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Laboratories for Research and Development

PROCEEDINGS

OF

ELECTRIC INITIATOR SYMPOSIUM · 1963

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THE FRANKLIN INSTITUTE
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PREFACE

The 1963 Electric Initiator Symposium was attended by 334 people from 36 government agencies and 105 industrial organizations. This symposium was sponsored by Picatinny Arsenal under contract DA-36-034-501-ORD-3115RD, to bring together those concerned with development, research, manufacture, and ultimate end product of electric initiators.

The quality of the papers made the meeting a successful one, under the careful hands of the several chairmen. The papers with their discussions are given in these Proceedings; of the twenty-eight papers (paper No. 20 having been omitted) three were presented "by title only," appearing in the Proceedings, although not presented orally. Four classified papers are bound separately so that the unclassified papers can be handled with greater freedom.

It would not be practical to list individually all those staff members of The Franklin Institute who contributed to organizing and arranging the Symposium. Mr. E. E. Hannum, Manager of the Applied Physics Laboratory, was general manager. Sharing responsibility for program arrangement and execution of the many details of planning and running the Symposium were Raymond G. Amicone and Gunther Cohn.

For additional copies of these Proceedings, the request should be sent to Defense Documentation Center, Cameron Station, Alexandria, Virginia, 22314. Proceedings of earlier Symposiums (all classified Confidential) can be obtained from the same source, as follows:

1st Detonator Symposium, 1954 - AD-66 001

2nd Electric Initiator Symposium, 1957 - AD-153 579

3rd Electric Initiator Symposium, 1960 - AD-323 117

TABLE OF CONTENTS

SESSION I – New Developments

SESSION II – Problem Areas and Future Requirements

TABLE OF CONTENTS (CONT.)

WELCOME

Francis L. Jackson, Director

Laboratories for Research and Development of

The Franklin Institute

It is my pleasure to welcome you to The Franklin Institute and to the Fourth Electric Initiator Symposium. Contributors to this Symposium include the Army, Navy, and Air Force as well as the National Aeronautics and Space Administration and many contractors of each of these departments. We are also happy to have a representative of the United Kingdom on the program.

We are pleased that the Laboratories for Research and Development of The Franklin Institute have been chosen as a meeting place for these very important sessions. The stimulation of ideas and the exchange of information that will occur here and that will be recorded in proceedings to be distributed in the near future will certainly advance the state of the art of electric initiators.

You probably know that The Franklin Institute was founded in 1824 and is a completely independent, not-for-profit corporation. It includes a memorial to Benjamin Franklin, a science museum, a technical library, a computing center, and the laboratories for research and development which I represent.

The laboratory staff of approximately 330 scientist and engineers is engaged in research and development in the solid state sciences, mechanical, nuclear, and electrical engineering, chemistry, operations research, applied physics, astronomy, and aerospace. We will soon acquire a new laboratory building which will be erected just across the street from here.

Our facilities here are at your disposal. If any of you desire to visit the laboratories or if you have any problems, please contact Gunther Cohn, who is in charge of the arrangements or call upon any member of the Laboratories.

We are honored to have you with us and hope that you will enjoy your stay.

OPENING REMARKS

Col. Henry H. Wishart, USA
Commanding Officer, Picatinny Arsenal

We are gathered today for this Electric Initiator Symposium which is the fourth such meeting held. As most of you know, these sessions have been held every three years and are sponsored by one of the military services. The Army has the privilege of sponsoring the meeting this year.

These symposiums are held for the purpose of exchanging information and stimulating new ideas relative to improving the reliability, the versatility, and the efficiency of electroexplosive devices. I personally feel that we do not emphasize strongly enough the importance of these devices: they are the starting point of all explosive actions.

I look forward to today's meeting as I am sure all of you are. The presentations for today and tomorrow promise to be of real interest. I think that the list of papers is impressive and I am sure that the papers are going to make our gathering here worthwhile.

In closing, I would like to express my personal appreciation to the people here at Franklin who have worked hard to make the next two days a success.

SESSION I - New Developments

ABSTRACTS

1. <u>Development of an EBW Propellant Ignition System</u>   Joseph Pelphry
   <u>for Davy Crockett</u>

This paper describes the electric initiation system developed for
activating the propellant charge of the Davy Crockett. Briefly the
system consists of a converter storage-firing unit and an exploding
bridgewire primer initiator.

2. <u>The Delay Detonators MK 84 MOD 0 and MK 85 MOD 0</u>   R. M. Hillyer
                                                              F. V. Lowry

The delay detonators MK 84 MOD 0 and MK 85 MOD 0, which have nominal
delay times of 8 and 14 milliseconds respectively, have been developed
for use in penetration type warheads. These devices have a tolerance
on functioning time of $\pm$ 15% over the temperature range of -65F to
+ 200F. Physical construction, production techniques, and explosive
compositions used are discussed.

3. <u>The Apollo Standard Initiator</u>   Wm. H. Simmons

One hot wire electric initiator is used on all pyrotechnic devices and
system throughout the Apollo spacecraft. The concept and applications
of the standard initiator, general design considerations, fool-proof
and reliability aspects are presented, together with the development
program and the requirements for complete traceability and collection
of firing data. A method of indexing the electrical connector end
after manufacture of the initiator is discussed.

4. <u>Development and Functional Characteristics of the</u>   R. E. Betts
   <u>XM-6 and XM-8 Squibs</u>

This paper discusses the development and functional characteristics of
two Army exploding bridgewire squibs - XM-6 and the XM-8. These squibs
offer extreme protection against the hazards of accidental initiation by
extraneous energy sources such as RF, electrostatic, or induced high
current. Presented are squib design, performance and safety characteristics.

5. <u>Exploding Bridgewire Initiation of RDX With 50</u>   R. M. Hillyer
   <u>Millijoules</u>   R. H. Stresau

RDX has been reliably initiated with as little as 50 millijoules in an
exploding bridgewire detonator. Attainment of this level of sensitivity
required the optimization of such parameters as confinement, state of
aggregation of explosive, bridgewire dimensions, and circuit design.
Such optimization, in turn, required development of detonator fabrication
techniques, explosive preparation and loading methods, and specially
constructed circuit components.

6. <u>Characteristics of a Small Insensitive PETN</u>   Donald Baker Moore
      <u>Electric Detonator</u>

This paper discusses the development of an all-PETN detonator designed to
contain a limited quantity of explosive, 0.1 gram, and to be electrically
initiated with one joule, but which must be immune to very strong microwave
radiation.

7. <u>High Temperature Percussion Primers for PAD Systems</u>   T. Stevenson
                                                            T. Q. Ciccone

Percussion primers are under development to meet projected requirements
for propellant actuated devices at operation temperatures as high as 400°F.
In addition, the new primers and the more common standard types of lead
styphnate percussion primers have been evaluated at selected temperatures
between 200°F and 500°F.

1. DEVELOPMENT OF AN EXPLODING BRIDGEWIRE PROPELLANT IGNITION SYSTEM FOR DAVY CROCKETT

Joseph G. Pelphrey

Picatinny Arsenal, Dover, New Jersey

The purpose of the study conducted was to provide a safer, more reliable and less cumbersome propellant ignition system for the Davy Crockett type weapons.

The present method of propellant ignition for the Davy Crockett type weapons utilizes a mild detonating fuse. The ignition system consists of a mechanical firing device which initiates an M47 Detonator. The detonator then initiates an 80 foot length Mild Detonating Fuse (MDF). The MDF initiates a length of pyrocore which ignites black powder causing the propellant to burn.

The Mild Detonating Fuse System has some undesirable qualities which should be eliminated.

On the other hand and Exploding Bridgewire (EBW) propellant ignition system would have several significant advantages: It would be safer because it eliminates the use of primary explosives. The reliability of this type initiator is extremely high. The specific conditions required for the normal functioning of the EBW make accidental initiation less likely and adds to the safety of the system.

In view of the above, an EBW Propellant Ignition System for the Davy Crockett Weapon was proposed.

Development of a suitable EBW Propellant Ignition System involved

two major phases. One was the development of the detonator and the other was the development of a power supply. The problem of the power supply is basically one of designing an exceptionally small and light-weight power pack capable of sufficient output to initiate an EBW.

The development of the detonator involved primarily design of certain critical areas in the internal configuration and making the external configuration compatible with the existing Davy Crockett System.

The development of a power supply would necessarily involve two units. One would be a small power pack. Design requirements were established that the power pack deliver four to six volts. The second unit would be a converter-transformer capable of building up the low voltage to approximately 2200 volts and discharging into an exploding bridgewire initiator.

A satisfactory power source was developed which consisted of four "D" size, flashlight type batteries. These batteries were connected in series in a moisture proof aluminum box approximately 3" x 3" x 4". The box is equipped with a moisture proof push button switch and an output connector. (This slide gives a view of the top of the battery box).

The development of a converter-transformer consisted essentially of fabricating in a small package, the necessary electronic equipment to transform, store and discharge an electric pulse of sufficient magnitude to explode the bridgewire. An important component of this electronic package was the spark gap tube. A number of spark gap tubes, each of which was used as a switch to discharge the capacitor, was tested by

1-2

subjecting to discharge at the rate of one discharge per 1½ seconds for approximately 1000 times. The breakdown voltage was recorded on a brush recorder. In preliminary tests conducted the average discharge voltage was inconsistant, running considerably lower than the spark gap tubes were rated. After several unsuccessful attempts, however, a spark gap tube was obtained which recorded an average discharge voltage of 2200 with all discharges being within 200 volts of the average. This type tube was installed in the converter-transformer.

Several converter-transformer units were procured from General Laboratory Associates. These units were subjected to environmental and vibration tests. The converter-transformer unit was subjected to accelerations of around 20 g's at 500 and 400 cycles per second for approximately 10 minutes at each frequency. After the vibration tests were completed, the converter-transformer unit was satisfactorily run for about 1000 pulses. The converter-transformer also functioned satis-factorily at temperatures of -40°F and +125°F. However, at -40°F, the unit ran about 20 pulses and then shut off. The pulse rate was noticeably slower than when the unit was warm, but it was quite evident that the unit would operate an exploding bridgewire at -40°F. The converter-trans-former was run for 1068 pulses after 48 hours storage at 125°F. The pulse repetition rate was 5.85 pulses per second. The test results were considered entirely satisfactory. This is a schematic wiring diagram of the CT unit.

The development of a detonator was the other major phase in producing

an Exploding Bridgewire Propellant Ignition System for the Davy Crockett type weapons. The detonator assembly consists of an exploding bridgewire plug assembled to a detonator case which in turn is assembled to a primer holder. The primer holder holds a mild end primer assembled to a pyrocore cord. This shows the EBW plug and the metal parts of the detonator and the parts assembled. The pyrocore cord extends into the black powder charge. The black powder is ignited by the pyrocore which in turn causes the propellant to burn. The propellant supplies the force necessary to deliver the projectile to its target.

The detonator assembly is connected to the converter-transformer by a 10½ foot two-conductor cable. The cable conducts the high voltage pulse to the exploding bridgewire detonator in the gun. (Show slide) This slide shows the detonator assembled to the 10½ foot cable with connector on the other end to the converter-transformer. The converter-transformer is energized by the power supply through an 80 foot two-conductor cable.

Based on previous experience a charge of 106-2 milligrams of **PETN** was used to give a desired density of .948 to .907 gm/cc in the detonator.

Using this design, Voltage Sensitivity Tests were conducted with different size capacitors to fire the detonator. The average all-fire voltage using a 1 microfarad capacitor was about 620 volts, and the average no-fire voltage was 600 volts. Twenty-five detonators were tested.

A second group of 25 detonators were tested using a 0.375 microfarad capacitor. The average voltage of the all-fire items was 968. From these

tests it was concluded that a 0.375 microfarad capacitor was satisfactory and would be incorporated in the system.

Voltage sensitivity tests were conducted to compare the sensitivity of a bridgewire material identified as Secon Alloy # 443, with a 99.9% pure gold bridgewire. These tests showed no significant difference in sensitivity between the two bridgewires. The average all-fire voltage was 945 volts with the Secon # 443 wire, and 960 volts when the gold wire was used.

Using the firing unit already described reliability tests were conducted at ambient temperature on 178 detonators. There was one failure, but it was determined that this was due to wire damage. The detonator end of the 2-conductor cable carrying the high voltage electric pulse to the detonator was exposed to the detonator explosions for a good many firings. This destroyed the insulation and caused a short circuit. Again, when 156 detonators were conditioned at -40°F and fired,there was one failure. This failure was also attributed to a damaged wire resulting in a short circuit.

Transportation-Vibration Tests were conducted using 25 detonators, according to MIL-Std 303. All 25 detonators fired when energized by the firing unit.

A no-fire test was conducted on 25 items by subjecting each detonator to a current of 2.5 amperes for a 2-minute pulse. None of the detonators fired or dudded.

To further test the reliability of our Battery-Converter firing unit

the maximum tolerable line resistance was determined. After conditioning at -40°F for 24 hours the maximum resistance at which the converter would function was approximately 1.5 ohms. Then, resistance tests conducted on 80 foot lengths of 2-conductor wire indicated that the wire must not be smaller than 18 gauge. Eighty foot of 18 gauge 2-conductor wire gave a line resistance of 1.02 ohms. This is approximately .50 ohm under the maximum resistance at which the converter operates, and should assure reliable functioning of the converter. However, to provide even higher functioning reliability 16 gauge wire was used. A 2-conductor cable especially made for extremely cold climates was procured from Hatfield Wire and Cable Company, Hillside, New Jersey, and proved satisfactory when tested at -40°F.

About 30 detonators were assembled, 15 each, with XM77 and XM92 propellant charges. They were packaged, and shipped to the Aberdeen Proving Ground, Aberdeen, Maryland to be tested for the XM28 and XM29 weapon systems.

Eight charges were fired from each system, half of which were temperature conditioned at -40°F and half at +125°F. All of the firings were conducted with both systems emplaced on the ground using a gun elevation of 45 degrees. The converter was placed on the ground and located approximately seven feet to the side of the weapons, and approximately one foot in front of the muzzle for all rounds fired. The average ambient temperature was approximately 50°F throughout the testing period. All components functioned satisfactorily during this test.

As a result of tests conducted it is concluded that an Exploding Bridgewire Initiator is a safe, reliable and convenient way to initiate the Davy Crockett Propellant Charge.

The system has not found application because of objection to the battery type power supply. Work is continuing to eliminate batteries as the basic power supply. The development demonstrates the application of the EBW in propellant initiation for Davy Crockett type weapons and might possibly be applicable to improve reliability and safety in other artillery pieces.

Figure 1

Figure 2
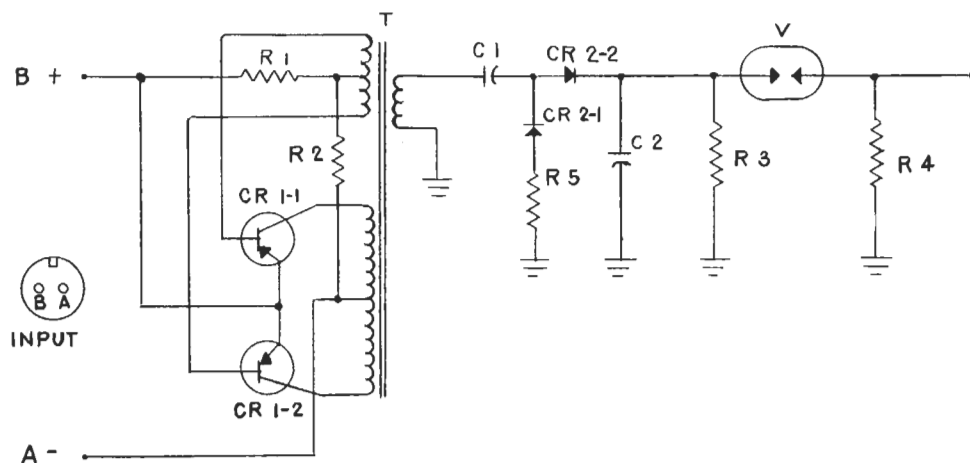
Figure 3
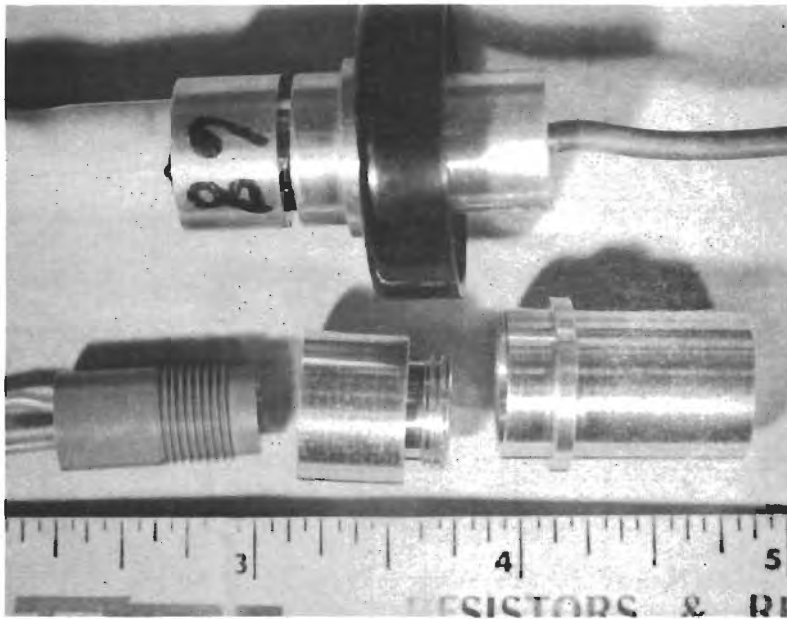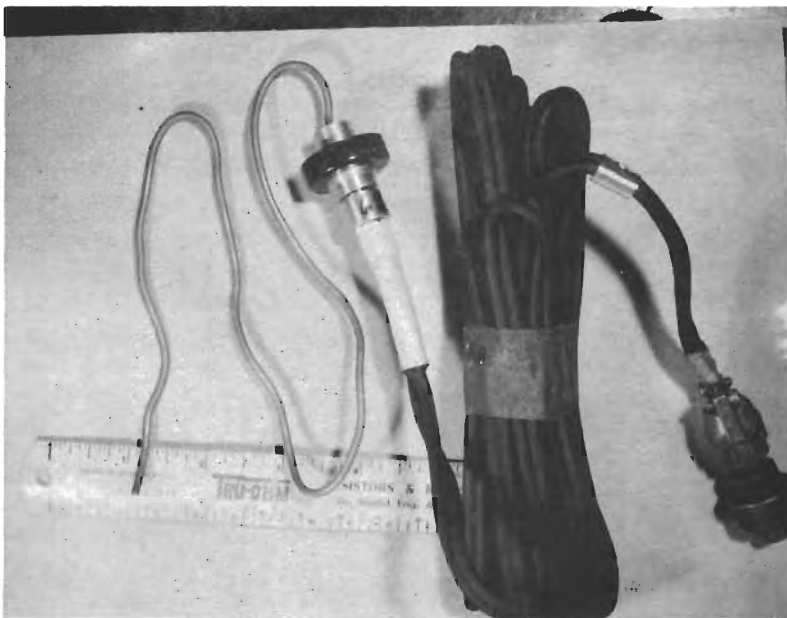
Figure 4

Figure 5

COMPARATIVE VOLTAGE SENSITIVITY BRIDGEWIRES OF
SECON ALLOY #433 AND OF GOLD, 99.9% PURE

	Secon	Gold
All-Fire Voltage	945	960
No-Fire Voltage	936	950
50% Fire Voltage	940	955

Figure 6

For Discussion Refer to Classified Supplement

2. THE DELAY DETONATORS MK 84 MOD 0 AND MK 85 MOD 0

R. M. Hillyer

F. V. Lowry

Naval Ordnance Laboratory, Corona

INTRODUCTION

The BULLPUP Missile System allows the launching pilot the selection of three warhead firing modes. Depending upon the type of target, he may select instantaneous firing or one of two delays. Such delays are effective in optimization of warhead effectiveness against various targets. Preliminary design studies indicated that a pyrotechnic delay system would be less expensive and more reliable than electronic delay systems, particularly in view of the extreme shock environments of warhead penetration of such targets as one inch armor or twelve inch concrete.

The requirement for pyrotechnic delays in BULLPUP has been satisfied to date with the delay detonators Mk 73 Mod 0 and Mk 74 Mod 0, which have delays of 6.5 and 12.5 milliseconds respectively. These detonators have performed satisfactorily but have several shortcomings including (1) ±20% tolerance on delay times, (2) a tendency for delay times to grow longer with storage, and (3) difficulty in assembly.

Accordingly, the delay detonators Mk 84 Mod 0 and Mk 85 Mod 0 have been developed, through reference (a), as replacements for the Mk 73 Mod 0 and Mk 74 Mod 0. The delay times have been adjusted to 8 ms and 14 ms to optimize warhead effectiveness in the more advanced BULLPUP B Missile.

DISCUSSION

The Delay Detonators Mk 84 Mod 0 and Mk 85 Mod 0 are identical with the exception of the composition and length of the delay charge. Table I gives the pertinent characteristics of these devices. Figure 1 is representative of both detonators.

Physical Construction

The basic design is hermetically sealed through a resistance weld at the flange. The flange was incorporated to improve the weldability in manufacture and to provide a mounting area for the detonator. The hermetic seal is required to maintain tolerance on the delay times as the burning rate of the delay composition is sensitive to moisture content. Previous detonators using this delay composition have depended upon an epoxy seal. A trend of increasing delay time with storage was noted. This has been attributed to the influx of small quantities of moisture. In addition the burning rate of the delay composition is somewhat sensitive to back pressure. Maintenance of a hermetic seal during burning gives a control of pressure. A pinhole leak will release the back pressure and allow 50% to 100% increases in the delay time.

The interior of the detonator is designed so as to prevent bypass around the delay charge. Interference fits between the Retainer and the Eyelet and between the Retainer and the Delay Charge Carrier confine all flame and products of combustion until the delay composition has been consumed.

A baffle and a wire mesh screen are included to assure that the delay charge is ignited non-violently and uniformly.

Explosive Charges

Table II lists the various explosive charge materials, quantities, and consolidation pressures. The intermediate and base charges are adjusted to give the same explosive output as the Mk 71 detonator. The igniter charge has been adjusted to reliably initiate the delay charge without bursting the case. Basic lead styphnate (milled to approximately 5 microns) was chosen to attain the desired bridge sensitivity yet withstand the upper temperature of 200°F. These charges are rather standard and require no further explanation.

The delay composition has been adjusted to the optimum for each delay time in this configuration. Fine adjustment - for each lot of delay composition - is attained by adjusting column height.

As mentioned previously the burning rate of the delay composition is sensitive to moisture content. Special precautions during manufacture are imperative to control moisture content of the explosives. The moisture content of all charges must be controlled to avoid migration of moisture from one charge to another after closure of the detonator. Moisture contents are limited to 0.1% by weight for all powders. In addition subassemblies are oven dried prior to closure.

The delay composition is also sensitive to vibration prior to consolidation. Vibration will cause the molybdenum to separate from the potassium perchlorate. It is therefore important that the bulk delay charge be isolated from sources of vibration during storage and that no vibrational loading aids be used in loading the delay charge.

Evaluation

The design has undergone a formal laboratory evaluation; the results are reported as references (b) and (c). This evaluation demonstrated the ability of the design to satisfy the requirements specified in Table I and the requirements of the following environmental tests:

MIL-STD-300	Jolt Test for Use in the Development of Fuzes
MIL-STD-301	Jumble Test for Use in the Development of Fuzes
MIL-STD-302	Forty (40) Foot Drop Test for Use in the Development of Fuzes
MIL-STD-303	Transportation Vibration Test for Use in the Development of Fuzes
MIL-STD-304	Temperature and Humidity Test for Use in the Development of Fuzes
Special Test	Aircraft and Missile Vibration Test for the BULLPUP Missile System

SUMMARY

The Delay Detonators Mk 84 Mod 0 and Mk 85 Mod 0, having nominal delay times of 8 milliseconds and 14 milliseconds respectively with a tolerance of ±15% over the temperature range, have been developed for use in the BULLPUP Guided Missile. These devices have initiation characteristics and explosive output similar to the Electric Detonator Mk 71 Mod 0. The development has been completed and the devices have been released to production. In the near future they will be characterized by the Franklin Institute, the resulting data to be included in the Electric Initiator Handbook.

References

(a) Contract N123(62738)25868A with Universal Match Corporation

(b) Aerojet General Corporation Report 0435-01(01)FP "Ex 9 and Ex 10
Delay Detonator Tests, Phase I", Contract N123(62738)24916A,
dtd January 1962

(c) Aerojet General Corporation Report 0435-02(02)FP "Ex 9 and Ex 10
Delay Detonator Test Program, Phase II", Contract N123(62738)
24916A, dtd March 1963
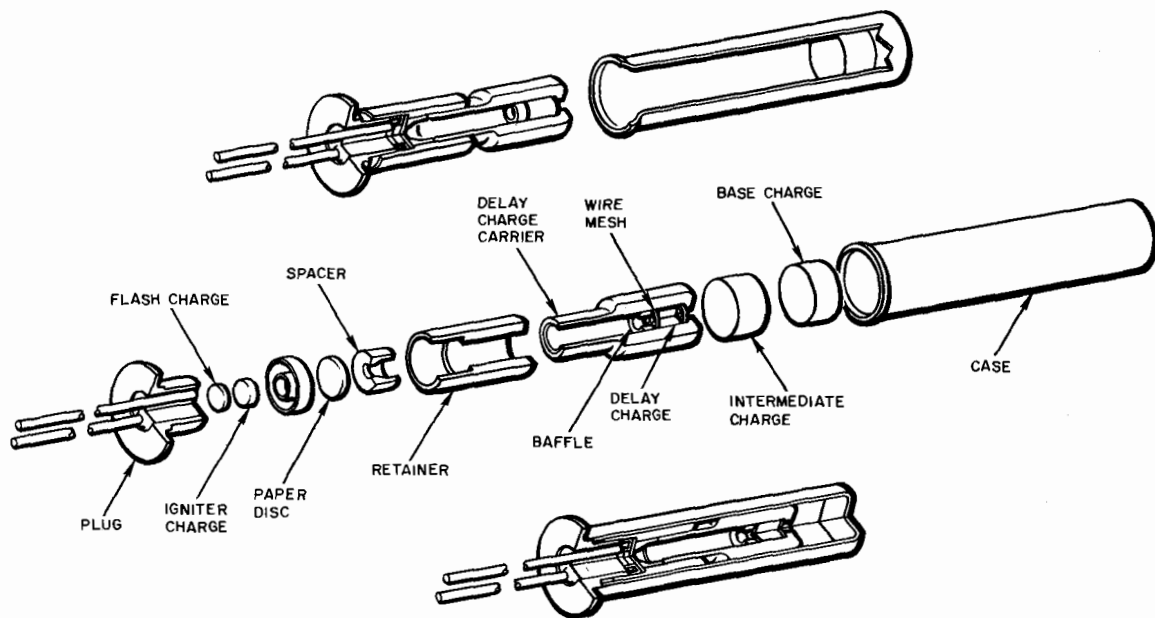
Figure 1.   DELAY DETONATORS, MK 84 Mod 0, MK 85 Mod 0

TABLE I

CHARACTERISTICS OF DELAY DETONATORS MK 84 MOD 0 AND MK 85 MOD 0

Size (inch)	790 x 193 dia
Bridge Resistance (ohms)	5 to 7
Insulation Resistance (megohms at 325 vdc)	50
Explosive output (dent in 1018 steel with detonator confined in polystyrene-mils)	9 min 12.5 min ave
Delay Time - milliseconds ±15% (tolerance applies over temperature range of -65°F to +160°F)	Mk 84 - 8 Mk 85 - 14
"All Fire" Pulse	1 ufd at 38.5 V
"No Fire" Pulse	1 ufd at 18 V
Applicable Specification	NAVWEPS WS 1639

TABLE II

EXPLOSIVE CHARGES USED IN THE DELAY DETONATORS MK 84 MOD 0 AND MK 85 MOD 0

Name	Material	Quantity (mg)	Consolidation Pressure - (psi)
Flash Charge	Basic Lead Styphnate	1.5	4,600
Igniter Charge	20/80 Zirconium/Lead Dioxide	5	1,200
Intermediate Charge	Lead Azide	90	2,000
Basic Charge	RDX	50	12,000
Delay Charge Mk 84	78/22 Molybdenum/Potassium Perchlorate	*	60,000
Mk 85	68/32 Molybdenum/Potassium Perchlorate	*	60,000

*Adjusted to obtain desired delay time.

For Discussion Refer to Classified Supplement

3. THE APOLLO STANDARD INITIATOR

William H. Simmons

Apollo Spacecraft Project Office
NASA Manned Spacecraft Center

CONCEPT DEVELOPMENT

Pyrotechnic devices and systems have been selected to perform many of the most critical functions in the Apollo spacecraft system because of their high power-to-weight ratio, their small size and their high reliability. These factors combine to permit the achievement of the extremely high reliability apportioned to the flight safety functions.

The philosophy adapted for the Apollo spacecraft is that the crew shall have the capability of abort during any phase of the flight mission. Since the electro-explosive initiator is the heart, and probably the most critical component of any electrically actuated pyrotechnic system, the reliability apportioned to the initiator has been established at 99.9 percent with a confidence level of 90 percent. To demonstrate this reliability for any initiator requires 2,303 firings without failure.

Obviously, if a number of "makes and models" were used in the spacecraft, the reliability demonstration of all of them would be prohibitive from the standpoints of both time and cost. If, on the other hand, a single initiator could be used, this demonstration could be more easily attained. By early 1964, over 4,000 initiators will have been fired in the Apollo program.

At the time the Standard Initiator concept was originally established for Project Apollo, it was desired to obtain a single device capable of performing three basic functions, namely, (1) initiate propellent charges, (2) initiate high explosive charges, and (3) operate directly small hot-gas-operated devices. It soon became apparent that while such a device might be within the state of the art, the time and cost of development were largely indeterminate. It was therefore necessary to modify the original concept and to use a conversion module for the detonation of high explosives. The Apollo spacecraft, therefore, uses a standard initiator which, by itself, performs two of the desired functions and is assembled into a standard detonator cartridge (Figure 1) to perform the third function.

SPACECRAFT APPLICATIONS

As an independent pressure cartridge the initiator directly operates a few small devices such as explosive switches in the electrical power distribution system and explosive valves in the command module reaction control system. The applications are relatively few however, and for most applications in the spacecraft the initiator is factory assembled (welded) into a family of general and special purpose cartridges (Figure 2).

Pressure Cartridges (Special Purpose)

For applications where a high pressure and/or a large volume of high pressure propellent gas is required, the standard initiator is assembled (welded) into appropriately sized pressure cartridges. At present, three such cartridges

are required:

    Type I: Drogue parachute mortar

    Type II: Main parachute pilot mortar

    Type III: Forward heat shield separation system (a thruster system).

The output of these three cartridges ranges up to 18,000 psi in a 10 cc
volume.

Igniter Cartridge (General Purpose)

This cartridge converts the output of the initiator to one suitable for
ignition of pyrogen units and pellet baskets of rocket motors. The output
of this cartridge is 600 calories (minimum) and 2,100 psi in a 10 cc volume.
The cartridge replaces the originally used EBW initiators to ignite the
three rocket motors in the launch escape system. The physical dimensions
of the cartridge were selected to retrofit directly into existing rocket
hardware. In the conversion from EBW to hot-wire ignition there has been
no discernable change in the motor ignition characteristics.

Detonator Cartridge (General Purpose)

This cartridge converts the initiator output to one having characteristics
suitable for reliable detonation of high explosive charges. Like the initi-
ator, the detonator cartridge is both field-assembled into explosive systems
and factory-assembled (welded) into specialized cartridges. As an independent
unit the detonator cartridge is used with various linear shaped charge systems
such as that used for separating the service module from the adapter after
insertion of the spacecraft into trans-lunar trajectory. The detonator,

welded into specialized cartridges, is used for such applications as the launch escape tower separation bolt.

Overall Usage in the Spacecraft.

Figure 3 shows the presently defined applications of the initiator and the initiator-based cartridges. These applications do not include any of those for the Lunar Excursion Module (LEM) since these have not yet been defined, however, all pyrotechnic functions in the LEM will be initiated by the Apollo Standard Initiator. Based on the experience of Projects Mercury and Gemini it appears very likely that the total number of initiators shown in Figure 3 will at least double during the course of development of the Apollo spacecraft system.

<div align="center">GENERAL DESIGN CONSIDERATIONS</div>

Size and Weight

As for all spacecraft devices, the size and weight of the initiator are extremely important. By itself the weight of the initiator is almost insignificant, however, the aggregate weight of all initiators carried in the spacecraft can be important. Every Apollo component is carefully analyzed to determine if even ounces can be eliminated, for 1 pound added to the spacecraft, requires carrying an additional 1.37 pounds of propellant for the spacecraft propulsion system. The size of the initiator is also critical; where it is not practicable or possible to provide redundant pyrotechnic devices the next best approach is to provide redundant initiators on each

device. If the size of the initiator is not sufficiently small then the
device may have to be enlarged.

Bridgewire Redundancy

Based on the experience of Project Mercury it is very probable that addi-
tional pyrotechnic functions will be added and the location and configura-
tion of now defined devices will be altered during the course of Project
Apollo. It may become necessary to provide for contingencies wherein only
a single initiator can be used in a device and where redundancy of devices
is impossible. In such instances the redundancy of the electro-explosive
interface in the initiator is essential, even though it would require
routing of the firing leads from both power sources through a single initi-
ator connector. To provide for such contingencies, a dual bridgewire system
(four pins) was selected for the Standard Initiator.

Environmental Conditions

The environmental conditions experienced by the initiators in the spacecraft
will vary according to their location and the degree of protection afforded
by the spacecraft structure. No specific degree of protection can be as-
sumed since all locations of the initiator are not yet defined. It is there-
fore imperative to establish "worst conditions" as the environmental require-
ments. The environments selected as the operating, or mission, environments
for the initiator are, essentially, those anticipated for equipment mounted
on the external surface of a lunar mission spacecraft with minimum special
protection. The more rigorous environments are outlined in Figure 4.

Naturally, the device must also meet the normal environmental requirements and those associated with storage, handling, and shipping.

Fool-proofing

An extremely important consideration in the design of initiators, in fact in the design of all pyrotechnic devices, is the prevention of misinstallation of the device and misconnection of firing leads. This problem frequently receives all too little consideration in the design of devices and systems. It must be assumed that if it is physically possible to install the device in the wrong place, or to connect the wrong firing leads, somewhere or sometime this will be done.

As a result of previous spacecraft experience the Apollo philosophy is to design every pyrotechnic device and system so that a person with very little training can install the devices properly (while wearing mittens, if possible) and, also, to design it so that he cannot install it elsewhere or connect the wrong firing leads.

Note (Figure 2) that the output ends of all threaded devices differ in size and thread with one exception, that of the detonator and igniter cartridge. This situation was unintentional and is being corrected. Since this example illustrates a dangerous trap for the unwary, an explanation is appropriate. At first, each systems design group had responsibility for procuring the pyrotechnic devices to be used in its systems; under these circumstances, the coordination and configuration control of the pyrotechnics was very difficult. The propulsion group procured EBW initiators for the

motors in the launch system and the mechanical devices group procured the
detonators for separation systems - and both groups specified 9/16-18UNF
threads. When motor ignition was changed to hot-wire it was desired for
the new igniter cartridge to retrofit existing rocket motor hardware in
order to prevent delay of the motor firing program. When it was discovered
that the two devices were interchangeable it was decided that the points of
installation of the igniter and detonator cartridges were sufficiently sep-
arated to reduce the possibility of misinstallation to an acceptable mini-
mum, especially since the physical configuration of the two devices differed
from each other. While this was acceptable as an interim solution, the
thread size of the igniter cartridge is being changed for spacecraft hardware.

Two positive actions have been taken by the prime contractor to preclude
similar situations from developing in the future, namely, (1) consolidation
of the responsibility for all pyrotechnic devices and systems (except rocket
motors) under a central "Ordnance Systems" group reporting to the Manager of
Structures Design, and (2) establishment of formal configuration control for
all pyrotechnics within the Ordnance Systems group.

The prevention of connecting the wrong firing leads to a pyrotechnic device
is another source of concern to the Apollo Spacecraft Project Office. An
obvious solution to such problems is, of course, the indexing, or clocking,
of the electrical connectors. Indexing low density items, however, intro-
duces logistics and cost problems and, in effect, converts general purpose
to special purpose items. The igniter cartridge is a low density item which
will illustrate the problem and its solution.

In the launch escape system of the Apollo spacecraft, two rocket motors
are mounted so that the installation points of the igniter cartridges are
only 8 inches apart (Figure 5). In this situation it is physically possible
for the four firing leads to be connected in a number of combinations re-
sulting in one of the following at abort initiation:

1. Launch escape motor fires (normal, desired action).

2. Tower jettison motor fires (catastrophic failure because of insuf-
   ficient thrust to lift the command module from the service module).

3. Both motors fire (catastrophic failure because the capability to
   jettison the tower and release the parachutes has been lost).

Initiator connector indexing could solve this problem, however it would in-
troduce logistics problems since only six igniter cartridges are required
per spacecraft, using the principle of commonality. Specializing the initi-
ators for these cartridges during initiator manufacture would aggravate the
logistics problem. It may be necessary to accept this solution because of
the importance of the functions involved, however, the proposed solution out-
lined below seems to be acceptable from both safety and logistics aspects and
is being considered.

Post-manufacturing System of Indexing

As indicated in Figure 6a, the initiator body (electrical end) can be manu-
factured with a number of undercut indexing slots, e.g., of trapezoidal cross-
section, so that keys, either flush with the inner surface (Figure 6b) or
protruding inwardly (Figure 6c), can be fitted into all slots except one.

