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DESIGN, TESTING, AND SAFETY CONSIDERATIONS OF AN OPTICALLY ISOLATED FIRING SET

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14. ABSTRACT

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Design, testing, and safety considerations of an Optically Isolated Firing Set

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ABSTRACT

Experimental investigations at the Air Force Research Laboratory's Munitions Directorate required a firing set to initiate detonators in ultra-high-voltage experiments, but commercial firing sets with adequate high voltage isolation could not be found. To resolve this issue a Directorate team designed, fabricated a new firing set, verified that it met all design requirements, and obtained safety board approval for its use. The patented design uses all plastic fiber optic cables, pneumatic controls, battery isolation, and redundant safety devices to withstand voltage differences of hundreds of thousands of volts between the operator and the experiment. This paper describes the efforts to develop a very reliable firing set that met the high standards required by explosive safety procedures. Design features include Faraday shielding, redundant lock out features, multiple safing circuits to handle a variety of fault conditions and fail-safe bleed down circuits to eliminate concerns with residual stored electrical energy. The high-voltage-tolerant firing set allows research in unexplored areas such as electro-explosive effects.

KEYWORD LIST

"High voltage tolerant explosive initiation," "Fiber optically controlled firing set," "Optically isolated firing set," "Explosive Birdgewire firing set"

1. INTRODUCTION

The detonation of explosives is routinely accomplished with a wide variety of capacitor discharge firing sets. The task of producing a precise detonation in an experimental arrangement can be complicated if part of the experiment operates at high voltage. The goal of the effort discussed here was to provide the Air Force Research Laboratory's Munitions Directorate with an explosive firing set capable of detonating explosives where part of experiment was operated at hundreds of thousands of volts. In these cases, the experimental arrangement required the removal of all metal leads extending out of the test apparatus while still providing a safe working environment for all personnel involved. The solution to these issues was achieved with the development of a battery-powered, fiber-optically controlled firing set. A secondary requirement, affordability, stemmed from the operational need to have the firing set close to the explosives where it was not expected to survive the event.

From its conception the firing set went through three phases of development before it received safety approval and was allowed for use on Eglin's test ranges. At the beginning of the ***design phase***, a concept design review was conducted with Eglin AFB's Range Safety personnel. The purpose of this review was to have individuals knowledgeable in safety and test range procedures identify any part of the design that might be unacceptable and/or any missing safety features that would be required for standard operation. Upon completion of the design phase but before the start of the fabrication phase, a second safety review was conducted to demonstrate a working prototype of the firing set and validate its safety features. During the ***fabrication phase,*** three generations of printed circuit cards were professionally manufactured and tested to insure they functioned correctly. In this phase several other design refinements were finalized and incorporated into the final version of the firing set. Extensive testing of the third generation printed circuit card followed before a set of ten firing set circuit cards were fabricated with all new electronic components. During the ***checkout phase***, AFRL personnel performed the final assembly and inspection of each of the ten firing sets. Each firing set was given an identification number and was extensively tested. Battery life tests were also carried out on a random sample of the firing sets.

2. DESIGN PHASE

2.1. Design technical requirements

The technical requirements for the new firing set were straight forward. Reliably, safely, and affordably initiate a standard Exploding Bridge Wire (EBW) detonator that was elevated to hundreds of thousands of volts. EBWs are routinely used on Eglin's test ranges; however, the firing set is usually in the control room and a high voltage firing line is run out to the test arena. Prior to a testing, the firing line is unhooked from the firing set and shorted. The firing set is in a "keyed-off" position and the key is removed and given to the explosive operators. With the key in their possession and the range cleared of all other personnel, Explosive Ordinance Disposal (EOD) technicians perform the final hook up of the detonator and explosives. When EOD return to the security of the control room, the firing line is un-shorted, hooked to the firing set, the firing set is keyed on, charged, and commanded to fire. This setup is unacceptable in electro-explosive testing because the firing line would connect the test apparatus to the grounded firing set in the control room. Attempts to isolate the firing line and firing set by standard techniques were deemed impractical and unsafe at the design voltage level of 300,000 volts.

The obvious solution was to move the firing set into the test apparatus with the explosives and control it via fiber optic cables. Figure 1 shows the components of a firing set that would meet the technical requirements to initiate EBW devices. The pulsed power, in the form of a battery, a DC-DC converter, a high voltage storage capacitor, and a closing switch are all shown enclosed in a cylindrical metallic case to provide electromagnetic shielding. Three fiber optic control lines are shown. The first fiber optic would be used to send a "Start" signal to the DC-DC converter to charge the capacitor. The second fiber optic would return a "ready" signal when the capacitor reached the desired charge level. The third fiber optic would be used to send a "Fire" signal. The enclosed firing set could then be elevated to the high voltage.

