Current Rate of Rise. Since the detonator initiation system circuit is an underdamped RLC circuit, the initial current rate of rise ($\dot{I}$) is approximately

V_o/L (Ref 6:284). Like the current frequency and V_o, $\dot{I}$ was calculated for every combination of capacitor, connector cable and return conductor at the three possible placements. Tabulated values of current frequency, V_o, and $\dot{I}$ are shown in Appendix B.

Comparison of Current Frequency to Specified Maximum Frequency. Having calculated the current frequency and $\dot{I}$ for the various combinations of capacitor, connector cable, and return conductor; these values were compared with the specified maximum frequencies and associated $\dot{I}$ values given in Table 2. It was found that all combinations had a current frequency less than the specified maximum frequency. The effects of individual components on the matching of the current frequencies and specified operating regions was varied. The .25 uF capacitor in the combinations always produced a current frequency closer to the center of the operating frequency region than did the .5 uF capacitor. For the .25 uF capacitor and a given connector cable, the different return conductors showed negligible difference in the current frequency. Using the .25 uF capacitor, the RG/U- 35, 34, 218, and 73 connector cables ranked best to worst in producing a current frequency closest to the center of the operating frequency region.

Combination Choice

The third procedure in the design of the firing set was to choose a combination of capacitor, connector cable, and return conductor at one placement. The .25 uF capacitor was chosen because it more closely matched the current frequency to the center of the operating region. The RG/U-218 connector cable was chosen for its availability at the AFWL. The Aluminum foil tube at the first placement was chosen for the return conductor. It was used because it structurally supported the detonator array during the testing of the initiation system and because of its symmetrical effect on a shock wave produced by the detonator array. Thus the series detonator initiation system has the following calculated circuit characteristics:

C - .25 uF

R_{CW} - 208 mΩ

R - 311 mΩ

L - 7.77 uH

V_o - 12.5 KV

I_b - 800 Amps

$\dot{I}$ - 1.61 KA/usec

current frequency - 114.1 KHz

Firing Set Design

The last procedure in the design of the firing set is the actual layout of the firing set circuit. This circuit consists of the .25 uF capacitor connected through a firing switch to the connector cable. This circuit also has a firing switch control circuit, a charge/dump circuit, system status lights, and a current viewing resistance.

Figure 7 shows the complete circuit of the firing set where the connections and the values of the components are:

HV1 - high voltage input (variable)

HV2 - 2 KV input

LV - 115 VAC input

GND - ground

FSO - firing set output

TI - trigger input

CM - current monitoring output

R1 - 15.4 MΩ (charging resistor)

R2 - 6.2 KΩ

R3 - 6.2 KΩ

R4 - 100 KΩ (dump resistor)

R5 - 470 KΩ

R6 - 1.2 KΩ

R7 - 4.4 MΩ

R8 - 33 mΩ (current viewing resistor)

C1 - .25 uF (main capacitor)

C2 - .25 uF

C3 - .01 uF

SW1 - toggle switch

SW2 - high voltage double pole single throw switch

SW3 - KN-6 Krytron (mfg by EG&G)

SW4 - GL-7703 ignitron (mfg by GE)