The keys and keyways can be of such relative size that any key can be withdrawn by a special tool, but not without the tool. The resulting configuration (Figure 6d) is that of the standard initiator. At this point, the initiator is a common item and can be assembled into any device.

The initiator can then be assembled into detonator and igniter cartridges. The one o'clock key is withdrawn from the detonator assemblies and the two o'clock key from the igniter assemblies (Figures 6e and 6f). A gage is used to insure that the proper keys have been withdrawn. Similarly, all pyrotechnic cartridges can be indexed as indicated in Figure 7a; when detonators are assembled into special cartridges the connector can be further indexed (Figure 7b).

Returning now to the specific problem of igniter cartridges, since commonality in the manufacture of initiators is achieved, the major logistics problem has been solved. Igniter cartridges received at any launch site (for example, Cape Canaveral) are all indexed 12-2 and are interchangeable between the three motors. When a flight kit is assembled for a specific spacecraft any six cartridges (plus spares) can be withdrawn from storage. The six flight articles can be indexed at this time to convert them for specific motors as shown in Figure 8 and the spares left as common items to be indexed as may be required later.

The indexing technique explained above does not depend on a twelve slot system; it is readily adaptable to any current indexing or polarizing systems such as the Bendix PT series adopted for the Apollo spacecraft.

Once the connectors are indexed for specific motors it is essential that one of the igniter cartridges be converted to a different thread size to insure that, for example, the cartridge indexed for the tower jettison motor cannot be installed in the launch escape motor. If the mating hole in the launch escape motor is slightly larger than that in the tower jettison motor, the common ignition cartridge can be adapted to fit this hole. To adapt the cartridge, a threaded adapter can be installed on the appropriate cartridge at the time the connector is indexed; with both ends of the cartridges now indexed, fool-proofing can be achieved. Indexing and installation of adapters can, of course, be performed at the cartridge vendor's facility as well as at the launch site. This technique of indexing is now being studied for application to all Apollo spacecraft pyrotechnics.

Although the foregoing has departed somewhat from the specific subject of initiators the importance of fool-proofing both ends of all pyrotechnic devices justifies this rather lengthy discussion.

Shorted Mating Electrical Connector

From the previous experience on Project Mercury, shorting springs, clips and other devices of similar nature are considered inadequate from the standpoints of safety in handling and protection of the initiator pins. Shorted, mating electrical connectors will be used on the Apollo Standard Initiator. It may be desirable, when using indexed connectors, to provide shaped, color coded and inscribed caps for the shorted connectors to facilitate identification of the specialized devices.

INITIATOR DESCRIPTION

Because of its developmental status the internal configuration of the initiator will not be described at this time; this description will be confined to a few of the salient features.

The initiator specification control drawing is shown in Figure 9. The body size has been minimized consistent with other requirements. The washer is used to weld the initiator into other assemblies and may be either integral with the initiator body or welded thereto. Provision is made for the use of an O-ring in the field assembly of the initiator to other devices. A goal of 60,000 psi internal pressure capability has been established since some of the Apollo pressure devices operate at over 18,000 psi at the present time.

The initiator will meet the Atlantic Missile Range no-fire requirement of 1 ampere and 1 watt for 5 minutes (at 165° F) and has an all-fire current of 3.5 amperes. The bridgewire system consists of two firing circuits (four pins), each with a single bridgewire of 1.0 ± 0.1 ohms resistance welded to the pins and flush against the ceramic header.

RELIABILITY ASPECTS OF THE STANDARD INITIATOR

The Apollo Standard Initiator is presently being developed by two sources to a performance specification. These two competitive designs are both being used in the development of the various spacecraft systems and both will undergo qualification and extensive other evaluation tests. When

sufficient data are available, one of the designs will be selected as the spacecraft design. A design, manufacturing and quality assurance specification will probably be written around the selected design to assure identity of all production items.

Since large numbers of initiators are being fired in supporting the development and qualification of the various pyrotechnic devices and systems for the spacecraft, design deficiencies will be rapidly discovered. Further, analysis of the performance of the two initiators in these development programs will assist in the evaluation of the competitive designs. Since the performance and external configuration of the two initiators are identical it is also possible to exchange available initiators from one system development program to another as required.

Other advantages also accrue through standardization. The Apollo Spacecraft Project Office considers the electro-explosive interface to be the most critical part of any pyrotechnic device. Because this interface is identical on all initiators the firing of the initiator in one device can provide data which can be directly related to firings in other devices thereby building confidence in the interface and in both devices at the same time. The use of a standard "header" was considered but was discarded in favor of the complete standardized unit because of the capability of performing lot acceptance firing tests on the initiators prior to their installation in cartridges and other pyrotechnic devices. Of course, in either the standardized header or complete item concepts, a failure in one device reflects unfavorably on the reliability of other devices. With the

standard initiator there is a bright side to the picture even in this case, for subsequent firings in a number of devices will rebuild confidence quite rapidly.

One technique that can be used to build confidence in the reliability of a specific pyrotechnic device is to procure all devices for qualification, reliability assurance, device and systems tests, flight tests, and operational flights from a single lot. The various lot acceptance and systems tests preceding the first flight will consume a large percentage of the devices; and this percentage (of devices fired) will increase with each succeeding flight until the last one, during which the last of the lot will be fired. In effect, this technique results in an extremely large sample size for lot acceptance testing. This technique is being used on Project Gemini and would probably be beneficial for many projects having a relatively short life, one within the normal storage life of pyrotechnic devices.

Project Apollo, because of its extended life expectancy, cannot adopt this technique in its entirety although a modification of the technique can be used. It is feasible to procure all initiators to be used on a given flight from the same lot and thereby enhance the reliability of the most critical area - the electro-explosive interface. Figure 10 illustrates the use of this single-lot technique for a single flight of the Apollo spacecraft (less the LEM) - for example, in an extended orbital mission. The first column shows the numbers of the various devices required for flight, the second column an arbitrary but realistic and experience-based number of spares, and the third column the number of devices expected to be fired by the launch facility in preflight tests; the total of these columns is the number

of devices required at the launch site to support a single mission. Similarly, the next group of columns indicates the numbers of devices for lot acceptance tests, verification tests (if desired), and the total number of devices which must be manufactured. Assuming that each device incorporates one initiator, the total number of initiators are indicated in the next column. Again lot acceptance and verification test quantities are indicated, resulting in a minimum lot size of 414 initiators to support the single mission.

Now, working from right to left and considering only the lot acceptance and launch activity tests in which initiators are used, a total of 238, or 67.6 percent of the manufactured initiators will have been fired prior to flight of the spacecraft. It should be noted here that the quantities required for "verification tests" have been deducted from the total manufactured devices and initiators. It seems reasonable that these tests, if performed, should be included in the totals since every initiator and device is serialized and complete traceability required; thus there can be no "behind-the-scenes" tests of production items. If all tests indicated are considered then the total fired rises to 72.5 percent of the manufactured initiators. These figures do not include tests of systems and sub-systems at prime manufacturer facilities; they would also be included if performed.

The single-lot technique can be used to cover more than one flight, provided that the storage life of the devices is not exceeded. This, as in Project Gemini, will result in progressive buildup of demonstrated reliability and confidence. On the other hand, should each vendor of pyrotechnic devices

use different initiators, the confidence and reliability demonstration would be based only on the devices themselves and would be considerably less than when using the Standard Initiator concept.

TRACEABILITY AND DATA COLLECTION

To achieve the maximum benefits from the standard initiator concept traceability of all pyrotechnic devices and collection of data from all firings of all devices are essential. The Apollo pyrotechnics program provides for complete and immediate traceability of every initiator manufactured. These records show, by lot and serial number, all shipments of the initiators, their marriages into next higher assemblies (for example, into detonators) and all shipments of these assemblies, with the result that the current location of every initiator is known at all times. Should it be necessary, every initiator and/or device from any given lot can be recalled or set aside for re-examination very rapidly.

The data system will also provide for immediate reporting of data taken during any firing of initiators or pyrotechnic devices. The reported data will be continually analyzed to detect any deviation from specifications, and periodic reports of the demonstrated reliability of the lots can be published. The traceability feature of the system will permit ready determination of compliance with the firing data reporting requirements. Thus the total firing history of any lot can eventually be determined. Further, special analyses of the recorded firing data in off-limit conditions can be made whenever desired.

At present, this data system is being established for the Apollo program only. It will, however, be readily expandable to include all Apollo initiators used by any activity. It appears that an expanded program would be of benefit to all concerned, for the firing and traceability records obtained from each user of the initiator could support all participating activities.

FUTURE PLANS

Several years ago the NASA Manned Spacecraft Center organized a "Pyrotechnics Panel" consisting of representatives of all MSC Project Offices, the research and development divisions, and the organizational elements concerned with safety, preflight and flight operations of manned spacecraft. One goal of this panel is the establishment of the performance and design requirements for a Standard Manned Spacecraft Initiator. Although all the requirements have not yet been formalized, many of the desired features have been incorporated into the Apollo Standard Initiator, which therefore represents an MSC interim-standard device.

Other panel committees are studying other aspects of pyrotechnic devices and systems such as test philosophy, methods, and instrumentation; storage and handling techniques; and identification and traceability methods. The results of panel activities are being incorporated into Project Apollo pyrotechnics insofar as the project schedule permits. The inclusion of the Apollo data collection system into an overall MSC data system for all spacecraft components will probably be accomplished in the relatively near future.

Figure 1. - Apollo standard initiator and Apollo standard detonator

Figure 2. - Apollo pyrotechnic cartridge family

Figure 3. - Apollo pyrotechnic functions & devices
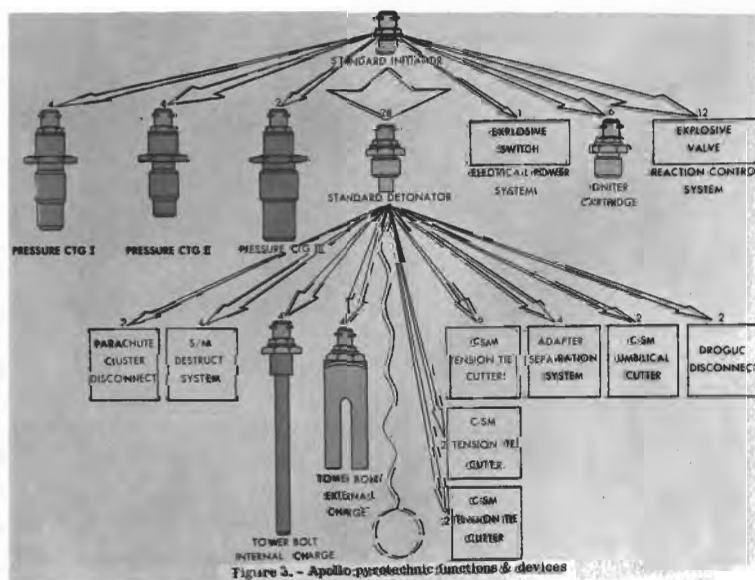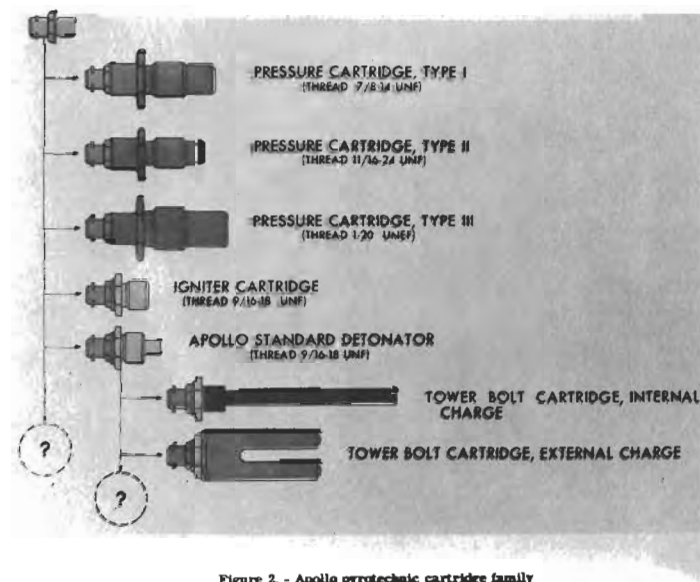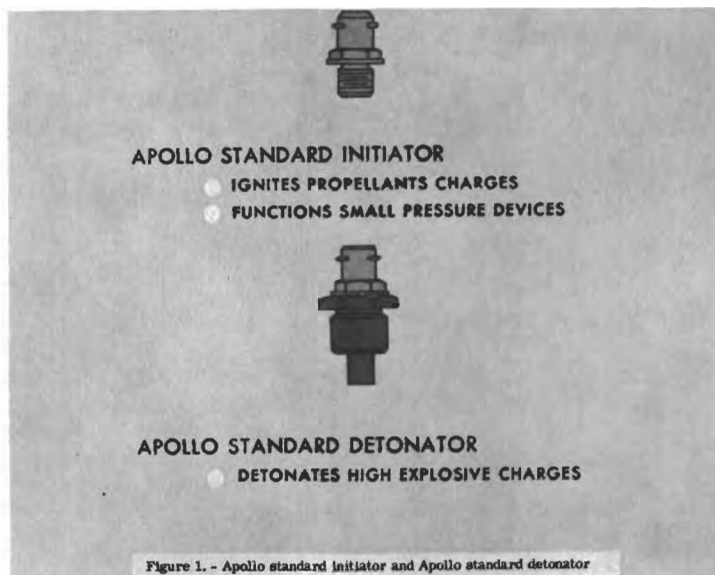
TEMPERATURE	-200 °F TO +300 °F
ACOUSTICS	4.7 TO 9600 CPS
	145 TO 168.5 DECIBELS
VIBRATION	COMBINED RANDOM AND SINUSOIDAL
	5 TO 2000 CPS
OXIDATION	100% OXYGEN @ 5 PSIA FOR 400 HOURS
VACUUM	7.5×10^{-10} mm Hg

Figure 4. - Apollo initiator environments (partial)

Figure 5. - Igniter cartridge installation problem

IGNITER CARTRIDGES

LAUNCH ESCAPE SYSTEM

⊙ IGNITER CARTRIDGES

PITCH CONTROL MOTOR

TOWER JETTISON MOTOR

8"

LAUNCH ESCAPE MOTOR

Figure 6. - Connector indexing system

(B)   (C)

(A)

INITIATOR (D)

DETONATOR (E)

IGNITER CARTRIDGE (F)

Figure 7a. - Indexed family of Apollo pyrotechnic cartridges

A-SCREW TYPE CARTRIDGES

OPEN KEYWAYS

12   APOLLO STANDARD INITIATOR

12 & 1   APOLLO STANDARD DETONATOR

12 & 2   IGNITER CARTRIDGE

12 & 3   PRESSURE CARTRIDGE TYPE I

12 & 4   PRESSURE CARTRIDGE TYPE II

12 & 5   PRESSURE CARTRIDGE TYPE III

Figure 7b. - Indexed family of Apollo pyrotechnic cartridges

12-1-6   CARTRIDGE, TOWER SEPARATION BOLT (INTERNAL CHARGE)

12-1-7   CARTRIDGE, TOWER SEPARATION BOLT (EXTERNAL CHARGE)

12-1-8   CARTRIDGE, DROGUE DISCONNECT

B-CARTRIDGE ASSEMBLIES USING DETONATORS AS INTEGRAL COMPONENTS

Figure 8 — Special indexing of igniter cartridges

KEYWAYS OPEN	APPLICATION
12-2-9	LAUNCH ESCAPE MOTOR
12-2-10	PITCH CONTROL MOTOR
12-2-11	TOWER JETTISON MOTOR

Figure 8. - Special indexing of igniter cartridges

Figure 9 — Apollo standard initiator specification control drawing

WASHER SHALL BE CONCENTRIC WITHIN .005

PIN B

.563 +.002 -.010

CONN TO MATE WITH BENDIX PIGMY PT06CE 8-4S

DRILL #60 (.040 DIA) 2 HOLES

PIN A

KEY

PIN C

PIN D

.060 MAX

.030 ± .005

.010 ± .003

.470 ± .005

.750 DIA

PERMANENT IDENTIFICATION
MFGR'S SYMBOL & SER. NO.
SCD DASH NO.
DATE OF MFG.

.720 DIA

45° ± 1°

.500 ± .005 DIA

60° ± 1° (TYP)

DETAIL OF WASHER USED TO PROVIDE FLANGE SHOWN IN SECT A-A

0.82 MAX

.317

.314 ± .005

.053 MAX

WASHER RESISTANCE WELDED AND BRAZED

3/8 - 24 UNF - 3A THD

.053 (REF)

.020 +.010 -.000 R (TYP)

.080 ± .015

SECTION A-A

WIRING DIAGRAM
A B C D

Figure 9. - Apollo standard initiator specification control drawing

Figure 10 — Initiators fired from one flight lot prior to launch

	LAUNCH SITE						PYRO DEVICE VENDOR					INITIATOR VENDOR
	FLIGHT ARTICLES	SITE TESTS	FLIGHT SPARES	TOTAL REQUIRED	LOT ACC TEST	VERIFICATION [1] (IF DESIRED)	TOTAL MANUFACTURED [2]	ORDERED (PREVIOUS COLUMN ± 10%)	LOT ACC TEST	VERIFICATION [2] (IF DESIRED)	TOTAL MANUFACTURED	
PRESS CTG TYPE I	4	16	4			28						
PRESS CTG TYPE II	6	24	12	13	6	42						
PRESS CTG TYPE III	2	8	4	4	2	14						
IGNITER CTG	6	24	12	13	6	42						
BOLT CTG, INTERNAL	4	16	8	8	4	28						
BOLT CTG, EXTERNAL	4	16	8	8	4	28						
DROGUE DISCONNECT, CTG	2	8	4	4	1	14						
DETONATORS, SEPARATE (1)	16	64	32	18	8	88	355	39	39	70	414	
INITIATORS, SEPARATE (1)	13	52	26	13	6	71						
MINIMUM FIRED BEFORE FLIGHT			114	85	42		39	90	39	70	298/332 [3] 67.6%	
TOTAL FIRED (INCL VENDOR FIRINGS)			114	85	42		39	120	39	70	300/414 [3] 72.5%	

NOTES:
1) DEVICES INSTALLED ON SPACECRAFT AS SEPARATE ITEMS
2) ARBITRARY QUANTITY. 1/2 OF LOT ACCEPTANCE SAMPLE
3) OMITS LOT VERIFICATION TESTS (62 UNITS)

Figure 10. - Initiators fired from one flight lot prior to launch

3. DISCUSSION

Mr. Cameron of Douglas Aircraft asked for a comment on the fact that EBW devices were not used.

Mr. Simmons said that EBW system was originally used in the launch escape system but was discontinued because of problems. Weight is another problem. There are 60 EEDs in the command and service module that consume precious weight allowance. It is our belief he added, that the development of EBWs is not as advanced as that of hot-wire devices. He pointed out further that the hot-wire devices are one-amp, one-watt and will meet AMR requirement for no-fire sensitivity.

Mr. Lipnick of Harry Diamond Laboratories asked if the effect of space radiation had been taken into account in these devices. Mr. Simmons affirmed that this could be a problem but cautioned that many facets of this problem were to this date undefined. Static electrical charges upon lunar orbit, separation, docking and re-entry ionization fields and other problems have yet to be completely defined.

The minimum all-fire current at -200°F was affirmed to be 3 to 3.5 amperes and the resistance of the EED/1 ohm, in answer to a request for this information by Mr. Massey of the Naval Weapons Laboratory.

A person from AFMTC asked if some flexibility was being lost by going to the coded system, for example in emergency repairs such as may be required on the moon. Mr. Simmons indicated that most of the components are inaccessible for repairs.

Mr. Beard of Atlantic Research Corporation asked how many wires were planned to be used with firing circuits. Mr. Simmons replied that two completely independent systems are used, including firing lines, batteries and controls. These batteries never see anything but bridgewires.

Mr. Rosenthal of STL asked if the 1 amp, 1 watt and functioning time at 3.5 amperes and 200°F had been qualified. Mr. Simmons said that these were aims, and that current developments were not up to qualification at this time.

Mr. Forbess of GLA asked if any stated RF environments must be met. Mr. Simmons replied that this area must still be defined. The current assignment is to determine what problems exist.

Mr. Forbess then asked what weight assignment had been given to the power source for the low voltage squib compared to that required for an EBW. Mr. Simmons answered that the batteries are small and that he has no comparative data on the weights of one system against the other.

Mr. Bankston of Hi-Shear asked if there were safe-and-arm devices for the EED. Mr. Simmons said that there are none in the launch escape system, and none in the spacecraft or command module. So far, none has been required on the adaptor separation system. If there is a service module system, we will probably have to safe-and-arm the propulsion of that system.

Mr. Bankston asked if there were weight limitations here. Mr. Simmons said there was, adding that ounces count. The launch weight is 90,000 lbs. and 6500 lbs are being brought back to earth. The weight penalty on LEM or command and service module is heavy.

Mr. Heinemann of Picatinny Arsenal said that a building-block technique was being used on Apollo. He asked if this same technique is being applied to other spacecraft areas, and in particular to the initiators being used.

Mr. Simmons replied that there is a Pyrotechnic Panel at MSC with wide representation from various activities and projects in MSC. Some criteria generated by the panel have been used in this initiator. It may be considered a first step in standardization. The hope is to collect a great amount of performance and reliability data on the initiator.

Mr. Beard of Atlantic Research asked if arming was to be remote or on the pad. Mr. Simmons said that the main pyrotechnic buss is armed before launch, as is the abort buss. The earth landing buss is not armed until it is needed. As soon as a task is completed, that particular function is removed from the buss to reduce chances of battery drain. Single failure philosophy is used, because double failure philosophy is just too rough.

Mr. Rosenthal of STL said that a Military Standard is being circulated that was generated by ASD of AFSC. Its purpose is to get standardization and essential cataloging of all ordnance items. He suggested that the services and NASA should get together on this and form an organization for initiators similar to the SPIA currently active in rocket propellants.

Mr. Brown of Bureau of Naval Weapons asked whether "in-house" or vendor capability was being used.

Mr. Simmons answered that vendors are currently being used in two parallel programs. After exhaustive testing one or the other will be chosen. Perhaps a design or manufacturing specification will be written so that no changes can be made unless MSC or North American says so.

4. DEVELOPMENT AND FUNCTIONAL CHARACTERISTICS OF THE XM-6 AND XM-8 SQUIBS

R. E. Betts

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Redstone Arsenal, Alabama

Past observations and tests proved that conventional types of squibs are subject to accidental firing by RF energy produced by radar and radio; electrostatic energy produced by aircraft, moving vehicles, machinery, and humans; and energy from other sources such as inductions from high current transmission lines. The squibs may be initiated not only by transmission of these energy forms through the bridgewire, but also by electrostatic discharges which occur within or through the pyrotechnic.

The increasing use of helicopters, more powerful radars, and other equipment producing high electrostatic and electromagnetic fields necessitated the development of squibs which would give the maximum protection against accidental ignition from these sources. This development was of vital concern to the Army Missile Command, as there is a continuing need to maintain the status of ignition technology in advance of missile requirements. Consequently, a program was initiated in the Command's Propulsion Laboratory to develop a safe and reliable squib.

The exploding bridgewire techniques were chosen for this work, since all past experience indicated this type of squib offered the greatest safety possibilities. The EBW squibs are superior to the conventional squibs in that the pyrotechnic is relatively insensitive to heat and the bridgewire must literally explode to produce ignition. The wire explosion is brought about by a sudden surge of very high electrical energy in the bridgewire, and the design of the squib can be controlled by matching the pyrotechnic to the wire explosion.

The program produced two highly satisfactory squibs -- the XM-6 and the XM-8. The XM-6 is a "screw-in" type, which was designed primarily for use with the HERCULES Missile. The XM-8, a "Phenolic plug aluminum case" type similar in size to the Mark-1 and M-3 squibs, was developed for general ignition use. The experimental work on the XM-6 was performed at Thiokol Chemical Corporation, Redstone Division, under contract from the Army Missile Command, while the XM-8 was developed in-house.

DESIGN REQUIREMENTS

In order to eliminate the hazard of electrostatic charges through the pyrotechnic, the initial designs provided for completely encasing the mixture in a Faraday shield and keeping the bridgewire free of explosive material. The wire explosion would be used to rupture the shield and ignite the encased pyrotechnic.

The functional design requirement (Table 1) specified that the squib must operate with the application of 2,000 volts from a 1-microfarad capacitor when discharged through 16 feet of 52-ohm coaxial cable. This was the nominal firing voltage and capacitance then being used by EBW firing units in the field. The nonfunctional specifications required that the squib not function with the application of 1 ampere current continuously applied for 8 hours (it was understood at this time that RF currents of 1 ampere had been measured in igniter circuits); that it not function with the application of 30,000 volts from a 3,000-micromicrofarad capacitor discharge, either through the leads or case to leads (these values were based on data from helicopter studies which gave the maximum voltage ever measured as 30 kilovolts at a 20-foot working altitude and the maximum capacitance measured at 2 feet); and that it not function when 28 volts from a low impedance source is applied to the bridgewire (this voltage was estimated to be the maximum that would exist on the missile or aircraft from battery sources). Also, the squib must not function when exposed to 220 volts, 400 cycles, either case-to-leads or through the leads (this voltage value was selected as the maximum power available at the HERCULES site for which the squib was intended), and it was proposed to use either arc gaps or diodes in the leads to meet the through-the-lead requirements. The squib must not function when a current from 0 to 100 amperes dc from low impedance sources is applied to the bridge.

This value was arbitrarily chosen because other EBW's were meeting

this requirement and, if the voltage requirement could be met, a

current of at least this value would be automatically obtained.

XM-6 SQUIB DESIGN

Figure 1 shows the final design of the XM-6 squib. Among the

features are a ceramic metal header hermetically sealed at the end,

and a metallic diaphragm which is part of the Faraday shield and sepa-

rates the pyrotechnic from the bridgewire. You will note that we

failed to meet one of our primary objectives, in that an explosive

composition is in contact with the wire. It was found that with this

physical shape we could not reliably rupture the diaphragm and still

maintain the safety requirements. Diaphragm materials of steel,

aluminum, and lead in thicknesses of 1 mil were tested with various

diameters of bridgewires of platinum, gold, their alloys, and pyrofuse

wire. It was decided that if the functional and safety requirements

could be met with an insensitive composition on the wire, the no-

material-on-bridgewire requirement would be waived. The composition

found to give satisfactory results was pentasil, which is PETN diluted

with sodium silicate.

It was found in early experimental models that the squib would

function when exposed to the 30-kilovolt electrostatic discharge case

to lead. This discharge occurred on the diaphragm base and caused

functioning either by local heating or by penetration of the diaphragm.

To overcome this, a metal ring was placed at the squib base (labeled "gasket") so that the path of least resistance would be between the ring and the bridgewire.

The functional characteristics of the XM-6 are shown in Table 2, the safety characteristics in Table 3, and the environmental characteristics in Table 4.

XM-8 SQUIB DESIGN

Figure 2 shows the XM-8 squib design. Here again we have the pyrotechnic encased in a Faraday shield. An aluminum cup holds the charge and forms an interference fit with the case; a plastic spacer supports the cup and controls the space around the bridgewire; a hole in the spacer permits the wire explosion to be concentrated at a point. In this design we were able to achieve our objective of keeping the bridge free of material.

The greatest problem encountered was making the diaphragm end of the cup sufficiently thin to give reliable functioning at the required energy level and yet remain within the specified safety limits. It was found that the requirements could be met by coining the end of the cup from .7 to 1.0 mils and adding a focusing spacer and a shear spacer. The shear spacer serves only to control the area of rupture: without this spacer the entire end area of the diaphragm would be deformed and, in some instances, rupturing would not occur.

Air gap holes were put in the plug to meet the high electrostatic requirement. A high-energy spark within the space around the bridge-wire would heat the residual air, causing a pressure burst effect at the thin end of the diaphragm, and this, in turn, would initiate the squib. The air gap causes the spark to be external to the space around the bridgewire.

The characteristics of the XM-8 are shown in Table 5.

RF PERFORMANCE TESTS

Tests performed on the XM-6 indicated that the squib would not fire, but could be dudded, by the application of 430 watts (3.65 mc) of RF power delivered directly to the bridgewire. Further tests showed that the dudded XM-6 squibs could be initiated with the application of high RF voltages (several thousand volts) across the squib; undudded squibs, however, could neither be dudded nor fired when exposed to the same high RF voltage.

In similar tests on the XM-8, the squib was fired with the input of 430 watts of RF energy. It was found that with this energy applica-tion the bridgewire burned in two, forming a semi-conductive path across the phenolic plug with resistances in the range of 10 to 70 ohms. The continued application of RF energy would thus heat the plug and cause squib functioning. In no case could an XM-8 or an XM-6 be initi-ated by RF energy transmitted by antenna coupling.

DESIGN IMPROVEMENT CONSIDERATIONS

It was found that with two opposing diodes placed in the squib circuit, giving the 220-volt, 400-cps protection, both the XM-6 and XM-8 could be fired reliably from the energy source of 1 microfarad, 2,000 volts. However, these diodes could be defeated if exposed to electrostatic sparking (7,000 volts, 500 micromicrofarad) in that the diodes could be shorted closed. It appeared that the use of arc gaps was the best approach to providing 220-400 cycle ac safety through the bridgewire. However, this problem was not pursued; it was felt that if specific missile systems required these gaps they could be made in an adapter and attached to the squib or placed in the squib circuit.

With the XM-8, efforts were made to create a gap at the bridge-wire by applying constant current or constant voltages to the wire to just over the fusion point. However, it was found that the gaps were not uniform and that reliable functioning did not occur. Another method tried was creating gaps in the bridgewire by pulsing the wire with current to produce thermal contraction and expansion. Several such pulses would result in a fracture in the wire, which would give gaps with voltage breakdowns of approximately 300-500 volts. Since the wire is not rigid and would undergo vibrations, it appeared impossible to keep the gaps uniform, and this approach was discontinued.

Efforts to seal the gaps with some dielectric adhesives resulted in an increase in the gap dielectric strength and affected the reliability of the squib.

Ordnance Corps drawings and specifications are available for the XM-6. The XM-8, although completely developed, is being remanufactured for proof of production.