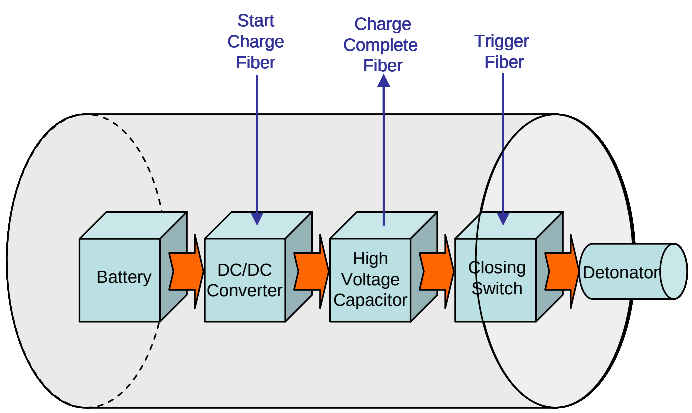

Figure 1 Basic Technical Requirements of Isolated Firing Set

2.2. Design safety features

While the conceptual design shown in Figure 1 meets the technical requirements, it did nothing to address the safety requirements. Without a lockout of the prime power for the firing set (and a key to be carried by the operators) the firing line cannot be hooked up to the explosives according to local safety regulations. To address this issue the conceptual design was modified to include a relay between the prime power and the DC-DC converter. To insure that this relay was not accidentally engaged, a frequency dependent fiber optic signal was used to enable the relay. This "fiber optic key" would then be physically controlled with a key switch on the firing set control panel. Two additional fiber optic lines were added to return positive information to indicate the position of the relay. The firing set would be considered "safe" when the relay is off, and the firing set would be "enabled" when the relay is energized. Additional safety features added to the design were bleed resistors (not shown) directly across the prime power and the high voltage capacitor. These bleed resistors would shorten the life of the prime power and prevent the high voltage capacitor from keeping a charge after the DC-DC converter is switched off. Figure 2 shows the conceptual design with the proposed safety features.

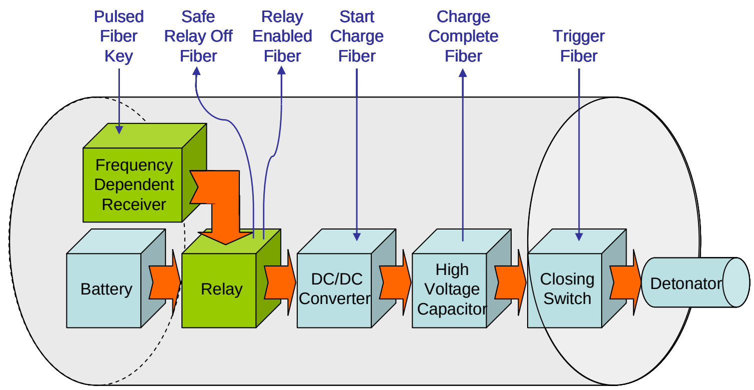

Figure 2 Proposed Safety Features of Isolated Firing Set

This conceptual design was proposed at the first meeting of a Range Safety Review Board. The representatives from the Explosive Ordinance Disposal (EOD), who are responsible for the final hookup of explosives on Eglin's ranges, did not approve the design. They felt that there should be a continuous read out of the high voltage storage capacitor back to the control area. While adding such a diagnostic was certainly possible, there was an additional concern that such a system could also provide false positive feedback. For example, if the analog to digital device that was monitoring the capacitor voltage failed it could send back a false zero reading for the capacitor voltage level. There also appeared to be a lack of trust for a fiber optic system whose workings could not be seen. After several considerable discussions and review of several options, a pneumatic safety switch was approved for the preliminary design. This single switch would perform several different functions. First when it was in its normal position, it would unhook the prime power from every thing in the firing set except a positive feedback fiber optic transmitter which would indicate that the firing set was safe. The pneumatic switch would also place a 200 ohm shunt resistor across the storage capacitor and a short circuit across the output of the firing set while it was in its normal position. The 200 ohm shunt resistor will drain the high voltage storage capacitor in less than one millisecond. When the pneumatic switch was energized with an air line, the prime power would be reconnected, the short

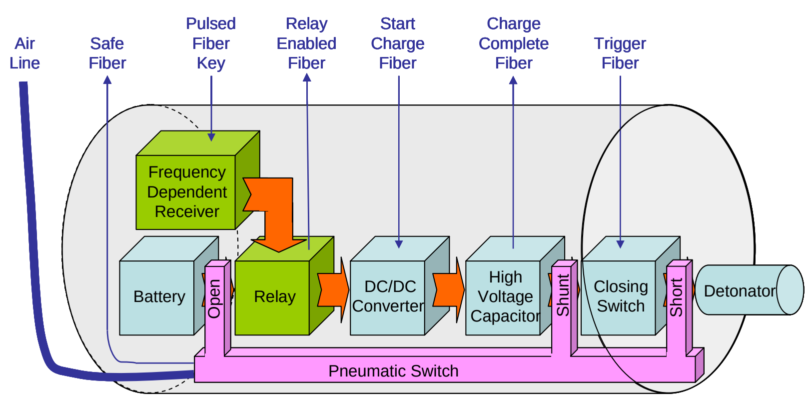

Figure 3 Inclusion of Pneumatic Safety Switch

circuits would be removed, and the safe indicator light would go out. Figure 3 shows the firing set with the agreed upon safety features.

One other design requirement was requested by the safety board. They wanted to know how long the battery and storage capacitor would remain energized if all control with the firing set was lost. This information was required to determine wait times under certain fault conditions. It was agreed that a second meeting with the safety board would be held once a working prototype was built.

2.3. Component selection and cost

Concurrent with the safety review process a search was underway to identify components needed to construct a safe, reliable, affordable firing set. Components for the firing set could be divided onto two categories, pulsed power and controls. The pulsed power train includes the items shown as blocks in Figure 1.