L1 - dumped status light

L2 - charging status light

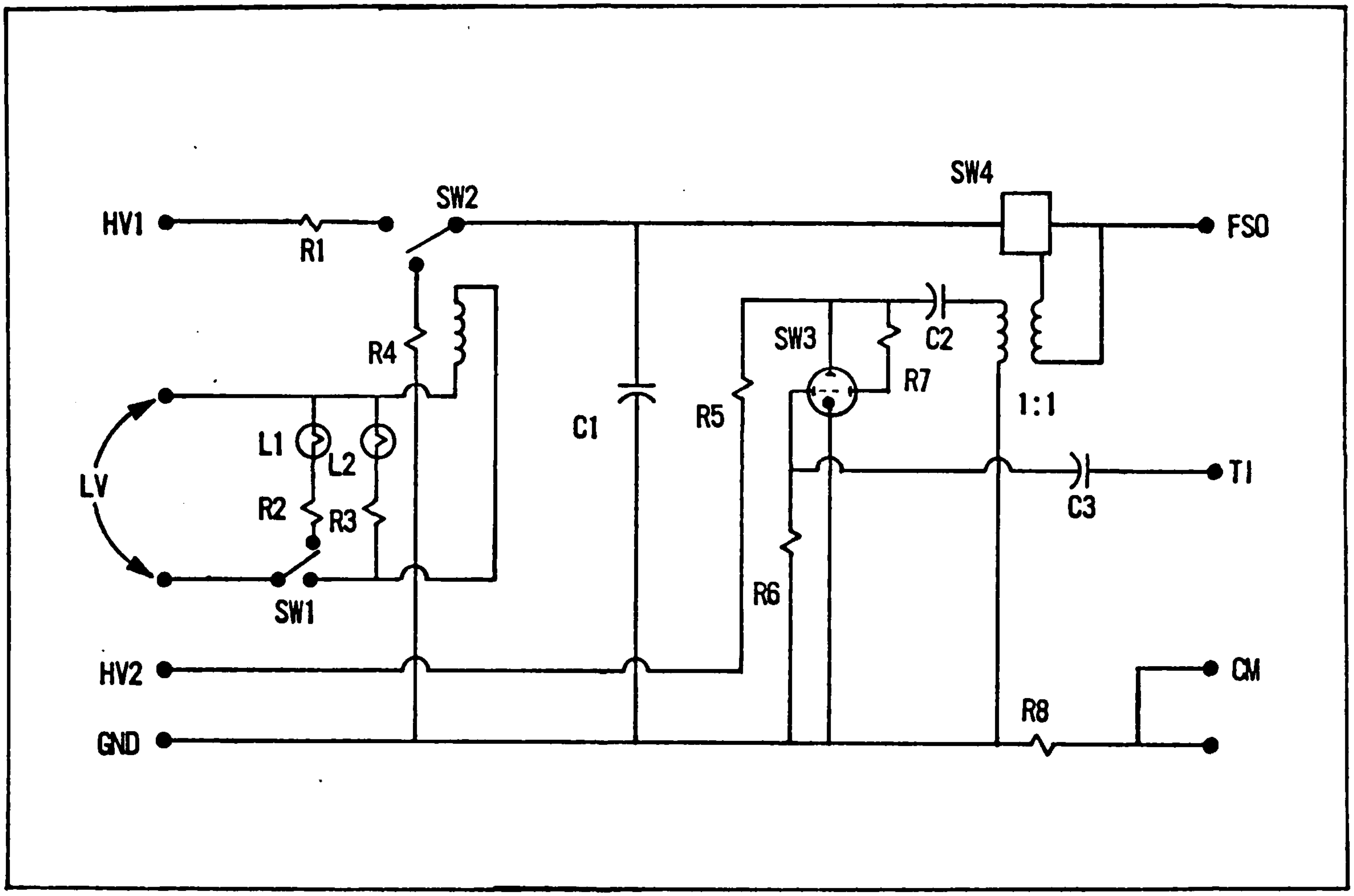

Fig 7. Firing Set Circuit

Firing Switch and Control Circuitry. The firing switch used in the firing set is a model GL-7703 ignitron (made by General Electric) that was fired by an external trigger source. This switch was used because it is readily available at the AFWL and its control circuit, built at the AFWL, already worked well with the external triggering sources used at the AFWL. The ignitron's control circuit was used unchanged in the firing set.

Charge/Dump Circuit. The charge/dump circuit consisted of a charging resistor, a dump resistor, and a high voltage single pole double throw switch connected to the main capacitor. The value of the charging resistor prevented the maximum current carried by the power supply from exceeding its rated value. The high voltage switch was built at the AFWL and was operated by a 115 VAC coil. This coil was controlled by a standard toggle switch.

System Status Lights. The system status lights were placed in the charge/dump control circuit of the firing set circuit. They indicate whether the firing set is in the dump or charging mode.

Test Resistor. The test resistor is a short length of Nickel-Chromium wire whose resistance of 33 mΩ was measured to the nearest milli-ohm. It allows the current flowing in the initiation system to be monitored directly.

V Testing of Detonator Initiation System

The next step in this thesis was to test the design of the detonator initiation system. This included building the initiation system, testing the delay and jitter of the initiation system, and analyzing the test results.

Due to uncontrollable circumstances at the AFWL, only 56 detonator models (detonators without explosives) were available for testing the initiation system. For this reason, dummy loads (shorting wires with the same resistances and inductances as the detonator model array/return conductor combinations) were used for the first part of the testing. In addition, the detonator models have the following dimensions which are different than the detonator's dimensions:

length - 4.12 cm

outer diameter - 1.12 cm

inner case diameter - .84 cm

Taking these different dimensions into account, the detonator initiation system has the following calculated circuit characteristics:

C - .25 uF

R_{CW} - 208 mΩ

R - 311 mΩ

L - 7.96 uH

V_o - 12.6 KV

I_b - 800 Amps

$\dot{I}$ - 1.58 KA/usec

current frequency - 112.7 KHz

Since the detonator models were used at a rate of 25 per shot, the 6 remaining detonator models were used at 3 per shot to adjust the timing of the streak camera used in the second part of the testing. When using the short array of detonator models, the initial current rate of rise was held the same as for the large array of detonator models by varying V_o. Therefore, the detonator initiation system with the short array of detonator models has the following calculated circuit characteristics:

C - .25 uF

R_{cw} - 25 mΩ

R - 308 mΩ

L - 7.65 uH

V_o - 12.1 KV

I_b - 1080 Amps

$\dot{I}$ - 1.58 KA/usec

current frequency - 115.0 KHz

Building of Initiation System

The construction of the detonator initiation system was fairly straight forward. The firing set box was built of plexiglass with the components placed to prevent corona

Table 5

Comparison of Dummy Loads to
Equivalent Detonator Model Arrays

load	resistance	inductance
small array dummy load	--	0.03 uH
small array	--	0.04 uH
large array dummy load	3 mΩ	0.38 uH
large array	3 mΩ	0.35 uH

and arc discharges. The charge/dump switch was the only component in the firing set that had to be built. The connector cable length was not measured exactly but was paced off due to the difficulty in handling it. The detonator array/return conductor combination was built by wrapping Aluminum foil around a 63 mil thick acrylic insulating tube. Viewing slots were cut in the cases of the detonator models and the return conductor tube. Two dummy loads were also built for the first part of the testing. Table 5 shows their resistances and inductances along with the calculated resistances and inductances of the two detonator model array/return conductor combinations that they replaced.