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|                          Table 1                              |
|                                                               |
|         DESIGN REQUIREMENTS FOR XM-6 AND XM-8 SQUIBS           |
+---------------------------------------------------------------+
|                                                               |
|  Functional -    Fire at 2,000 v; 1 μf; 16 ft of 52-ohm cable.|
|                                                               |
|  Nonfunctional:  1.  1 amp for 8 hrs                          |
|                                                               |
|                  2.  Discharge of 30,000 kv, 3,000 μμf        |
|                                                               |
|                  3.  28 v, battery source                    |
|                                                               |
|                  4.  220 v, 400 cps                          |
|                                                               |
|                  5.  0-100 amp dc                            |
+---------------------------------------------------------------+
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+---------------------------------------------------------------+
|                          Table 2                              |
|                                                               |
|          FUNCTIONING CHARACTERISTICS OF XM-6 SQUIB            |
+---------------------------------------------------------------+
| 1 | Functioning time (2,000 v, 1 μf) unaffected from -65°F to |
|   | 160°F or altitude (250,000 ft).                           |
|   |                                                           |
| 2 | Functioning time < 0.5 msec over temperature range and    |
|   | altitude.                                                 |
|   |                                                           |
| 3 | Recommended firing energy - 2,000 v from 1.0 μf through   |
|   | 16 ft of 52- or 7-ohm coaxial cable.                      |
|   |                                                           |
| 4 | Capable of firing after bridgewire fusion from < 5 amp.   |
|   |                                                           |
| 5 | Functioning probability:  *50%   - 770 v  ]               |
|   |                           *95%   - 880 v  } 1.0 μf        |
|   |                           *99.9% - 1,000 v ] 16 ft cable  |
+---------------------------------------------------------------+
| *95% confidence                                               |
+---------------------------------------------------------------+
```

Table 3

SAFETY CHARACTERISTICS OF XM-6 SQUIB

No-fire at:
1. 1 amp for 16 hrs at $165°F$.

2. 0 to 200 amp.

3. 0 to 36 v.

4. 500 vdc, 1.0 μf

5. 30 kv, 3,000 μμf (1350 mj) case to leads.

6. 25 kv, 3,000 μμf (937 mj) through leads.

7. 220 vac, 400 cps, case to leads.

8. $600°F$ for 8 hrs.

Table 4

ENVIRONMENTAL CAPABILITIES OF XM-6 SQUIB

Functions satisfactorily after:

1. Mil-std-304.

2. Mil-std-306.

3. 240 days at $160°F$.

4. Sequential exposure to temperature cycling, acceleration, shock, and vibration at extremes of temperature and altitude.

Table 5

CHARACTERISTICS OF XM-8

Functioning: 1. Functioning time < 4.0 msec from 2,000 v,
                  1.0 μf. 20 ft of 52-ohm coaxial cable
                  through -100°F to 200°F.

               2. 50% probability 1,350 v, 1.0 μf.

               3. Average delay 1.3 msec - σ 0.38 msec.

No-fire safety: 1. 1 amp, 16 hrs, 165°F.

                2. 0 to 50 v, 0 to 350 amp.

                3. 220 vac, 400 cps; also 1,600 vac, 60 cps
                   (case to leads).

                4. Dielectric strength case to leads, 4,000 vdc.

Environmental - Satisfactory functioning after:

               1. Mil-std-304.

               2. -100°F to 212°F thermal shock.
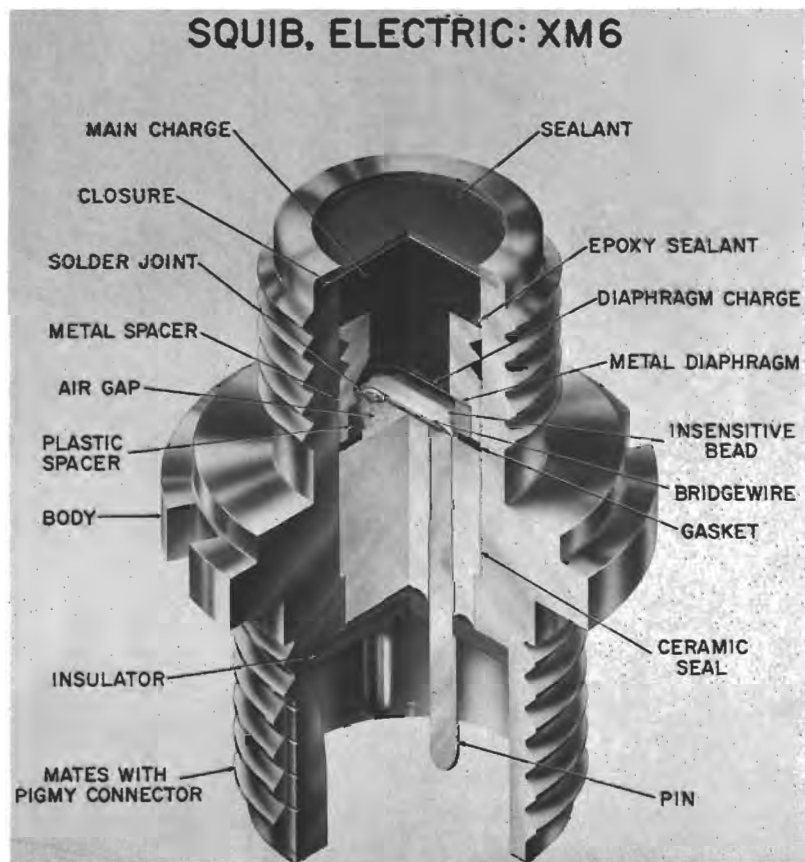
               3. 1.0 mm Hg (155,000 ft).
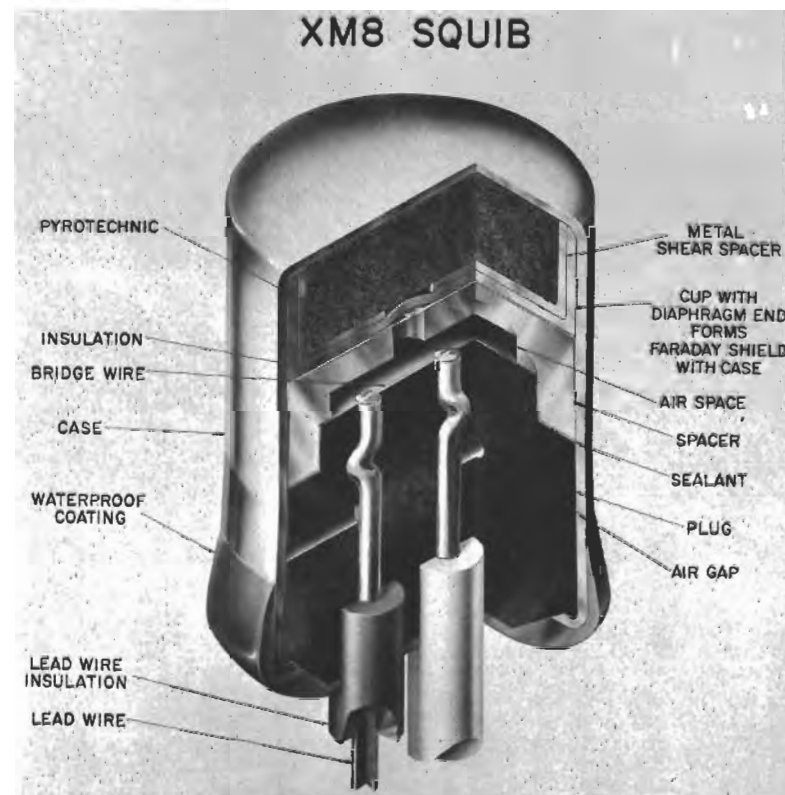
Figure 1

Figure 2

5. EXPLODING BRIDGEWIRE INITIATION OF RDX WITH 50 MILLIJOULES

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INTRODUCTION

With the rapid advancement in the state of the art of guided missile design, increased emphasis is being placed on improving the efficiency of the warheads and in particular the conventional high explosive warheads. Efficiency is usually considered to be a function of kill probability, for a given set of target intercept conditions, and of the weight and volume absorbed by the warhead. Of the schemes being considered to improve the efficiency of these warheads one of the most promising appears to lie in the use of detonation wave shaping to control fragmentation and directionality. Such shaping requires the use of explosive lenses, baffle plates, or multiple point initiation. Of these, multiple point initiation is most flexible.

Because of the mechanical problem of arming multiple explosive trains in one missile, it is proposed to use electric detonators "in-line". Although such in-line use of detonators is in direct violation of current stated Navy Bureau of Naval Weapons safety policy, the precedent has been well established. Electric detonators which contain only secondary explosives initiated directly by exploding bridgewire (EBW detonators) are in current use in-line with the main charges of weapons used by all three services.

The safety of an EBW detonator derives not only from the elimination of primary explosives but also from the resulting specialized electrical conditions necessary for firing; energy - about one joule, power - about a megawatt, and rate of rise of current - about 10^9 amperes per second. A firing energy source capable of simultaneously firing the large number of such detonators which would be required for shaping the detonation wave in the warhead main charge would, at the present state of the art, be too heavy and bulky to be carried in most missiles and would certainly out-weigh the gains in warhead efficiency attained through the use of multiple initiation in the first place.

In view of this the feasibility of a detonator containing only secondary explosives, which is initiated with much lower energy, was investigated. Preliminary investigations and calculations indicated two possibilities: (1) detonators which use a burning-to-detonation principle, and (2) refined exploding bridgewire detonators (or other similar device with the exploding bridgewire replaced with a semiconductor or a spark gap).

Safety considerations immediately eliminated the burning-to-detonation principle. This would not be acceptable in Navy weapons for obvious reasons. Further, the scatter in functioning time which is attainable through burning-to-detonation would be unacceptable in an application for detonation wave shaping.

Preliminary calculations indicated that it should be possible to initiate RDX explosive high-order with less than 50 millijoules of energy. The exploding bridgewire appeared to offer the most effective means of delivering this energy to a concentrated area in the explosive. Accordingly a research

program was instituted which investigated an initiation system with the following characteristics:

(1) Initiation by a medium energy pulse (0.05 joules as a design goal).

(2) Only Secondary Explosives (less sensitive than standard tetryl as a design goal, but consider pure RDX).

(3) The design concepts to be adaptable to a detonator of minimum size.

(4) A functioning time tolerance of ±0.25 microsecond as a design goal.

The safe use of such a device is open to argument and discussion. At first glance its use would appear as a regression. It might be argued that the primary motive for the use of EBW detonators in conventional ordnance is the improbability of accidental initiation from spurious signals such as those derived from static charges or electromagnetic radiation. Therefore, the argument continues, safety is being compromised by the reduction of required firing energy. It should, however, be noted that the joule or so required to fire the usual EBW detonator is not much energy, only a watt second or a quarter of a gram-calorie. It is therefore not the total energy requirement which makes the properly designed EBW detonator safe to use in the in-line condition. It is rather the specialized manner in which the pulse must be delivered, i.e., the short rise time and high peak power. The same criteria apply to the lower energy EBW. Further the lower energy device would, in all probability, require a pulse of even more specialized wave form than does the usual one-joule detonator. As will be shown, the

circuitry design is most critical in the initiation of RDX with 50 milli-
joules. A second consideration is that these devices are being considered
for multiple use. In application it should be possible to design the
ordnance package in such a manner as to connect the detonators in series
or parallel, inside a Faraday shield, in such a manner that they will
equally divide the energy of spurious signals (as well as the firing sig-
nal) and so that any mechanical failure would cause the device to "fail-
safe".

In view of the above the Naval Ordnance Laboratory, Corona instituted
the investigation of such devices. The R. Stresau Laboratory, Inc., Spooner,
Wisconsin was contracted to assist with theoretical and empirical studies.

TECHNICAL DISCUSSION

Although the initiation of detonation in secondary high explosives by
means of exploding bridgewires has gained wide acceptance as a solution to
the explosive safety problem, the physical and chemical mechanisms involved
are not yet understood in complete quantitative detail. In particular, the
mechanism whereby the electrical input energy is transmitted to the explosive
does not seem to the writers to have been adequately described. The strengths
of observed air shocks are insufficient to account for more than a small
fraction of the input energy or to establish detonation in a secondary high
explosive. Heat transfer due to normal conduction, convection, or radiation
is too slow for the combination of dimensions, energies, and times associated
with EBW initiation. Such mechanisms as condensation of metal vapor on
explosive surfaces, transfer from plasma carrying high density electrical

currents, and magnetohydrodynamic effects are probably involved. In any case, by careful circuit and detonator design, it is possible to concentrate, as heat in the "reaction nucleus" of the detonator, more energy than the "heat of detonation" of an equivalent volume of the high explosive. The resulting temperature, higher than that in a normal detonation reaction zone, quite obviously, causes the explosive to react at a rate higher than that associated with stable detonation, liberating hot gasses at such a rate that a shock wave must inevitably develop.

As has been pointed out in References 1, 2, and 3 and in many other discussions of the subject, explosive initiation is a matter of energy balance. When conditions are such that the energy liberated by explosive reaction exceeds losses from a reaction nucleus, the vigor of the reaction is bound to increase. For practical purposes, such conditions, once established, must prevail until a charge is expended, if it is to be considered adequately initiated. As is pointed out in Reference 1, the growth of explosion may progress through a number of phases (self heating, burning, deflagration, and detonation) in which various mechanisms (conduction, convection, and pressure - displacement waves) dominate energy transfer involved in both the propagation of reaction and in losses. From the very short functioning times of EBW devices as well as the fact that the explosive is initiated by a non-chemical explosion, it is apparent that detonation is established almost immediately in such detonators and pressure-displacement (specifically shock) waves dominate transmission of energy.

As Eyring et al[4] have shown, the relationship between losses and chemical

energy release in a detonation can be characterized in terms of the relationship of front curvature to reaction zone length. This inter-relationship was applied to the growth of detonation from sources of subcritical dimensions in Reference 5. Reference 5 suggests that critical conditions separating those for growth from those for failure of an expanding spherical detonation can be plotted in coordinates of pressure vs a_i/R (where a_i is the reaction zone length of an ideal plane wave detonation and R is the radius of curvature of the detonation front). It is shown that the critical pressure increases monotonically with a_i/R. For small values of a_i/R, the form of this curve depends upon the kinetics of the explosive reaction. However, as the radius of curvature becomes small, the energy contribution of the chemical reaction becomes negligible (per unit area of shock front) and the curve approaches that for spherical attenuation of a nonreactive shock. The spherical attenuation of a non-reactive shock is, essentially, a matter of conservation of energy. Below a certain source size (characteristic of the explosive and its state of aggregation) the energy required to initiate an expanding spherical deto-nation becomes a constant independent of the size of the source. From a qualitative consideration of the principles outlined in References 4 and 5, it is quite apparent that the order of magnitude of this minimum initiation energy is the heat of detonation of the quantity of explosive which is contained in a sphere of the same diameter as the failure diameter of an unconfined column of explosive (which is related to the reaction zone length).

The volumetric energy content of secondary organic explosives varies rather little (from one to two calories per cubic millimeter) so the minimum threshold energy for EBW initiation might be expected to vary almost directly with the cube of the failure diameter of the explosive used. Table 1 includes failure diameters of several common explosives under a variety of conditions. It may be noted that the minimum threshold energy which would be predicted for a PETN loaded EBW detonator on the basis of the considerations discussed above and the 0.04 inch failure diameter for poor confinement would be of the order of a quarter of a gram-calory or about one joule (the failure diameter quoted was determined using PETN obtained by dissecting Primacord.) This value is somewhat higher than threshold firing energies of PETN loaded EBW detonators which are reported in the literature [6,7]. This difference might be expected to result from the fact that the PETN used in the detonators discussed in these references[6,7] was of special preparation to attain particle size distribution and configuration particularly adapted for EBW initiation.

It may be noted, Table 1, that failure diameters correlate with sensitivity, as might be expected. The failure diameter of RDX, is about twice that of PETN. Assuming the cubic relationship mentioned above, the minimum threshold energy of an RDX loaded EBW detonator would be about eight times that of a PETN loaded item. Meanwhile, the design goal of 0.05 joule is only a fraction of the energy requirement of the most sensitive EBW detonator with which the writers are familiar. Such a combination would seem to require a rather drastic departure from current EBW design practices.

Referring again to Table 1, it may be seen that failure diameters are

affected substantially by particle size and confinement as well as composition. The effect of particle size, as reflected in minimum threshold firing energy, has been exploited in the development of EBW detonators. Although there may be room for further reduction of firing energy requirements by control of particle size and shape, it would seem that the rather extensive effort in this area must have resulted in a rather close approach to the optimum state of aggregation. With explosives other than PETN, the possibilities of particle size and shape control and its effect upon EBW sensitivity are largely unexplored. It is possible that such exploration might lead to the discovery of a more nearly ideal EBW explosive than any now known. This is mentioned as a possibility, but it is not suggested that it form the basis of any strong hopes.

The effects of confinement on failure diameter are at least as great as those of particle size (Table 1). It might be expected that confinement should have a similar effect upon EBW sensitivity. A detonator patented by one of the authors [8] in which PETN confined in the presence of a bridgewire between two glass surfaces a few mils apart was initiated by as little as 6000 ergs. Although their large sizes and other factors make them unsuitable for the application which the results motivated the experiments described herein, the results obtained with this type of detonator illustrate the possibility of initiating suitably confined secondary explosives with relatively low energy electrical pulses. The fact that the energy available in the present application is over eighty times the threshold energy for the device described in Reference 8 encouraged

the hope that a detonator of the desired input characteristics would be possible, with explosives appreciably less sensitive than PETN.

With a well confined system, like that of Reference 8, the possibility must be considered that it may grow to detonation after initiation of burning, deflagration or other "low order" reaction. The acceptability of an item with such capability would, from the point of view of safety, be somewhat doubtful. It is believed that advantage can be taken of the various aspects of confinement to increase EBW sensitivity without promoting the growth of detonation. Confinement of detonation or shocks involves the reflection of shock waves. Confinement of burning or deflagration requires a strong, leak proof container. In the development of a secondary explosive detonator which depends upon a transition from burning to detonation, it was found that either leakage or rupture resulted in "dudding". It should be possible, in an EBW detonator, to provide confinement for a highly convulsive process, such as a wire explosion and the nearly direct initiation of detonation thereby, combined with relief ports or rupturable components which will reliably quench burning, deflagration or other "low order" reactions.

Confinement can have either of two functions in an EBW system. It can contribute to the growth from low to high order detonation or it can confine the initial reaction, thereby reducing the energy necessary to establish a self propagating reaction. To accomplish the latter, the volume of the confined cavity must be small enough that the firing energy, uniformly distributed in the cavity, will have an energy density of the order of the chemical energy density of the explosive to be initiated (about a calory per

cubic millimeter). The 0.05 joule requirement of the present application would call for a cavity of about a quarter millimeter diameter. The fore-going delineated the principal design and fabrication problem as that of confining an initial charge of explosive in the presence of a bridgewire in a cavity of fractional millimeter dimensions.

The "curved front" theory of Eyring et al [4], with a little algebra, yields the following expression for the effectiveness (K) of a confining medium:

$$K = 1 - 1.76 \sin\left(\tan^{-1} \frac{\rho}{\rho_c} \sqrt{\left(\frac{D}{D_c}\right)^2 - 1}\right) \tag{1}$$

where ρ is the density of the explosive, ρ_c is the density of the confining medium, D is the detonation velocity of the explosive, and D_c is the shock velocity in the confining medium.

Numerical values of this constant (K) for a given combination of explosive and confining medium may be substituted in:

$$D/D_i = 1 - \frac{(1-K)}{2} \cdot \frac{a}{R} \tag{2}$$

Where D is the detonation velocity of a column of explosive of radius R, D_i is the ideal detonation velocity of an infinite charge, and a is the reaction zone length.

For values of K approaching zero, Equation (2) approaches that for a bare charge. Note that, as K approaches one, diameter effects tend to disappear (according to these equations) and the detonation velocity of a charge of any size approaches the ideal velocity. In Equation (1) this condi-tion of "perfect confinement" may be seen to result when the shock velocity in the confining medium (D_c) is equal to the detonation velocity (D) of the explosive. Experimental data[9] casts a certain amount of doubt on this

theoretical result. Other experiments suggest[10] that the effectiveness
of a medium in the confinement of a detonating explosive can be character-
ized in terms of the ratio of its "shock impedance" $(\rho_c D_c)$ to the "deto-
nation impedance" (ρD) of the explosive. Still other experiments[11]
suggest that, for confinement of incipient detonation, strength and
density combine, perhaps with other properties, to determine the effective-
ness of a confining medium.

Regardless of which of the above mentioned criteria is used, the best
confining medium of all materials for which handbook data are available is
tungsten and the best of the more commonly available materials is steel.
However, the mounting of a bridgewire in a cavity 0.010 inch in diameter,
with electrical leads large enough and well enough insulated for the
efficient delivery of a pulse conducive to bridgewire explosion, presents
a rather difficult problem of design and fabrication where the confining
medium is an electrical conductor. The effectiveness of electrical insulators
as confining media has not been the subject of as much experimental investi-
gation as that of metals. The more easily worked insulators, such as plastics,
have been found[11, 12], as would be predicted by any of the criteria suggested,
to be rather poor confining media. (As predicted by Equation (2), the dia-
meter effects have been observed to be more severe for a charge confined
in a media which exhibits a negative K (Equation (1)), than for a bare
charge.) Glass and ceramics, which may, according to some criteria, be
very effective confining media, have been the subject of relatively few
experiments. In addition to being the most available electrical insulator,

glass has the advantage over most ceramics of being nonporous. According to Equations (1) and (2), glass should afford complete and perfect confinement for explosives at the densities used in EBW devices. In any case, the ratio of the acoustic impedance of glass to the detonation impedance of such low density explosives is almost exactly the same (3.2 - 3.7) as that of the acoustic impedance of steel to the detonation impedance of military explosives as they are usually loaded. For these reasons, several of the earlier designs involved glass confinement. However, since a source of glass components of the needed precision could not be established, efforts were redirected to culminate in the design shown in Fig. 1.

As has been shown in Reference 1, the energy required to initiate an explosive device is nearly proportional to the volume of material affected by the initiating impulse. In the case of hot bridgewire EEDs, this volume is so nearly proportional to that of the bridgewire, that it is possible to predict energy required to fire an item with considerable precision by multiplying the bridgewire volume by a number characteristic of the explosive. The energy requirement for threshold (50%) firing of PETN loaded EBW detonators, as obtained from Bruceton test data[6,7] is very nearly 2.5 millijoules per cylindrical mil (the volume of a cylinder one mil in diameter by one mil long). Values obtained by Hedges[6], using a 1-1/2 mil diameter gold bridgewire 40 mils long, and Maninger[7], using a 2 mil platinum bridgewire 100 mils long, were nearly identical when reduced to energy per unit birdgewire volume. The data obtained for RDX by Maninger[7], using a two mil diameter by sixty mil long platinum bridgewire reduces to about 4.4 millijoules per

cylindrical mil. Comparing these values with the energy necessary to vaporize the metal, starting from room temperature, 0.57 millijoules per cylindrical mil for gold and 0.95 millijoules per cylindrical mil for platinum) it may be seen that most of the energy is delivered after the wire has been vaporized. The difference in the values obtained with RDX and PETN indicate that energy delivered after the wire is vaporized plays a significant role in the initiation process. Experimental evidence is in general agreement that the initial shock wave leaves the surface of the wire at an instant very close to that at which this quantity of energy (enough to vaporise the wire) has been delivered. [7,13,14]. It follows that the volume in which the firing energy is distributed is that of the shock wave envelope at the time the pulse is complete. For typical EBW shock velocities of one to several millimeters per microsecond and typical pulse durations of over a microsecond, this volume may be several cubic milli-meters and the density of the input energy, if uniformly distributed, is only a small fraction of a gram-calory per cubic millimeter. It would seem that the use of higher power would result in greater energy concentration and reduce the quantity of energy necessary to fire any given explosive in any given system.

From the familiar direct current relationship ($P = V^2/R$, where P is power, V is voltage, and R is resistance) it would seem that power can be increased by the relatively simple expedients of raising voltage or lower-ing resistance. In a transient, however, the peak current is limited by the pulse impedance of the circuit ($Z = \sqrt{L/C}$, $I = V/Z$, where L is inductance, C capacitance, and I current). If, for example in a capacitance discharge

circuit, it is hoped to increase power while decreasing energy by raising

the voltage, a reduction of capacitance is indicated since the energy ($\mathcal{E}$)

stored in a condenser is given by $\mathcal{E} = CV^2/2$. Now, if the capacitance is

reduced to a point where $C < 4L/R^2$, the discharge will become oscillatory

with a peak power of:

$$P = I^2R = \frac{V^2}{Z^2} R = \frac{V^2CR}{L} = \frac{2\mathcal{E}R}{L} \tag{3}$$

Note that voltage cancels out and that the peak power is proportional to

energy. This is consistent with the fact that energy is equal, by definition,

to the time integral of power and the decay time of a damped oscillatory

discharge is equal to $r = 2L/R$.

It can be shown that the most rapid energy transfer in a discharge circuit

is attained with a critically damped circuit (in which $CR^2/4L = 1$). An

important facet of the art of designing circuits suitable for EBW actuation

has been that of reducing the inductance of such circuits sufficiently to

result in critical damping. To maintain or increase power while reducing

energy will require further refinement of this art. For example (from

Equation (3)) to deliver 0.05 joules to a one ohm load at a megawatt peak

power would require an inductance less than 0.025 microhenries, (which is

the inductance of about four inches of RG-SU coaxial cable or of a half

inch or so square loop of wire). Although it may be difficult to attain

such a low inductance in a firing circuit, it may be approached by the design

of all components as parts of a single low impedance "flat" cable. A deto-

nator which requires such a specialized circuit to fire it would be quite

safe against initiation by accidental or environmental electrical phenomena

and should meet any reasonable safety criteria.

DESIGN AND PREPARATION OF EXPERIMENTAL MATERIALS, DEVICES, AND APPARATUS

As implied by the foregoing technical discussion, to attain to milli-joule sensitivity in an exploding bridgewire detonator requires not only special detonator design, but also specifically prepared explosives and circuits of unusual characteristics.

1. Detonator Inert Assemblies   As delineated in the technical dis-cussion, the principal design and fabrication problem is that of confining an initial charge of explosive surrounding a bridgewire in a cavity of fractional millimeter dimensions. The bridgewire, of course, must be well enough insulated from any metal components to preclude establishment of shunting paths when subjected to input potentials of some thousands of volts.

(a) Early Designs. A number of designs were considered in which glass was to serve as the confining medium. None of these were ever made because a source could not be found which indicated either capability or willingness to attempt the fabrication of glass components of the required precision. A few relatively crude attempts were made, in the laboratory, to construct assemblies incorporating the essential features of these designs. Their failure to detonate, even with a two joule input, may be attributable to the crudeness of fabrication or to the fact that neither electrical conditions nor the state of aggrevation of the explosive had been optimized at the time of these experiments.

A rather small number of tests were made using a "sandwich" structure in which two metal plates were separated by a Mylar* film. An indentation

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*Mylar is a DuPont trade mark for polyester film. Its stated dielectric strength is 4000 volts per mil.

in the surface of one of the metal plates (when covered by the other) forms

the explosive charge cavity. The bridgewire, which is laid between the plates

perpendicular to the charge cavity groove, is passed through the film in such

a manner as to form an electrical bridge between the plates at the charge

cavity. In tests using this arrangement, local reactions were evidenced by

enlargement of the charge cavity indentation, but propagating detonation

was never observed.

After more promising results had been obtained with the design illus-

trated in Figure 1, experiments with the earlier designs were abandoned.

It is possible that, with the right combination of circuit conditions and

explosive state of aggregation, any or all of the design concepts considered

might lead to detonators of interesting and useful characteristics.

(b) Design Used in Most Experiments. The general design which first

gave promising results is shown, schematically, in Figure 1. To describe

the fabrication of detonators of this general design, some of the materials

used must first be described.

Wollaston wire is a coaxial bimetallic material made by insert-

ing a wire of one material (usually gold or platinum) in a tube of another

(usually silver) after which the combination of tube and core is drawn

through dies to a smaller size. The outer tube may be dissolved by an acid

leaving the core, which may be much smaller than a wire could be drawn by

any other process. The usual motive for the use of the Wollaston process,

that of obtaining such fine wires, was not necessarily applicable in this

program, as will be seen. It may be noted that most of the Wollaston wire

used in this work had cores larger than the smallest available drawn wire.

High temperature double bore thermocouple insulating tubing (made of Mullite, a refractory ceramic compound of alumina and silica) is available as a catalog item in sizes down to 1/32" outside diameter. Since the O.D. of the ceramic tubing is the lower limit of the charge cavity diameter in the design shown in Figure 1 and since 1/32" is larger than theoretically desirable for this dimension, an order was placed for the smallest double bore Mullite tubing which the supplier believed to be feasible using his current practices. This turned out to be 0.027 inch.

Stainless steel tubing in fractional inch outside diameters and a variety of nominal wall thicknesses is available from stock. Tolerances accumulate to a point where inside diameters may differ from those predicted from nominal dimensions by 20% or more in this size range. Although relatively small orders of tubing custom drawn to quite close tolerance are not prohibitive in cost, the tubing used in these experiments was obtained by ordering a number of stock sizes for which the range of possible inside diameters included the desired sizes. As expected, this yielded an assortment of inside diameters, including very close fits to each of the sizes of ceramic tubing which had been received. It was found that, within each lot of steel tubing received, the inside diameter varied only a few ten thousanths of an inch at most.

Copper clad phenolic sheet, for use in etched circuitry, is available in a variety of thicknesses and grades of phenolicwith copper coating of various weights on one or both sides.

The detonator inert assemblies (Figure 1) were fabricated in the following series of operations:

(1) A "hairpin" of Wollaston wire was threaded through the two holes

of a short (about 1/8") length of ceramic tubing.

(2) The ends of the Wollaston wire were soldered to the copper coatings of a strip of copper clad phenolic.

(3) A "bead" of epoxy resin cement was applied to join the ceramic tube to the phenolic strip, and cured at an elevated temperature.

(4) An ohmmeter was connected to measure the resistance between the two copper coatings of the copper clad phenolic (which is essentially that of the wire "hairpin"). The tip of the ceramic (where the curve of the hairpin is exposed) was then immersed in nitric acid. When the resistance approached the value calculated for the core diameter and desired bridge length, the tip was withdrawn from the acid, washed in distilled water and dried at an elevated temperature.

(5) A stainless steel tube was slipped over the tip, the ceramic tube coated with epoxy resin cement, and the steel tube slipped down to the shoulder formed by the bead (step (3) above). The epoxy cement was cured at elevated temperature.