- *Main Closing Switch* - Used to deliver the capacitor energy to the firing line. Model number GP489, manufactured by PerkinElmer then EG&G Optoelectronics, rated at 4,000 volts and 10,000 amperes in pulsed discharge, approximate cost $400.
- *Trigger Transformer* - Used to activate the main closing switch. Model number TR-2206, manufactured by PerkinElmer then EG&G Optoelectronics, designed for the GP489 switch will produce 4,000 volts from an input of 20 volts in pulsed discharge, approximate cost $56.
- *Energy Storage Capacitor* - Used to store enough electrical energy to drive the firing line and activate the EBW device. Model number KM100, manufactured by Custom Electronics, Inc., rated at 5,000 volts and 0.3 micro farads in pulsed discharge, approximate cost $160.
- *DC-DC Converter* - Used to step up battery voltage to the high voltage required for the energy storage capacitor. Model number GM12-3KVP, manufactured by Advance Hivolt, rated at 1.5 watts, 12 volts in and 3,000 volts out, approximate cost $64.
- *Battery* - Common nine volt alkaline battery, several manufacturers available, approximate cost $4.

For the control circuitry all of the components except the pneumatic switch were readily available from electronics supply catalogs. Plastic fiber optic cable was chosen for the control link because the required runs were short and the plastic fiber can easily be cut, polished, and terminated on the test range.

- *Fiber Optic Receivers* - Model number HFBR-2524, manufactured by Agilent Technologies then Hewlett Packard, approximate cost $8.
- *Fiber Optic Transmitters* - Model number HFBR-1524, manufactured by Agilent Technologies then Hewlett Packard, approximate cost $7.
- *Plastic Fiber Optics Cable* - Model number HFRB-RUS100, manufactured by Agilent Technologies then Hewlett Packard, approximate cost $80 for 100 meters.
- *Filter Latch (Tone Decoder)* - Model number LM567C, manufactured by National Semiconductor, approximate cost less than $1.
- *Voltage Regulator* - Model number LM2931AZ-5.0, manufactured by Motorola, approximate cost less than $1.
- *Miniature Relays* - Model number TQ2E-5V, manufactured by Aromat Corporation, approximate cost $3.
- *Other electronic components* - Resistors, Capacitors, Diodes, and Transistors, procured through Newark electronics supply company, approximate cost $40.

A supplier for a pneumatic switch that had the desired number of poles, a 2,000 volt rating, and fit within the allotted space could not be found. In house expertise was used to build the pneumatic switch and the aluminum firing set casing. For these parts a good comparative cost is not available, but it was estimated that the machining time was on the order of two days for each firing set. With a $1,000 for commercial parts and $1,600 for in house fabricated parts, the total cost of a firing set was estimated at $2,600. The cost of one controller is estimated at $1,000.

2.4. Bread board

Once the parts were identified and purchased, a bread board prototype was assembled. This working prototype not only allowed the circuitry to be verified; but provide the first actual data on the current draw from the prime power battery and verification that the output current met the design specks. Figure 4 shows the bread board circuit. On the top edge of the card are the fiber optic transmitters and receivers. The square component with black sides is the DC-DC converter and the large yellow component is the high voltage storage capacitor. A single 9 volt battery fits into the holder in the center and provides all the power. The prime power bleed resistors and a filter capacitor can be seen soldered across the battery holder terminals. By the time this picture was taken, the pneumatic switch had been removed and was being copied for the actual firing set. A close look at the circuit board reveals where solder pads have been peeled off around connections that operate up to 2000 volts for added voltage standoff.

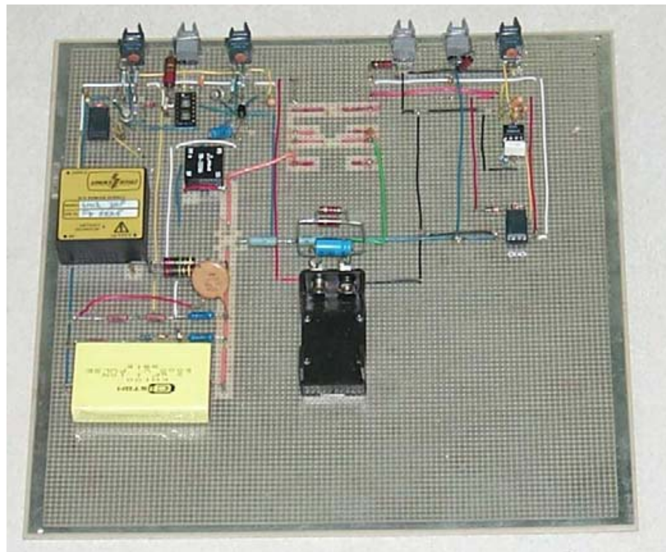

Figure 4 Photograph of Early Bread Board of Firing Set

2.5. Controller

To operate the firing set circuit, it was necessary to build a fire set controller. The layout of the front panel of the controller is shown in Figure 5. Its operation will be discussed in the sequence of typical operation, which is basically from the left side to the right side of the front panel. The power switch turns on the AC power and causes the red "ON" LED to light. If a powered up firing set is connected at this time the green "SAFE" LED will also light. Note because the air key switch is off there is no power to any of the other controls. Keying on the air key switch does two things: First, it activates the pneumatic switch in the firing set which cause the positive feedback "SAFE" LED to go out. Second, it provides power to the rest of the controller. Keying on the optical key switch will send a 10 kHz pulsed light signal to the firing set closing the relay between the prime power battery and the rest of the