Testing of Initiation System

The testing of the detonator initiation system consisted of two phases. The first phase used the dummy loads to test the delay and jitter of the firing switch.

The second phase used the bridgewire bursts in the detonator models to test the delay and jitter in the firing of the individual array elements.

Test Set-Up. For testing, the current monitoring terminal of the firing set was connected to an oscilloscope and the viewing slots of the detonator model array/return conductor combination were aligned with a streak camera. A trigger generator simultaneously triggered the firing set and oscilloscope and triggered the streak camera after a preset delay time. For the first testing phase, the streak camera was disconnected.

The only parameter in the firing set that can be varied is V_o. This voltage was set, using a voltage meter on the power supply that was accurate to the nearest 100 V, to one of the two previously calculated values depending on what array size was being used.

The time measurements were made to the nearest 50 nsec for the first testing phase and to the nearest 10 nsec for the second testing phase.

First Testing Phase Results. The delay and jitter of the firing switch was obtained from photographs of the current traces. Six current traces were made with each dummy load. Figure 8 shows one of the current traces using the large array dummy load. This trace, which is typical of all the current traces that were obtained,

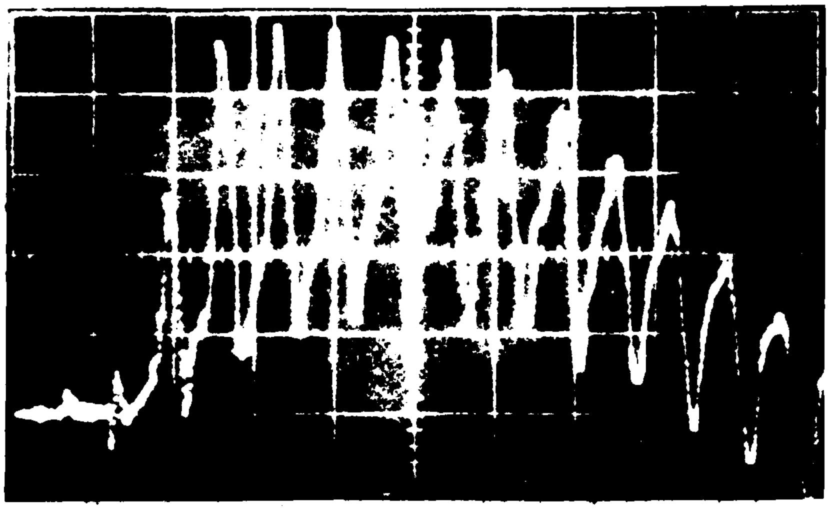

Fig 8. Initiation System Current Trace with Large Array Dummy Load

shows the delay of the firing switch and the main current oscillation with ringing from the connector cable superimposed on it. Besides the firing switch delay time, the initial current rate of rise and the main current period (T) can be determined. Table 6 gives the firing switch delay time and the initial current rate of rise for each current trace made with the two dummy loads. The first testing phase results are summarized in Table 7 which gives the average firing switch delay time, the maximum firing switch jitter, the average initial current rate of rise, the main current period, and the initiation system inductance for each dummy load array size. The system inductance was calculated from $V_o/\dot{I}$.

Table 6

Firing Switch Delay Times and Initial Current Rates of Rise

number	delay time	$\dot{I}$	number	delay time	$\dot{I}$
(small array dummy load)			(large array dummy load)		
1	750 nsec	1.8 KA/us	1	700 nsec	1.7 KA/us
2	700 nsec	1.8 KA/us	2	700 nsec	1.8 KA/us
3	700 nsec	1.8 KA/us	3	750 nsec	1.8 KA/us
4	750 nsec	1.9 KA/us	4	750 nsec	1.8 KA/us
5	750 nsec	1.7 KA/us	5	750 nsec	1.9 KA/us
6	750 nsec	1.9 KA/us	6	700 nsec	1.8 KA/us

Table 7

Summarized First Testing Phase Results

	small dummy load	large dummy load
average firing switch delay time	733 nsec	725 nsec
maximum firing switch jitter	50 nsec	50 nsec
average $\dot{I}$	1.82 KA/usec	1.80 KA/usec
T	8.1 usec	8.3 usec
L	6.65 uH	7.00 uH

<u>Second Testing Phase Results</u>. The delay and jitter in the firing of the individual array elements was obtained from streak photographs of the bridgewire bursts. While the streak photographs for both short array firings turned out, the streak camera malfunctioned on the second large array firing. Table 8 gives the delay times of the indivi-

Table 8

Bridgewire Burst Delay Times for Individual Array Elements

number	delay time	number	delay time
(small array, shot 1)		(small array, shot 2)	
1	1.34 usec	1	1.34 usec
2	1.36 usec	2	1.35 usec
3	1.35 usec	3	1.34 usec
(large array, shot 1)			
1	1.33 usec	14	1.30 usec
2	1.33 usec	15	1.31 usec
3	1.32 usec	16	1.31 usec
4	1.31 usec	17	1.32 usec
5	1.31 usec	18	1.32 usec
6	1.31 usec	19	1.32 usec
7	1.30 usec	20	1.32 usec
8	1.30 usec	21	1.32 usec
9	1.30 usec	22	1.32 usec
10	1.30 usec	23	1.33 usec
11	1.30 usec	24	1.33 usec
12	1.30 use	25	1.34 usec
13	1.30 usec		

dual bridgewire bursts in the three arrays for which the streak photograph turned out. The second testing phase results are summarized in Table 9 which gives the average bridgewire burst delay time, the average time of burst

Table 9

Summarized Second Testing Phase Results

	small array	large array
average delay time to bridgewire burst	1.347 usec	1.314 usec
times of burst (T_b)	614 nsec	589 nsec
maximum jitter in bridgewire burst	20 nsec	40 nsec

(bridgewire burst delay time minus firing switch delay time), and the maximum jitter in the firing of the individual array elements for the two array sizes.