2. Explosives

(a) Government Furnished. All explosives used in these experiments were RDX (cyclotrimethylene trinitamine) which had been furnished by the U. S. Naval Ordnance Laboratory, White Oak, Maryland. Materials used were identified as follows:

   RDX, X-177, 44 micron, Lot WAF - 3 - 69

   RDX, X-178, Wabash, Type A, Lot 548-53

   RDX, X-334, Holston, Type B

All of this material may be presumed to have been made in compliance with Reference 15. The RDX, X-177 and RDX, X-178 are Type A RDX made at the Wabash River Ordnance Works by the Woolwich, nitric acid process which yields nearly pure RDX (cyclotrimethylene trinitramine). The RDX, X-334 is Type B-RDX made at the Holston River Ordnance Works by the Bachman acetic anhydride process which normally yields a mixture of RDX with about 10% HMX (cyclotetramethylene tetranitramine).

Of these materials, only the RDX, X-177 is of fine enough granulation to be a reasonable candidate for exploding bridgewire initiation. The other materials were dissolved and reprecipitated as described below. In a photomicrograph of RDX, X-177 Figure 2, it is apparent that the 44 microns referred to in the identification is the maximum dimension of the largest particles (the material probably passed a U. S. Standard Sieve No 325 as required in the specification[15] for Class E, RDX). The average size appears to be about thirty microns and some particles as small as one or two microns seem to be present. Since attempts to initiate RDX, X-177 by means of an exploding bridgewire were not particularly successful, it was decided to attempt the preparation of finer grained RDX.

(b) Preparation of Fine Particle RDX by Precipitation. To prepare RDX of fine particle size, the RDX was dissolved in boiling acetone and the solution poured into chilled distilled water while stirring the water vigorously. 8.5 grams of RDX to 100 milliliters of acetone (about 55% saturation) was used in the preparations of materials used in experiments reported herein. The quantity of water used was twice that of the acetone.

Maximum dimensions of particles precipitated in this manner ranged from about two to twenty microns (Figure 3) with average and peak of the distribution close to ten microns. Most of the data reported herein was obtained with RDX, XF-1 made from RDX, X-178, and RDX, XF-2, made from RDX, X-334.

(c) Loading. The explosive was stemmed into the charge cavities at ram pressures ranging from 40 to 240 pounds per square inch. The "press" used for this loading consists of a small (1/16" max capacity) chuck mounted at the bottom of a shaft which passes through a "bushing" of hypodermic needle tubing and has a platform at the top about one inch in diameter. The weight of the chuck, shaft and platform is 8.5 grams, which corresponds with a pressure of 40 pounds per square inch on the smallest ram used. Higher dead loads are applied by means of weights of appropriate sizes, placed on the platform. The stemming is accomplished by slipping the detonator upward over the ram until the ram, chuck, shaft, platform, and weights are lifted to clear a stop which ordinarily supports them.

The "flash charges" were loaded as follows: The open end of the detonator assembly was pushed into the side of a small heap of the flash charge explosive, which was nudged into the hole with a spatula made by grinding the end of a piece of 0.065 inch diameter hypodermic needle tubing at an acute angle. The explosive was shaken down (presumably around the bridgewire) by snapping the side of the tube against the edge of a plate glass table top with a finger nail. After repeating this sequence, the charge was stemmed as described above.

The "base charge" was loaded by pushing the detonator, open end vertically downward, into a flat container of the base charge explosive and then

stemming as described above, repeating this sequence until the charge
cavity was filled flush with the end. Although no measurement was made
of the quantity of explosive loaded per increment, the number of increments
required to fill a detonator indicated that the loaded increment lengths
resulting from this method average about one caliber.

3. Firing Circuits

In the earlier experiments, a Firing Switch, Mk 88, was used. The
Firing Switch Mk 88 was originally intended as a weapon component firing
source for relatively insensitive exploding bridgewire detonators. It
consists of a transistorized power supply which charges a one microfarade
condenser to two thousand volts and a triggered spark gap which discharges
the condenser through an external circuit. The energy delivered to a
detonator by the Firing Switch, Mk 88 was reduced, for purposes of these
experiments, by connecting a condenser in series with it at the detonator.
Considering only nominal properties of the circuit components, such a cir-
cuit would be expected to deliver exactly the same pulse to the detonator
as would be delivered by the Mk 88 with a smaller condenser (of the effective
capacitance of the internal and external condensers in series). Although the
energy delivered should be that predicted on this basis, the power and rate
of rise are limited by the inductance of the circuit (which, as pointed out
in the technical discussion, must decrease in proportion to the capacitance
to maintain a constant peak power).

In an effort to approach the ideal, proposed in the technical discussion,
of a circuit in which the condenser, switch and cable form a single unit of
continuously distributed parameters, two firing circuits, shown schematically
in Figure 4, were fabricated in the laboratory. Laboratory fabrication of

all components from sheet copper, gold, and Mylar film makes such unitization much more complete than would have been possible in an assembly of separate components. Each circuit consists of a hand stacked capacitor of sheet copper and Mylar, a manually operated double throw switch in which the "charge" position affords a positive contact but the firing discharge occurs when two gold electrodes are brought within sparking distance, and a "flat" cable about a foot long. The switch is as nearly two dimensional as possible, constructed of sheet copper and gold in the configuration shown in the inset of Figure 4, and is separated from a return line sheet of copper by a thin (about 0.010 inch) layer of mica.

Two firing circuits, designated "H-1" and "H-2", were constructed, differing significantly only in the capacitance of their firing capacitors. The firing condenser of the H-1 Firing Circuit had a design value of 0.06 microfarad and a measured capacitance of 0.0454 microfarad. The H-2 had a design value of 0.02 microfarad and a measured value of 0.0144. The differences between measured and design values was in the direction which was anticipated since edge effects and air gaps due to surface irregularities were not considered in the design.

EXPERIMENTAL PROCEDURES AND RESULTS

The experimental effort of this project consisted mainly in the fabrication and loading of groups of detonators and the determination, (usually by Bruceton tests) of the threshold (50%) conditions for high order detonation.

1. The Bruceton Procedure

The so called "Bruceton" test procedure was used in most tests reported

herein. In this procedure, the first trial of a test is performed at one of a series of pre-established conditions or "steps". If a detonation results, the next trial is performed at the adjacent step in the direction of lower input energy. If it misfires, the next trial is performed at the adjacent step in the direction of increasing energy. The test is continued in this manner, the conditions of each trial being determined by the results of the previous trial, to yield a pattern of up and down staircases on a crossed grid data sheet.

Data obtained in a Bruceton test may be analyzed to obtain estimates of the mean (the condition at which 50% will detonate) and standard deviation of the test variable and of the errors of these estimates. The validity of such estimates rests on the assumption that the probability of detonation is normally distributed with respect to the test variable or the function thereof used in establishing the series of "steps". Experience with explosive sensitivity in general and particularly with electric initiators tends to favor the use of logarithmic progressions of steps. However limitations of experimental apparatus made other step progressions more convenient. The effect of such non-normalizing step progressions upon the accuracy of the estimation of the mean is rather small, but the "standard deviations" should be considered rough estimates of comparitive variability. In analyzing Bruceton data, values of mean and deviation are first calculated in terms of steps. They were converted to millijoules by multiplying values in "steps" by the size of the particular step interval within which the mean value fails for each test.

The series capacitors used with Electronic Switch, Mk 88 the varied in even intervals of 0.025 microfarad so the progression for these tests was nearly linear.

The H-1 and H-2 firing circuits were charged by means of the Mk 88. The voltage was reduced by the use of shunting condensers to distribute the charge. Since the shunting capacitors were in even 0.05 microfarad intervals, the reciprocals of voltages were in even steps while the energies are of course proportional to the squares of voltages.

2. Results - General

The results are consolidated in Table 2. It may be noted that the mean energy requirements of most of the items tested is less than the design goal of 50 millijoules, although, for most, the deviation is large enough that the reliability at 50 millijoules would be lower than required for ordnance items. At least one, the first item listed with the 0.4 mil platinum bridgewire, shows promise of adequate reliability at the 50 milli-joule level, if the standard deviations derived from the non-normalized Bruceton data is to be believed.

3. Effect of Charge Cavity Diameter

In Graph I, threshold firing energies are plotted versus the cube of charge cavity diameters. It may be noted that they are nearly proportional - as might be predicted from considerations mentioned in the technical discussion. However, other factors so complicate the relationship that the scaling, particularly over the short range of the lower curve, may be largely fortuitous. The energy density indicated in the lower curve is only about seventy millijoules per cubic millimeter, less than a tenth of

the density of available chemical energy in the explosive. It would appear that the exploding bridgewire initiation process is somewhat more complex than that assumed in the technical discussion.

4. Effects of Firing Circuit Parameters

The 4/1 ratio of threshold firing energy of the same detonator when fired by means of the Mk 88 and H-1 respectively illustrates the importance of controlling inductance and impedance of firing circuits for exploding bridgewire devices. It should be kept in mind that the Mk 88 was designed to fire an EBW device, but the introduction of series capacitors increased inductance while making it less tolerable.

It may be noted, Table 2, that the threshold energy requirement of the detonators with the smaller bridgewires is less with the H-2 Firing Circuit than with the H-1 firing circuit, while with the largest Bridgewire used (0.6 mil), this relationship is inverted. This may be explained, for the smaller, high resistance wires in terms of the need for a smaller condenser to maintain a shorter RC discharge time, for the larger wires, perhaps the lower circuit impedance resulting from the large capacitance of the H-1 unit provides a better match to the lower detonator resistance.

5. Effects of Bridgewire Diameter

In Graph II, mean threshold energies (lowest values obtained with each Bridgewire diameter) are plotted versus bridgewire diameter. It would seem that, below 0.4 mil bridgewire diameter, energy requirement becomes nearly independent of diameter and above this size, the energy requirement increases with increasing wire size. It is of interest to note that, for the larger wires, the energy requirement per cylindrical mil of bridgewire volume is

between 3.5 and 4.0 which may be compared with the 4.4 millijoules per cylindrical mil computed from Maninger's[7] data for RDX. In view of the many differences between Maninger's experiments and those discussed herein, this agreement is quite remarkable. The "plateau" of 25-27 milli-joules for wire sizes below 0.4 mil diameter may be a limiting condition for the charge cavity diameter, explosive particle size, firing condenser, or the particular combination used in these experiments. Smaller charge cavities, explosive particles, or firing condensers might result in lower threshold firing energies maintaining the constant energy requirement per cylindrical mil noted above.

6. Effects of Loading Pressure

Threshold firing energy is plotted as a function of loading pressure in Graph III. It may be noted that there is evidence of an optimum pressure which results in a minimum energy requirement. These data were obtained using 0.5 mil diameter bridgewires and 35 mil diameter charge cavities with flash charges of RDX, XF-1. Briefer and somewhat less organized experiments indicate that similar optimum loading pressures apply to other combinations of bridgewire and charge cavity diameter and explosive granulation, but that the optimum differs for each such combination. Not enough data has been obtained to characterize the interrelationships involved except that there appears to be a trend toward increasing optimum loading pressures with increasing ratios of bridgewire diameter to charge cavity diameter. In Table 2, where only one loading pressure is used with a given combination, the pressure is the optimum as estimated by a "cut and try" procedure.

density data for RDX, XF-2, which is believed to be typical of materials used in this study, are given in Table 3.

7. Output

A steel bar dent test was used as the criterion of detonation in the Bruceton tests. Any detectable dent was accepted as evidence of detonation. For some "misfires", the case was burst or shattered, although no dent was produced. For others, the case was intact, although the audible effects were indistinguishable from those of detonations. Other misfires were much milder, including ejection of unconsumed explosive and burned out bridge-wires.

In a few experiments, it was determined that the smallest of these detonators (with explosive columns 0.028 inches in diameter) are capable of initiating leads of SPX-2[15], a finely divided RDX, desensitized with 1.5% calcium stearate to meet the Navy criterion that booster explosives shall be no more sensitive than tetryl.

CONCLUSIONS AND RECOMMENDATIONS

The feasibility of producing an RDX exploding bridgewire detonator which can be fired with an input energy of 50 millijoules has been demonstrated. The energy requirement of such a detonator is a rather complex function of confinement, dimensions of components, state of aggregation of explosives, and the waveform of the firing pulse. Although the experiments which have been described give some clues as to the trend of some of these relation-ships and generally seem to agree with theoretical predictions, much work remains to be done before a satisfactory ordnance system can be designed to take advantage of these possibilities. It is recommended that experiments be continued until this goal is achieved.

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Table 1 FAILURE DIAMETERS (in inches) AS AFFECTED BY CONFINEMENT

CONFINEMENT

EXPLOSIVE	Bare Charge	Fabric or Plastic	Aluminum)0.006 in wall tube)	Lead (Pb) (MDF)	Heavy Brass or Steel
PETN		~ 0.04 (a)	< 0.050(f)	< 0.010 (g)	< 0.050 (h)
RDX		0.085 (c)		< 0.016 (g)	< 0.050 (h)
RDX/Ca Stearate 98/2		> 0.140 (d) < 0.170 (d)	> 0.075 (f) < 0.100 (f)		< 0.075 (h)
Tetryl	< 0.5 (b)		> 0.100 (f) < 0.125 (f)		< 0.075 (h)
TNT (granular)	> 0.5 (b) < 0.7 (b)	~ 0.500 (e)			< 0.100 (h)
TNT (25 micron)		< 0.100 (e)			

(a) R. Stresau Laboratory Report 61-10-1

(b) Picatinny Arsenal Technical Report 2389

(c) R. Stresau Laboratory Report 62-5-1

(d) Private Communication, W.M. Slie, NOLW

(e) OSRD Report 5611, Explosive Research Lab. Bruceton Pa.

(f) NAVORD Report 4082, NOLW

(g) Private Communication, David Andrew, Ensign-Bickford Co.

(h) NAVORD Report 2282, NOLW

Table 2. Threshold Firing Energies

Wire Mat.	Dia. (mils)	Res.[b] (ohms)	Lgth[c] (mils)	Chge. Dia. (mils)	Explosive Flash Chge	Explosive Base Chge	Ldg. Press.	Frg. Cir.	Energy Req. (millijoules) Mean	Std.Dev.
Pt	0.2	4.5	36	28	XF-1	XF-2	40	H-2	25.2	5.5
Pt	0.2	3.9	31	35	XF-1	XF-2	40	H-2	35.5	(a)
Pt	0.3	2.0	36	28	XF-3A	X177	80	H-2	27	5.4
Pt	0.3	2.0	36	28	XF-1	XF-1	130	H-2	40.5	(a)
Pt	0.3	1.25	23	35	XF-1	XF-1	40	H-2	34	(a)
Pt	0.3	1.9	34	35	XF-1	XF-1	80	H-1	44	(a)
Au	0.32	0.39	35.5	28	XF-1	XF-1	40	H-2	25.2	4.6
Au	0.32	0.7	60	28	XF-1	XF-2	40	H-2	27.2	(a)
Au	0.32	0.25	21	35	XF-1	XF-2	40	H-2	32.6	(a)
Pt	0.4	1.37	44	28	XF-1	XF-2	60	H-2	26.2	2.5
Pt	0.4	1.25	40	28	XF-2	XF-2	60	H-2	31.2	(d)
Pt	0.4	1.25	40	28	XF-2	XF-2	125	H-2	36.3	(d)
Pt	0.4	.96	31	35	XF-1	X177	80	H-1	64	12.5
Pt	0.5	0.77	38	28	XF-1	XF-2	60	H-2	32.5	5.1
Pt	0.5	0.77	38	28	XF-1	XF-2	60	H-1	36	(a)
Pt	0.5			35	XF-1	X-177	40	H-1	47	(d)
Pt	0.5	0.75	37	35	XF-1	XF-2	80	H-2	57	(a)
Pt	0.5	0.70	35	35	XF-1	X-177	80	H-1	42	9.8
Pt	0.5		40-45	35	XF-1	X-177	90	H-1	48	6.3
Pt	0.5		40-43	35	XF-1	X-177	90	88(f)	202	28
Pt	0.5			35	XF-1	X-177	100	H-1	49	(d)
Pt	0.5			35	XF-1	X-177	160	H-1	63	(d)
Pt	0.5			41	XF-1	X-177	(h)	H-1	90	(d)
Pt	0.5		25	70	XF-1	X-177	(h)	88(f)	1333	(d)
Au	0.5	0.17	35	28	XF-1	XF-2	80	H-2	32.5	(a)
Au	0.5	(e)	35	28	XF-1	XF-2	120	H-2	31	(a)
Au	0.5	(e)	35	28	XF-1	XF-2	120	H-1	37	(a)
Pt	0.6	0.4	29	28	XF-1	XF-2	240	H-2	44	3.7
Pt	0.6	0.4	29	28	XF-1	XF-2	240	H-1	37.4	4.2
Pt	0.6	0.39	28	35	XF-1	XF-2	155	H-1	40.2	8.0

(a) Too small sample for estimate of deviation.

(b) Average of measured resistances of items used in Bruceton test.

(c) Calculated from average resistance.

(d) Estimated from a few data.

(e) Only spot checks of resistance made to assure that no significant shift occurred.

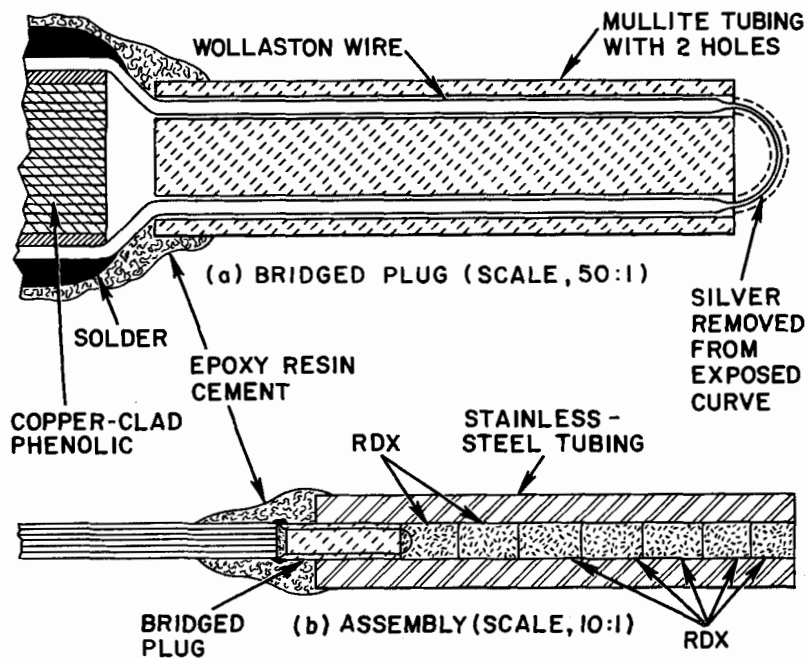(f) 88 - Electronic Switch, Mk 88 Mod 0 with series capacitors.

Table 3

Loading Pressure and Density Relationships of RDX, XF-2

Loading Pressure (pounds per square inch)	Density (grams per cubic centimeter)
40	1.08
80	1.13
160	1.18
250	1.23

Bulk Densities:

As Poured   .44 grams/cm^3

Shaken Down   .55 grams/cm^3

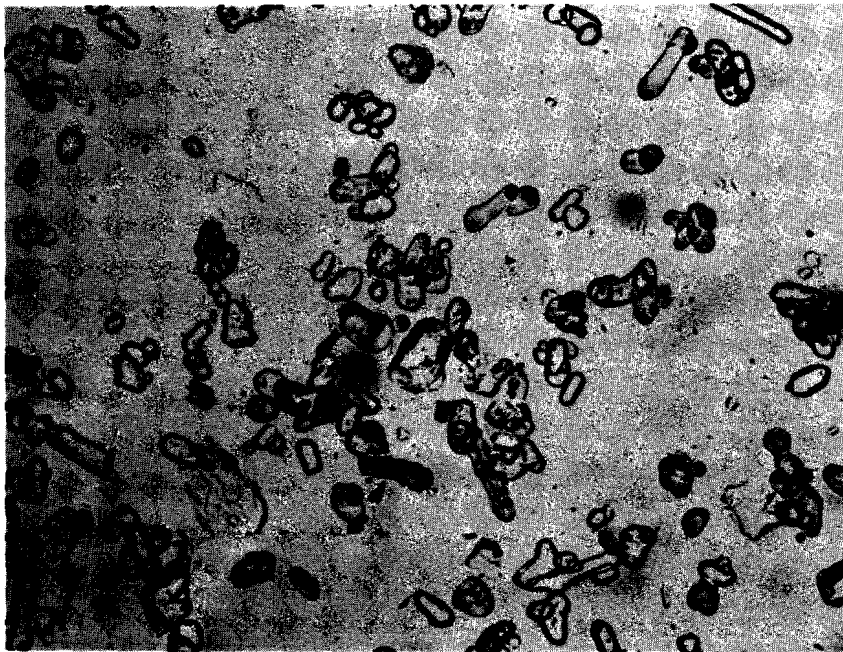## FIGURE I. MEDIUM ENERGY EXPLODING BRIDGE WIRE DETONATOR

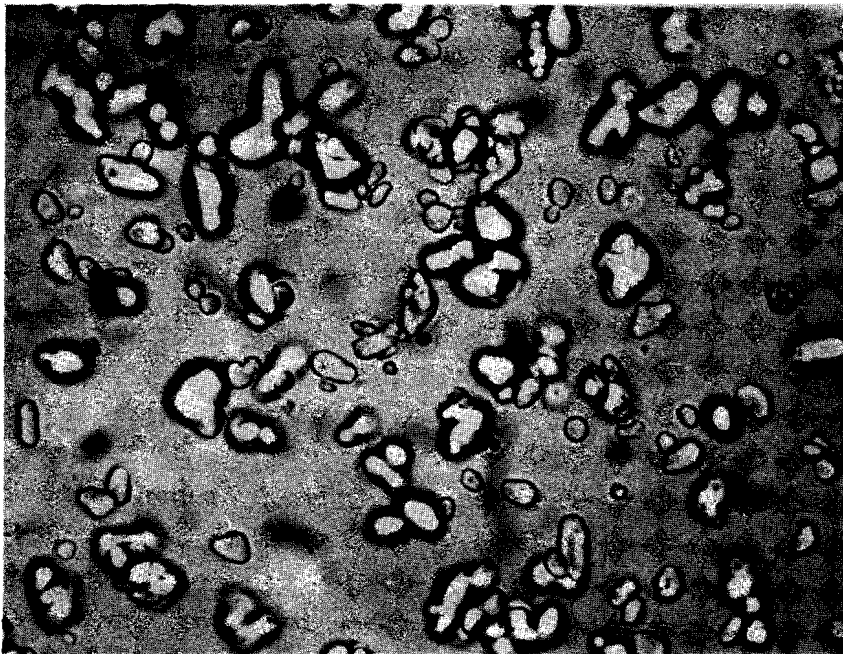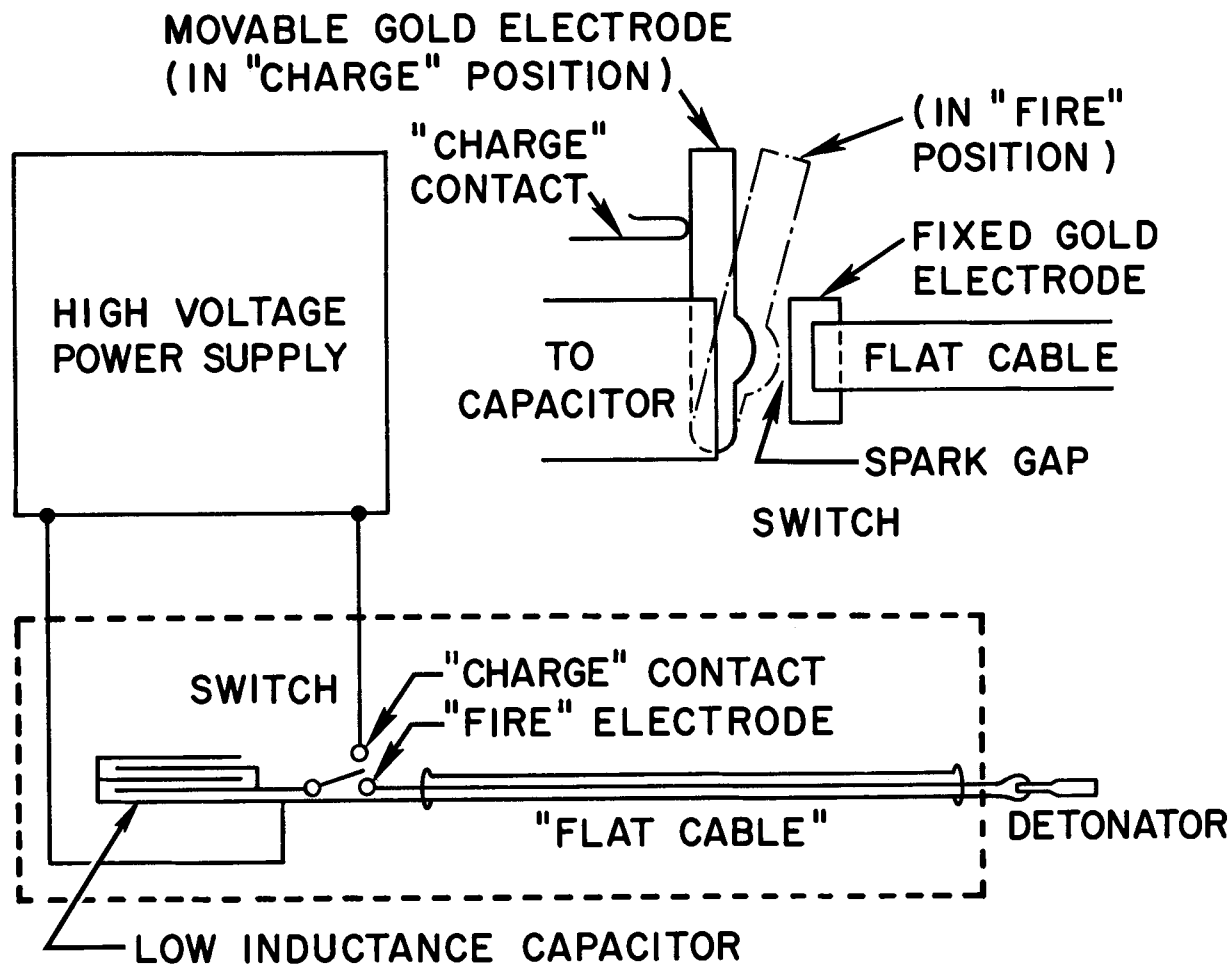Figure 2: Photomicrograph of RDX X-177
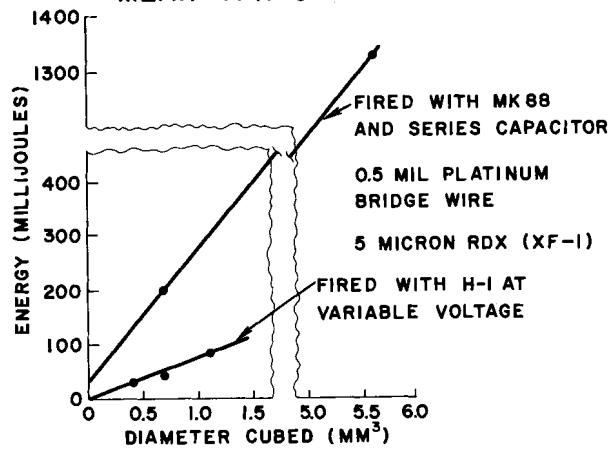(250 diameters magnification)

Figure 3: Photomicrograph of RDX XF-1
(750 diameters magnification)

FIGURE 4. CIRCUITRY USED IN EXPERIMENTAL FIRING H-I FIRING CIRCUIT

GRAPH I: EFFECTS OF FIRING CIRCUIT AND CHARGE CAVITY DIAMETER ON MEAN THRESHOLD ENERGY

FIRED WITH MK 88
AND SERIES CAPACITOR

0.5 MIL PLATINUM
BRIDGE WIRE

5 MICRON RDX (XF-I)

FIRED WITH H-I AT
VARIABLE VOLTAGE

ENERGY (MILLIJOULES)

DIAMETER CUBED (MM³)

GRAPH II: MEAN THRESHOLD ENERGY
VS
BRIDGE WIRE DIAMETER

POINTS PLOTTED ARE THE LOWEST
50% POINTS OBTAINED WITH ANY
COMBINATION OF LOADING PRESSURE
CHARGE CAVITY DIAMETER
AND EXPLOSIVE.

● PLATINUM
○ GOLD

MEAN THRESHOLD ENERGY

BRIDGE WIRE DIAMETER (MILS)
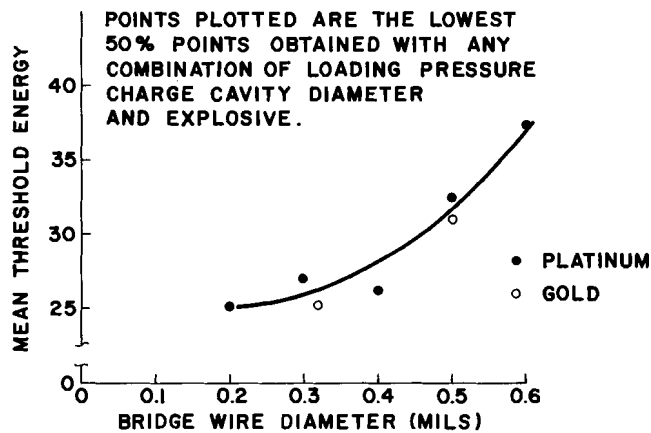
GRAPH III: MEAN THRESHOLD ENERGY
VS
LOADING PRESSURE

BRIDGE WIRE :
0.5 MIL PLATINUM

CHARGE CAVITY
DIAMETER : 0.035 IN.

MEAN THRESHOLD
ENERGY (MILLIJOULES)

LOADING PRESSURE (PSI)

5-34
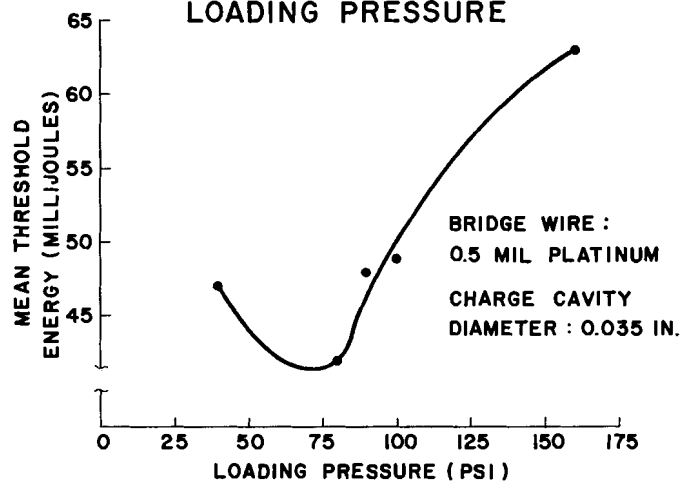
5. DISCUSSION

Mr. Seeger of Picatinny Arsenal asked if a hot-wire initiation of this device had been tried instead of the EBW approach. Mr. Hillyer answered that this was a difficult question to answer. He said that the sensitivity of the system to inductance is an indication of EBW phenomenon. In addition attempts to fire with more energy at a lower power level results in bridgewire burnout without functioning.

Mr. Bankston asked for information on functioning time, column length and density of RDX, and means of detecting that a detonation had occurred. Mr. Hillyer answered that functioning time had not actually been measured but functioning appears to be simultaneous within a fraction of a microsecond at times. Functioning time is not entirely defined at this point.

Mr. Stresau said that column length was from 1/4 to 3/8 inch and density from 1.08 and 1.23. These were pressed at 40 to 250 psi. Pressure was optimum at different magnitudes for changes in other variables. For a .004-inch bridgewire, 60 psi was optimum; for a .006-inch bridgewire, 250 psi was maximum. He warned that this information is based on limited data. Degree of detonation was determined by the dent made in a steel block.

Column length was not varied intentionally, although there were variations. He expressed intent to investigate length effect.

Mr. Moore of Stanford Research Institute commented that the lack of simultaneous functioning, when it occurred, could be due to a deflagration proceeding for a new millimeters before detonation.

Mr. Stresau said that this was not likely in light of the short energy delivery time of the circuit and in light of the great circuit effects.

Mr. Moore added that in some work that he had done with Mr. George Muller under similar conditions a reaction started with a velocity of 1 or 2 mm per microsecond for perhaps 12 mm and then accelerated to high order detonation. Mr. Stresau said that he considered velocity of 1 to 2 mm/microsecond a low-order detonation, a shock propagated reaction. He concluded that this is a matter of definition.

Mr. Adams of GLA asked if the circuit was critically damped or subject to damped oscillation. Mr. Stresau said that attempts were made to make the circuit criticially damped. Mr. Hillyer added that attempts were made to measure circuit inductance without success. This gives an idea of the small value of inductance.

Mr. Adams asked if critical damping would not be outlined by adding resistance and if this would not also, in fact, degrade performance. Mr. Hillyer said that damping could also be obtained by decreasing inductance, which is supposed to have advantages in this application.

6. CHARACTERISTICS OF A SMALL INSENSITIVE PETN ELECTRIC DETONATOR*

Donald Baker Moore

Stanford Research Institute, Menlo Park, California

This is a report on a program to develop a detonator containing no primary explosives, but which must be actuated by the discharge of a 1/2- to 1-microfarad condenser charged to between 2 and $2\frac{1}{2}$ kilovolts. Other requirements will be touched on in the report but consist, briefly, of certain geometric restrictions, a desire to minimize the total amount of explosive, insensitivity to strong radio-frequency fields, and, of course, 100% reliability.

The explosive had been previously determined to be PETN in some form, with the possibility of mixing it with graphite as desired to increase electrical sensitivity. Graphite appears to be one of the materials which can be mixed with PETN to change its electrical behavior without appreciably increasing its mechanical sensitivity.

Earlier work had pretty well established the general approach to the design. It consists of an axial needle inserted into a prime charge of 20 to 50 milligrams of mixed PETN and graphite. This, upon being ignited by an electrical discharge, induces deflagration in a short column of loosely packed PETN which evolves into a detonation which in turn initiates another short column of high density PETN (1.6 grams per cubic centimeter). This

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detonation is sufficiently energetic that, upon emergence from the cap sheath, it will initiate additional explosives such as MDF or shaped Prima- cord.

Although direct electrical initiation of PETN has been accomplished regularly, it was our problem to do this with a minimum of energy and rela- tively strict conditions upon charge dimensions. This has led into the funda- mental problem of examining the basic initiation mechanisms.

EXPERIMENTAL DETAILS

The power supply used in these experiments was our version of the common gap-triggered capacity storage unit. This could be varied within the capacity and voltage limits desired. It was arranged in a coaxial sys- tem to minimize inductance and signal noise. This is shown in Fig. 1.

The precise circuit parameters were found to vary slightly with adjustment, but were usually about 2 microseconds ringing time into a short circuit, with an estimated residual inductance of between 0.2 and 0.26 microhenry, and an internal resistance of about 0.1 ohm or larger. It was found that the spark gap itself had an apparent resistance value which varied with current in the approximately inverse fashion characteristic of arc discharges. This also changed with gap adjustment.

The circuit was commonly used with a 1/2-microfarad condenser charged at from 2 to 4 kilovolts and would deliver a peak current of more than 3000 amperes with a rise time of approximately 1/4 microsecond into a short circuit.

Instrumentation consisted of Tektronix oscilloscope records showing the discharge current as measured in a series resistance of 0.0108 ohm, the voltage across the device (using a Tektronix high voltage dividing probe), the time rate of change of current di/dt as measured by a small wire loop near the discharge circuit, and the time integral of the current was plotted by using a type "O" operational amplifier. These four plots were sometimes supplanted by ionization switch or optical probe measurements in attempts to measure reaction velocities.

In addition to the active instrumentation, the most important observation was simple terminal observation to check damage. In particular, the obvious desired result was successful initiation of shaped MDF.

Applying this instrumentation to discharges with noninductive wire resistors substituted for the active load, it was possible to calculate R_o, the residual circuit resistance primarily attributed to the spark gap. This can be readily done where di/dt = 0. The results are shown in Fig. 2. This is seen to change with current and also gap adjustment. The points shown with the slash mark are obtained where di/dt $\neq$ 0 and yield an estimate of inductance of 0.26 microhenry. This compares with an estimate of 0.20 obtained by short circuit ringing measurements, but with slightly different gap adjustment.

DETONATOR DESIGN

Figure 3 shows the principal version of detonator under study. As has been mentioned, the basics of this device had been previously fixed.

The 0.110-inch-diameter chamber contains 25 to 50 milligrams of PETN-graphite mixture at about 85% to 15%, loaded to a density of about 1.6 around the needle. Immediately adjacent to this is a loose charge of approximately 17 milligrams of PETN at a density of about 1.0 for a length of about 0.135 inch. Finally, the cap is terminated in a booster charge of about 0.210 inch of 1.6 density PETN weighing about 60 milligrams. Figure 4 is a slightly different one.

The PETN-graphite mixture is shown in Fig. 5. Many mixtures have been tried. This particular one shows feathery needles of PETN in the order of 100 microns long with sporadic lumps or deposits of graphite particles in the order of 10-microns size. Better uniformity has been obtained with recrystallized PETN in sizes of about 10 microns, but without appreciably greater success.

As yet no special effort has been made to design this device to be RF-proof. It is seen that its coaxial connection, and the solid metal walls inside the external metal sheath, may already comply with safe design criteria. The weak point in the experimental model is the plastic base plug which can readily be altered in a production design.

EXPERIMENTAL RESULTS

Figure 6 shows a detonator set up to test, together with the aluminum "witness" plate and the shaped MDF to test for successful detonation. Figures 7 through 11 show a typical shot set up and fired in the shooting chamber. Figure 10 shows a failure and Fig. 11 shows a satisfactory shot in which the shaped MDF detonated properly.

Some 300 shots have been fired on this program. These have included both new tests and verification of the previous conclusions about the following variables: PETN-graphite ratio and composition, initial resistance (electrical), location of needle in primer, composition density and length of booster charge, sharpness of needle point, desirability of insulation on needle point (to prevent low voltage or supplementary breakdown), reaction velocity, and others.

Three typical shot records are shown in Figs. 12, 13, and 14. Figure 12 shows a shot fired at 2 kilovolts. The current is quickly quenched and the capacity is not fully discharged. The voltage does not return to zero and the storage capacitor retains approximately 400 volts. There is no evidence of reaction. Figure 13 shows a shot fired at 3 kilovolts. There is no inductive oscillation and from the charge record behavior it appears probable that most of the stored energy has been dissipated in the explosive. The pin record shows a pip at 7.2 microseconds from first energy input. (This trace is on a different time scale with different zero from the others.) This is evidence of a high-order detonation and is confirmed by the MDF having severed the witness plate. Figure 14 shows a shot identical to that in Fig. 13, but there is a poorly damped ringing discharge. This indicates a low resistance in the detonator. The voltage trace shows resistance changes whose significance will be discussed later. Such a discharge is clearly inefficient in initiation.

Figures 15 and 16 show two shots fired at 2 and 2.5 kilovolts. The first is strongly damped and resulted in a detonation. The second is a

ringing discharge and failed to initiate. Calculation of the resistance as a function of time in such shots has yielded the curves shown in Figs. 17 and 18. Breakdown occurs very rapidly, in less than 1/10 microsecond. The resistance decreases during this time from its initial high value of from 10 to 10^4 ohms. In failures the resistance then continues to decrease (as shown in Fig. 18). In successful shots the resistance reaches a plateau, then increases temporarily. In the following long term it may finally increase further, or decrease again.

An increase in arc resistance implies an increase in pressure and/or mechanical disruption of the circuit. Both these mechanisms can be brought about by the onset of chemical reactions. If this is the case, the time of first inflection in the resistance curve, T, may be identified as an induction time. This does not always have to be determined by laborious calculation of R_p since the actual oscillograms clearly show the difference between proper and improper primer functioning (see Figs. 15, 16, etc.). In a complete shot the discharge is strongly damped, in a failure it is oscillatory.

OBSERVATIONS

An attempt can be made to compute the energy input as a function of time in the detonator. Table I is a result. Notice that the induction time; T, decreases as input energy at time T decreases. This implies that other factors than E_T are most important in determining T.

If T is indeed a chemical reaction or induction time, one might expect it to be controlled by ΔT, the temperature rise in the system. There

is insufficient energy to heat the entire primer mass of 25 milligrams to a temperature high enough to cause reaction. For induction times of less than 1 microsecond one would expect ΔT of the order of $1000°$ C.

Calculation of ΔT for discrete regions requires a knowledge of the volume of such regions and how they are affected by the voltage across the system and the current flow. It is interesting that the energies in the range of 0.1 joule available would raise a cylindrical volume of PETN (specific heat of 0.3 cal/gram) 1 mm long by 1/4 mm in diameter to about $1000°$ C.

Some scattered results indicate that raising the voltage tends toward oscillatory discharges which would imply that the energy is being dissipated inefficiently in multiple low temperature regions.

CONCLUSIONS

Although appreciably less than one-half the shots have been a success, we feel that we have found an instrumentation technique which can be used to study the fundamental initiation process which in our system uniformly determines subsequent success. This critical region exists in the first 1/4 microsecond of the energy input. It is extremely difficult to examine because of the very limited volume, short time duration, sensitivity to instrumental perturbations, and dependence on confinement and boundaries.

The precise method in which the electrical energy is transferred into the explosive is of considerable interest. Some contend that this involves a sort of streamer or corona discharge with highly local heating at the needle point. There is alternatively the possibility that no appreciable

energy transfer can take place until the gap breaks down along one or more conducting paths. The nature of the effect the graphite has is poorly understood. It may merely produce multiple high field regions to facilitate electrical breakdown. There is some possibility that residual gas could alter the early electrical behavior. It has been suggested that extremely fine (10-micron) needle points might prevent redundant breakdown which is apparently inefficient.