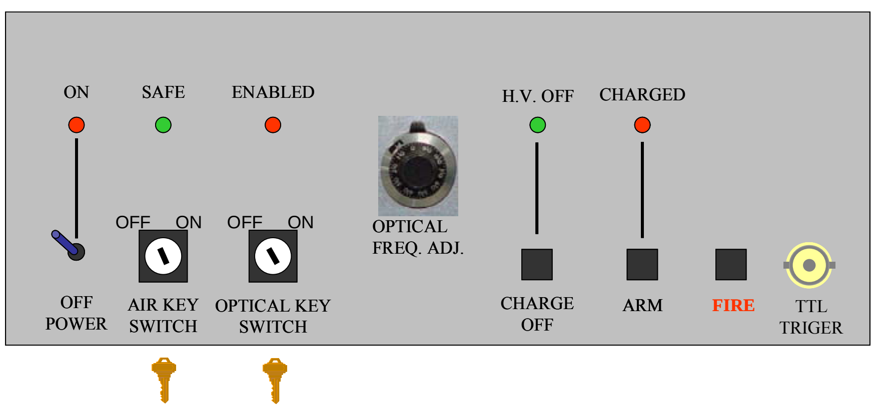

Figure 5 Layout of Controller Front Panel

firing set circuit. When the relay closes, a positive feedback signal is sent to the controller and the red "ENABLED" LED lights up. Occasionally, the red "ENABLED" LED would chatter on and off, possibly due to temperature drift. This problem can be resolved by small adjustments in the center potentiometer to adjust the frequency of the light signal to the firing set. At this point the green "H.V. OFF" LED is lit, indicating that an arming command has not been sent. Next, the square "ARM" button is pushed and the green "H.V. OFF" LED goes out and a charge command is sent to the firing set. When the energy storage capacitor in the firing set reaches the minimum charge voltage of 1640 volts, a positive feedback signal is sent to the controller to light the red "CHARGED" LED. At this point the firing set is ready to operate, and one of two things can be done. First, the square fire button can be pressed or a TTL trigger signal can be used to initiate the firing sequence and detonate the experiment. Second, if an abort is desired, the square "CHARGE OFF" button can be pressed to remove the charge signal to the firing set.

3. FABRICATION PHASE

With the completion of the design phase and data from the bread board test, the project was ready to go into the fabrication phase. However, before starting fabrication, a second meeting was held with the range safety people. The purpose of this meeting was to show that the firing set could be built as conceived in the first safety meeting. It was also a chance to make sure that no new safety issues had arisen. Since the firing set was built as planned no new concerns were raised.

3.1. Iterations of circuit board design

The design called for the circuit cards to be commercially etched and soldered for reliability and safety reasons. This would insure that all the final firing sets were identical. In-house capabilities were not available, so a local vender was used. A circuit diagram and some general lay out direction were provided and in relatively short time a pair of etched cards was returned. These cards were reviewed for correctness. While the circuit was close to right, the vender did not have any experience with high voltage and current on circuit cards. Some rearranging of components was necessary, high voltage traces were given at least one quarter inch clearance, and high current traces were widened. With this information, a second generation card set was made and stuffed with circuit components. This second generation card was very rigorously tested and evaluated. Some unanticipated results were identified. One of these results was the repeated loss of the voltage comparator chip with repeated use of the card. Several filter capacitors were added to remove possible noise spikes during the discharge of the high voltage storage capacitor. Once reliable operation was achieved, ten sets of the third generation of cards were ordered with the circuit components soldered in place. Figure 6 shows the finished firing set circuit card. In this picture, the cards are being powered from a power supply instead of a battery. The pneumatic switch and storage capacitor are not visible since they are mounted on the back of the cards.

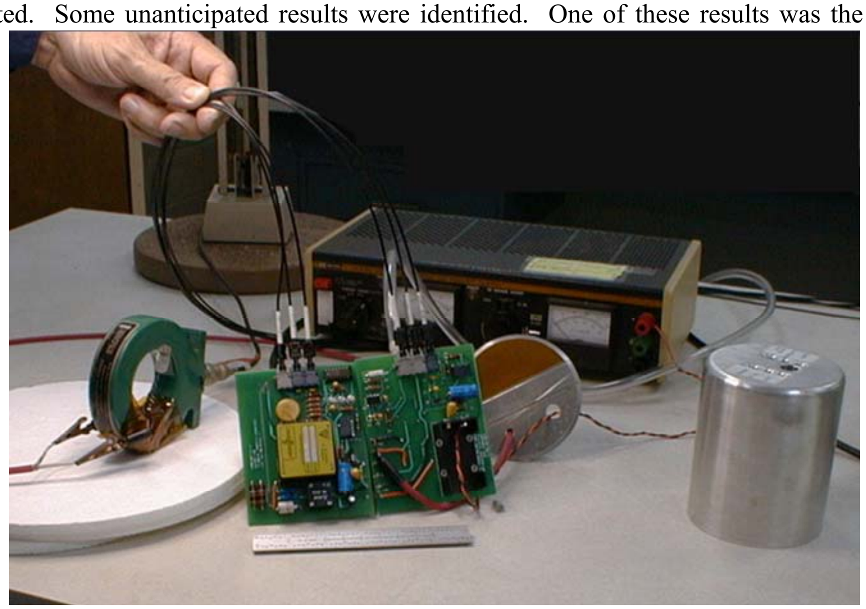

Figure 6 Photograph of Circuit Board Under Test

3.2. Pneumatic switch

The physical mechanical lockout of the firing set is achieved with a three pole pneumatic switch that was fabricated in house by the technical staff. A photograph of the switch mounted on a circuit board is shown in Figure 7. The switch is a spring loaded plunger device that in its normally closed position provides the system safe indicator, shunt for the energy storage capacitor, and short for the output terminals off the firing set. Only when sufficient air pressure is supplied to shift the plunger into the operating position, does the switch connect the prime power battery source to the rest of the firing set circuit. Since the shorting points will see relatively high voltage the "throw" is on the order of ¼ inch to maintain adequate voltage standoff during use. Initial plans were to have the output pulse routed through the switch, but the high current caused the contacts to weld and stick, so this idea was abandoned. The fittings connecting to the air supply are plastic and nylon to avoid conducting shapes that might induce corona or other electric field stresses.