Analysis of Test Results

The analysis of the test results concentrates on two areas. First, the acceptability of the observed jitters in the firing switch and the bridgewire bursts in the individual array elements were considered. Second, the predicted characteristics of the detonator initiation system were compared with the actual characteristics.

To analyze the first area, a quantitative standard was needed. For the intended use of this system at the AFWL, a jitter of less than 100 nsec was desired for both the firing switch and the bridgewire bursts in the individual array elements. These jitters were met with a good margin for both array sizes.

To analyze the second area, the calculated times of burst (T_b) were compared with the measured times of burst given in Table 9. The burst current was calculated first using Eq. (2). The values of V_o, C, G, and E_w were the same as specified or calculated earlier. The values of L were taken from Table 7. A range of 0-308 mΩ for the small array and a range of 0-311 mΩ for the large array were used as the values for R, which was less than the calculated values. Plugging these values into Eq. (2) gave calculated burst currents of 1135-1148 Amp for the short array and 828-846 Amp for the long array. Using the initial current rates of rise from Table 7 and $T_b \simeq I_b/\dot{I}$, the calculated times of burst are 624-631 nsec for the short array and 460-470 nsec for the long array.

The calculated T_b for the short array matched the measured T_b within the accuracy of the time measurements. This was not the case for the large array where the measured T_b was more than 125 percent of the calculated T_b. The discrepancy in the predicted T_b for the large array stems from the dependence of the burst current on G, W_w, V_o, L, C, and R as stated by Cnare in Eq. (2). However, the test results indicate that the burst current is only dependent on G and E_w.

VI Conclusions and Recommendations

The purpose of this thesis was to design, build, and test a detonator initiation system capable of detonating a series array of 25 modular detonators. The performance criteria used to judge the detonator initiation system were its ability to fire the series modular array of detonators with low jitter, high reliability, and high reproducibility. This chapter reviews the steps taken in the design of the initiation system and the results of the tests run on it. This chapter also gives some recommendations for improvements and for future studies.

Design Steps

In designing this detonator initiation system, previous works on the relationships between the burst current and the detonator parameters; the burst current and initiation system circuit parameters; and the time of burst and the initiation system circuit parameters were used or extrapolated as the case required. First, the minimum burst current and maximum current frequency required for successful detonator initiation were calculated. Second, the equivalent circuits for different possible detonator array/return conductor combinations and connector cables were derived. Third, the actual layout of the firing set circuit was made. And last, the detonator initiation system was built and tested.

During the design of the initiation system, some simplifying assumptions were made. The resistance of the modular detonators and the contact resistances between them were neglected. The inductance of the firing set was neglected. And the capacitance of the detonator array/return conductor combination was neglected. The effects of these assumptions are covered in the next subsection.

Test Results

The testing of the detonator initiation system consisted of two phases using dummy loads or detonator models. The first phase tested the delay and jitter of the firing switch using dummy loads (shorting wires with the same resistance and inductance as the detonator model array/return conductor combination) in place of the detonator model array. The second phase tested the delay and jitter of the bridgewire bursts in the individual detonator models (detonators without explosives). These testing phases were done for arrays of 3 and 25 detonator models.

The results of the first testing phase showed that the firing switch had an average delay time of 733 and 725 nsec respectively when the small and large array dummy loads were used. In both cases, the maximum firing switch jitter was 50 nsec which was measurement limited. The results of the second testing phase showed that the detonator model array had average times of burst of 614 and 589 nsec respectively for the small and large arrays. While the time of burst for the small array matched its predicted value within the measurement accuracy, the time of burst for the large array was 125 percent of its predicted value.

For the intended use of this system at the AFWL, a jitter of less than 100 nsec was desired for both the firing switch and the bridgewire bursts in the individual array elements. These jitters were met with a good margin for both array sizes. The discrepancy in the predicted time of burst for the large array stems from the interdependence of the burst current and the firing circuit parameters as derived in Cnare's work (Ref 2).

The effects of the assumptions made in the design of the detonator initiation system on the system's characteristics was minimal. While the neglected resistances are comparable to the resistances taken into account, the burst current would have changed no more than 20 Amp as shown in the subsection on the analysis of the test results in the preceding chapter. The neglected capacitance and inductance were more than an order of magnitude smaller than the firing set capacitance and the conductor cable inductance. They produced no detectable effects in either of the two testing phases.

Recommendations

The recommendations of this thesis fall into two categories, improvements to the detonator initiation system and further studies. The improvements to the detonator initiation system include a more accurate means of voltage regulation and a non-position sensitive firing switch. These changes would improve the reproducibility of the system and eliminate the one operating position limitation that the system now has. Two recommendations are made for further studies. The first is to repeat the tests run for this thesis several more times so that the results can be based on more extensive data. The second is to study the relationship between the detonator array size and its burst current, initial current rate of rise, and time of burst. This would include studying why Cnare's work is not applicable to this detonator initiation system.