These significant factors can be approached with present techniques and with improvements in such methods as miniature ionization switches to measure reaction rates, micro-optical or electronic photography of the first millimeters of the reaction, and more thorough knowledge of the precise chemical and physical characteristics of the explosive mixtures used.

We feel that we can obtain a useful device from the present work which will satisfy specific requirements. We are more confident that continuing basic studies will tend to produce information which will permit intelligent explosive designs, rather than the trial-and-error approach so often necessitated by urgencies of time and application.

TABLE I

ENERGY DISCHARGED THROUGH PRIMER

SHOT NO.	RESULT	τ^* (μsec)	Q_τ/Q_{max}	$(R_p/\Sigma R)_\tau$	$(R_p)_\tau$ (ohms)	E_τ (joules)	$E_\tau(R_p/\Sigma R)_\tau$	V_0 (kv)	E_τ/E_{max}	E_{max}
276	Deton.	0.42	0.354	0.825	1.60	0.96	0.79	2.54	0.58	1.64
280	Deton.	0.33	0.270	0.822	1.71	0.77	0.63	2.54	0.47	1.64
279	Deton.	0.26	0.198	0.850	1.86	0.37	0.31	2.02	0.36	1.04
278	Partial	0.21	0.172	0.830	2.23	0.33	0.27	2.04	0.31	1.06

$$Q_\tau = \int_0^\tau idt$$

$$E_\tau = \frac{1}{2}\frac{Q_0^2}{C} - \frac{1}{2C}\left[Q_0 - Q_\tau\right]^2$$

$$E_\tau = \text{expended energy} = V_0 Q_\tau - \frac{Q_\tau^2}{2C}$$
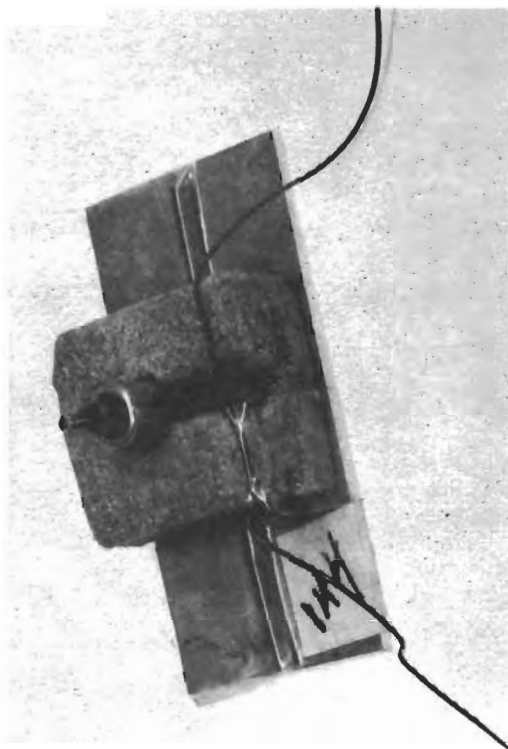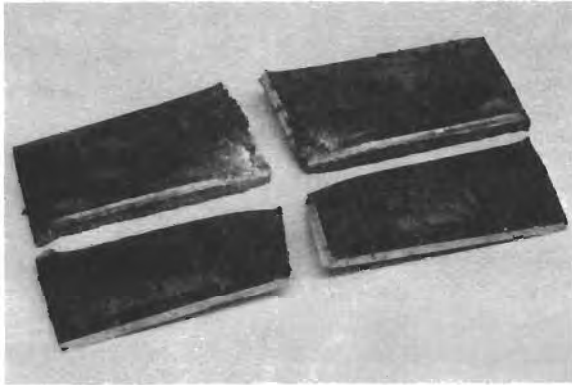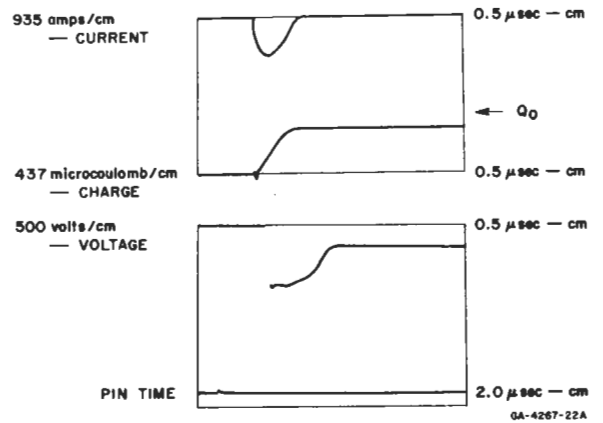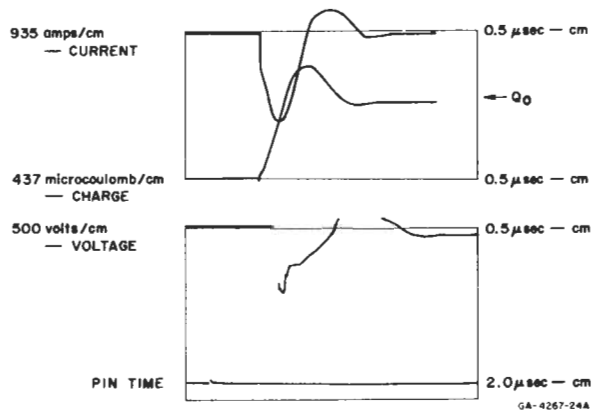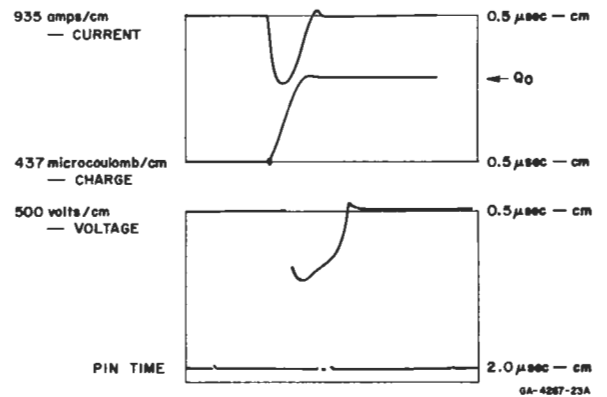
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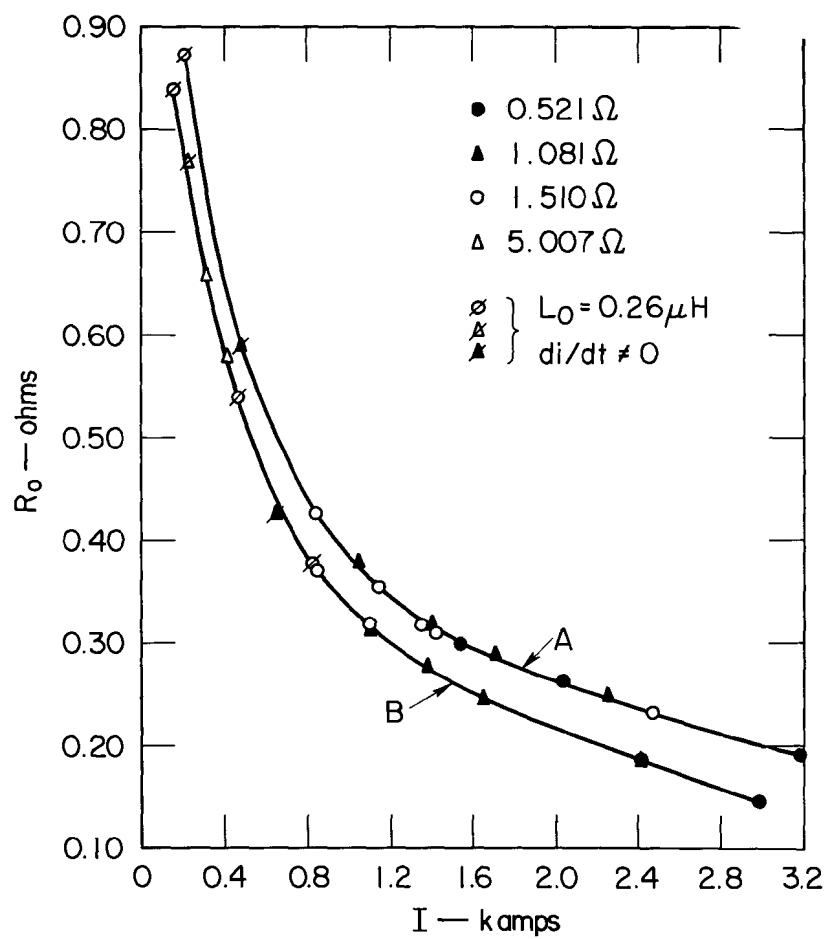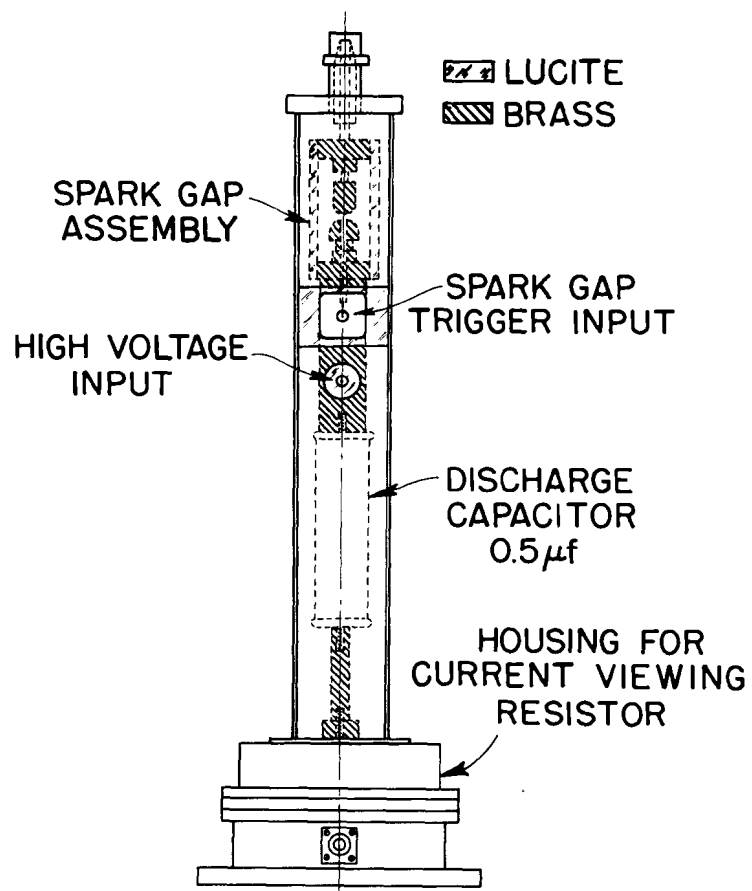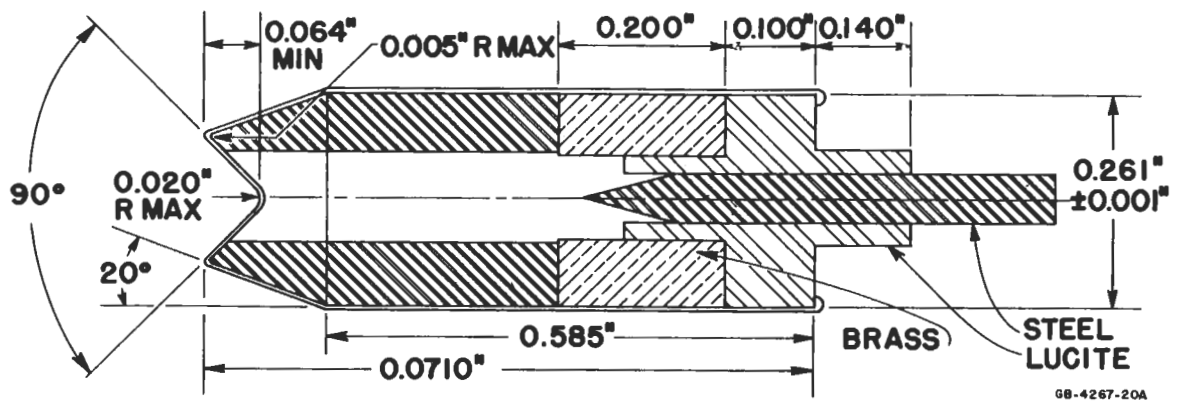
Figure 1
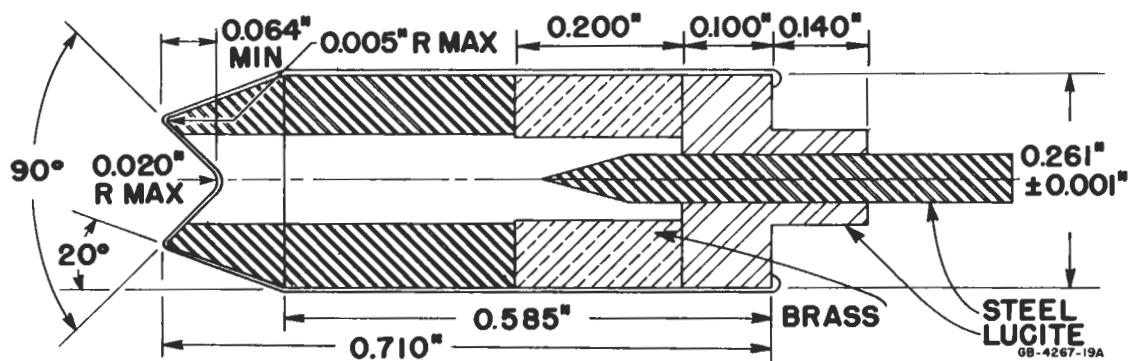
Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

6-11
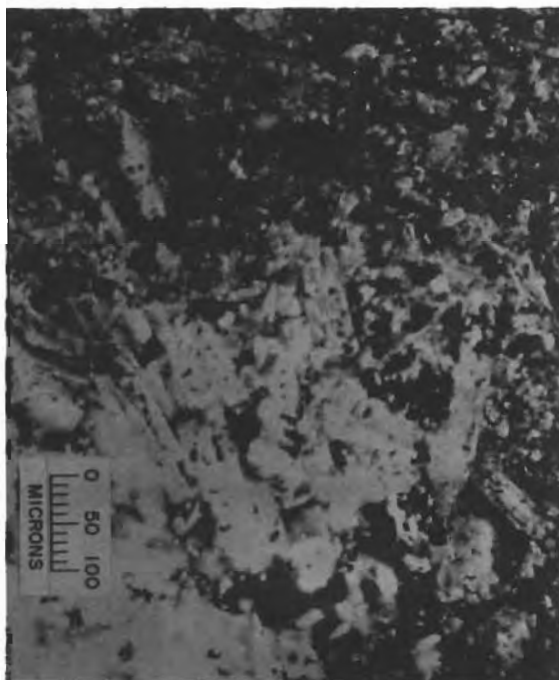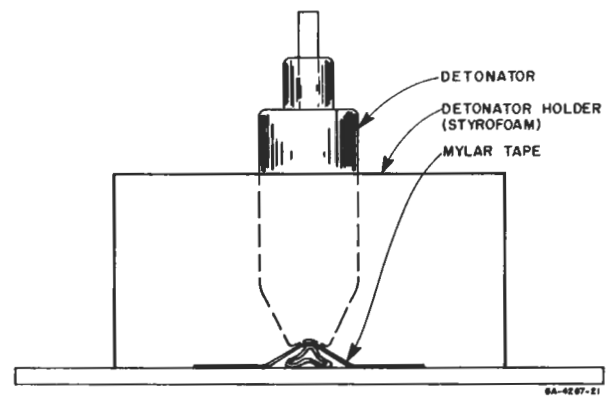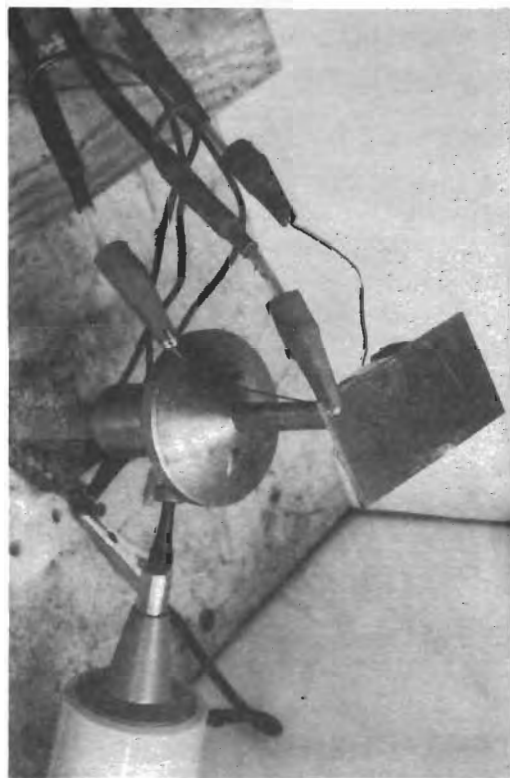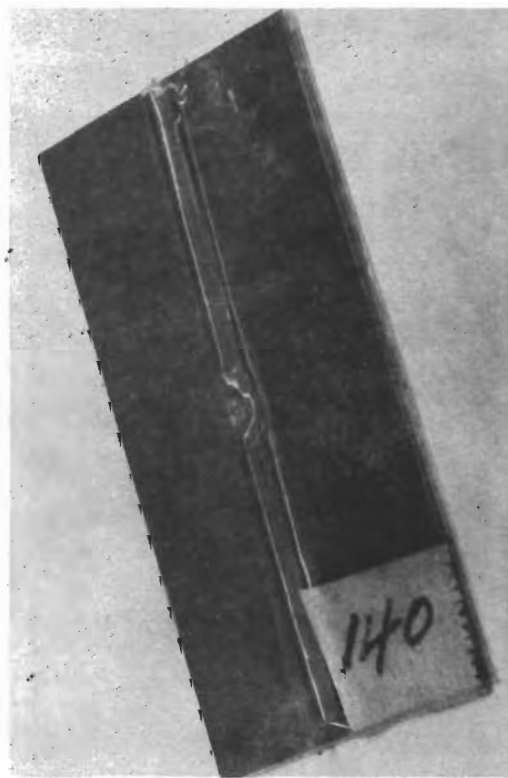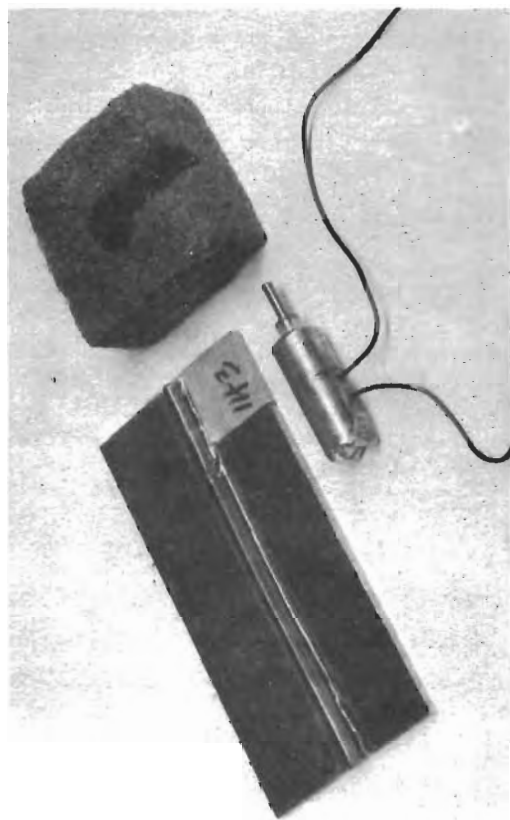
Figure 8

Figure 10

Figure 7

Figure 9

Figure 11

935 amps/cm
— CURRENT

0.5 μsec — cm

← Q₀

437 microcoulomb/cm
— CHARGE

0.5 μsec — cm

500 volts/cm
— VOLTAGE

0.5 μsec — cm

PIN TIME

2.0 μsec — cm

GA-4267-22A

Figure 12

935 amps/cm
— CURRENT

0.5 μsec — cm

← Q₀

437 microcoulomb/cm
— CHARGE

500 volts/cm
— VOLTAGE

0.5 μsec — cm

0.5 μsec — cm

PIN TIME

2.0 μsec — cm

GA-4267-24A

Figure 13

935 amps/cm
— CURRENT

0.5 μsec — cm

← Q₀

437 microcoulomb/cm
— CHARGE

0.5 μsec — cm

500 volts/cm
— VOLTAGE

0.5 μsec — cm

PIN TIME

2.0 μsec — cm

GA-4267-23A

Figure 14

6-13

Figure 11

Figure 12

Figure 13

Figure 14

6-13

935 amps/cm
— CURRENT

437 microcoulomb/cm
— CHARGE

500 volts/cm
— VOLTAGE

dI/dt

0.5 μsec — cm

0.5 μsec — cm

0.5 μsec — cm

2.0 μsec — cm

Figure 15

935 amps/cm
— CURRENT

437 microcoulomb/cm
— CHARGE

500 volts/cm
— VOLTAGE

dI/dt

0.5 μsec — cm
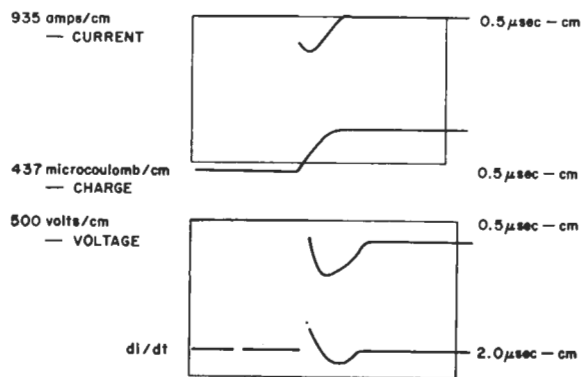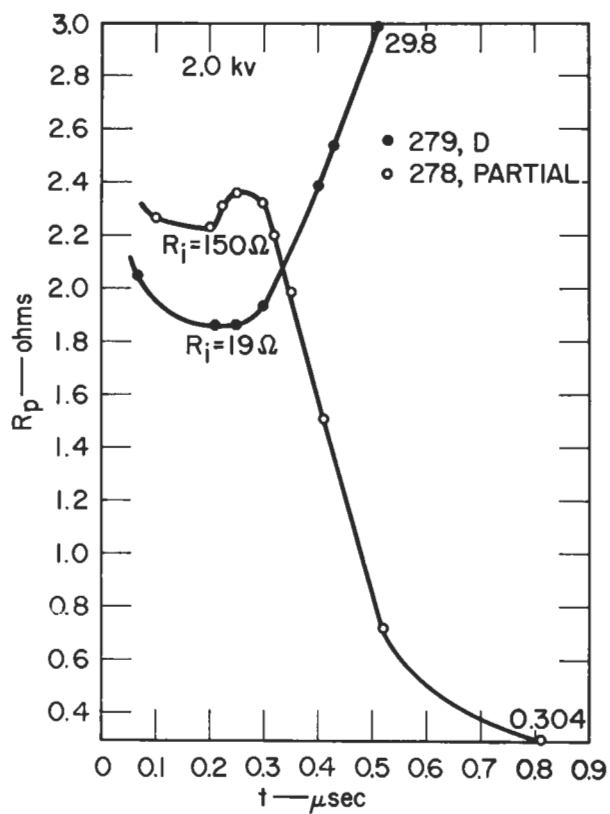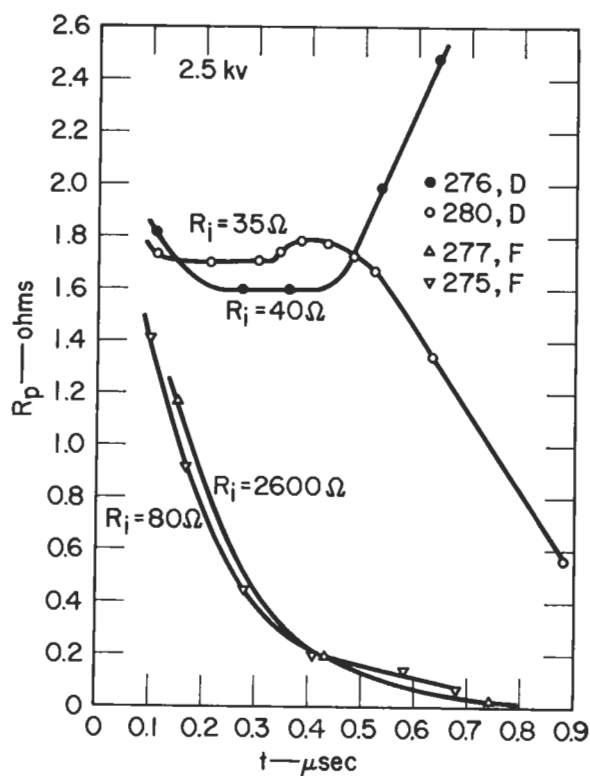
0.5 μsec — cm

0.5 μsec — cm

2.0 μsec — cm
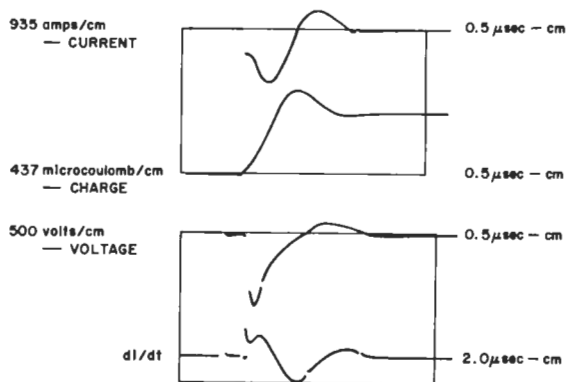
Figure 16

Figure 17

Figure 18

6. DISCUSSION

Mr. Austing of IIT Research Institute asked about the particle size distribution in the conductive mix and how input resistance was controlled. Mr. Moore answered that with the exception of the reprecipitated PETN the particle size was intended to be between 50 and 150 microns. These particles are feathery or filamentary particles. He added that there was no control on resistance; one batch might range from 4 to 40 ohms and the next in the hundreds or thousands of ohms. The finer the graphite and PETN, the more uniform the resistance within a given batch. He continued that there was no correlation observed between initial resistance and performance.

7. HIGH TEMPERATURE PERCUSSION PRIMERS FOR PAD SYSTEMS

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INTRODUCTION

The widespread use of power cartridges in many locations of aircraft flying at supersonic velocities imposes the requirement of relatively high temperature stability for the explosives components of the cartridge. Although electric initiators have found widespread use in many applications, it has been the continued policy of the Air Force to use percussion primed power cartridges to avoid the use of an independent, auxiliary power supply. In addition, the use of these percussion systems over a period of approximately fifteen years has produced a high degree of refinement of design and reliability of performance which would be extremely difficult to match by the introduction of another initiating system. Early recognition of the hazards of stray electromagnetic radiation on electric initiators was also a factor in influencing the policy of maintaining the percussion type initiator.

In considering the problem of exposure to high temperature, the percussion element is of prime importance in the chain of explosive

events, and its performance must be described in terms of a tempera-
ture-time relationship. The 400°F requirement for temperature was
specified by the Air Force; the exposure time that was generally
mentioned for the devices was in the range of perhaps 4-8 hours. It
was reasoned that a truly temperature-resistant primer should be
stable over an extended period of time, and an arbitrary limit of
2000 hours was decided upon.

Although PAD devices generally employ several sizes of percussion
primers, this program was limited to a caliber .30 size, and the goal
of performance requirements included all-fire in the range of 60 inch-
ounces of energy, and a capability of functioning both at 400°F and
after exposure to 400°F for 2000 hours.

The primer studies discussed in this paper were conducted by
Frankford Arsenal and Remington Arms Company, Inc. The major portion
of the work on the percussion primer development was done under a
contract[1] with Remington Arms Company.

COMPOSITIONS AND INGREDIENTS

Early in the development work it was realized that the standard
or common kinds of priming compositions would not be stable at 400°F.
For example, the two most commonly used oxidizers for percussion
primer compositions are potassium chlorate and barium nitrate, both
fairly heat stable within the temperature range under investigation.

These oxidizers, however, are usually mixed with fuels of the class of compounds known as primary explosives from which the composition derives its impact sensitivity. Common to this class of explosive fuels are such metal organic compounds as mercury fulminate, lead styphnate, lead azide, etc., none of which have high temperature stability. Usually small quantities of organic explosives, such as, tetracene and friction agents are added to these basic ingredients to further increase sensitivity. Table 1 gives a list of primer ingredients which were included in this investigation. Table 2 gives the principal ingredients used in the commonly used lead styphnate primers.

Not all the ingredients listed in Table 1 proved satisfactory. For example, DATB and TATB reported to be stable in this temperature range, rendered the compositions less impact sensitive. Others, such as lead azide and pentaerythrite tetranitrate, although good sensitive fuels, were not stable at 400°F.

Table 3 gives the formulas for the compositions found to be best for stability at 400°F within the prescribed sensitivity range with G-11 and G-16 compositions giving best results to date. Except for G-11 which contains a high temperature explosive compound, Tacot, developed especially for high temperature stability by E. I. DuPont, it will be seen that these formulas are of the simple oxidizer-fuel type most often found in the non-gaseous types of many pyrotechnic compositions.

The compound, Tacot is, however, an explosive producing gaseous products during primer composition reaction. This characteristic helps reduce the tendency of these simple oxidizer-fuel compositions to give squibs, i.e., slow initiation upon impact and it also imparts more force to the resultant explosion.

The purity of the chemical ingredients in priming compositions, always important, is of even greater importance at elevated temperatures. This was found to be especially true for the antimony trisulphide used in these compositions. The free sulphur content in the commercial grade of antimony trisulphide used for this high temperature work was reduced to 0.02 per cent by resmelting. The purified material is then reground to size. The stability of G-11 and G-16 compositions in early tests was found to be poor at 400°F when they were prepared with the regular specification grade of antimony trisulphide.

As a basis of comparison for this investigation, standard Caliber .30 lead styphnate primers, which had been manufactured by three different facilities, were evaluated for heat stability at temperatures of 250°, 300° and 350°F and labeled A, B and C in Figures 1, 2 and 3.

A number of other explosive compounds were tried, such as, potassium lead styphnate-lead hypophosphite, ferric styphnate-ferric hypophosphate, normal lead picrate, and lead azide without significant improvement. Composition G-1 not included in Table 3 contains potassium chlorate as a substitute for barium nitrate in the basic lead styphnate primer formula.

Red phosphorus priming composition X-975 formula is given in Table 3. This composition was prepared with stabilized red phosphorus and a combination of bis-phenol epoxide and phenolformaldehyde resins was used as the composition binder. Aluminum clad cups and zinc plated brass anvils were used because red phosphorus is not stable in contact with brass or copper. A paper foil prevents direct contact of the anvil with the composition.

Primer Charging

The type of percussion primer used for the long term storage test at 400°F given in this paper is illustrated in Figure 5. These primers at present carry a Remington Arms Company, Inc. designation of 73M Percussion Primer and were manufactured by Remington.

The primer loading or charging process employed is known as the dry charging process. This process consists briefly of dropping the prescribed quantity of dry priming composition into the primer cups. Immediately prior to this, however, a drop of 5 per cent shellac-alcohol solution is first applied to the inside bottom of the cups. This solution coats the cup metal and permeates the dry composition granules to aid consolidation of the primer pellet. The composition is then covered by a paper foil and pressed under controlled pressure. The primer anvils are pressed into the charged cups.

It has been found that the shellac coating inhibits the reaction of the priming compositions with the brass cups at 400°F to a con-

siderable extent. However, excess shellac in the composition reduces impact sensitivity. Therefore, a series of experiments are being conducted to determine the critical quantity of shellac in the composition consistent with impact sensitivity and the best techniques for applying the shellac to the metal components. Although the results of these experiments with shellac are not available for inclusion in this paper, the experiments are mentioned because of the importance of the shellac on the stability of primers at 400°F.

STORAGE CONDITIONS AND SENSITIVITY TESTS

The oven used for the storage tests is an ultra-temperature oven with a temperature range of 66°C to 650°C and is capable of maintaining 400°F ± 3°F throughout the storage period.

The loose primer storage tests were conducted by placing the primers in open metal cans and placing the cans on the steel shelves in the oven. Bruceton type sensitivity drop tests were conducted by holding the primer in a steel die which in turn is held in position in the standard government type testing apparatus.

The primed case tests were conducted by first inserting the primers into standard NATO 7.62 mm brass cartridge cases. The primer pockets in the case were sealed by a 0.010 inch aluminum disc as illustrated in Figure 6. The primed cases were tested for impact sensitivity in the standard government testing apparatus. Primed brass cartridge cases were used to simulate the aluminum primer heads

because of immediate availability of unlimited quantities and the
relative low cost of the cases. A difference in sensitivity results,
however, was found between primers in brass cases and primers in
aluminum heads. This difference, believed to be caused by the greater
free volume in the primer cavity in the M73 aluminum heads tends to
produce squibs and can be seen by comparing Figure 6, the primed case
drawing and Figure 7, the M73 aluminum head drawing.

New aluminum primer heads and aluminum cartridges are being de-
signed with reduced volume for the primer pockets. This increased
confinement should eliminate squibs. The primer pocket in the new
cartridge design will be integral with the cartridge case.

After removing the primers and primed cases from elevated tempera-
ture storage, they were allowed to cool at ambient conditions for one-
half to one hour; then conditioned at 72°F and 65% relative humidity
for one to two hours before testing for sensitivity.

IMPACT SENSITIVITY RESULTS AFTER STORAGE

Throughout this work primer impact sensitivity was used as a
measure of stability since it was not considered reasonable to de-
termine the exact degree of chemical decomposition, products of de-
composition and their relationship with sensitivity and function when
none of the current kinds of primers approach the goal of stability
at 400°F. These primers commonly called lead styphnate types are
used primarily for center fire caliber .30 rifle cartridges by the

commercial manufacturers and the government. They are also used as initiators in a number of current cartridges for Propellant Actuated Devices. However, the results reported here indicate that it will be possible to replace the lead styphnate primers with new G-11 or G-16 primers for use at elevated temperature.

Commercial Primers

Three regular brands of lead styphnate percussion primers, labeled A, B and C, were stored at 250, 300 and 350°F to provide a basis of comparison with the new high temperature primers under development. In addition, modified commercial compositions G-1 and G-7 were included for storage since some improvement in stability was expected by substituting potassium chlorate for the barium nitrate oxidizer in G-1, and the double salt of basic lead picrate-lead nitrate for lead styphnate in G-7. The other composition numbered 5107 is essentially the same as the commercial lead styphnate composition labeled lot "C" on the graphs, except the tetracene normally used as a sensitizer was omitted.

Figures 1, 2 and 3 give the impact sensitivity results of the commercial and modified types of primers after storage periods shown on the graphs. These lots of primers were tested for sensitivity by the Bruceton type test with 25 primers at each storage period. These limited tests do not reflect the most accurate value of the all-fire height. However, the results aae sufficiently accurate to show the important changes with storage time for these temperature conditions.

It will be noted in Figures 1, 2 and 3 that the primers with compositions G-1, G-7 and 5107 before storage are either border line with respect to meeting the specification impact energy level or as in the case of 5107 definitely outside this level. The standard commercial brands A, B and C on the other hand fall well within specification for impact sensitivity prior to storage.

Figure 1 gives the sensitivity results after storage at 250°F. After the first few hours storage all the primers showed an increase in sensitivity. After the first few hours however, the impact sensitivity decreased and remained outside the specification level. The increase in sensitivity is believed to have been caused by the loss of 1 mole of water of hydration from the lead styphnate. The decrease in sensitivity after 8 hours is caused by the decomposition of tetracene used as a sensitizer. Compositions G-1 and G-7 appear to be stable to 168 hours and possible longer. However, to insure adequate function, these primers would require some increase in impact energy while compositions A, B, C and 5107 would require considerably more impact.

Except for the effect of loss of water of hydration and tetracene not being as clearly apparent at 300°F as for 250°F storage, the results shown in Figure 2, for 300°F storage, are about the same as discussed for the data in Figure 1.

Figure 3 gives the storage results of the primers at 350°F. It will be seen that except for lot G-7 which appears to be useful to

about 80 hours at this temperature, the other compositions A, B, C, G-1 and 5107 have extremely limited stability to the point of being not useful at 350°F.

Experimental Primers

Figure 4 gives the storage results of Frankford Arsenal red phosphorus composition X-975 at 350°F. The borderline sensitivity level shown in this figure is caused by the combination of aluminum clad brass primer cups and the resins found to be necessary in the composition to improve stability. The stability of this primer appears to be very good up to 1000 hours at 350°F and probably appreciably beyond this time. However, primers stored at 400°F were found to be stable to only 336 hours. In addition, examination of these primers several months after prolonged storage at 350°F revealed that the resin binder decomposed causing the primer pellets to crumble and become loose.

Figure 8 gives the results of primers stored in brass cartridge cases with aluminum seals at 400°F for 3528 hours. These primers are remarkably stable and contain G-11 and G-16 priming compositions. The formulas are given in Table 3. The impact sensitivity data shown in Figure 8 was obtained by conducting complete run-down sensitivity tests, testing 25 primers at each height from no fire to all fire after each storage period and is therefore reliable. The data was calculated by the specification method and plotted two ways, i.e., the average

height, $\overline{H}$, the height where 50% of the primers fire and $\overline{H} + 3\sigma$ or

the average height in inches plus 3 times the standard deviation

which is also given in inches. The value of 3 times the calculated

standard deviation, σ, added to the value for $\overline{H}$ fixes the acceptance

level of the primers for sensitivity and uniformity. It will be seen

that the sensitivity level of these primers is borderline since $\overline{H} + 5\sigma$

shall be no greater than 15 inches with a 4 ounce ball to meet the

specification requirement for standard primers. However, the excellent

stability results obtained has initiated design changes in the PAD

cartridge firing mechanisms to increase the firing pin impact energy.

These design changes will produce reliable firing energy for the new

high temperature primers.

Figure 9 gives the results of G-11 and G-16 priming compositions

stored at 400°F as loose primers, i.e., not primed into brass cartridge

cases. Again the primers show remarkable stability. This test was

conducted to obtain data on the stability of the primers without the

influence of the brass case and aluminum seal. The tests were con-

ducted at each of two drop heights with a 4 ounce ball, i.e., 10 inches

and 12 inches testing 50 primers of each lot at the end of each storage

period. The percentage of primers firing out of 50 tested at 10 inches

and at 12 inches was plotted. The results approximate the results

shown in Figure 8 for the same primers in brass cartridge cases. The

data are slightly erratic because of the loose primer test method and

the limited tests. However, the data show that G-11 is more sensi-

tive than G-16 composition at 10 inches and there appears to be some

slight loss of sensitivity for both lots after 3024 hours. Despite

the limited testing these differences are considered significant

because the trend develops over a long period of storage time.

FIRING RESULTS IN CARTRIDGES

Table 4 gives the results of standard and experimental primer-

propellant ignition studies at 70°F, 200°F and -65°F. Standard 72M

Remington primers for comparison with G-11, G-16 and X975 experimental

primers were used for the tests. Each lot of primers were assembled

into M73 cartridges containing HES 5808 propellant and black powder,

and fired in M3A1 Initiators. The 72M, G-11 and G-16 primers used

for these tests were fresh primers held at ambient primer storage prior

to being brought to the conditioning temperatures of 70°, 200° and

-65°F for firing.

The only X-975 primers available at this time were primers which

had been stored previously for 500 hours at 350°F and removed for

ambient storage for several months prior to conducting these cart-

ridge firing tests. It was found by subsequent examination of the

misfired primers that the resin binder in the priming composition broke

down causing the primer pellet to crumble.

All of the initiators which fired gave results within the limits

specified in Frankford Arsenal P.D., M1-2225, Revision 2.

The experimental primers gave results approximating the results

obtained with the 72M standard primers. Slightly higher peak pressures were obtained for the G-11 primers at 70°F and -65°F. The reason for this is not understood since higher pressures were not obtained at 200°F where it might be expected that a primer of greater propellant igniting power would produce even higher peak pressures. However, the data reported in Table 5 for G-11 primers gives some indication of this expected result.

Table 5 gives results of standard and experimental primers assembled into M73 cartridges and fired in M5 Initiators after first being conditioned at 70°F and 400°F for 4 hours. This firing program was conducted to test the experimental primers G-11 and G-16 in combination with HES 6573.1B, one of the more promising temperature resistant propellants. Included for comparison at 70°F is a lot consisting of standard M73 cartridges containing the current standard primer and propellant and a lot with a standard Remington 72M primer and the new propellant, HES 6573.1B.

All the experimental cartridges produced higher peak pressures than the standard M73 cartridges. The cartridges primed with the G-11 primers gave the highest average peak pressures. The ignition time delay and rise times were only slightly less for the standard cartridges. However, the cartridges primed with G-11 and G-16 primers gave higher peak pressures and faster burning times after being conditioned at 400°F for 4 hours. These results may be explained by

the fact that the primers and propellant were initially at higher energy levels during the 400°F firing tests. The results are considered acceptable.

CONCLUSIONS

1. The standard lead styphnate primers have limited stability at temperatures of 250°, 300° and 350°F; stability decreasing with temperature rise.

2. The red phosphorus composition X-975 appeared to be stable for 1000 hours at 350°F and 336 hours at 400°F, breakdown of the resin binder under prolonged storage at ambient conditions indicates that further studies with this primer would be required to meet the goal of 2000 hours.

3. Both G-11 and G-16 primers more than meet the goal for chemical stability of 2000 hours at 400°F originally set forth for these studies. However, slightly higher impact energy and increased primer cavity confinement to eliminate a tendency to squib after prolonged storage at 400°F, are required for acceptable firing reliability.

FUTURE EFFORTS AND TRENDS

Immediate plans include qualification testing and subsequent standardization of the M73 primer with G-11 mixture. It is quite definite that, inasmuch as the performance of this primer depends on confinement, the geometry of the primer container or pocket will be specified. A project has been initiated to redesign the firing mechanism to increase the impact energy sufficiently to obtain reliable firing in all items in which the new primers may be used. It is also anticipated to continue work on both primer manufacturing processing and design of components. The use of the laminated anvil shown in Figure 10 and currently under development, will serve to completely contain the primer pellet and thereby provide greater resistance to vibration, in addition to the added benefit of designing a confinement medium into the primer. Assessment of the storage life at temperatures of 450°F and 500°F will also be made, although a much shorter period of useful life will exist in this range.

REFERENCES

1. "High Temperature Percussion Primers", Contract No. DA-19-020-ORD-5153.

TABLE 1

INGREDIENTS FOR PERCUSSION PRIMING MIXTURES

SUBSTANCE	MELTING POINT °C	°F	DECOMPOSITION TEMPERATURE °C	°F
POTASSIUM PERCHLORATE			400	752
POTASSIUM CHLORATE	368	694		
BARIUM NITRATE	592	1098		
LEAD DIOXIDE			290	550
PHOSPHORUS, RED	590	1094		
ZIRCONIUM				
ANTIMONY TRISULFIDE	550	1022		
CALCIUM SILICIDE	1840	2804		
GLASS (GROUND)	136	280		
PENTAERYTHRITE TETRANITRATE				
LEAD AZIDE	EXP 350	662		
LEAD STYPHNATE	EXP 160	320	290	550
TETRACENE				
TACOT			400	752
DATB				
TATB				
BASIC LEAD PICRATE LEAD NITRATE (DOUBLE SALT)	>315	>600		
RESIN BINDER				

TABLE 2

COMMERCIAL BRANDS OF STANDARD CALIBER .30 LEAD STYPHNATE PRIMING MIXTURES

PRINCIPAL INGREDIENTS
- LEAD STYPHNATE   40–45%
- BARIUM NITRATE   40–45%
- TETRACENE   APPROX 5%

OTHER INGREDIENTS
- PENTAERYTHRITE TETRANITRATE
- ANTIMONY TRISULFIDE
- CALCIUM SILICIDE
- ALUMINUM
- NITRO CELLULOSE
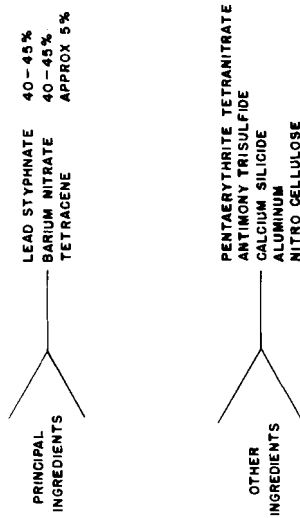
TABLE 3

COMPOSITION OF EXPERIMENTAL PERCUSSION PRIMING MIXTURES FOR HIGH TEMPERATURE

SUBSTANCE	MIXTURE G-7	G-11	G-16	S107*	X975
POTASSIUM CHLORATE	45.5	53	53		
BARIUM NITRATE					63.5
TACOT		10			
DOUBLE SALT OF BASIC LEAD PICRATE AND LEAD NITRATE	36				
ANTIMONY TRISULFIDE	9	25	30		
CALCIUM SILICIDE	7.5	12	17		
PHOSPHORUS, RED					26.3
GLASS (GROUND)					3.7
RESIN BINDER **					6.5

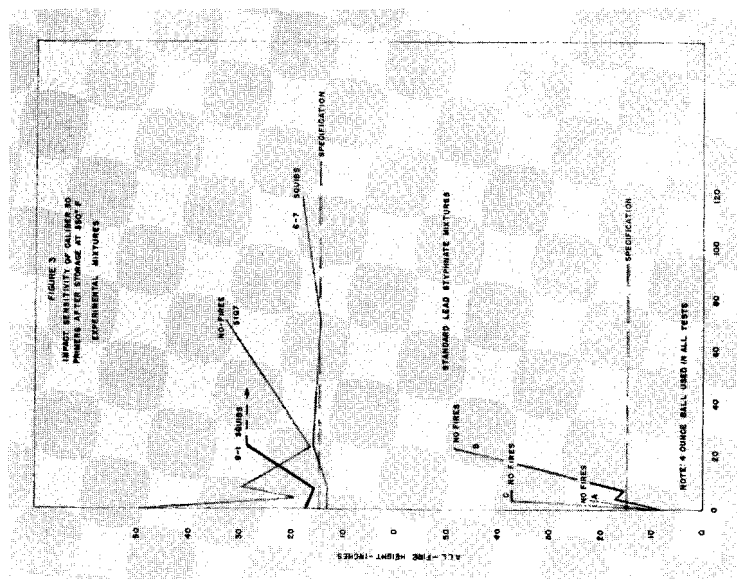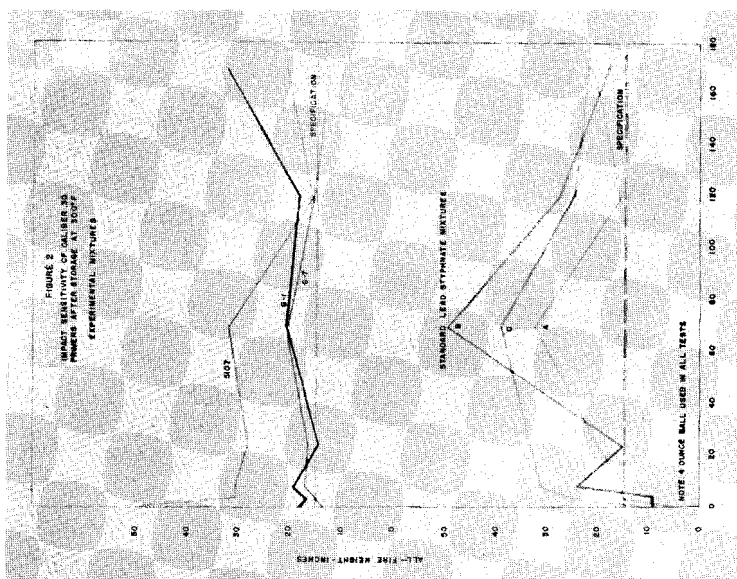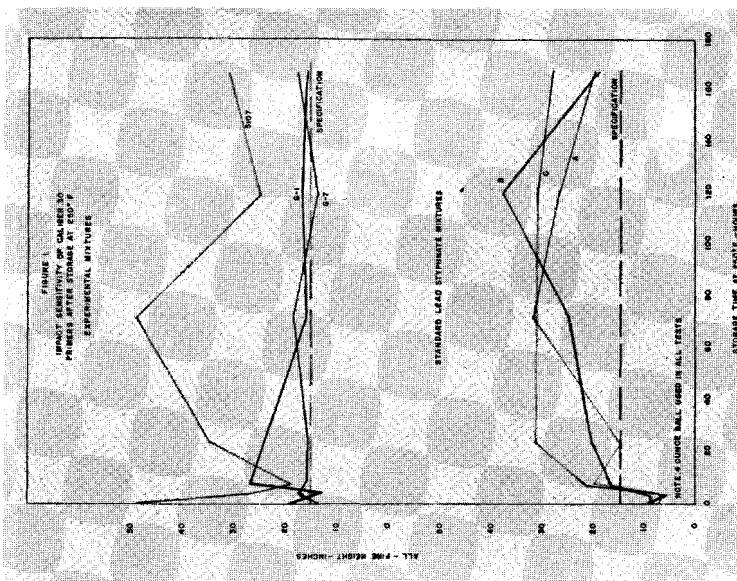*SAME AS COMMERCIAL BRAND "C" EXCEPT CONTAINS NO TETRACENE

**MIXTURE OF BIS-PHENOL EPOXIDE AND PHENOL-FORMALDEHYDE RESINS

TABLE 4

RESULTS OF PRIMER – PROPELLANT IGNITION STUDIES
CONDUCTED IN M3A1 INITIATORS AT AMBIENT,
HIGH AND LOW TEMPERATURES

PRIMER	NUMBER OF INITIATORS FIRED	IGNITION DELAY TIME M.S.	RISE TIME M.S.	PEAK PRESSURE PSI
CONDITIONED AT 70° F				
REM 72M	3	15	18	1220
X975	3 *	—	—	—
G-11	3	14	19	1340
G-16	3	15	22	1290
CONDITIONED AT 200° F				
REM 72M	3	15	18	1400
X975	3 **	32	16	1430
G-11	3	16	17	1390
G-16	3	15	19	1450
CONDITIONED AT-65° F				
REM 72M	3	17	27	910
X975	3 **	38	13	970
G-11	3	16	20	1050
G-16	3	20	30	970

* THREE PRIMERS MISFIRED
** TWO PRIMERS MISFIRED

TABLE 5

RESULTS OF PRIMER – PROPELLANT IGNITION STUDIES
IN M5 INITIATORS CONDITIONED 4 HOURS AT 70° AND 400° F.
USING HES 6573 1B PROPELLANT

PRIMER	NUMBER OF INITIATORS FIRED	AVERAGE IGNITION DELAY TIME M.S.	AVERAGE RISE TIME M.S.	AVERAGE PEAK PRESSURE PSI.
CONDITIONED AT 70° F.				
STANDARD M73	5	12	18	1060
REMINGTON 72M	5	16	19	1310
G-11	5	13	20	1450
G-16	5	16	20	1290
CONDITIONED AT 400° F.				
G-11	5	9	15	1600
G-16	5	12	15	1460

FIGURE 3
IMPACT SENSITIVITY OF CALIBER 30
PRIMERS AFTER STORAGE AT 250°F

EXPERIMENTAL MIXTURES

STANDARD LEAD STYPHNATE MIXTURES

NOTE: 4 OUNCE BALL USED IN ALL TESTS

STORAGE TIME AT 250° HOURS

FIGURE 2
IMPACT SENSITIVITY OF CALIBER 30
PRIMERS AFTER STORAGE AT 300°F

EXPERIMENTAL MIXTURES

STANDARD LEAD STYPHNATE MIXTURES

NOTE: 4 OUNCE BALL USED IN ALL TESTS

STORAGE TIME AT 300°F - HOURS

FIGURE 1
IMPACT SENSITIVITY OF CALIBER 30
PRIMERS AFTER STORAGE AT 250°F

EXPERIMENTAL MIXTURES

STANDARD LEAD STYPHNATE MIXTURES

NOTE: 4 OUNCE BALL USED IN ALL TESTS

STORAGE TIME AT 250°F - HOURS

7-18

FIGURE 4
IMPACT SENSITIVITY OF CALIBER .30
PRIMERS AFTER STORAGE AT 350° F
EXPERIMENTAL MIXTURE X975

FIGURE 5
73 M PERCUSSION PRIMER
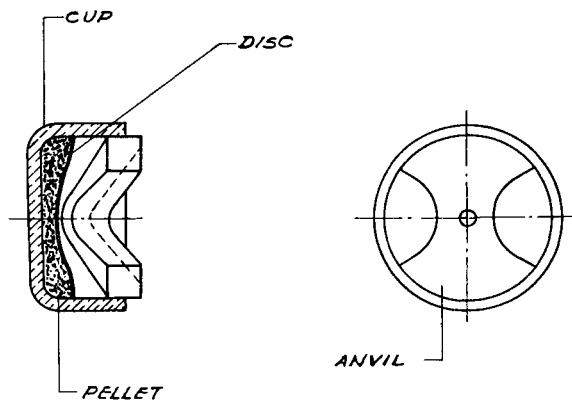
FIGURE 6
BRASS CARTRIDGE CASE WITH ALUMINUM SEAL
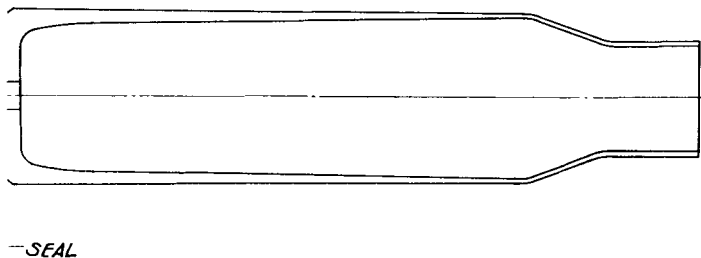
FIGURE 7
M. 73 PRIMER HEAD - ALUMINUM
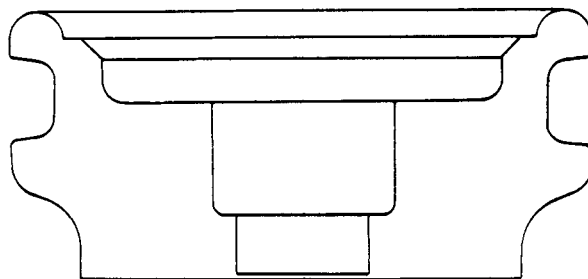
FIGURE 8
IMPACT SENSITIVITY

FIGURE 8
IMPACT SENSITIVITY

STORAGE TIME AT 400°F — PRIMED CASES
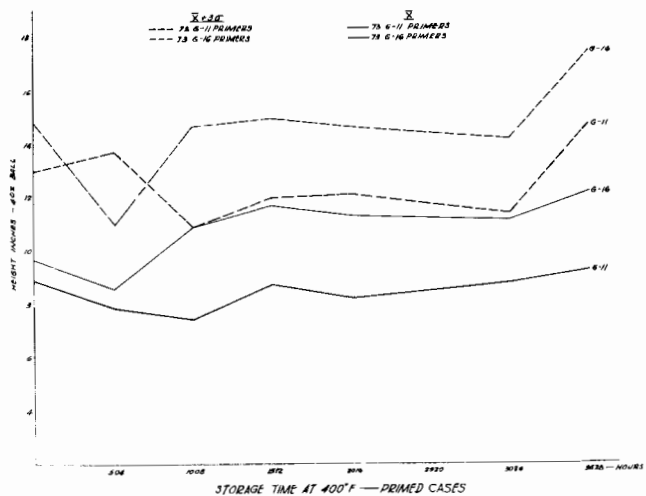
FIGURE 9
IMPACT SENSITIVITY

STORAGE TIME AT 400°F — LOOSE PRIMERS
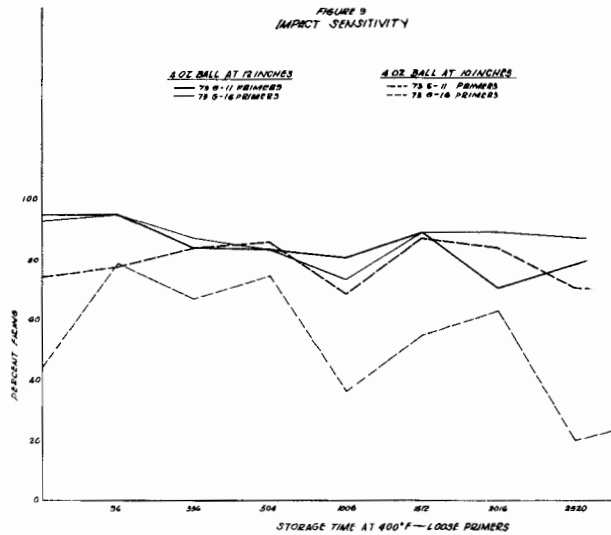
FIGURE 10
LAMINATED PRIMER ANVIL

BRASS LAMINATE
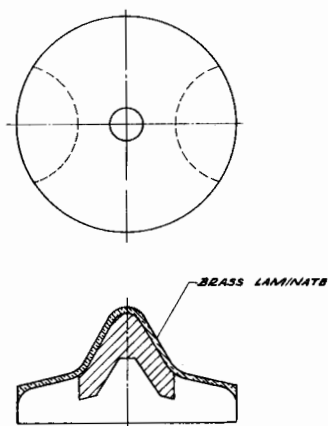
ABSTRACTS

8. <u>Discourse on MIL-I-23659 (WEP)</u>   J. Max Massey
                                                             Andrew J. Steppe

"Military Specifications MIL-I-23659 (Wep), Initiators Electric, Design
and Evaluation of," was approved by the Bureau of Naval Weapons in
March 1963. The philosophy underlying the choice of certain electrical,
functional, and environmental requirements of the specification is
presented. Quality assurance provisions are discussed in relation to
these requirements.

9. <u>Range Safety Policy on Ordnance Standards With Regard</u>   T. E. Fewell
    <u>to RF Radiation Hazards</u>

Following comments on background and reasons for adoption, the statement
of policy is presented, with a copy of approval form, for information
and to provide opportunity for questions and discussions.

10. <u>Estimation of High and Low Probability EED Functioning</u> J. N. Ayres
    <u>Levels</u>   I. Kabik
                                                                   L. D. Hampton

Some difficulties in estimating extreme EED functioning probabilities arise
from test plan limitations, extrapolation problems, sampling errors and
dud-rate. These limitations are discussed along with improved techniques
and methods for making the estimates.

11. <u>Comments on Constant-Current Initiation Characteristics</u> A. G. Benedict
    <u>of Hot-Wire-Bridge Squibs, with Particular Reference</u>
    <u>to Log-Current Log-Time Firing Curves</u>

Certain initiation characteristics of squibs are reviewed, and some
advantages in use of log-current log-time firing curves are discussed. A
simple method for analyzing small sample test results is outlined;
special test sequences such as that of the Bruceton Method are not required.

8. DISCOURSE ON MIL-I-23659(WEP)

A. J. Steppe

J. Max Massey

Warhead and Terminal Ballistics Laboratory
Cartridge Actuated Devices Division
U.S. Naval Weapons Laboratory
Dahlgren, Virginia

September 1963

ABSTRACT

Military Specification MIL-I-23659(Wep), Initiators,Electric,
Design and Evaluation of, was approved by the Bureau of Naval Weapons in
March 1963. The philosophy underlying the choice of certain electrical,
functional, and environmental requirements of the specification is
presented. Quality assurance provisions are discussed in relation to
these requirements.

INTRODUCTION

Prior to MIL-I-23659 there did not exist in the Navy a document which
provided general design requirements or quality assurance provisions for
electric initiators. Since these requirements and assurance provisions
did not exist, electric initiators were designed and tested solely on their
ability to perform in the originally proposed device of intended appli-
cation thereby precluding any hope of design and test standardization or
secondary usage without further extensive testing. The fact that, under
these conditions, the Navy per se could not exercise proper control over
electric initiators accepted for service was recognized by BUWEPS.

In 1962 BUWEPS assigned to NWL, Dahlgren the task of preparing
a specification for the design and evaluation of electric initiators.
This specification was to provide general design requirements and
quality assurance provisions for the greatest possible item coverage in
the entire electric initiator field. Since the spectrum of usage for
electric initiators is so diverse it was recognized from the outset that
no one general specification could possibly cover all facets of design
and quality assurance provisions. However, it was decided that certain
minimum requirements could be imposed on all electric initiators with
few exceptions. To provide for these exceptions, it was decided to
incorporate in the specification a means whereby specification requirements
which were in conflict with application requirements could be circum-
vented. This is provided in a "Special Requirements" paragraph. Further,
it was felt mandatory that some procedure be available to allow for the
orderly transition of electric initiators from the design stage to a
Navy standard stocked item. This was taken care of by providing four
types of release to service. These will be discussed in more detail
later.

PURPOSE

This specification was prepared to insure that some semblance of
standardization exist in the design, testing and acceptance of electric
initiators for Navy use. The specification sets forth the minimum re-
quirements and quality assurance provisions for Navy approved electric
initiators. To provide the widest possible coverage of the electric

initiator field, only minimum requirements have been included. They impose restrictions and demands on the design, electric characteristics, and environmental resistant qualities of electric initiators.

The testing program established by this document is for the purposes of determining:

(a) that the initiator can be expected to perform satisfactorily under normal and adverse conditions in the device of intended application;

(b) that the initiators are safe for handling, transportation, storage and use; and,

(c) that the initiators do not deteriorate to a degree which would render their performance or safety doubtful under adverse storage conditions.

The specifications further provides for the orderly flow and acceptance of electric initiators into the Navy supply system from the design stage to a standard stock item.

SCOPE