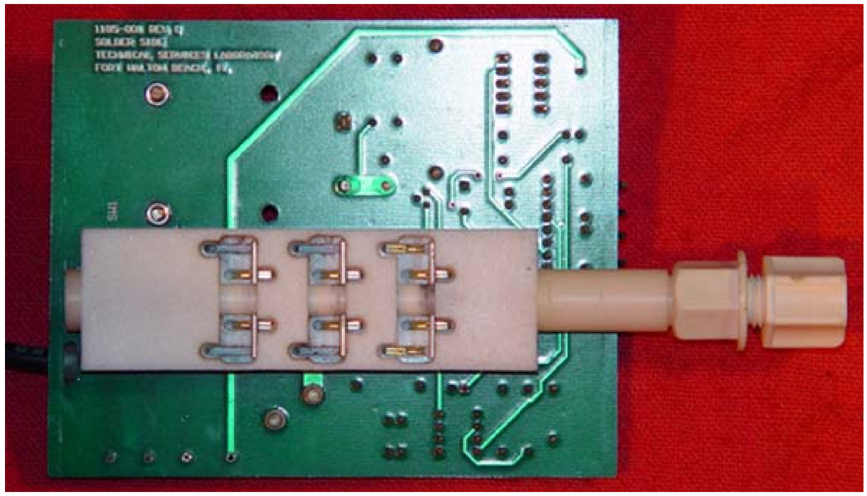

Figure 7 Close up View of Pneumatic Switch

3.3. Case/packing

The entire firing set circuitry and battery are enclosed in a right circular cylinder approximately 4.5 inches long and 3.5 inches in diameter. Solid end plates cover both ends of the cylinder with minimal sized holes to allow for the feed-through of the firing line, control/feed-back fibers and air line. This metallic case provides electromagnetic shielding for the circuit components inside. A fully assembled firing set is shown in Figure 8 with the finished controller. The firing line is shown to the left of the firing set and the control lines feed in from the right.

Figure 8 Photograph of Controller and Firing Set

4. CHECKOUT PHASE

With the completion of fabrication of ten identical firing sets, an extensive checkout phase began. First and foremost, the firing set was required to output a current pulse that could promptly vaporize the wire element in an EBW device. Reynold's, the manufacturer of most of the detonators used by this research group, specifies that a rate of current rise of 10^9 amp/sec will reliably initiate their detonators. The curve with the square markers in Figure 9 is reproduced from the Reynold's catalog as a typical current waveform for firing one of their EBW devices. Also shown in Figure 9 is a measured current waveform from the firing set driving a Reynolds bridge-wire. Note that the rate of rise requirement is exceeded and that the actual bridge-wire burst time is considerably earlier than the published, typical result.

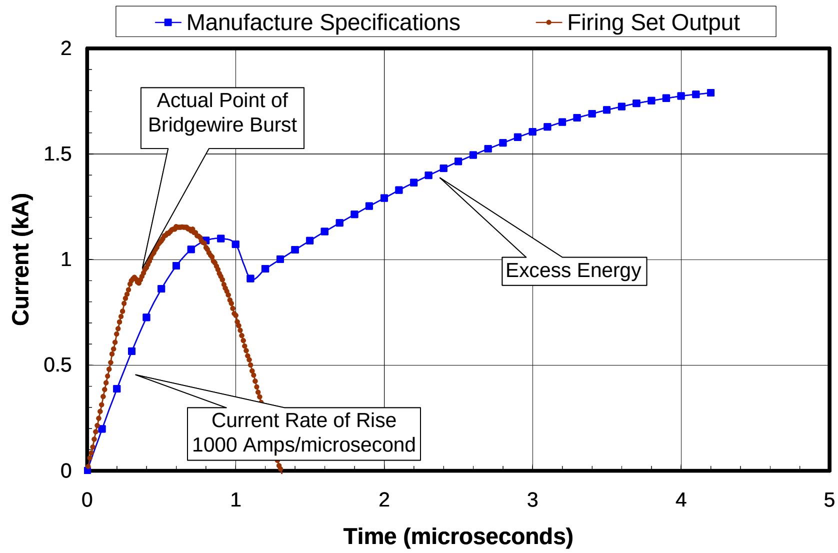

Figure 9 Measured Current and Manufacturers Specifications

It was also necessary to quantify the firing set's battery life as required by the safety board. Next, the operation of each firing set was repeatedly tested to insure it provided the correct electrical output when commanded and did not provided any electrical output at any other time. Finally, during this checkout phase, it was necessary to develop and document the normal operation for the firing set before going back to the safety board for a final review of the device.