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Appendix A: Inductance Calculations for the Detonator Array/Return Conductor Combination

The derivation of the equivalent circuit for the detonator array/return conductor combination requires the calculation of its inductance. The methods used to calculate this inductance are slightly different for the two types of return conductors. However, both methods use formulas given in Inductance Calculations by Grover (Ref 5:31-47).

Copper Wire Return Conductor

The method used to calculate the inductances of the detonator array/return conductor combination with the copper wire return conductors was to calculate the inductance of the detonator array by itself, the inductance of the return conductor, and the mutual inductance between them. These values were then combined to give the total inductance.

Simplified Detonator Model. In calculating the inductance of the detonator array by itself, a simplification of the modular detonator's geometry was made. The simplified model is the same length as the modular detonator, but only consists of a 26 gauge wire for 4/10's of its length and a tube with the radial dimensions of the detonator's case for 6/10's of its length. The model assumes the conductors are centered on a common axis and that their adjacent ends lie in a plane perpendicular to the common axis. Figure 9 shows this

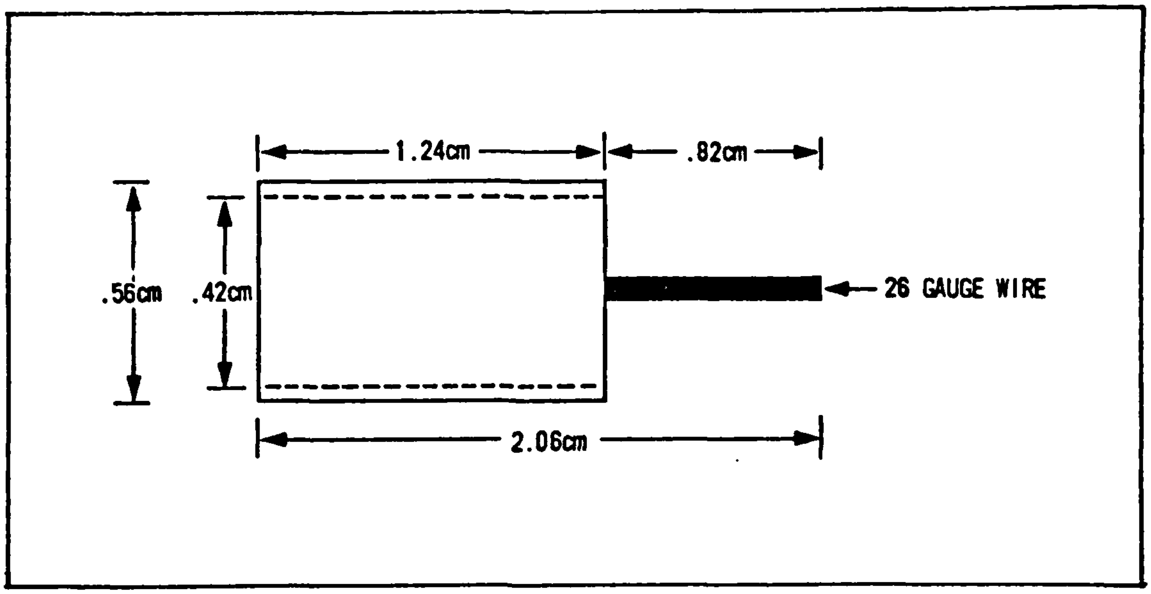

Fig 9. Simplified Detonator Model

simplified model. This model takes into account the inductance of the wire lead from the terminal to the bridgewire, and the inductance of the detonator's case. It does not take into account the non-perpendicular current flow from the bridgewire to the detonator's case and from the detonator's case through the case end to the terminal of the next detonator. It also does not take into account the inductance of these inter-connecting conductors.

<u>First Calculations Method</u>. Using this simplified model, the inductance of the detonator array is calculated in three steps. First, the self-inductance of the individual sections of tubes and 26 gauge wires were calculated using the self-inductance formulas given in Grover's book (Ref 5:35). Then the mutual inductances between the sections of tubes and 26

gauge wires were calculated using the unequal parallel filament mutual inductance formulas in Gover's book (Ref 5:46). Last of all, these values were combined to give the inductance of the detonator array by itself (Ref 5:39). The calculated inductance of the detonator array by itself is .63 uH.

Second Calculation Method. For the accuracy of the calculated inductances that was used in this thesis, another method for calculating the detonator array inductance exists. Using the self-inductance formulas (Ref 5:35), the inductances of a 26 gauge wire and a tube with the radial dimensions of the detonator's case, both as long as the detonator array (51.1 cm), were calculated. Forty percent of the inductance of the 26 gauge wire was added to sixty percent of the inductance of the tube. This gives the same inductance as calculated above because the mutual inductances between the individual sections of tubes and wires in the detonator array are very small.