The specification furnishes general requirements for design and establishes uniform methods of testing electric initiators and electric initiator subassemblies. The purpose of the testing program is to determine the electric characteristics, soundness of mechanical design, output, and resistance to deleterious service environments. The term electric initiator includes such items as hot wire initiators, exploding bridgewire initiators, conductive mix initiators, and in general any single discrete unit, device, or subassembly whose actuation is caused

by the application of electric energy which in turn initiates an explosive, propellant or pyrotechnic material contained therein. The term electric initiator does not include complete assemblies which have electric initiators as subassemblies but includes only the subassemblies themselves. RF susceptibility requirements and tests have not been included in this specification because the general requirements and necessary tests are not available at the present state-of-the-art. Implicit in the one watt and one ampere maximum no-fire requirements of this specification is the recognition of the hazards of electromagnetic radiation to ordnance (HERO). This one watt and one ampere requirement in conjunction with other design requirements stated herein does not solve the HERO problem; however, they do serve as means of reducing hazards from all spurious electric sources including electromagnetic radiation.

TYPES OF RELEASE

In order to exercise control over electric initiators used in Naval equipment from the design stage to the point where they become a standard stock item, there are four types of release provided. They are as follows:

Type I -

Safety of handling and installation. Certification as to safety of handling and installation is required prior to installing an electric initiator in Naval equipment.

Type II -

    Interim service release. This type of release is required prior
to any use of electric initiators or devices containing electric
initiators involving Naval personnel.

Type III -

    Full service release. This type of release is required for admission
of the electric initiator into the Bureau of Naval Weapons Supply System
for fleet use.

Type IV -

    Use of an approved electric initiator in a new application. This
type of release is required for an initiator which has had a Type III
release and will be used in an application other than the originally
intended application.

    In this manner the contractor or developer has the choice of using
either a newly designed initiator or a standard stock initiator that was
originally designed for another application. In the interest of economy
the Navy prefers that an initiator that has had a Type III release be
used in new applications where possible.

<center>REQUIREMENTS</center>

    Prior to formulating the design, electric, and environmental require-
ments to be incorporated in the specification, Government and contractor
personnel in the fields of underwater ordnance, missiles and aircraft
were contacted. From their diverse requirements we endeavored to present
a composite of minimum requirements that would be applicable in the

<center>8-5</center>

majority of cases. By no means are the requirements stated in the specification to be considered the optimum for any one application.

Design -

Of the design requirements given in the specification, three warrant mention here. Most, but not all, applications require the initiator to be hermetically sealed. When the sealing requirement is waived, the environmental requirements are relaxed to the extent that the leakage, temperature and humidity cycling, and salt spray requirements are deleted. Due to the multitude of troubles (such as the low reliability and high sensitivity) experienced in the Navy with carbon bridged initiators, carbon has been excluded as a bridge material. As an additional precaution against spurious electrical hazards, the bridge circuit insulation and insulation barrier requirement was included. This requires that the bridge circuit be electrically insulated from the case, thus eliminating all case-grounded circuits, and that a continuous insulation barrier be provided between the case and any explosive, propellant or pyrotechnic material which is in contact with the bridge circuit.

Electric Characteristics -

The electric characteristics incorporated in this specification establish minimum requirements to reduce hazards from all spurious electric sources. They also require that initiators have uniform sensitivity to firing pulses such that the power supply requirements can be readily stated. In the past, initiators were often designed to be compatible with the available power supply or the power supply was designed around the electric

sensitivity requirements of the initiator - nothing standardized, ergo a vicious circle.

As may be noted in the specification, initiators have been divided into two groups (Group A and Group B). Power requirements for Group A span a relatively narrow range at the low end of the power spectrum while the power requirements for Group B initiators span a relatively narrow range at a higher level in the power spectrum. By partitioning the spectrum in this manner, virtually all application requirements could be embodied. This partitioning did not preclude uniformity, at least by groups, in the electrical sensitivities of initiators.

Requirements for Groups A and B - We will not discuss all the electrical requirements but we would like to justify those of a controversial nature. First, Group A is defined to include any initiator that is capable of being actuated within one second (exclusive of delay element time, if present) from a 28 ± 2 volt d. c. source capable of delivering not less than 10 amperes. Group B includes any initiator that is not capable of being actuated within one second (exclusive of delay element time, if present) from a 28 ± 2 volt d. c. source capable of delivering not less than 10 amperes. These definitions are not requirements but serve only to establish a criterion for placing an electric initiator in either Group A or B.

Electric Requirements, Group A - The electric requirements for Group A include:

(a) The maximum no-fire currents shall be not less than 1 ampere per bridge.

(b) The maximum no-fire power shall be not less than 1 watt

per bridge.

(c) The initiator shall not fire from a 500 micromicrofarad

capacitor charged to 25,000 volts when discharged through a

5,000 ohm resistor connected in series with one bridge.

(d) The minimum 50 millisecond all-fire current shall not exceed

5 amperes per bridge.

(e) The minimum 50 millisecond all-fire power shall not exceed

5 watts per bridge.

The maximum no-fire current and maximum no-fire power requirements for

Group A were chosen to be consistent with the requirements issued by the

Safety Division, Office of the Inspector General, Headquarters, Air Force

Systems Command. The minimum 50 millisecond all-fire current and minimum

50 millisecond all-fire power requirements insure that initiators can be

actuated using power supplies compatible with the weapon system in most

applications. The capacitor discharge requirement simulates the discharge

of static electricity from the human body. This is expected to preclude

inadvertent firing from that source.

Electric Requirements, Group B - The requirements for initiators in

Group B are intended to include exploding bridgewire initiators. However,

they are not intended to exclude other types or exclude any new design or

principle of operation so long as the requirements are met. It is for

this reason that initiators are referred to by group rather than by their

more common names.

The requirements for Group B include:

(a) The maximum no-fire stimulus shall be a potential of not less than 500 volts when discharged from a 1 microfarad capacitor through a 1 ohm resistor and a 10 microhenry inductor connected in series with one bridge.

(b) The initiator shall not fire from a 230 volt 60 cycle a. c. source capable of delivering not less than 30 amperes when this source is connected across the bridge circuit.

(c) The initiator shall not fire from a 500 micromicrofarad capacitor charged to 25,000 volts when discharged through a 5,000 ohm resistor connected in series with one bridge.

(d) The minimum 50 millisecond all-fire stimulus shall be a potential which does not exceed 3,000 volts when discharged from a 1 micro-farad capacitor through a 1 ohm resistor and a 10 microhenry inductor connector connected in series with one bridge.

For the most part, these requirements are less stringent and allow greater latitude in the sensitivity of initiators than do present day detailed specifications. For example, the minimum 50 millisecond all-fire potential was chosen to be 3000 volts in lieu of the more typical selection of 2000 volts. This is to allow for the use of more insensitive secondary explosives than the popular PETN and RDX formulations presently used in many applications. As was the case for Group A initiators, the requirement that the initiator shall not fire from a 500 micromicrofarad capacitor charge to 25,000 volts is expected to preclude inadvertent firing from the discharge of static electricity from the human body.

Environmental and Functional Requirements -

We will not go into detail here for we feel sure most of you are familiar with the mechanics of the environmental and functional requirements imposed by the Navy on ordnance items used in aircraft, missiles, and underwater ordnance. It should be noted that the environmental and functional requirements enumerated in MIL-I-23659 are essentially more stringent than those given in older specifications. The more stringent requirements were necessary in order to keep abreast of the state-of-the-art in Naval ordnance. For each requirement listed in MIL-I-23659 there is a test procedure provided in Section 4 that is to be followed in conducting the test. Suffice it to say that in order to grant full service release (Type III) to an electric initiator, it must successfully fulfill the requirements of Table III of the specification. Subsequent to the environmental treatments of Table 3 and upon completion of the firing program, the specification provides for statistical analysis of the data and establishes the minimum reliability and confidence limits that are to be used for acceptance or rejection of the initiator for service use.

Special Requirements -

It is a foregone conclusion that all weapons requirements will not coincide with those of MIL-I-23659. It is for this reason that a "Special Requirements" paragraph is included. This paragraph serves to clarify the course to be taken regarding these conflicting requirements. Those weapons requirements which are more stringent than the requirements of

this specification shall automatically take precedence. Other conflicting requirements will be resolved in favor of the special requirements only if necessary for satisfactory operation of the initiator in the unit of proposed use and they shall be subject to the approval of the cognizant government contracting agency. It is recognized that the one watt and the one ampere no-fire requirement cannot be imposed on all weapons systems because of limited power supplies or dimensional requirements which limit the ability of the initiator to dissipate one watt for 5 minutes. Where the maximum no-fire requirements of Group A are irreconcilable with the available power supply or dimensional requirements the contractor shall come as close as possible to the requirements of the specification, compatible with the weapons system, and must get written authority from the cognizant government contracting agency to deviate from these requirements.

QUALITY ASSURANCE PROVISIONS

The "Quality Assurance Provisions" section merely details how the test for each requirement is to be conducted and in some cases specifies the equipment to be used. In most instances the number of initiators to be tested is given. However, the statistical procedure to be used in determining the maximum no-fire stimulus and the minimum 50 millisecond all-fire stimulus is not explicitly specified.

The specification provides that the cognizant government contracting agency has the prerogative of specifying the test procedures and methods of statistical analysis which will be used to determine the no-fire and all-fire points or may accept a procedure proposed by the testing laboratory.

In addition to the more commonly used Bruceton or Probit method of statistical analysis the Naval Ordnance Laboratory, White Oak, Maryland has developed a statistical technique that gives an excellant estimate of the no-fire and all-fire points with a reliability of 99% at a confidence level of 95%. This test is more refined and believed to be more accurate than the Bruceton or Probit; however, it is more time consuming and expensive. The Naval Ordnance Laboratory technique is described in Section 4 of the specification.

The remainder of Section 4 is devoted to test procedures that are to be used to determine if an electric initiator fulfills the requirements of Section 3. It should be noted that Section 4 is so written that all electric initiators are subjected to a standardized test program regardless of end application. In some instances the test procedure is specified even though the requirement that an initiator be designed to pass the test is optional.

<div align="center">SUMMARY</div>

In summation it may be said that Military Specification MIL-I-23659 imposes minimum design, electric, environmental, and functional requirements on all new electric initiators entering the Navy supply system. Further, it establishes uniform methods of testing electric initiators and electric initiator subassemblies. And finally, it states the criteria for acceptance of an electric initiator for each of the four types of release given.

These requirements and quality assurance provisions, coupled with the criteria for acceptance, are expected to guarantee that Navy standard stocked initiators:

(a) be safe for handling, transportation, storage, and use;

(b) perform satisfactorily under normal and adverse conditions in the device of intended application;

(c) do not deteriorate to a degree which would render their performance or safety doubtful under adverse storage conditions and;

(d) have uniformity of design to increase interchangeability.

There will always be exceptions taken to MIL-I-23659 but, to a large extent it should aid in furnishing the Navy safe, sound, standardized electric initiators having higher reliability and wider application than are presently available.

8. DISCUSSION

Mr. Feller of Lockheed asked why a loophole was provided for the leakage requirement in view of the scope of this MIL Spec. Mr. Steppe answered that there are certain devices now in use, in flares for example, that are not required to be hermetically sealed. The loophole is to allow use of these devices and new similar devices as the need arises. The same waiver applies to environmental requirements.

Mr. Rosenthal asked what information was available in the specification on dudding as a result of environment such as RF. Mr. Steppe answered that all items must be exposed to the maximum no fire input and then function at the minimum all fire input.

Mr. Rosenthal asked if this meant that a DC test was used in place of RF. Mr. Steppe replied that they believe this to be the best course of action at this time.

Mr. Nobel of Eitel McCullough asked if the isolation of the bridgewire from the case also meant independent grouping of the case and one of the leads and if this excluded the coaxial or unbalanced detonator.

Mr. Steppe answered that the coaxial arrangement is excluded unless the application is important enough to warrant a waiver.

9. A PRESENTATION OF RANGE SAFETY POLICY ON ORDNANCE STANDARDS WITH REGARD TO R-F RADIATION HAZARDS

Thomas E. Fewell

Range Safety Division, Hq. AFMTC

The R-F radiation hazard to electro-explosive devices began to become a problem at Cape Canaveral in 1957 on the Vanguard Program. As time passed, the problem became worse, requiring more and more R-F silence periods to be scheduled; work schedules were interrupted (Range time has been estimated at $60,000 per hour); and at times, The Range was unable to support the requirements of Range Users.

It became apparent that the problem needed to be studied and properly identified. Studies and R-F measurements were made and the results published in 1959 and is now identified as R-F Radiation Hazards, DDC AD 260-721.

From these studies and making reasonable predictions about the increase in power, as well as the number of R-F radiating devices, a conclusion was reached that less sensitive electro-explosive devices were needed.

The problem of establishing a no-fire sensitivity level was carefully considered, various ordnance manufacturers were consulted, and a no-fire sensitivity of 1 watt, 1 ampere was chosen.

On 7 September 1961, an AFMTC policy letter was sent to all project offices, subject: AFMTC Ordnance Standards with Regard to R-F Radiation. On 5 October 1962, a very similar letter went from AFSC (SCIZ) to all subordinate levels. As many of you know, much controversy resulted; however, the policy has stood the test of time. As an additional matter of interest, this policy has been accepted by the Range Commanders Conference.

My purpose today is to present the AFMTC Range Safety Policy on Ordnance Standards with Regards to R-F Radiation Hazards. This is merely detailed implementation and validation of the basic policy.

Before proceeding farther, I think, perhaps, a few slides showing various R-F radiating devices at Cape Canaveral would be of interest to you.

          Show Slides #1   (10)   #4   (14)
                     #2   (12)   #5   (FPQ-6)
                     #3   (13)   #6   (Ship)

I hope the slides just shown have helped to give you a better grasp of the R-F problem at Cape Canaveral. I might add that there are similar problems at downrange islands and aboard ships.

Time is fleeting so let's proceed with the policy - this policy is Annex "A" to AFMTCP 80-2, General Range Safety Plan, Volume I.

Show slides of each page of Annex "A" and discuss each item as necessary.

RANGE SAFETY POLICY ON ORDNANCE STANDARDS
WITH REGARD TO R-F RADIATION HAZARDS

1. PURPOSE.

    1.1 This policy prescribes minimum acceptable ordnance electrical characteristics. These minimum values will ensure safety of personnel and facilities during ordnance operations in the present and future AMR radiation environment.

    1.2 Neither the existence nor non-existence of requirements of this policy shall be interpreted as an intentional restraint or limitation to the development of R-F safe EEDs. Special consideration will be given by the Air Force Missile Test Center to any new EED concept or design which can be demonstrated to provide superior selectivity in response between direct current and radio frequency energy while maintaining customary reliability.

2. EXPLANATION OF TERMS.

    2.1 Certification - A signed statement by a responsible representative of a missile program certifying that the Category A ordnance systems:

        2.1.1 have been tested and evaluated in accordance with the requirements of this policy.

        2.1.2 comply with the criteria established by this policy.

    2.2 Electroexplosive Device (EED) - A single electrically actuated explosive initiator of either the heated bridgewire type and its variations or the exploding bridgewire (EBW) type.

    2.3 Exploding Bridgewire System - The combination of EBW initiator and firing circuit.

    2.4 EBW Initiator - The EED itself, that part of the EBW system which initiates the explosive train.

    2.5 EBW Firing Circuit - The wiring and components which provide the high voltage and trigger circuits for the EBW initiator.

    2.6 Fire - The ignition of the prime explosive surrounding the bridgewire.

2.7   Initiation Sensitivity:

      2.7.1 Power Sensitivity - The least amount of electrical power required to initiate a particular EED at a specified probability and confidence when conditions of EED temperature and power application are specified.

      2.7.2 Current Sensitivity - The least amount of current required to initiate a particular EED at a specified probability and confidence when conditions of EED temperature and power application are specified.

2.8   No-Fire:

      2.8.1 The failure of an EED to fire upon the application of electrical energy, or

      2.8.2 The rendering of an EED to a permanent inoperative state without any ignition process occurring (dudding).

2.9   No-Fire Current - The current sensitivity at which no more than one EED per thousand will fire with a confidence of 95%.

2.10 No-Fire Power - The power sensitivity at which no more than one EED per thousand will fire with a confidence of 95%.

2.11 R-F Field Intensity - The power flux density of electro-magnetic waves passing through a surface normal to the direction of propagation.

2.12 R-F Field Strength - The magnitude of the electric or magnetic field vector (E or H) at a given location resulting from the passage of radio waves.

2.13 R-F Susceptibility - The magnitude of the smallest electric field expressed as an R-F field intensity or R-F field strength capable of producing the no-fire current or no-fire power in an EED.

2.14 Shield - A metallic barrier which completely encloses a device for the purpose of preventing or reducing induced external energy.

2.15 Standard Statistical Test Procedures - Bruceton or Probit statistical tests, see references in Bibliography.

3. REQUIREMENTS (CATEGORY A).

3.1 Electroexplosive Device.

3.1.1 The no-fire current shall not be less than 1 ampere as the result of the application of a direct current for five minutes.

3.1.2 The no-fire power shall not be less than 1 watt as the result of the application of a direct current power for five minutes.

3.1.3 Requirements 3.1.1 and 3.1.2 above must be complied with, without the use of external shunts.

3.1.4 Firing circuit shielding for 1 amp/1 watt EEDs must provide a minimum of 40 db attenuation from 150 KC to 10,000 MC.

3.2 Firing Circuit.

3.2.1 Firing circuit conductors including EED leads will be twisted to maintain electrical balance and reduce induction.

3.2.2 EED firing circuits including EED leads will be isolated from other electrical circuits and each other by means of individual shields before, during, and after installation of the EED. Shielded EED circuits may be routed together in a common secondary shield. There should be no electrical discontinuity or gaps in shields.

3.2.3 Firing circuits to EEDs will be balanced to and isolated from the EED case and other conducting parts of the vehicle. If a circuit must be grounded, there will be only one inter-connection with other circuits. Static discharge resistors of 100,000 ohms or more may be connected to firing circuits.

3.2.4 An EBW firing circuit must not operate uninten-tionally when subjected to the radiation level specified in para-graph 3.3.1.

3.3 Ordnance System Survival - Optional Requirements - Parts 3.2 and 3.3.

3.3.1 In lieu of the requirements of Section 3.1, the Range User may validate the survival of each electroexplosive

device, before installation, during installation, and after installation in the following electromagnetic fields:

FREQUENCY RANGE	FIELD INTENSITY
150 KC up to and including 50 MC	2 watts per square meter (28 volts per meter)
Above 50 MC	100 watts per square meter (194 volts per meter)

3.3.2 In addition to validation of system survival, the Range User must comply with paragraph 3.2 requirements for firing circuits.

4. VALIDATION PROCEDURES AND REQUIREMENTS. Two copies of the validation data will be submitted to MTORS.

4.1 Requirements Paragraph 3.1 and 3.2.

4.1.1 Validation of compliances with Paragraph 3.1 and 3.2 will be by AFMTC Form _____.

4.1.2 Validation data supplied to and approved by AFMTC will be compiled for the use and benefit of all Range Users.

4.1.3 Validation of compliance with the requirements of paragraph 3.2 will be necessary in each and every case regardless of whether or not the electroexplosive device itself has previously qualified.

4.2 Optional Requirements Paragraph 3.2 and 3.3.

4.2.1 Validation of compliance with Paragraph 3.2 and 3.3 will be by the appropriate AFMTC Form _____ and supplementary data sheets as required and described in paragraph 4.2.4 below.

4.2.2 Validation procedures must determine the R-F susceptibility of each type of EED when considered as an absorber of R-F energy. Consideration will be given to impedance mis-match, shielding of wiring and components, and wire-lead configurations as an antenna or pick-up device. The number of test frequencies will be

such as to establish the R-F susceptibility from 0.150 to 10,000 MC.
A suggested test plan is as follows:

TEST FREQUENCY	NO. OF FREQUENCIES
0.150 - 100 MC	3
100 - 150	1
225 - 260	1
400 - 550	1
1200 - 1400	1
2200 - 2900	1
5400 - 5900	1
8500 - 10,000	1
	10 frequencies

4.2.3   Validation must include the following:

   4.2.3.1   Evaluation of R-F current and R-F power
sensitivities for a 0.001 probability of initiation with 95% con-
fidence. The sensitivities obtained must be representative of the
basic EED with the shortest practical external leads.

   4.2.3.2   Determination of and reporting the smallest
field intensity capable of producing in the EED, with normal pre-
installation lead wires, the power determined in paragraph 4.2.3.1
above. The determination shall be based on the most favorable con-
ditions for induced power, but the EED wire leads will not be dis-
torted beyond those configurations which are reasonable to expect
during routine handling, processing, transport, and storage. The
configurations considered need include only those possible with the
EED terminal leads shorted. Data will be presented as described in
paragraph 4.2.4 below.

   4.2.3.3   Evaluation of the EED as an R-F system
during installation. The evaluation will consist of determining and
reporting the minimum R-F field intensity or field strength required
to produce in the EED the power determined in paragraph 4.2.3.1 above.
The evaluation will include the most favorable conditions for induced
power during installation, including unshorted, uninstalled terminal
lead conditions, but wiring terminal leads will not be distorted
beyond those configurations which are reasonable to expect during
installation. Data will be presented as described in paragraph 4.2.4
below.

4.2.3.4 Evaluation of the EED system after installation. The evaluation will consist of determining and reporting the minimum R-F field intensity or field strength required to produce in the EED the power determined in paragraph 4.2.3.1 above after ordnance installation but with access ports open. Data will be presented as described in paragraph 4.2.4 below.

4.2.4 The R-F susceptibility of each device will be presented in graphical form. The ordinate scale will be in relative DB above or below a 0 db reference level. The 0 db reference will be the applicable ordnance survival level defined in paragraph 3.3.1.

50 MC and below: $DB = 10 \log \dfrac{P_1}{2}$ or

$$DB = 20 \log \frac{E_1}{28}$$

Above 50 MC: $DB = 10 \log \dfrac{P}{100}$ or

$$DB = 20 \log \frac{E}{194}$$

4.2.5 Positive DB values will indicate EED susceptibility to R-F fields of larger magnitude than the survival levels contained in paragraph 3.3.1 and, therefore, represent safer conditions than negative DB values. Data will be presented on standard semilogarithmic paper 8 1/2 by 10 1/2 inches with linear DB scale and logarithmic frequency scale. Graphical data will be limited to the following frequency ranges per graph maximum:

0.100 to 100 megacycles.

100 to 10,000 megacycles.

4.2.6 Graphical data depicting the R-F susceptibility of each EED within each frequency range for the four conditions described in paragraph 4.2.3 are required. Where no sacrifice in clarity will result, the four conditions may be plotted as four curves on one graph for each frequency range.

4.2.7 A description of the test equipment and test procedures used to obtain the data in paragraph 4.2.3 will be provided to MTORS.

4.2.8 An EED shall have complied with the requirements of this policy when MTORS has evaluated the test procedures and test equipment, and the magnitude of the EED R-F susceptibility equals or exceeds the survival levels of paragraph 3.3.1 as evidenced in the graphical data.

5. EXCEPTIONS.

5.1 Category A EEDs.

5.1.1 No Category A EED will be excepted from the requirements of this policy.

5.2 Category B EEDs.

5.2.1 Category B EEDs are not required to comply with the requirements of this policy.

5.2.2 R-F protection for Category B EEDs will be the sole responsibility of the Range User.

6. COMPLIANCE DATES.

6.1 All programs using the AMR prior to 1 January 1963 will conform to the requirements of this policy by 1 July 1964. All new programs after 1 January 1963 must comply with this policy. Programs submitting PRDs after 1 January 1963 are considered new programs.

7. R-F RADIATION SILENCE.

7.1 The AFMTC will continue to schedule R-F silence periods in accordance with existing policy to 1 July 1964. Special silence periods will be scheduled on a continuing basis only when no other means of providing safety are available.

8. BIBLIOGRAPHY.

8.1   Naval Weapons Design Guide to Preclude Hazards from Environmental Electromagnetic Fields, WR-27, dated 12 February 1962, by Bureau of Naval Weapons.

8.2   Design Techniques to Reduce the Hazard of Inadvertent Firing of Electroexplosive Devices by Electromagnetic Energy, Naval Ordnance Test Station - TP-2629.

8.3   A Filter as a Fix for the R-F Radiation Hazard to Electroexplosive Devices, U. S. Naval Weapons Lab. Tech. Memo No. W-10/61.

8.4   Investigation of the Susceptibility of an Experimental Exploding Bridgewire Explosive Initiator to Electromagnetic Energy, Naval Weapons Lab. Report No. 1772.

8.5   A Method to Determine Electromagnetic Coupling to Ordnance Devices Aboard Ships, Jansky and Bailey, Tech. Report No. 5456 prepared for U. S. Naval Weapons Laboratory.

8.6   Electromagnetic Coupling Due to Apertures in Missile Bodies; Jansky and Bailey, Tech. Report No. 5455, prepared for U. S. Naval Weapons Laboratory Contract N178-7604.

8.7   Statistical Analysis for a New Procedure in Sensitivity Experiments; ASTIA Document ATI-34558 (Bruceton Test).

8.8   Statistical Methods Appropriate for Evaluation of Fuze Explosive-Train Safety and Reliability; ASTIA Document AD-66428 (Bruceton and Probit Tests).

8.9   Methods and Equipment for R-F Sensitivity Evaluation of Electroexplosive Devices; The Franklin Institute, October 1961, prepared for the Lockheed Aircraft Corp., Report No. LM-A2369-2.

8.10   R-F Sensitivity Specifications for Electroexplosive Devices; The Franklin Institute, 13 March 1962.   Conference Paper by E. E. Hannum presented to AIEE.

8.11   Development of a Two Conductor Shielded Cable Connector for Use in Missile Firing Circuits -- Final Technical Progress Report - 28 June 1962, Amphenol-Borg Electronics Corp., prepared for Naval Weapons Lab, Contract N178-7933.

8.12 Study and Testing of Radio Frequency Insensitive Electro-explosive Matches (Squibs); October 1961, Air Force Special Weapons Center Report AFSWC-TR-61-88, SWC-TR61-88.

8.13 Investigation of Premature Explosions of Electroexplosive Devices and Systems by Electromagnetic Radiation Energy; Confidential; April 1962, Midwest Research Institute USAF Contract AF42(600)22447.

8.14 Explosives Safety Manual - USAF Manual 32-6.

8.15 Electromagnetic Radiation Hazards; Technical Manual USAF TO31Z-10-4.

8.16 R-F Radiation Hazards, Air Force Missile Test Center, July 1961, ASTIA Document AD260-721.

8.17 Radiation Hazards to Ordnance Devices; January 1962; The Franklin Institute.

8.18 Preliminary Measurements Related to Procedures for Measuring Systems Susceptibility. Proceedings of the Eighth Tri-Service Conference on Electromagnetic Compatibility - October 1962.

AFMTC FORM _____   VALIDATION OF COMPLIANCE
AIR FORCE MISSILE TEST CENTER PAMPHLET 80-2, VOLUME I
APPENDIX A, PARAGRAPHS 3.2 and 3.3

MISSILE AND PROGRAM DATA

1. Security Classification:	2. Test Program:	3. AFSC System Code:
4. Program Requirement No:	5. Missile Contractor:	6. Validation Date:

ORDNANCE DATA

7. Ordnance Manufacturer:	8. Manufacturer's Part No:	9. Missile Contractor's Part No:
10. Ordnance Type:	11. Ordnance Purpose:	12. Location Stage:

13. Ordnance item is installed at: ☐ Missile Assembly Building ☐ Launch Pad
☐ Factory ☐ Other _____

14. Ordnance item is installed by: ☐ Missile Contractor ☐ Range Contractor
☐ USAF ☐ Other _____

15. EED Bridge Type: ☐ Bridgewire ☐ Carbon Film ☐ Exploding Bridgewire
☐ Other _____

16. EED Input: ☐ Two Wires ☐ Three Wires ☐ Four Wires ☐ Other _____

17. Number of bridgewires per two wire circuit: _____

18. Net resistance (ohms) of bridgewires per two wire circuit: _____

19. AFMTC Category: ☐ A, Hazardous ☐ B, Non-Hazardous
(NOTE: If item is Category B, no further information is required.)

20. No-fire DC current for a probability of initiation of 0.001 with 95 percent confidence _____ amperes.

21. Recommended firing current _____ amperes.

22. Reliability corresponding to recommended firing current: _____

PARAGRAPH 3.2
FIRING CIRCUIT

23. This is to certify that the firing circuit for the electroexplosive device described above conforms to the requirements of paragraph 3.2 except as noted below.

24. Exceptions: (If none, so state.) _____

PARAGRAPH 3.3
EED RF SUSCEPTIBILITY

25. Plot the RF susceptibility of the EED as described in paragraph 4.2.4 and as determined in paragraph 4.2.3.1. Attach the graphical data to these sheets.