4.1. Battery life tests

Certain battery life information on standard alkaline batteries is readily obtained from battery manufacturers. They have extensive documentation and graphs available. One of the simplest graphs showed the battery life for different resistive loads. In order to determine the battery life, an understanding of firing set equivalent resistance is required. Since the circuit changes as the firing set is stepped through its operation or States, an equivalent resistance is needed for each State to determine battery life for that State. Table 1 identifies the six different States and describes what is happening in the firing set at that time.

Table 1 Firing Set States

State	Controller Action	Firing Set Response
0	No Action, Everything is Keyed Off	Only Green "SAFE" LED Is On
1	Key On Air key Switch	Pneumatic Switch Engages, And Green "SAFE" LED Goes Off
2	Key On Optical Key Switch	Relay Latches, And Red "ENABLED" LED Comes On
3	Press Arm Button	DC-DC Converter Is Started, High Voltage Capacitor Begins To Charged
4	No Action	When Storage Capacitor Reaches 1640 Volts, Comparator Lights Red "CHRGED" LED
5	Press Fire Button	Output Switch Closes Connecting Storage Capacitor To Detonator, Firing Set Returns To State 2

To quantify the firing set as an equivalent resistance, a voltage controlled power supply used to drive the firing set while the current draw was monitored as the firing set was stepped through its different States. Figure 10 shows the resulting different current levels that range for 32mA to 450mA. It is important to note that States 3 and 5 are transient states and the firing set will not stay in them for long periods of time. From this information, the equivalent resistance of States 0, 1, 2, and 4 can be calculated to be 174Ω, 250Ω, 48Ω, and 26Ω respectively.

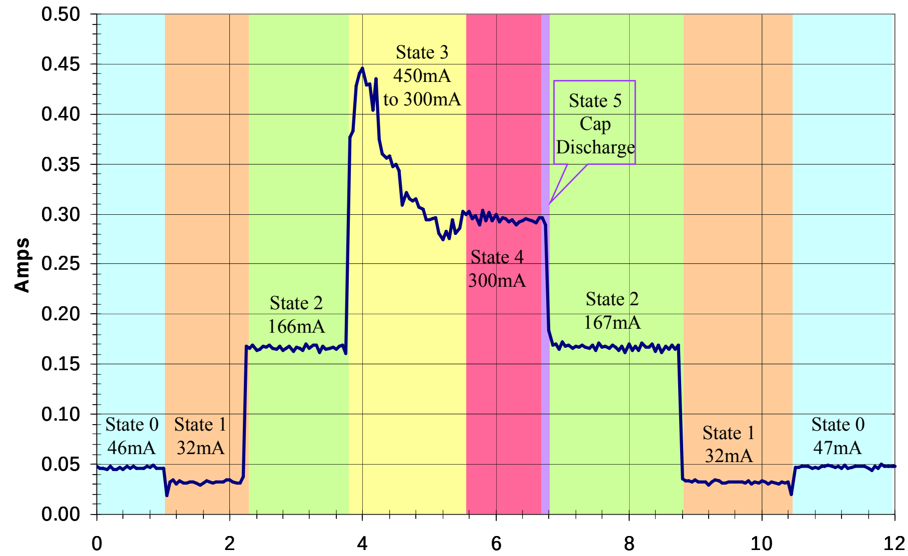

Figure 10 Battery Current Draw for Various States of the Firing Process

At least three battery life tests were performed on the firing sets in each of the four stable States. The results are shown in Figure 11. Manufacturer data from Energizer® and Duracell® has been added to the graph by enlarging and interpolating charts found on their web sites. As should be expected, the firing set battery life tests are in close agreement with equivalent resistance data from the manufacturer. This battery life information was used to determine the wait time to impose on the firing set assuming all control was lost.

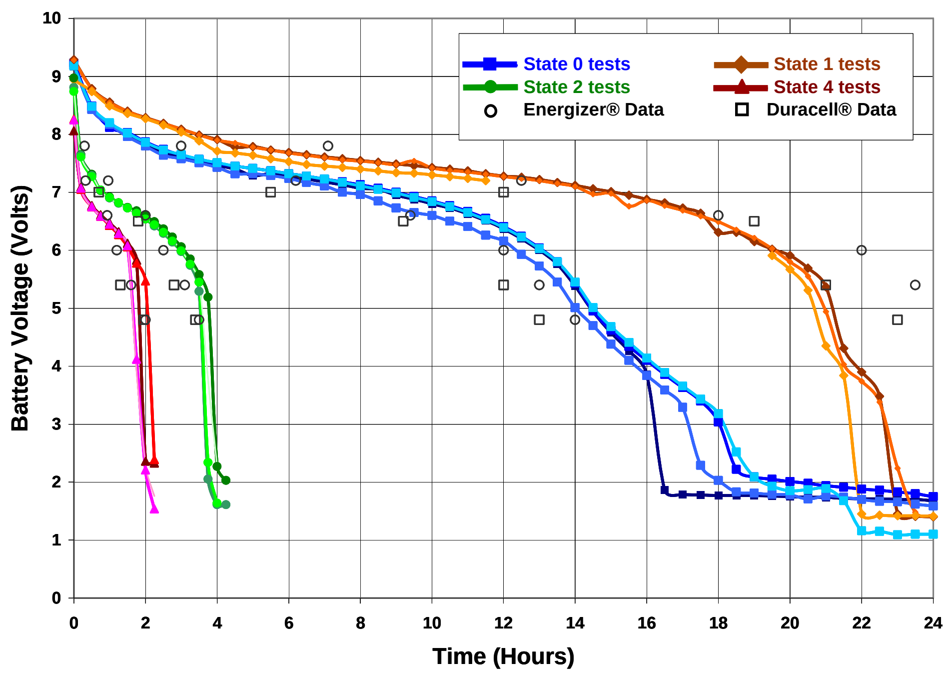

Figure 11 Battery Voltage versus Time in Battery Life Tests

From the data in Figure 11, it can be seen that the longest possible battery life is over 22 hours. Such a long wait time would have serious effects on any test schedule. However, two other factors need to be considered when determining a safety wait time. First, how safe is the state that the firing set is in and second, how low does the battery need to decay.