Return Conductor Self- and Mutual Inductance. The self-inductance of the return conductors were calculated using the self-inductance formulas (Ref 5:35). The mutual inductance between the detonator array and the return conductor was calculated using the equal parallel conductors mutual inductance formulas in Grover's book (Ref 5:34). Table 10 gives the calculated values of the self-inductances and mutual inductances for the four Copper

Table 10

Self-Inductance of Return Conductor and Mutual Inductances of Detonator Array/Return Conductor Combination for Copper Wire Return Conductors at Different Placements

return conductor	placement of return conductor					
	first		second		third	
	L (uH)	M (uH)	L (uH)	M (uH)	L (uH)	M (uH)
24 gauge wire	0.78	0.46	0.82	0.28	0.95	0.18
25 gauge wire	0.79	0.46	0.84	0.28	0.97	0.18
26 gauge wire	0.80	0.47	0.85	0.28	0.98	0.18
27 gauge wire	0.81	0.47	0.86	0.28	1.00	0.18

wire return conductors at the three possible placements. These values were combined with the inductance of the detonator array to give the total inductance of the detonator array/return conductor combination.

Aluminum Tube Return Conductor

To calculate the inductance of the detonator array/ return conductor combination with the Aluminum tube return conductor, the simplified model of the modular detonator and a calculation method similar to the second calculation method presented earlier were used. A calculation method similar to the second calculation method was used because of its simplicity and sufficient accuracy. This method was checked by calculating the inductance of the return conductor by itself (Ref 5:35), the mutual inductance between the return conductor and the individual sections of tubes

Table 11

Inductances of Coaxial Return Circuit
for Different Inner Conductors and Placements of
Outer Return Conductor of Aluminum Tube Return Conductor

inner conductor	placement of return conductor first L (uH)	second L (uH)	third L (uH)
26 gauge wire	0.34	0.53	0.64
tube with radial dimensions of detonator's case	0.05	0.24	0.35

and 26 gauge wire (Ref 5:46), and combining them with the inductance of the detonator array by itself (Ref 5:39). The result is the same as from the method described here.

Using the coaxial return circuit inductance formula in Grover's book (Ref 5:41), the inductance of a coaxial return circuit as long as the detonator array was calculated for two different inner conductors. In the first case, the inner conductor is 26 gauge wire. In the second case, the inner conductor is a tube with the radial dimensions of the detonator's case. For both cases, the outer conductor was the Aluminum tube return conductor. Table 11 gives the inductances calculated for both cases with the return conductor at the three possible placements. The total inductance of the detonator array/return conductor combination was calculated as 40 percent of the first case plus 60 percent of the second case inductance.

Appendix B: Detonator Initiation System Circuit Characteristics

The detonator initiation system circuit characteristics presented in this appendix are the calculated total circuit resistance (R), excluding bridgewires, total circuit inductances (L), current frequency, initial firing set capacitor voltage (V_o), and the initial current rate of rise ($\dot{I}$). Tables 12, 14, 16, 18, and 20 give the calculated total circuit resistance, excluding bridgewires, and total circuit inductance for every combination of connector cable and return conductor at the three possible placements. Each table is for a different return conductor. Tables 13, 15, 17, 19, and 21 given the calculated current frequency, initial firing set capacitor voltage, and initial current rate of rise for every combination of capacitor, connector cable, and return conductor at the three possible placements. Again, each table deals with a different return conductor. Each table is arranged so that the current frequency, initial firing set capacitor voltage, and initial current rate of rise for a particular combination of capacitor, connector cable, and return conductor at one placement can be easily found. In addition, both tables dealing with a particular return conductor were placed on the same page.

Table 12

Total Initiation Circuit Resistance and Inductance (excluding bridgewires) for 24 Gauge Copper Wire Return Conductor

cable (RG/U-)	placement of return conductor: first R(mΩ)	first L(uH)	second R(mΩ)	second L(uH)	third R(mΩ)	third L(uH)
34	624	11.32	629	11.73	637	12.06
35	465	11.32	470	11.73	478	12.06
73	1403	8.33	1408	8.74	1416	9.07
218	351	8.09	356	8.50	364	8.83

Table 13

Initiation Circuit Current Frequency, Initial Firing Set Capacitor Voltage, and Initial Current Rate of Rise for 24 Gauge Copper Wire Return Conductor

cable (RG/U-)	capacitance and placement of return conductor: first .25 uF	first .50 uF	second .25 uF	second .50 uF	third .25 uF	third .50 uF
	(current frequency in KHz)					
34	94.4	66.6	92.8	65.5	91.5	64.6
35	94.5	66.7	92.8	65.6	91.5	64.7
73	109.2	76.5	106.7	74.7	104.7	73.4
218	111.8	78.9	109.1	77.0	107.0	75.6
	(V_o in KV)					
34	14.3	13.7	14.5	13.9	14.7	14.0
35	14.2	13.5	14.4	13.7	14.5	13.9
73	13.9	13.3	14.1	13.5	14.2	13.6
218	12.7	12.0	12.8	12.2	13.0	12.3
	($\dot{I}$ in KA/usec)					
34	1.26	1.21	1.24	1.18	1.22	1.16
35	1.25	1.19	1.23	1.17	1.20	1.15
73	1.67	1.60	1.61	1.54	1.57	1.50
218	1.57	1.48	1.51	1.44	1.47	1.39