26. Plot the RF susceptibility of the EED as described in paragraph 4.2.4 and as determined in paragraph 4.3.2.2. Attach the graphical data to these sheets.

27. Plot the RF susceptibility of the EED as described in paragraph 4.2.4 and as determined in paragraph 4.3.2.3. Attach the graphical data to these sheets.

28. Plot the RF susceptibility of the EED as described in paragraph 4.2.4 and as determined in paragraph 4.2.3.4. Attach the graphical data to these sheets.

29. Remarks: _____

30. Signature:	31. Title:	32. Location:

AFMTC FORM _____   VALIDATION OF COMPLIANCE
AIR FORCE MISSILE TEST CENTER PAMPHLET 80-2, VOLUME I
APPENDIX A, PARAGRAPHS 3.1 and 3.2

MISSILE AND PROGRAM DATA

1. Security Classification:	2. Test Program:	3. AFSC System Code:
4. Program Requirement No:	5. Missile Contractor:	6. Validation Date:

ORDNANCE DATA

7. Ordnance Manufacturer:	8. Manufacturer's Part No:	9. Missile Contractor's Part No:
10. Ordnance Type:	11. Ordnance Purpose:	12. Location Stage:

13. Ordnance item is installed at: ☐ Missile Assembly Building ☐ Launch Pad
☐ Factory ☐ Other _____

14. Ordnance item is installed by: ☐ Missile Contractor ☐ Range Contractor
☐ USAF ☐ Other _____

15. EED Bridge Type: ☐ Bridgewire ☐ Carbon Film ☐ Exploding Bridgewire
☐ Other _____

16. EED Input: ☐ Two Wires ☐ Three Wires ☐ Four Wires ☐ Other _____

17. Number of bridgewires per two wire circuit: _____

18. Net resistance (ohms) of bridgewires per two wire circuit: _____

19. AFMTC Category: ☐ A, Hazardous ☐ B, Non-Hazardous
(NOTE: If item is Category B, no further information is required.)

PARAGRAPH 3.1
ELECTROEXPLOSIVE DEVICE CATEGORY A

20. No-fire DC current for a 5 minute exposure and probability of initiation of 0.001 with 95 percent confidence _____ amperes.

21. No-fire DC power for a 5 minute exposure and probability of initiation of 0.001 with 95 percent confidence _____ watts.

22. Bruceton Sample Direct Current Test Data:

			Characteristic Considered Normally Distributed:
a. Number of sample which fired	_____	=x	
b. Number of no-fires	_____	=0	
Sample size	_____ total		
c. Calculated mean "m"	_____ amperes		☐ Log of Current
d. Calculated value of "M"	_____		
e. Tabular value of "s"	_____		☐ Current
f. Calculated value of " σ "	_____ =ds		
g. Tabular value of "G" corresponding to "s"	_____		☐ Other
h. Standard error of the mean " σ_m "	_____		
i. Standard error of sample standard deviation " σ_σ "	_____		
j. Tabular value of "H" corresponding to "s"	_____		
k. Recommended firing current	_____ amperes		
l. Reliability corresponding to recommended firing circuit	_____		

PARAGRAPH 3.2
FIRING CIRCUIT

23. This is to certify that the firing circuit for the electroexplosive device described above conforms to the requirements of paragraph 3.2 except as noted below.

24. Exceptions: (If none, so state.) _____
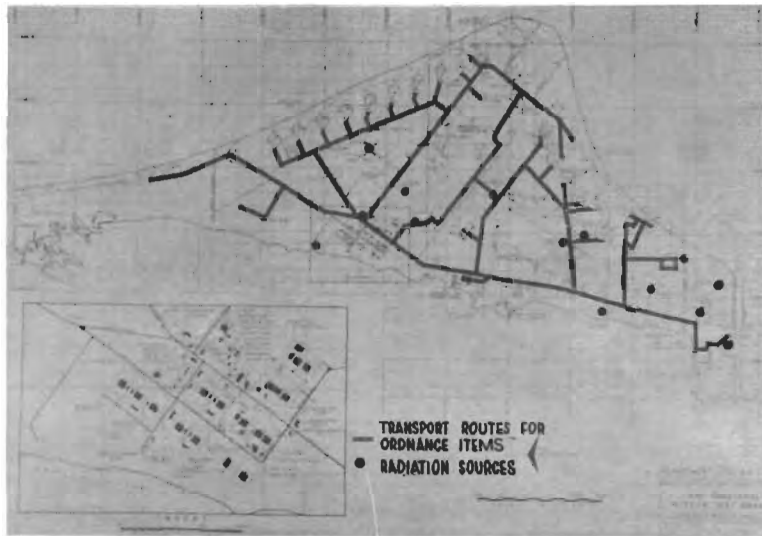
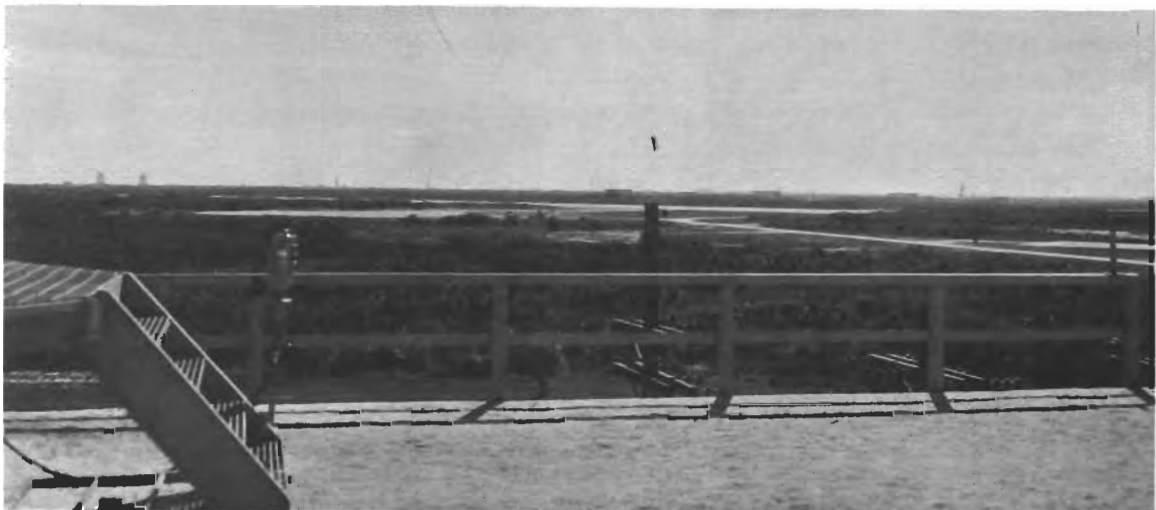| 25. Signature:	26. Title:	27. Location:

Figure 1

Figure 2

Figure 3

Figure 5

Figure 4

Figure 6

For Discussion Refer to Classified Supplement

9-14
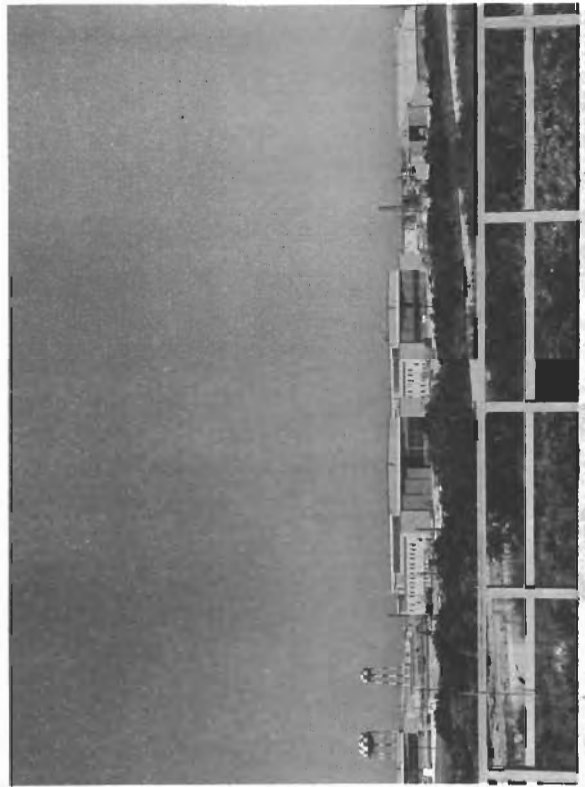
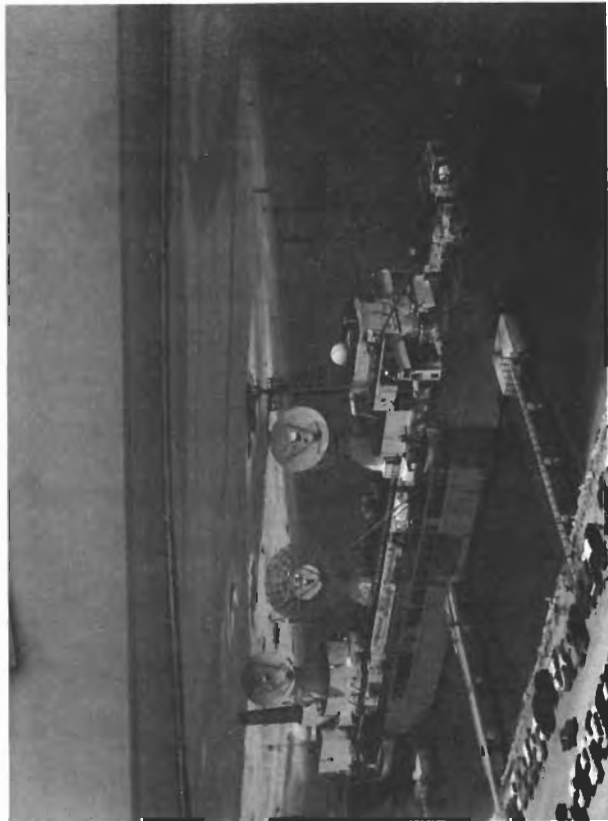## 10. ESTIMATION OF HIGH AND LOW PROBABILITY EED FUNCTIONING LEVELS

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INTRODUCTION

In this paper the authors wish to address themselves to the problem where, with a limited number of samples, it is desired to predict the stimulus corresponding to an extreme functioning probability level for a given electric initiator population, or conversely the estimated response at a stipulated stimulus. This problem is becoming increasingly important to both the military and the space agencies. In the past the military could frequently tolerate weapons having a relatively large degree of unreliability and then compensate for this unreliability by firing large numbers of weapons to attain the desired target kill, For example, the firing of projectiles or the dropping of bombs in large quantities. However, complex modern weapons, their high cost and their great destructive power often preclude firings in large numbers. High reliability (and safety) must be achieved and demonstrated for the individual weapon. As for space ventures the complexity of operations, the necessity for accuracy, the high cost, the prestige value, and the stake in human lives make mandatory components having a high level of reliability and safety.

High reliability (or safety) in the sense that we will use it here is a functioning probability of 99.5% or higher

at a specified input level. Such reliabilities are not
excessive for electro-explosive devices. Experience based
on thousands of manufacturers' firings of conventional primers
and detonators show that such reliabilities are in fact
usually exceeded by ordinary production techniques. During
the course of development however, it is often necessary
to predict the response of EED's to given stimuli. For
example, in assessing hazards of electromagnetic radiation
it may be necessary to predict the response at a very low
stimulus level. To determine whether a given power supply
in a particular weapon is capable of reliably firing an
EED it is necessary to estimate the response of the EED to
the input stimulus of the power supply.

The direct demonstration of a 99.5% or better response
at 95% confidence of an EED to a given stimulus is often
too costly in material, time, and manpower to be seriously
considered. It would require the firing of approximately
750 items without a failure.

Before discussing the general philosophy for making
logically the required estimates, some discussion appears
warranted about the present, most frequently used method.
This is the Bruceton method.

It is the authors' observation that the Bruceton test
method is being used extensively for determining the response
(sensitivity) of electric initiators. When properly used
it is a good method. It is rapid and economical. The

algebraic manipulations required to produce the statistical quantities are simple to carry out. It is because of these features that the Bruceton test has found such widespread application. Unfortunately it has been frequently used in situations where the results obtained are inaccurate and misleading.

For making studies around the 50% response level the test is most often highly acceptable and advantageous. When estimates are made by the Bruceton method beyond the 75% response level difficulties can be anticipated. The authors have spelled out in detail the reasons for the difficulty in a paper presented before the last HERO Congress[1]. The salient reasons, without detail, are worthy of repetition:

(a) The Bruceton method gives a very poor estimate of the standard deviation. Even Bruceton tests of 100 samples will often underestimate the true standard deviation by 50 per cent or more.

(b) Since most all of the data are collected between the 25-75% firing points, long extrapolations must be made to the points of interest, along a curve which is usually unknown.

When it is not feasible to demonstrate directly a response at an extreme firing point, estimates of the response are usually made by a process of extrapolation and curve fitting. The extrapolation process is basic to the approach. This principle should be kept firmly in mind.

All of us as technical people are very familiar with making extrapolations and the principles involved. The statistical problems are really no different. What is desired is an extrapolation from measured response points to points removed from the region of measurement. Our extrapolations become better as the length of the extrapolation becomes smaller. They also become better when the general shape of the curve being extrapolated is known; from the statistical standpoint, when the response function or distribution function is known in the region of extrapolation.

There is no single best method for making estimates of extreme functioning probability points. Various methods are available for use. Those which can be used for best results depend on such factors as sample size available, the degree of accuracy needed, data available from other tests, and the remoteness of the desired functioning level.

PRESENT SENSITIVITY TESTING METHODS

Sensitivity tests are of different types. Each type has certain advantages and disadvantages. These should be considered to make an intelligent selection of the test to be used. In certain situations one test would be selected, while in others a different test would be chosen. We shall consider some of the tests which are frequently used, along with their advantages and disadvantages. First, however, it would be wise to state some principles which will be general in their applications.

In most tests the analysis involves fitting a frequency distribution function to the observed data. In other words the test consists of an experiment in which the sensitivity is determined at each of two or more stimulus levels. From these data we attempt to predict either the response at some other level or the level which will have some desired response. In order to do this we must assume some frequency distribution function. One which has been widely used in the explosives field is the log-normal function. Experience has shown that this is a fairly good fit and entirely adequate for many purposes. However, recent work at The Franklin Institute[2] and at the Naval Ordnance Laboratory[3] has shown that the log-logistic function gives a somewhat better fit. Even this is not a perfect fit.

In general, predictions based upon interpolation from observed data are fairly safe since the function assumed in the interpolation will ordinarily coincide closely with the true function over the range of the observed data. On the other hand the assumed and true functions may differ considerably outside this range. For this reason extrapolation is always dangerous because of the uncertainty in the choice of distribution function. The larger the extrapolation the greater the resulting error is likely to be. The use of extrapolation cannot be avoided in estimates of very high or low response points. However, it can be kept small by proper choice of test plan at the cost of testing an increased number of items.

A second point to be considered is the possibility of
bias. Some tests have a tendency to over or underestimate
the quantity which is being determined. This tendency is
known as bias. Some bias might be tolerated if it were
in the direction of making a more conservative estimate.

Another point to be considered in planning sensitivity
experiments is the allocation of items to the stimulus
test levels. A trial made at a stimulus level at which
almost all trials are expected to result in fires or fails
gives us less information than one made near the fifty per
percent point. To obtain an equal amount of information
at each level we must assign larger numbers of items at
levels farther from the fifty per cent point. By this
method we can give each of the levels equal weight.

Another consideration is the total number of items to
be tested. Of course, the larger this number the more
information we obtain. This, then, usually becomes a
compromise between the amount of information we would like
to have and what we can afford to spend in time and money
in order to get it. Some tests are more efficient than
others in obtaining information from a given number of trials.

One type of test which is quite largely used is the
up-and-down or stair-step test, the best known being the
Bruceton test. This test concentrates the trials near the
fifty per cent point. All, or nearly all, of the data will
be from observations concentrated between the 25 and 75 per
cent points. The weights of the observations at the test

levels will show an even greater concentration around the
fifty per cent point. Investigations in England and at
the Naval Ordnance Laboratory have indicated that the
Bruceton test has a serious bias in the estimation of
the standard deviation, giving a value which is too small.
The effect of this bias would be to predict too much
reliability and safety for an item which is tested in this
way. The error becomes even more serious since the concentra-
tion of trials near the fifty per cent point makes the
prediction of reliability or safety depend upon extreme
extrapolation. Consideration of the characteristics of
the Bruceton test shows that it is a good test for anyone
who is interested in determining the fifty per cent point,
but a poor test for determining high or low per cent points.

Another test which has some of the characteristics of
an up-and-down test is the Bartlett test. Stimulus levels
are set up and testing continued at each level until two
reversals are observed. A reversal is a fire, or fail,
when the other response is expected. The Bartlett plan
gives an increasing number of trials as we get farther
from the fifty per cent point. Thus the weights of the
observations at the different levels are made approximately
equal. It also reduces the extrapolation required for very
high or low response points and therefore is a good test
for making estimates of extreme functioning levels. It
is fairly easy to show, however, that estimates of sensitivity
obtained by this plan are biased. Sixty per cent of the

tests will give estimates of the sensitivity which are too low at the upper end of the range and too high in the lower end. This bias is not as serious as that shown by the Bruceton test since it is in the direction of conservatism. It should be emphasized that the Bartlett test requires very large samples. In two instances[2,3] the sample sizes were approximately 8000.

A third type of test is one which has been analyzed by Golub and Grubbs[4] of the Ballistic Research Laboratory at Aberdeen, Maryland. In this type of test a comparatively small number of items is tested at different levels of stimuli with possibly only one item at each level. This type of plan is especially applicable to tests in which the stimulus level cannot be exactly controlled but can be measured. Ford Motor Company[5] has recently done some work on a similar type of test. Since the sample size for either of these tests is usually small, the results are subject to the uncertainty always associated with small samples.

Finally, a plan which is quite frequently used is one that has been called the run-down test. This type and the up-and-down tests include most of the sensitivity tests which are made. The plan calls for making a specified number of trials at each of two or more stimulus levels. We shall describe here in detail, as an example of tailoring tests to specific situations, a run-down test plan which calls

for testing at two stimulus levels. This plan was devised
to determine high probability of firing estimates for electro-
explosive devices of one of the Navy's most important missiles.
Only 200 EED's per sample were available for test. This
test plan was optimized to fit the specific needs but may
be useful to others faced with a similar problem. The
probability points of interest are estimated by extrapolation
based on observed responses measured in the neighborhood
of the 65 and 90 per cent points. If we have previous
experience with similar items we may use this experience
as the basis for choosing these two test levels. Lacking
this experience we can use a short Bruceton test. Suppose
that we use twenty of the two hundred items in the preliminary
Bruceton test. Then the remaining one hundred eighty are
used for the main test at the two levels. Fifty items will
be allocated at the expected 65 per cent level, and the
remaining one hundred thirty will be tested at the expected
90 per cent level. If, after testing the fifty items at the
first level, it appears that the response is much higher than
the expected 65 per cent point we can revise our plan by
using this as the second level rather than the first. In
this case a new level is selected as the first, somewhat
nearer the 50 per cent point, and fifty items tested at
the new level. The following is a step-by-step procedure
for firing the two hundred items.

a. Fire twenty items in a Bruceton test to obtain
   preliminary estimates of the mean, m, and the
   standard deviation, s. A log-transform of the
   dosage (current, potential, energy) is taken
   as the stimulus.

b. Compute the first and second test levels as
   the mean of the Bruceton test plus 0.4s and
   1.3s respectively.

c. Test fifty items at the first stimulus level.

   (1) If five or fewer fails are observed,
       redefine the first level as the second
       and continue firing at this level until
       one hundred thirty are tested. Test the
       remaining fifty at a stimulus level m + 0.2s.

   (2) If more than five fails are observed (the
       usual case) test the remaining one hundred
       thirty units at the original second level.

The analysis of the data obtained from a test of this
kind would require fitting a frequency distribution function
as was pointed out earlier in this paper. As was also pointed
out the log-logistic function is the preferable one. The
procedure for fitting this function to these data would be
as follows. First, convert the observed number of fires, x,
and fails, y, for each level into logits by the relation
$L = \ln \frac{x}{y}$. Plot these values of L against the stimulus
(log-current, log-potential, or log-energy). Draw a straight

line through these two points. To interpret the graph
in terms of per cent response for any stimulus read the
result in logits and change to per cent by the relation
$L = \ln \frac{p}{100 - p}$ where p is the desired per cent.

A test of this general type has the good feature of
minimizing the necessary extrapolation. It is free from
bias such as is found in the Bruceton or Bartlett tests.
The items are allocated to the test levels so as to give
nearly equal weight to the observations. Two hundred items
is about as small a number as can be used in order to give
a good estimate of a high or low per cent point.

NEW APPROACHES

NOL is looking for ways for improving extreme-probability
estimation methods by using information in addition to Go/No-Go
firing data.

As has been pointed out, the estimation of very high
or low probabilities on the basis of Go/No-Go data always
requires extrapolation towards the asymptotic All-Fire and
No-Fire limits. The extrapolation is a risky business. Can
we avoid this extrapolation? We think that it is possible.
By using data from such sources as nondestructive measurements
of EED thermal parameters in conjunction with sensitivity
data we can interpolate rather than extrapolate.

For instance, we can show with the Mk 1 Squib that a
current of 50 milliamperes through the bridge would cause
a maximum elevation of the bridgewire temperature above
ambient of about 10°Centigrade. By figuring backwards from

a maximum acceptable elevation of the bridgewire temperature,
we can deduce an even higher maximum current which would
be acceptable not only as a safe current but also one which
will not deteriorate the EED. In this fashion we can
establish a true No-Fire current level.

Once a non-zero No-Fire level is available we should
be able to estimate a very low probability of firing by
interpolation between the No-Fire level and experimentally
observed low-probability firing data.

A similar use of the electro-thermal data in conjunction
with limits of variability of EED configuration and explosive
ignition temperatures should permit the computation of a
finite All-Fire point (provided there are no Q-C defects).
With this All-Fire point and appropriate firing data we
should be able to interpolate to find a high reliability point.

In either case, the interpolation can be carried out
only if some distribution function can be assumed to connect
the data. There are many expressions which can be devised
to describe a distribution which is (1) approaching zero
probability tangentially at a non-zero positive No-Fire point,
(2) approaching a probability of 1 at a finite All-Fire point,
and (3) a fit through observed firing data. What basis do
we have for selecting the proper function?

To handle this problem, we are investigating the field
of non-parametric or distribution-free statistics. The
general approach in this technique is to find facts which

apply to whole classes of distributions. It is assumed, on the basis of experience, that the EED distribution, though unknown, falls in a general class. If appropriate boundaries or limits for the class of distributions can be found then it will be possible to set conservative bounds on the EED probability estimates.

For instance, if it can be assumed that:

(a) The Probability Density Function is unimodal, i.e., the Cumulative Distribution Function (C.D.F.) has a single inflection point which corresponds to the mode above, and

(b) The two distribution functions are zero at the true No-Fire level

then we can say that a straight line drawn on the C.D.F. from the No-Fire point to the inflection point will always be more conservative for safety estimates than any distribution which satisfies the above criteria. This is because the C.D.F. will always be concave upward in this range.

The trouble with the above example is the difficulty in experimentally locating the point of inflection of the C.D.F.

CONCLUSIONS

We advise caution and forethought in carrying out sensitivity determinations. Ready made test plans (such as those previously mentioned) have been devised to answer specific needs and have been based on assumptions which are often implicit. If these needs and assumptions are

not relevant to the current problem, trouble can arise.
A cookbook firing plan, applied blindly, can be a waste
of time, money, and materiel.

The experimental and computational procedures should
therefore be carefully designed before the investigation
is started. The questions to be answered should be clearly
stated. All relevant background and previous knowledge
should be considered. After an experimental program has
been proposed, the interpretations of all foreseeable sets
of results should be hypothesized before any firing is
commenced. If the possible or likely outcomes are inconclusive,
then the experimental program should be modified appropriately.
The aid of a statistician throughout this planning stage
is very necessary. It will reduce the probability of obtaining
useless, errant, or meaningless results.

And for results to be useful to those other than the
experimenter, the background information, the assumptions,
and statistical procedures should be a part of the data.
They should be given in enough detail to permit reconstruction
of the logic used throughout the investigation.

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10. DISCUSSION

Mr. Webb of Thiokol asked if the implication was that results of tests of less than 200 items were not accurate. Mr. Hampton answered that accuracy is a relative matter that usually ends up as a compromise, considering time and money. He claimed that standard deviation estimates from Bruceton tests of less than 200 EEDs is poor. He referred to the paper of Mr. Martin that would be presented by title only, that shows standard deviation to be a function of the chosen step size. In any case, he continued, with less than 200 items it is difficult to estimate standard deviation.

Mr. Einstein of Douglas Aircraft Co. asked if the rundown test was tried on actual data and how many times. Mr. Hampton answered that this was the intent. Mr. Einstein replied that it could not be concluded that this method was better than the Bruceton or the Bartlett, to which Mr. Hampton replied that this new test should be better because points one and three are better satisfied than they are in the Bruceton. The objection to the Bartlett is that it gives a very conservative estimate of safety. Mr. Einstein said that a report published in 1946, written by Burnett or Bartlett, stated that the Bruceton will give a better estimate of the standard deviation than the Probit (which, he thought, Mr. Hampton was calling the Bartlett).

Mr. Hampton answered that the Probit is a method of analyzing data that can be applied to data collected by any one of numerous test plans for collecting data such as the Bartlett.

Mr. Davis said that he had missed the explanation of the relationship of X to Y. Mr. Hampton said that X and Y are the number of fires and fails. If, for example, 50 were tested at one level and 43 would fire and 7 would fail; X would be 43 and Y would be 7.

Mr. Davenport pointed out that the speaker did not mean to say that this method does not involve extrapolation. The point here is that extrapolation is less.

Mr. Hampton agreed that this was true. In order to avoid extrapolation, tests must be made above the 99.9% point, and this is not done.

Mr. Dietrich of Atlas Chemical Industries expressed his interest in the practical aspects of being able to express an adequate minimum all fire stimulus. He asked for an opinion on the method of computing the standard error from the applied mathematics report to determine the confidence levels based on the mean and the standard error. Mr. Hampton stressed that these methods were used to obtain the 99% point with 95% confidence. Instead of having only 5% wrong, we had 15% or 20% wrong for a confidence limit of 80% by experiment with 200 samples.

Mr. Dietrich asked if he had calculated a point, say the 99.99%, and used standard error would he then need an additional limit on this. Mr. Hampton answered in the affirmative repeating that his point of 95% confidence was found to be only 80%.

Mr. Dietrich said that the AMP (Bruceton) procedure appears to work in practice. Mr. Hampton added that his understanding was that Mr. Dietrich used the AMP procedure to calculate the point with 95% confidence and then put an additional increment on the functioning variable. Dietrich said that the point itself is selected by this procedure but he added that many other factors enter, such as subsequent testing at the stimulus level selected, efficiency of the firing system, and other factors. Mr. Hampton said that the Bruceton may be a very good preliminary test if supplemented by additional tests.

Mr. Stresau of Stresau Labs asked for a comment on the method that involves estimation of the 5% and 95% points and subsequent exposure of ten items at each of these points. If results were none out of 10 on the 5% point and 10 out of 10 at the 95% points, 95% confidence limits were placed on these data. Mr. Stresau's belief was that this resulted in conservative estimates.

Mr. Hampton expressed belief that this was correct and offered to elaborate on the board. He explained that a Bruceton test was run and the high and low points inferred as is shown in Figure 10D. The responses R1 and R2 are selected to correspond to the respective stimuli X1 and X2. These points are usually chosen so that the devices will not fire at X1 and will all fire at X2. Ten devices are then exposed to each of these two stimuli and from these results confidence intervals can be placed on the response functions. These have been indicated by U1 for the upper confidence limit on R1, and by L2 for the lower confidence limit on R2.

These limits are usually calculated at 95% confidence, although another limit could be used. A straight line is then drawn between Ul and L2. This having been done, one may extrapolate response and stimulus functions along this line to the right of X_2 with the confidence used to compute Ul and L2. This is illustrated by the response R3 that can be achieved by applying the stimulus S3 with whatever confidence was chosen.
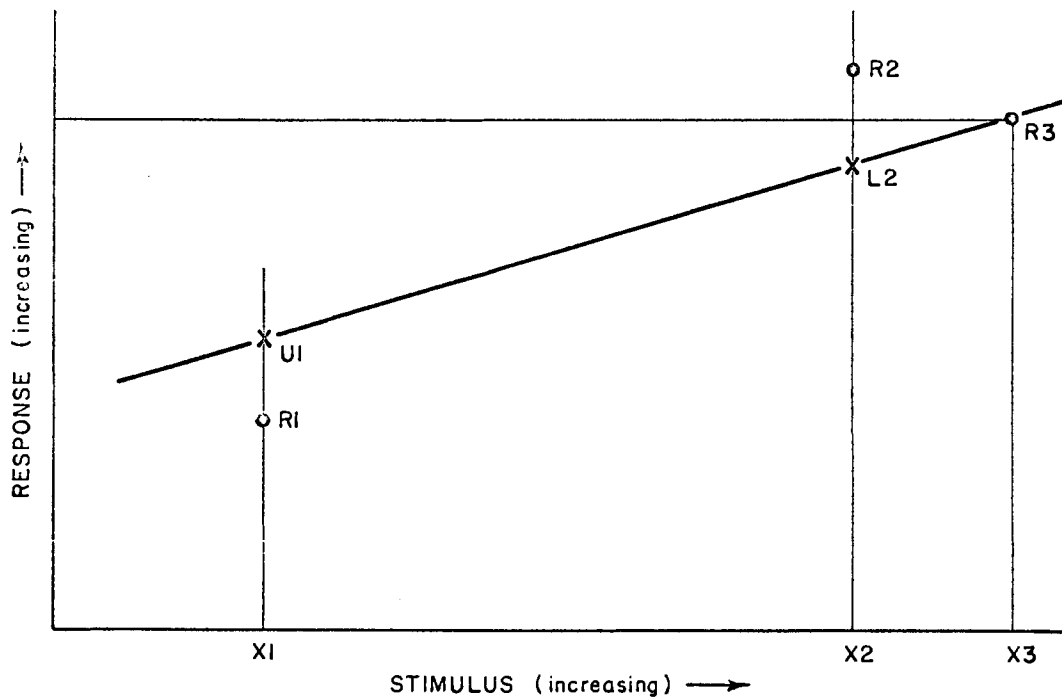
FIG. IOD. METHOD FOR APPROXIMATION OF RESPONSE WITH
CONFIDENCE FROM A GIVEN STIMULUS

11. COMMENTS ON CONSTANT-CURRENT INITIATION CHARACTERISTICS OF HOT-WIRE-BRIDGE SQUIBS, WITH PARTICULAR REFERENCE TO LOG-CURRENT LOG-TIME FIRING CURVES*

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ABSTRACT

Certain initiation characteristics of squibs are reviewed, and some advantages in use of log-current log-time firing curves are discussed. A simple method for analyzing small-sample firing test results is outlined; the method does not require special test sequences such as those of the Bruceton procedure.

INTRODUCTION

The initiation characteristics of squibs such as the typical squib shown in Fig. 1 depend on:
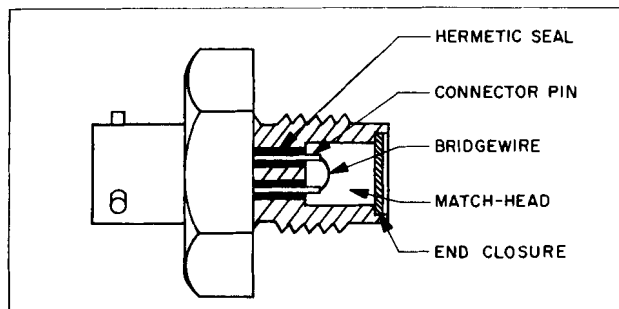
Fig. 1. Typical connector-type
hermetically-sealed squib

1. The geometry, size, and materials of the squib body, pins, seals, and closure,

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2. The type of match-head used,

3. The type of bridgewire, and

4. The diameter and length of the bridgewire,

but the quantitative significance of none of the variables has been established precisely, and second-order effects are so manifold that design efforts often degenerate into haphazard cut-and-try approaches.

Our discussion of initiation characteristics will be in two main steps:

1. We first assume an imaginary type of squib, assign to it an arbitrary firing curve, rationalize the curve in a very primitive fashion, and then use the same primitive hypotheses to predict the effect of changes in bridge- wire diameter only.

2. We then tabulate some major and minor differences between practical squibs and our imaginary squib and show qualitatively how these differences may reveal themselves in actual firing curves.

The author believes that use of idealized curves such as those postulated in the first step is not only convenient in design and testing, but may also lead to early recognition and possible correction of anomalous behavior.

Log-current log-time firing curves based on constant-current initiation will be used for illustrative purposes; the appropriate modifications for constant-voltage or even capacitor-discharge initiation will be obvious.

A glossary of some of the terms used is included in Appendix A.

INITIATION CHARACTERISTICS OF AN IMAGINARY TYPE OF SQUIB

As noted in the Introduction, we first assume an imaginary type of squib and assign to it an arbitrary firing curve. For this purpose we use the firing curve indicated by the solid portions AB and BC of the intersecting lines AM and NC in Fig. 2; specific current and time values have been assigned for illustrative purposes only.

The line BC is a line of constant current, and represents the "no-fire" portion of the curve; the line AB is a line of I^2t constant, and represents the "all-fire" portion; our imaginary squibs all fire along the line AM, but none fire below the intercept B.
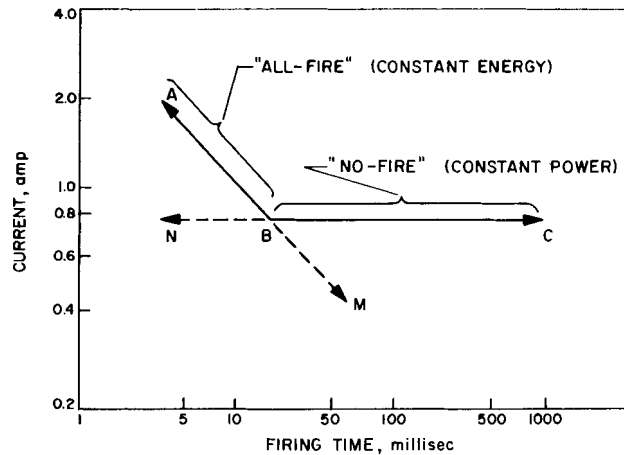
Fig. 2. Idealized firing curve

The firing curve of Fig. 2 may be rationalized by assuming that all heat generated by passage of current through the bridgewire goes into heating the bridgewire for current levels above BC, but that for current levels below BC all heat is conducted away through the match-head; this assumption practically endows the squib with intelligence, but is a useful artifice.

Assuming further that our bridgewire resistance remains constant, the line AB becomes a line of constant energy and, with other obvious assumptions, a line of constant temperature (θ); with equally obvious assumptions, line BC becomes a line of constant power.

The following symbols will be used:

I current through the bridgewire, amp

t time to fire, millisec

R_s specific resistance of bridgewire, ohms per circular mil-ft

ρ density of bridgewire alloy, grams/cc

H_s specific heat of bridgewire alloy, calories/gram

θ firing temperature, °C

θ_a ambient temperature, °C

d wire diameter, thousandths of an in.

K thermal conductivity of match-head, gram calories per square centimeter per second per °C per centimeter

Assuming each elemental length of bridgewire acts independently of its neighbors, and that the bridgewire characteristics are independent of temperature, it is a simple matter to derive the following equation -

"All-fire" line AB:

$$I = Md^2 \rho^{\frac{1}{2}} H_s^{\frac{1}{2}} R_s^{-\frac{1}{2}} t^{-\frac{1}{2}} (\theta - \theta_a)^{\frac{1}{2}} \tag{1}$$

where M is a constant dependent only on the system of units used.

"No-fire" line BC:

$$I = Nd^2 R_s^{-\frac{1}{2}} K^{\frac{1}{2}} (\theta - \theta_a)^{\frac{1}{2}} \tag{2}$$

where N is also a constant dependent only on the system of units used.

The ratio between the "all-fire" current and the "no-fire" current is sometimes taken as a basis for comparing the relative merits of two squibs, with low ratios being preferred. Division of Eq. (1) by Eq. (2) for a fixed firing time leads to

$$\frac{I_{all-fire}}{I_{no-fire}} \propto d^{\frac{1}{2}} \rho^{\frac{1}{2}} H_s^{\frac{1}{2}} K^{-\frac{1}{2}} \tag{3}$$

and at first glance it would appear desirable to select a bridgewire material having either a low density or a low specific heat; unfortunately the two are in conflict, as the product $\rho^{1/2} H_s^{1/2}$ varies only over a small range between various metals and alloys. Again, it appears desirable to keep the diameter down, but the manufacturing problems often limit the minimum diameter which can be handled.

Equations (1) and (2) are both derived on the assumption that the bridgewires are of circular section; if the perimeter is increased without changing the area, the theoretical "no-fire" can be increased without a corresponding change in the "all-fire." The consequent prospect of reduction in the ratio of "all-fire" to "no-fire" naturally makes thin-film and ribbon-type bridges attractive.

Some squib designs have used 2 small-diameter bridgewires in parallel between the same pair of pins, purportedly for improvement of " bridgewire reliability "· as might be expected, such squibs show a