If control of the firing set is lost and the firing set is in State 0 or 1, the battery life is long, but there are 4 and 3 events, respectively, that must happen to get from these states to a firing event. It was considered very unlikely that this could happen. If control of the firing set is lost and the firing set is in State 2 or 4, the battery life is short, however only 2 and 1 event, respectively, is needed to go from these states to a firing event. This was considered to be the major safety concern.

From a large amount of test data, it was known that the firing set would only work about one out of four times when the battery voltage was at 6.5 volts, and was never observed to fire when the battery voltage was below 6.5 volts. The battery voltage has dropped below 6.5 volts for both States 2 and 4 with in two hours. This minimum time was then doubled to four hours to include a safety factor.

4.2. Consistency and reliability

Two different tests series were conducted to show consistency among the ten firing sets. The first of these test series measured the battery current draw for their four stable states on each firing set. The resulting data showed an average battery current of 46.7mA, 27.3mA, 167.9mA, and 258.1mA for the States 0, 1, 2, and 4, respectively. No state current varied by more than 3% for any of the ten firing sets. The second test series involved firing the firing set into a low impendence load and measuring the current for four different charge levels. The resulting data showed an average output current of 1030A, 955A, 909A, and 844A for the input voltages of 9.0v, 8.5v, 8.0v, and 7.5v, respectively. No output current varied by more than 8% for any of the ten firing sets. These test series provided strong evidence that the firing sets were operating identically. To address the reliability issue, a third test series was conducted that operated each firing set ten times for four different input voltages. In this test series a total of 400 successful tests were conducted on the firing sets.

One additional very important number is required for reliable firing set operation. Since the firing set is designed to bleed down the battery for safety reasons, there is a maximum time after which a reliable discharge will no longer be possible. To determine this time a fresh 9 volt battery was placed into a firing set and the voltage was monitored during three tests over a two hour period. The resulting voltage is shown in Figure 12.

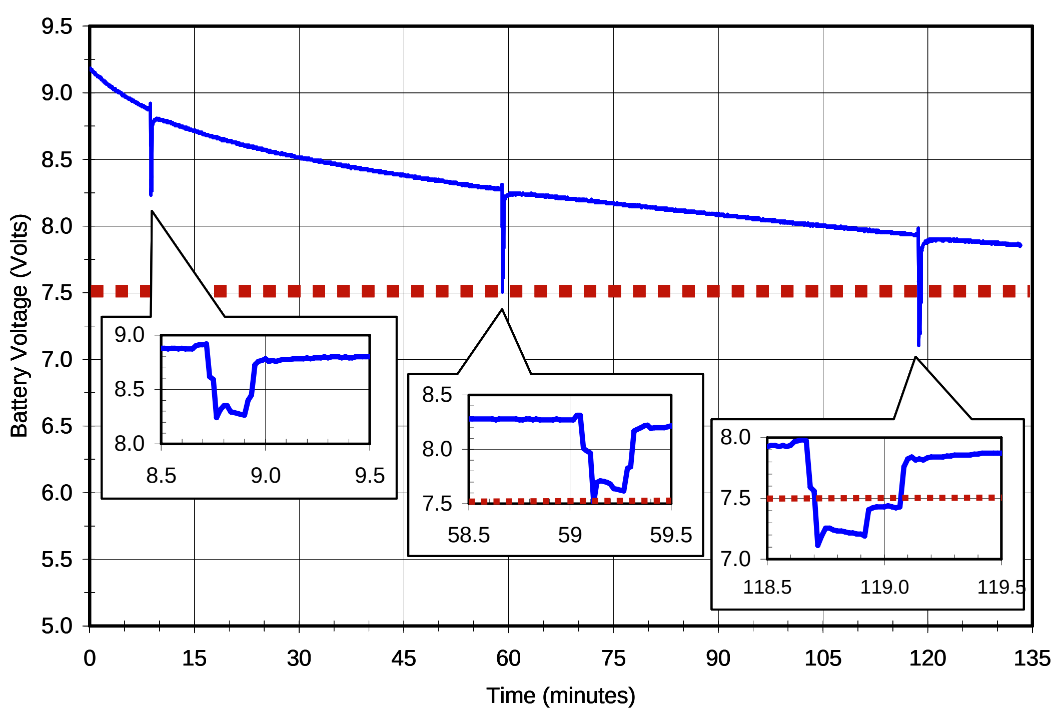

Figure 12 Battery Voltage versus Time for Three Discharges

About ten minutes after installing the battery, the firing set was keyed on, charged, and discharged to represent a firing line test. At the end of this first charge cycle, the battery voltage was around 8.2 volts and can be seen in the insert on the left of Figure 12. One hour after battery insertion, a second discharge was conducted. The battery voltage at the end of the second charge cycle is about 7.7 volts, and can be seen in the middle insert of Figure 12. The critical minimum voltage of 7.5 volts has been highlighted in a dashed dark red line for both the main graph and the inserts. Two hours into the battery life a third discharge was attempted. In this attempt, the battery voltage was down to about 7.2 volts at the end of the charge cycle. This third charge attempt did not get a Charge Complete indication light because of the low battery voltage, and a reliable discharge could not be guaranteed. Note; the battery voltage stays at the 7.4 volt level for about ten seconds because the firing set was not keyed off immediately after the discharge attempt. From this test, a maximum time of one hour and a maximum of one firing line test were imposed on a fresh battery in order to insure a reliable discharge.