Table 14

Total Initiation Circuit Resistance and Inductance (excluding bridgewires) for 25 Gauge Copper Wire Return Conductor

cable (RG/U-)	placement of return conductor					
	first		second		third	
	R(mΩ)	L(uH)	R(mΩ)	L(uH)	R(mΩ)	L(uH)
34	636	11.33	641	11.74	652	12.07
35	477	11.33	482	11.74	493	12.07
73	1415	8.34	1420	8.75	1431	9.08
218	363	8.10	368	8.51	379	8.84

Table 15

Initiation Circuit Current Frequency, Initial Firing Set Capacitor Voltage, and Initial Current Rate of Rise for 25 Gauge Copper Wire Return Conductor

cable (RG/U-)	capacitance and placement of return conductor					
	first		second		third	
	.25 uF	.50 uF	.25 uF	.50 uF	.25 uF	.50 uF
	(current frequency in KHz)					
34	94.4	66.6	92.7	65.4	91.4	64.5
35	94.4	66.7	92.8	65.5	91.5	64.6
73	109.1	76.4	106.6	74.6	104.7	73.3
218	111.7	78.9	109.0	77.0	106.9	75.5
	(V_o in KV)					
34	14.4	13.7	14.6	13.9	14.7	14.0
35	14.2	13.5	14.4	13.7	14.6	13.9
73	13.9	13.3	14.1	13.5	14.2	13.6
218	12.7	12.1	12.9	12.2	13.0	12.4
	($\dot{I}$ in KA/usec)					
34	1.27	1.21	1.24	1.18	1.22	1.16
35	1.25	1.19	1.23	1.17	1.21	1.15
73	1.67	1.59	1.61	1.54	1.56	1.50
218	1.57	1.49	1.52	1.43	1.47	1.40

Table 16

Total Initiation Circuit Resistance and Inductance (excluding bridgewires) for 26 Gauge Copper Wire Return Conductor

cable (RG/U-)	placement of return conductor					
	first		second		third	
	R(mΩ)	L(uH)	R(mΩ)	L(uH)	R(mΩ)	L(uH)
34	650	11.34	657	11.75	670	12.09
35	491	11.34	498	11.75	511	12.09
73	1429	8.35	1436	8.76	1449	9.10
218	377	8.11	384	8.52	397	8.86

Table 17

Initiation Circuit Current Frequency, Initial Firing Set Capacitor Voltage, and Initial Current Rate of Rise for 26 Gauge Copper Wire Return Conductor

cable (RG/U-)	capacitance and placement of return conductor					
	first		second		third	
	.25 uF	.50 uF	.25 uF	.50 uF	.25 uF	.50 uF
	(current frequency in KHz)					
34	94.3	66.6	92.7	65.4	91.4	64.5
35	94.4	66.7	92.7	65.5	91.4	64.6
73	109.0	76.3	106.5	74.6	104.5	73.2
218	111.6	78.8	108.9	76.9	106.8	75.4
	(V_o in KV)					
34	14.4	13.7	14.6	13.9	14.7	14.1
35	14.2	13.5	14.4	13.7	14.6	13.9
73	14.0	13.3	14.1	13.5	14.3	13.6
218	12.7	12.1	12.9	12.2	13.0	12.4
	($\dot{I}$ in KA/usec)					
34	1.27	1.21	1.24	1.18	1.22	1.17
35	1.25	1.19	1.23	1.17	1.21	1.15
73	1.68	1.59	1.61	1.54	1.57	1.49
218	1.57	1.49	1.51	1.43	1.47	1.40

Table 18

Total Initiation Circuit Resistance and Inductance (excluding bridgewires) for 27 Gauge Copper Wire Return Conductor

cable (RG/U-)	placement of return conductor first R(mΩ)	first L(uH)	second R(mΩ)	second L(uH)	third R(mΩ)	third L(uH)
34	668	11.35	677	11.77	694	12.10
35	509	11.35	518	11.77	535	12.10
73	1447	8.36	1456	8.78	1473	9.11
218	395	8.12	404	8.54	421	8.87

Table 19

Initiation Circuit Current Frequency, Initial Firing Set Capacitor Voltage, and Initial Current Rate of Rise for 27 Gauge Copper Wire Return Conductor

cable (RG/U-)	capacitance and placement of return conductor first .25 uF	first .50 uF	second .25 uF	second .50 uF	third .25 uF	third .50 uF
	(current frequency in KHz)					
34	94.3	66.5	92.6	65.3	91.3	64.4
35	94.3	66.6	92.7	65.4	91.4	64.5
73	109.0	76.2	106.4	74.4	104.4	73.1
218	111.5	78.8	108.8	76.8	106.7	75.4
	(V_o in KV)					
34	14.4	13.7	14.6	13.9	14.8	14.1
35	14.2	13.6	14.4	13.8	14.6	13.9
73	14.0	13.4	14.1	13.5	14.3	13.7
218	12.7	12.1	12.9	12.3	13.1	12.4
	($\dot{I}$ in KA/usec)					
34	1.27	1.21	1.24	1.18	1.22	1.17
35	1.25	1.20	1.22	1.17	1.21	1.15
73	1.67	1.60	1.61	1.54	1.57	1.50
218	1.56	1.49	1.51	1.44	1.48	1.40

Table 20

Total Initiation Circuit Resistance and Inductance (excluding bridgewires) for 10 mil Thick Aluminum Tube Return Conductor

cable (RG/U-)	placement of return conductor: first R(mΩ)	first L(uH)	second R(mΩ)	second L(uH)	third R(mΩ)	third L(uH)
34	584	11.00	582	11.19	581	11.31
35	425	11.00	423	11.19	422	11.31
73	1363	8.01	1361	8.20	1360	8.32
218	311	7.77	309	7.96	308	8.08