4.3. Fault testing

In addition to the reliability testing, each firing set was fault tested. These tests consisted of sending the firing set control singles in the wrong order. In addition to the prescribed shut down sequence, four different incorrect control sequences were identified. From a full state of charge, each of the ten firing sets was tested ten times for each of the five shut down sequences shown in the Table 2. Five hundred shutdown tests were conducted with four hundred of these tests being preformed in a non prescribed sequence. During this entire testing not once did the firing set discharge into the load.

Table 2 Sequence of Switching During Shutdown
1) Charge Switch Off, Optical Key Off, Air Key Off (Prescribed Shutdown Method)
2) Charge Switch Off, Air Key Off
3) Optical Key Off, Air Key Off
4) Air Key Off
5) Controller Power Off

4.4. Operating instructions

Documenting the operating procedures is a critical step in getting safety approval for a new piece of potentially dangerous hardware that will be used on Eglin's ranges. This documentation is usually in the form of a safety Operating Instructions (OI). The safety OI identifies who is responsible, who to contact in case of an accident, what safety equipment is required, and a detailed list of the operating instructions for normal and fault conditions. In the safety OI for the Optically Controlled Firing Set, documentation included operating scenarios for the firing set in normal, abort, and misfire conditions.

4.4.1. Normal operation

The normal operations are basically the sequence of steps described in the section above on the controller. Normal operations of the firing set start when everything else involved in the test is ready. A fresh nine volt battery is placed into the firing set and a one hour shot clock is started. With just a fine wire across the firing line, the firing set is keyed on and discharged. This is the final firing set system check before a detonator and explosives are hooked up. The test area is cleared and secured, and EOD has possession of the fire set keys and performs the final detonator and explosive hook up. Once EOD is secure inside the control room, the test can proceed. After positive indications that the electrical / explosive event transpired correctly, the high voltage supply is keyed off and EOD returns to the test area to verify that no explosive residue is left. Since the explosives detonated, the condition/state of the firing set is irrelevant from a safety point of view.

4.4.2. Abort scenarios

The operating instructions for the abort scenario are very critical. An abort can be called at any time during the normal operations of the firing set up to the actual initiation of the firing sequence. If for some reason such as diagnostic instrumentation problems, a decision is made to abort the test, the abort operating instructions are followed. The key to an abort is to shut down the firing set and have the green safe light to come back on. With the green safe light on, it is known that the pneumatic switch has disconnected the nine volt battery, placed a shunt across the storage capacitor, and placed a short across the output leads. EOD can now safely approach the firing set and disconnect the detonator and explosives. If for some reason the green safe light does not come back on, a mandatory wait of four hours is observed in order to let the nine volt battery drain though the bleed resistors.

4.4.3. Handling a misfire

A misfire is the greatest safety concern when working with explosives. Under the misfire scenario, the firing sequence has been initiated and for some reason the explosives do not detonate. Several things can cause this sort of misfire; the fire set did not function right, the detonator did not initiate, or the explosive charge did not initiate. As of result of any of these problems, there are unexploded explosives left in the test area that must be cleaned up. The steps for a misfire are the same as the steps for an abort. The firing set is shut down and keyed off. If the green safe light comes on, the firing set is considered safe and standard safety procedures and wait times are applied to the explosive. If the green safe light does not come on, the firing set is not considered safe and a four hour wait time is applied to the firing set. Note; EOD will determine the necessary explosive wait time, and the wait time will be which ever is longer.

4.5. Operational testing

The firing set has proven to be an extremely valuable addition to test range capabilities. It has proven to be reliable in firing a variety of Reynolds, Inc. EBW detonators including RP-1, RP-87, RP4-SC and RP4-SFF both with and without the presence of high voltage. In pulsed high voltage tests the firing set has functioned properly when elevated in voltage by a MARX capacitor bank, a pulsed-high-voltage step up transformer, and a pulsed charged resonate capacitor circuit.

In an excursion from normal firing set duty, the set was used to produce a spark that triggered the first stage of a high voltage capacitor bank. Here again, the firing set performed well although some fore-shortening of the lifetime of the voltage comparator chip and the fiber optic receivers in the circuit card was noted. Versions of this firing set with larger energy storage capacitors and powered by AC-DC power sources are in use in AFRL/MN ranges and through all the subsequent modifications the device remains a safe, reliable component of explosive testing.

5. CONCLUSIONS:

In today's test environment, safety is everyone's responsibility. Early discussions with the safety board and range personnel resulted in the development of a firing set design that proved to be more than satisfactory in performance and safety features. Upon completion of the design, safety approval, and operational demonstration of the firing set, a U.S patent application was filed. The U.S. Patent and Trademark Office assigned the "Optically Isolated Firing Set" or "High Voltage Tolerant Explosive Initiation" the patent number 6,732,656 and an issue date of 05/11/04.