Table 21

Initiation Circuit Current Frequency, Initial Firing Set Capacitor Voltage, and Initial Current Rate of Rise for 10 mil Thick Aluminum Tube Return Conductor

cable (RG/U-)	capacitance and placement of return conductor: first .25 uF	first .50 uF	second .25 uF	second .50 uF	third .25 uF	third .50 uF
	(current frequency in KHz)					
34	95.8	67.6	95.0	67.1	94.5	66.7
35	95.9	67.7	95.1	67.1	94.6	66.8
73	111.4	78.0	110.1	77.1	109.3	76.6
218	114.1	80.6	112.7	79.6	111.9	79.0
	(V_o in KV)					
34	14.2	13.5	14.2	13.6	14.3	13.6
35	14.0	13.3	14.1	13.4	14.1	13.5
73	13.8	13.1	13.8	13.2	13.9	13.3
218	12.5	11.9	12.6	11.9	12.6	12.0
	($\dot{I}$ in KA/usec)					
34	1.29	1.23	1.27	1.22	1.26	1.20
35	1.27	1.21	1.26	1.20	1.25	1.19
73	1.72	1.64	1.68	1.61	1.67	1.60
218	1.61	1.53	1.58	1.49	1.56	1.49

VITA

Kevin Olmscheid was born April 3, 1960 in Richmond, Minnesota. He graduated from high school in Paynesville, Minnesota in 1978 and attended the University of Minnesota. He graduated with high distinction from the Institute of Technology, University of Minnesota with a degree of Bachelor of Electrical Engineering in June of 1982. Upon graduation, he received a commission in the USAF through the ROTC program. He entered the School of Engineering, Air Force Institute of Technology in June of 1982.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION
UNCLASSIFIED

1b. RESTRICTIVE MARKINGS

2a. SECURITY CLASSIFICATION AUTHORITY

2b. DECLASSIFICATION/DOWNGRADING SCHEDULE

3. DISTRIBUTION/AVAILABILITY OF REPORT
Approved for public release, distribution unlimited

4. PERFORMING ORGANIZATION REPORT NUMBER(S)
AFIT/GEO/EE/83D-6

5. MONITORING ORGANIZATION REPORT NUMBER(S)

6a. NAME OF PERFORMING ORGANIZATION
Air Force Institute of Technology

6b. OFFICE SYMBOL *(If applicable)*
AFIT/EN

7a. NAME OF MONITORING ORGANIZATION

6c. ADDRESS *(City, State and ZIP Code)*
Wright-Patterson AFB, OH 45433

7b. ADDRESS *(City, State and ZIP Code)*

8a. NAME OF FUNDING/SPONSORING ORGANIZATION
Air Force Weapons Lab

8b. OFFICE SYMBOL *(If applicable)*
AFWL/RNAA

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER

8c. ADDRESS *(City, State and ZIP Code)*
Kirtland AFB, NM 87117

10. SOURCE OF FUNDING NOS.

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT NO.

11. TITLE *(Include Security Classification)*
See block 19

12. PERSONAL AUTHOR(S)
Kevin L. Olmscheid, 2dLt, USAF

13a. TYPE OF REPORT
MS Thesis

13b. TIME COVERED
FROM ______ TO ______

14. DATE OF REPORT *(Yr., Mo., Day)*
December 1983

15. PAGE COUNT
68

16. SUPPLEMENTARY NOTATION
Approved for public release; IAW AFR 190-17

Lynn Wolaver 7 Feb 84

17. COSATI CODES

FIELD	GROUP	SUB. GR.
19	05	

18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*
EBW Detonators, Detonator Initiation System, Magnetic-flux Compression Generators

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

Title: SERIES DETONATOR INITIATION SYSTEM (UNCLASSIFIED)

Thesis Chairman: Tim L. Skvarenina, Maj, USAF

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT
UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS ☐

21. ABSTRACT SECURITY CLASSIFICATION
UNCLASSIFIED

22a. NAME OF RESPONSIBLE INDIVIDUAL
Kevin L. Olmscheid, 2dLt, USAF

22b. TELEPHONE NUMBER *(Include Area Code)*
513-255-5533

22c. OFFICE SYMBOL
AFIT/EN

Abstract:

The purpose of this thesis was to design, build, and test a high voltage detonator initiation system capable of firing a series modular detonator array. This initiation system was designed to optimally fire a detonator array of 25 detonators, but is capable of firing detonator arrays of different lengths.

The procedures used to develop this initiation system included four steps. First, the minimum burst current and the maximum current frequency required for successful detonator initiation were determined. Second, the equivalent circuits of the detonator array/return conductor combination and connector cable were derived. Third, the design of the initiation system was made. Fourth, the initiation system was built and tested.

The testing of the initiation system using array sizes of 3 and 25 detonator models was limited. These tests showed that the firing switch had an average delay time of 733 and 725 nsec respectively for the small and large arrays. The maximum firing switch jitter was 50 nsec, which was measurement limited, for both array sizes. The maximum jitter of the bridgewire bursts in the individual array elements was 20 and 40 nsec respectively for the small and large array.

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3-84

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