relatively good "all-fire" "no-fire" ratio, but tend to exhibit a bad spread in firing characteristics because of random variations in the relative lengths or spacings of the adjacent wires.

If we hold all parameters fixed, other than d, Eq. (1) and (2) may be expressed as simple proportionalities:

"All-fire" line AB $\qquad I \propto d^2 t^{-\frac{1}{2}}$ $\qquad\qquad$ (4)

"No-fire" line BC $\qquad I \propto d^{\frac{3}{2}}$ $\qquad\qquad\qquad$ (5)*

From (4), the firing time at fixed current is given by

$$t \propto d^4 \qquad\qquad\qquad (6)$$

Again, holding all parameters fixed, other than d, the locus of the intercept B is given by the proportionality

$$t \propto I^{\frac{2}{3}} \qquad\qquad\qquad (7)**$$

Thus, if our assumptions were real (which we know they are not), we would need only two test firings to completely determine the initiation characteristics of our imaginary squib. Furthermore, knowing the firing curve for one diameter of bridgewire, by using Eq. (4) and (5), we could produce a family of firing curves for different diameters of bridgewire as in Fig. 3.

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*It is interesting to note that the proportionality of Eq.(5) appears to have been first applied to the fusing of wires in air by Sir W. H. Preece (1834-1913); in 1905 Schwartz and James modified Preece's formula to allow for end effects. In typical cases, they found the appropriate index ranged from 1.1 to 1.7.

**Equation (7) could be expressed in the form "milliseconds at one ampere"; such an expression is sometimes convenient for comparing the relative merits of various "families" of squibs from the standpoint of their "all-fire"-"no-fire" ratios (Eq. 3).
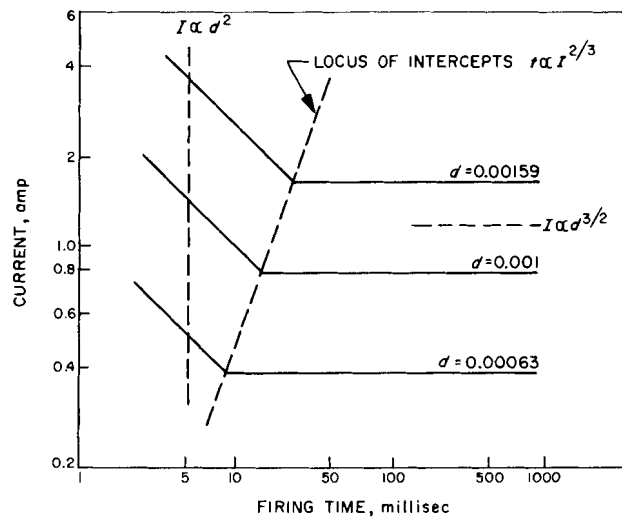
Fig. 3. Family of firing curves for
various diameters of bridgewire

INITIATION CHARACTERISTICS OF ACTUAL SQUIBS

In the preceding Section, we assumed that our imaginary squib had
a firing curve as in Fig. 2; actual firing curves differ, as illustrated by
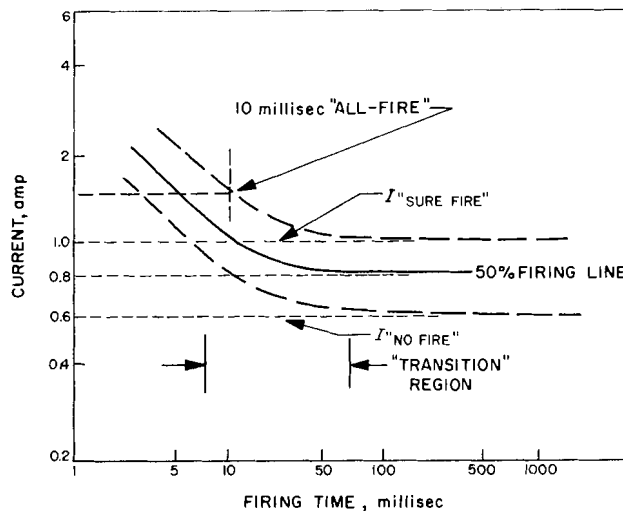Fig. 4, from the curve of Fig. 2 mainly in that they:

Fig. 4. Firing curves typical for
an actual squib

1. Are bands rather than lines, and

2. Exhibit a nonlinear transition region between the "all-fire" and "no-fire" areas; in this region, the thermal conductivity of the match-head is becoming increasingly more important as firing time increases.

First attempts to apply the proportionalities of Eq. (4) through (7) to actual firing curves are often very discouraging; even outside the transition region nothing seems to behave as we might like.

Nevertheless, the proportionalities of Eq. (4) through (6) serve as useful starting points, and can be modified, at least qualitatively, to account for many apparent discrepancies.

We may now tabulate certain practical aspects which affect initiation characteristics as determined by actual tests:

1. The "all-fire" and "no-fire" equations for the imaginary squib assumed that no heat was conducted away by the match-head under "all-fire" conditions; the nonlinear transition region of an actual firing curve represents the area where this approximation is grossly inaccurate.

2. The equations for our imaginary squib, particularly for "no-fire," were inherently based on steady-state thermal conduction; this state is, of course, again only an approximation.

3. The equations for our imaginary squib made no provision for the effect on the match-head of prolonged heating; such effects appear typically as a lengthening of the transition region.

4. The firing time of squibs is variously measured from time of application of current to bridgewire burnout, mechanical reaction as sensed by a vibration pickup, start of rise of pressure as sensed by a pressure transducer, or flash as sensed by a photodiode. These terminal events do not usually coincide in time, and may introduce a constant time offset which upsets the relationship of Eq. (4), particularly for fast firing times. Of the

various terminal events, bridgewire burnout is probably the most artificial indication of initiation.

5. Heat is conducted away from the bridgewire not only through the match-head, but also through the bridge-wire terminals. This affects the relationship of Eq. (5), becoming more significant as the ratio between bridgewire diameter to bridgewire length increases.

6. Our imaginary squib assumed no thermal gradient through the bridgewire; this is a poor approximation if the thermal conductivity of the match-head is high, or if the bridgewire is in contact with a surface of high thermal conductivity.

7. We assumed for our imaginary squib that the bridge-wire characteristics were independent of temperature; quantitative corrections for this assumption are prac-tically impossible, particularly for those squibs which appear to fire only after their bridgewires have passed through a liquid phase into a gaseous state.

8. Tests are sometimes conducted using constant-current pulses of predetermined duration, and resultant hang-fires may lead to misinterpretation of results.

9. As indicated by Eq. (1), our firing times are a function of the ambient temperature; it sometimes happens that firings at a low temperature are inadvertently compared with those at a high temperature. The error introduced is, however, often swamped by more significant factors.

10. Random variations in manufacture produce random variations in initiation characteristics. Among some of the more common sources of random behavior are:
    (a) Run of solder along bridgewires;
    (b) Variations in the spacing of the bridgewire from adjacent surfaces, particularly the bottom or top of the match-head, and also from the top of the pins when the bridgewire is spot-welded to their centers;
    (c) Variations in pin spacing;

(d) Nonuniformity of match-head;

(e) Inclusion of voids within the match-head;

(f) Minor imperfections, such as nicks, in the bridge-
wire.

Unless such random variations are kept to a reasonable
level not only within one lot but also between lots, design
will of necessity always remain in the realm of cut-and-
try.

A highly simplified electrical analogy of the thermal characteristics
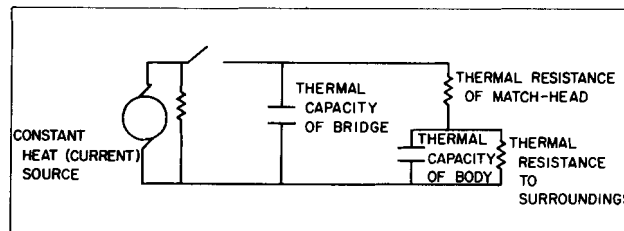of a squib is given in Fig. 5, and the effects of some factors on our idealized
firing curves are illustrated in Fig. 6.

Fig. 5. Highly simplified electrical
analogy of thermal "circuit"
of squib

The squib fires when the tempera-
ture (voltage) across the bridge
"capacitance" reaches the appro-
priate value. In actual squibs
there are a multitude of individual
thermal resistors and capacitors,
intricately interconnected.

Before continuing, it is important to note that no cure for design
problems has been offered; we have, in effect, done little more than
review the areas about which we have so much to learn.

Although not strictly relevant to initiation characteristics, it may
be appropriate at this point to comment briefly on the postfiring resistance
of squibs, a squib characteristic which is frequently a matter of concern.
Such postfiring resistance (or conductance) is of interest insofar as bat-
tery drain is concerned, but a high postfiring resistance is often taken
erroneously as an indication that squibs may be fired successfully in

a) CONSTANT TIME OFFSET — MEASURED TIME OF IGNITION EXCEEDS TRUE TIME
b) REDUCTION IN PIN SPACING
c) DECREASE IN CLEARANCE BETWEEN BRIDGEWIRE AND THERMALLY CONDUCTIVE
    SURFACE
d) DECREASE OF THICKNESS OF MATCH-HEAD COVERING BRIDGEWIRE OR VOIDS
    IN MATCH-HEAD
e) BRIDGEWIRE DIAMETER REDUCED, NO-FIRE HELD CONSTANT BY CHANGE IN
    ALLOY
f) DECREASE IN THERMAL CONDUCTIVITY OF MATCH-HEAD

Fig. 6. Effects (illustrated by broken lines) of
various factors on idealized firing curves

parallel; squibs which exhibit good postfiring resistance may exhibit dead shorts during firing, and thus be a potential source of trouble in parallel firing arrangements.

ADVANTAGES INHERENT IN USE OF LOG-CURRENT LOG-TIME FIRING CURVES

One of the most common forms for presentation of firing curves is the linear-current linear-time plot as illustrated in Fig. 7. By comparison, the log-current log-time presentation of Fig. 4 offers several advantages:
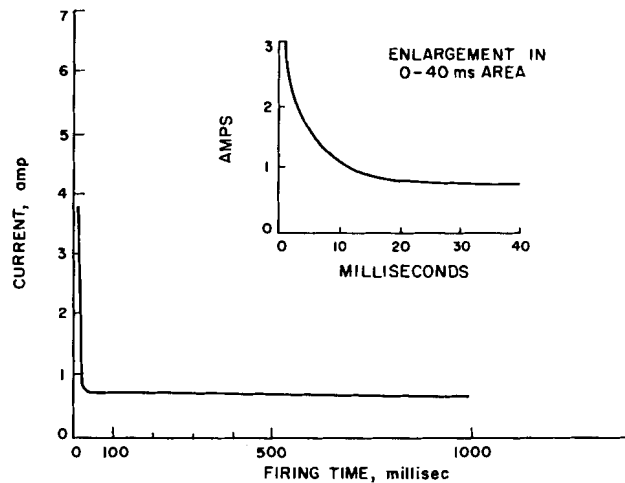
Fig. 7. 50% firing curve of Fig. 4. replotted with linear-linear coordinates

1. Equal intervals on either ordinate represent equal percent changes; the presentation is inherently one of uniform percentage accuracy.

2. The linear "all-fire" and "no-fire" sections can be readily distinguished from the transition area, making the initiation characteristics easier to comprehend at a glance.

3. The linear characteristics of the "all-fire" and "no-fire" areas enable sketching of preliminary firing curves based on as few as two test firings, one well up

on the "all-fire" line, and the other well "out" on the "no-fire" line. So useful is this feature that with as few as four additional samples, the original points can be confirmed, the transition area defined, and the random spread estimated, all to a degree of accuracy adequate for most preliminary purposes.

4.   The linear locus of the intercept between the "all-fire" and "no-fire" lines facilitates extrapolation of test results from one bridgewire diameter to another, and in the early assessment of the "all-fire" "no-fire" ratio of a particular type of squib design.

Although extrapolation from one bridgewire material to another or from one match-head to another might appear attractive, the designer will probably find it preferable to obtain, by actual test, at least one firing curve for each likely combination of bridgewire alloys and match-heads, and to restrict his extrapolations to changes in bridgewire diameter.* Such extrapolations will not always prove successful, but should not need more than possibly six samples for a check by test.

A NEW METHOD FOR ANALYZING SMALL-SAMPLE TEST FIRING RESULTS

As discussed earlier, the line AB of Fig. 2 is a line of constant energy, and the line BC is a line of constant power. Provided actual firing curves such as those of Fig. 4 exhibit such sections of constant energy or constant power, any test results within these sections may be used to make an estimate of firing probabilities within these sections.

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*Some designers estimate a change in "no-fire" for a change in bridgewire material by making the assumption on which Eq. (2) is based, namely that the heat which can be dissipated is proportional to the bridgewire diameter. If a firing curve for a particular combination of bridgewire alloy and match-head is not available, such an estimate may save time by indicating that, while a particular diameter of a particular alloy may meet a specified bridge-wire resistance requirement, the alloy in that diameter would have an entirely unsuitable "no-fire" level when used with the selected match-head.

The author has had no success in isolating useful values for the θ of Eq. (1) and (2), nor for the K of Eq. (2); it is for this reason that extrapolation appears practical only between bridgewire diameters, and even here second-order effects generally convert extrapolations into approximations at best.

The method is outlined simply as follows: Assume we have possibly 3, 5, 10, 100, or any number of firing times corresponding to various currents above the transition region. Calculate the product I^2t for each of these, then obtain the mean value and standard deviation of the products. If $\overline{X}$ is the mean value, σ the standard deviation, and TF the tolerance factor appropriate to some combination of confidence level and probability, the appropriate range for I^2t is given by

$$I^2t = \overline{X} \pm TF\sigma \tag{8}$$

We can now separate I and t, and plot one as a function of the other on our log-current log-time scales, for any desired probability at any desired confidence level.

The method is open to no objections which are not also applicable to the Bruceton or Probit techniques, and has several advantages:

1. Test intervals need not be preselected; any valid test results may be "retrieved" from records for the analysis.

2. Unlike the Bruceton technique, in which half the results must be discarded, all valid results are useful.

3. The number of samples may be much less than the 40 or 100 often considered to be minimums acceptable for Bruceton tests.

APPENDIX A.   GLOSSARY OF TERMS AS USED

The Glossary summarizes the intended meaning of some of the terms used, and may conflict with usage elsewhere.

"All-fire"
: The term all-fire is generally used for that current which will initiate a squib within a specified length of time--frequently 10 millisec. In this paper, the term has also been loosely used to describe that section of firing curves in which the energy input for initiation is substantially constant.

End Effects
: The heat sink characteristics of bridgewire terminations are referred to as end effects.

Hang-Fire
: A condition in which an abnormal delay occurs because the magnitude or duration of the applied current is insufficient to produce positive ignition of the match-head.

Initiation
: Initiation is used to indicate positive ignition of the match-head by heating of the bridgewire; alternatively it may be taken to imply the commencement of application of a current adequate for such ignition. It may be noted that the time at which the match-head ignites is practically impossible to sense directly.

"No-fire"
: The maximum continuous current which can be passed through a squib without causing the squib to ignite. The term can be qualified by assignment of a probability such as 99.9%; the duration of current is sometimes limited by definition to times such as 5 min. In this paper the term has also been used loosely to describe that portion of the firing curves in which the power input is substantially constant.

Squib
: An electrically initiated cartridge, particularly one initiated by passage of current through a metallic bridgewire of circular cross-section.

| Sure-fire | The minimum continuous current required for initiation of a squib; as for the "no-fire," the term may be qualified by assignment of a probability. The 0.1% sure-fire corresponds to the 99.9% "no-fire." |
| Transition Region | This term is used to describe the nonlinear portion of firing curves tangential to the "all-fire" and "no-fire" lines. |

APPENDIX B. DERIVATION OF EQUATIONS

Equation (1):

Electrical energy per unit length = Heat energy per unit length

$$I^2 \frac{R_s}{d^2} t \propto \rho d^2 H_s (\theta - \theta_a)$$

from which

$$I = M d^2 \rho^{\frac{1}{2}} H_s^{\frac{1}{2}} R_s^{-\frac{1}{2}} t^{-\frac{1}{2}} (\theta - \theta_a)^{-\frac{1}{2}}$$

where M = 0.81 for the system of units used in the text. It is interesting to note that, for a typical 1-w 1-amp squib using 2-mil nichrome and firing in 2 millisec at 4 amps, the temperature rise calculated by use of the above equation is over 2300°C, yet nichrome has a melting point of about 1400°C.

Equation (2):

Electrical power input = Thermal power conducted

$$I^2 \frac{R_s}{d^2} \propto K d (\theta - \theta_a)$$

from which

$$I = Nd^{\frac{3}{2}}R_s^{-\frac{1}{2}}K^{\frac{1}{2}}(\theta - \theta_a)^{-\frac{1}{2}}$$

where N = 1.0 for the system of units used in the text.

Equation (7):

$$I_{\text{all-fire}} \propto d^2 t^{-\frac{1}{2}} \qquad \text{(Eq. 1)}$$

$$I_{\text{no-fire}} \propto d^{\frac{3}{2}} \qquad \text{(Eq. 2)}$$

for

$$I_{\text{all-fire}} = I_{\text{no-fire}}, \qquad d^2 t^{-\frac{1}{2}} \propto d^{\frac{3}{2}}$$

from which d $\propto$ t. But

$$I_{\text{no-fire}} \propto d^{\frac{3}{2}}$$

Therefore,

$$I_{\text{no-fire}} \propto t^{\frac{3}{2}}, \qquad \text{and} \qquad t \propto I^{\frac{2}{3}}$$

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ABSTRACTS

12. Development of Improved Static Tests for Detonator-   W. P. Taylor
    Booster Output   W. L. Smith
                                                          M. R. Smith

Methods of static output testing investigated by Lake City Ordnance
Plant included substituting steel discs for lead discs and modified
dent test using steel, sintered brass, and sintered iron blocks. A
contract awarded Franklin Institute resulted in the ionization switch-
photomultiplier method of measuring intervals between shock front and
flash.

13. Diode Testing System   Morris Brenner

Cold cathode diodes are used as energy transfer components in the firing
circuits of certain ordnance devices. The performance characteristics of
the diode are expressed in terms of voltage breakdown, energy transfer,
and energy transfer time. A system for the automatic and simultaneous
observation and recording of these three parameters has been designed.
The system can be used as working tool both in R&D and in production to
provide realistic test data rapidly with significant savings in cost and
personnel.

14. A Review of Explosive Output Testing   Vincent J. Menichelli

Various methods have been used to evaluate the output of an explosive
device. Usually the characteristics which output tests measure do not
correlate with the ability of the devices to perform properly in the end
item. A review of various output tests is given and the effectiveness of
each test is discussed.

15. An Adequate Initiator Development Program   Ruth E. Trezona

A program for the development of electric initiators and testing them
under normal and adverse conditions is described. The pitfalls of
correlating simulated or laboratory tests with "in service" tests are
discussed.

16. Prepulsing Studies (U)   V. W. Goldie

An experimental procedure, known as a successive increment test, has been
used to demonstrate the effect of prepulses on the normal firing
sensitivity of EED's. Laboratory tests performed on some commonly used
EED's have illustrated that prepulsing can cause serious sensitivity
degradation.

17. Effect of Cold Temperature on Sensitivity   Leonard Shainheit

The functioning characteristics of various electric initiators at ambient
and cold (-65°F) conditions are discussed. The effect of cold on both
input and output is outlined.

18. **High Speed Photography Applicable to the**   Howard S. Leopold
     Development of Electroexplosive Devices   Diane F. McVaney

Photographic techniques used at NOL, White Oak, for investigations pertaining
to electroexplosive devices are described. Smear camera methods are
described for observing the growth of explosion from a bridgewire, detonation
transfer at explosive interfaces, shock waves from exploding wire, and
propagation in a detonator. Examples of the use of framing cameras for
measuring simultaneity and for interpretation of explosive events are given.

19. **Instrumentation for Testing Electric Initiators**   Charles T. Davey

The measurable parameters involved in testing electric initiators are discussed
along with methods and instrumentation used to obtain these parameters.
Examples of complete instruments are presented.

12. DEVELOPMENT OF IMPROVED STATIC TESTS FOR DETONATOR-BOOSTER OUTPUT

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M. R. Smith
Franklin Institute

For many years the criteria for determining by static means whether 20mm fuze detonator-booster output was satisfactory, was based on puncturing of a lead disc or discs. The technique for performing this test had remained relatively unchanged. It consisted of assembling a detonator-booster train in an aluminum sleeve equipped with a firing pin, positioning the assembly on a lead disc or discs, functioning the detonator by dropping a ball on the firing pin and thereby functioning the booster. The booster output had to be sufficient to completely perforate either two lead discs, each .125" thick or one lead disc .250" thick. The perforation could be of any diameter. Detonator output was measured in a similar manner. Such a measure of static detonator-booster output was perhaps useful as a process control test. However, it became increasingly evident, as production of 20mm HEI cartridges incorporating the M505 fuze increased and low order functioning of the fuze occurred periodically, that there was no real correlation between the results of static output tests and those of fuze functioning tests. Also, it was suspected that booster output, although static tests results were comparable, might not be adequate or there might be wide variation in uniformity within lots, from lot-to-lot or between manufacturers.

In 1958 a steel disc (.049" thick) was substituted for the lead disc with a requirement of complete penetration. This test appeared to provide better differentiation among satisfactory and unsatisfactory detonator-booster combinations, but correlation with functioning test results still was not good.

Accordingly, other techniques and methods for measuring 20mm fuze detonator-booster output were studied. Among these were: 1) directing the output to move a pendulum and measuring the vertical displacement of the pendulum "bob"; 2) measuring the initial velocity of a steel ball propelled by the impulse of the output; 3) measuring the movement of a column of mercury in an open "U" tube when the explosive output is applied to one end of the tube; 4) utilizing the Denver Research Institute electronic equipment developed under the supervision of Picatinny Arsenal; and 5) the Naval Ordnance Laboratory dent test. It was finally concluded that some adaptation of the dent test using available drop test equipment and test fixtures would be the most economical and reliable means of performing the desired output tests. Problems encountered and overcome in this adaptation were: obtaining a measurable smooth dent by means of an intermediate steel ball, using a relatively inexpensive metal witness block for indentation, keeping the surface of this block free from powder burns and other distortions that could prevent accurate measurement of the indentation depth and devising a rapid and accurate technique of measuring the dent depth.

As time went on further refinements of the method for obtaining detonator-booster output were introduced, such as using the detonator-booster assembly in a fuze body instead of a sleeve and the use of sintered metal blocks instead of steel discs. Sintered iron was found to be the best of the blocks tried because of better dent depth differentiation and cost advantage.

Since practical correlation of static output tests with fuze functioning was the goal of the improvement program being conducted by the Industrial Engineering Division it was felt that before any effort was made to correlate

dent test results with fuze functioning results - a lengthy and expensive program - an effort should be made to determine whether there was a better means of measuring output than those already explored and in use. Accordingly, the Franklin Institute was awarded a contract to determine whether it was possible to devise a static output test more meaningful than that in use at the present time.

The initial portion of the Franklin Institute study was devoted to an examination and analysis of the static test procedures now being used for quality control in 20mm ammunition. All the static tests in use depended upon the measurement of the depth of a dent produced by the explosive component in a block of known hardness to indicate the output level. Those dent block criteria used in the static tests of detonators and boosters to indicate functional quality were simple and easily interpreted, but, as mentioned before, there is some doubt as to the degree of correlation between the performance of these detonators and boosters in the static tests and their performance in firing tests.

The M505 series fuze for 20mm ammunition contains two explosive elements, a detonator and a booster. It is intended that the output of the detonator shock the booster into high order detonation, which in turn will shock the main explosive charge into high order detonation. There are, of necessity, gaps between each of the elements in the explosive train. To simplify the analysis we can assume that the reaction in the train is transferred from one element to another solely by shock waves. If we consider the case where the detonator, once initiated, goes high order and produces a shock wave of significant magnitude then the initiation of the booster might proceed as in Figure 1. At time t_1 the shock wave from the detonator is shown already in the booster material. If energy is continually fed across the gap, the

condition at time t_2 may follow in which the chemical reaction has begun to develop a pressure front. Because the explosive through which the shock wave has passed is now at a higher energy state, the pressure front or reaction front proceeds along the explosive column at increasing velocity reducing the separation from the shock front as shown at times t_3 and t_4. The separation between the reaction front and the shock front becomes constant when, as at time t_5, the ideal detonation velocity of the explosive has been reached. Behavior of this sort, where the shock front first outruns the reaction front, then is overtaken after the chemical reaction has built up to the critical stage, is most common where the explosive train has been interrupted or in explosive columns of varying sensitivities or densities. In the case of the relatively short columns of secondary explosive such as those used in the booster of the M505 series fuzes we expect the pressure profile of the reacting region might appear as shown in Fig. 2. We think it reasonable to suppose that a measurement of the time or distance separation between the shock front and the reaction front will be indicative of the level of reaction and velocity of propagation in the explosive component under test. However, the separation of the shock front and the reaction front is probably so small in the case of primary explosives or in long columns of the more sensitive explosives that its measurement would appear to be difficult.

We therefore developed a technique to measure the time separation of these two zones in the booster column. A fuze body with detonator and booster installed in-line is placed in a test fixture so as to rest with the end of the booster on an ionization switch. A photo-multiplier type flash detector is focused at this same point. When the shock front emerges from the booster,

the passage cuases the air in the ionization switch to become more conductive. The following reaction front is indicated by the presence of visible light as it emerges from the booster column. Time separation of these two events was measured with an oscilloscope. A chronograph counter might also be used. Typical oscillograph records are shown in Fig. 3. Record 3a is of three high-order detonations. The sweep rate from right to left is 2 microseconds per division. The upper trace is the output from the photodetector indicating the presence of visible light. The lower trace is the ionization switch output which also serves as the sweep trigger. Time separations in tests from which this record was chosen were in the range 1.5 to 4.0 microseconds. Record 3b is of a low-order detonation. The sweep rate in this case is 5 microseconds per division, also from right to left. In this group of test shots, time separations in the range of 20 to 25 microsecondsdwere recorded.

As a result of this study and experimentation we have been able to determine a difference between fuzes which detonate low order and those which detonateehigh order by means of the time separation between two phenomena associated with the explosive reaction. This output test promises to be useful in the production testing of fuzes because of its ease of performance and interpretation and the apparent low cost of the testing operation.

AT t_1

PRESSURE →

—SHOCK FRONT

DISTANCE →

AT t_2

PRESSURE →

—REACTION FRONT

DISTANCE →

AT t_3

PRESSURE →

DISTANCE →

AT t_4

PRESSURE →

DISTANCE →

AT t_5

PRESSURE →

DISTANCE →
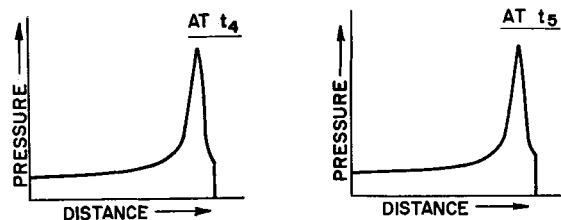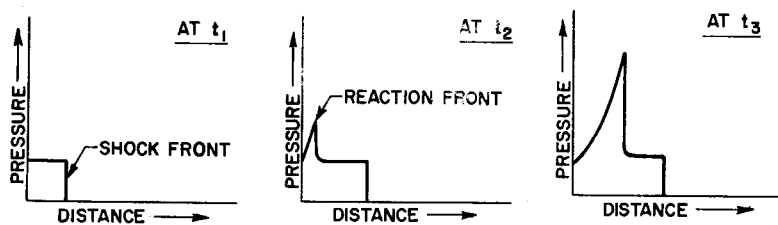
FIG. I. RELATION OF SHOCK FRONT AND
REACTION FRONT IN A COLUMN

PRESSURE →

CHAPMAN-JOUGET
POINT

REACTION
FRONT

SHOCK
FRONT

EXPANDING
PRODUCT
GASES

REACTION
ZONE

INTACT
EXPLOSIVE

DISTANCE ALONG COLUMN →
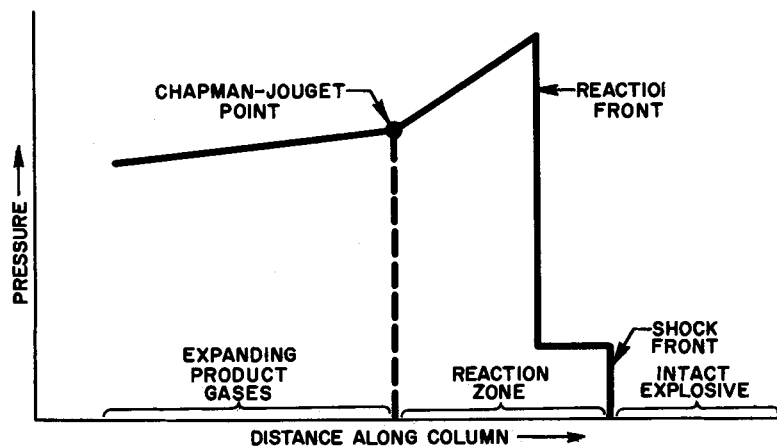
FIG. 2. PRESSURE PROFILE OF DETONATION IN AN EXPLOSIVE COLUMN

(a) HIGH ORDER FUNCTION

316

317

318
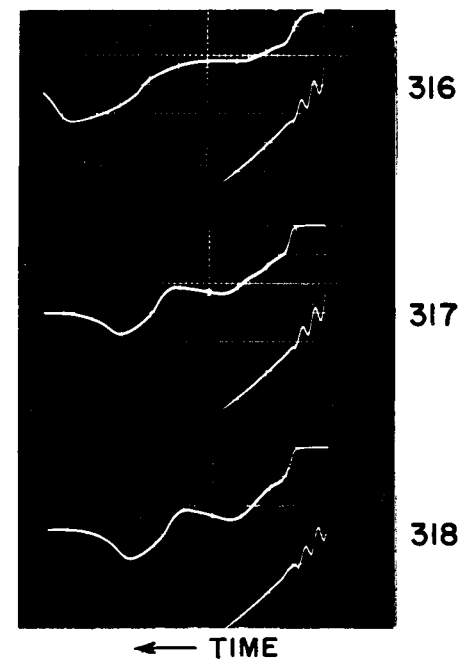
← TIME

(b) LOW ORDER FUNCTION

324
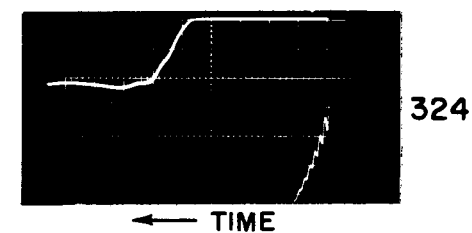
← TIME

FIG. 3. TIME SEPARATION RECORDS

12. DISCUSSION

A person asked if consideration had been given to the fact that some liquids, when compressed, produce a voltage. Mr. Taylor was not familiar with this aspect of the program, and an unidentified person answered that interest was detecting pressure at the surface. By viewing this pressure a direct measure would be obtained of delay time, which is actually what is required.

Mr. Taylor agreed that Lake City, a high-production facility, wished as sophisticated a method of measuring output as possible; the method must be simple enough for the average line operator to use and interpret. Mr. Stresau of Stresau Labs asked if anyone present could explain the hydrodynamics of the stable situation where a shockwave of fairly small initial pressure rise increased to several times that of the initial shock. Mr. Stresau recalled that the von Neumann theory predicts a higher pressure from the non-reactive shock than from anything behind it. Many people, he continued, have made efforts to trace the reaction of an inner detonation by measurement of the pressure decay from the non-reactive shock down to the Chapman-Jouget point.

Mr. Hannum of FIL answered that Mr. Stresau was probably best qualified to answer this question and pointed out that no attempt is being made to measure pressure, only the time difference between emergence of the shock wave from the booster and the appearance of light from the reaction.

A representative of AVCO Corporation asked how much the current test costs and how long it takes to run it. Mr. Taylor estimated the time at about 20 minutes for a series of boosters.

A person from the Sandia Corporation asked if there was a fair degree of certainity that the large amplitude pulse was not due to the shock wave in air in front of the booster.

Mr. Kelly of The Franklin Institute, explained that there is no positive proof that the light is not from the shock wave other than comparison of the low order reaction. The low order was forced by putting barriers between the detonator and booster. This caused a greater separation of the two signals. Mr. Stresau's comments, Kelly continued, pointed out that this entire field is hazy. It is felt that the test involving delay of shock and light has possibilities in detecting the difference between high and low order detonation.

Mr. Amicone of The Franklin Institute said that he believes that the shock wave can produce the first light, and that this can be checked by a gauge developed at NOL. The gauge is prevented from being triggered by ionization. A pressure actuated collapsible gauge of thin copper is used. Mr. Lipnick of Harry Diamond Laboratories asked if details of this test had been worked out for explosives of varying geometrical forms and brisance in an effort to apply this test universally. Mr. Taylor replied that it would be applicable to other explosive trains but that this study had been confined to 20 mm rounds. Mr. Smith of The Franklin Institute said that although this test was applied to components of the M505 fuze, it would probably not be applicable to primary explosives because of the small separation distances.

13. DIODE TESTING SYSTEM

Morris Brenner

Harry Diamond Laboratories

ABSTRACT

Cold cathode diodes are used as energy transfer components in the firing circuits of certain ordnance devices. The performance characteristics of the diode are expressed in terms of voltage breakdown, energy transfer, and energy transfer time. A system that provides for simultaneous observation and automatic recording of these three test parameters has been designed. The development of a system for the automatic testing of explosive components, based on the principle of the diode tester, is under consideration.

This technique supplies a working tool for both R & D and Production to generate realistic test data rapidly and accurately, with significant savings in cost and personnel.

INTRODUCTION

A cold cathode diode is used as a voltage reference in the transfer of energy to explosive devices in certain ordnance items. Diodes for this purpose are selected on the basis of their performance characteristics. Three of the most critical parameters, in this regard, are breakdown voltage, energy transfer, and energy transfer time. Ordinarily, each of these parameters is measured independently. Since these parameters are interdependent rather than independent, the performance data from this type of testing

13-1

lack the realism provided by the simultaneous observation of the three parameters.

The outcome of a study to provide such information resulted in an automatic testing system useful in both Production and R & D, which, in addition to observing the test parameters simultaneously, provides a permanent record in the form of a printed tape.

Although the system was designed primarily for diode work, it should be useful in the testing and evaluation of electric initiators in general, both in cases where the initiator completes a circuit through a diode and in cases where energy is transferred to an initiator through a simple switch closure.

The system as applied to the testing of diodes will be described to provide background information after which its use in the study of electric initiators will be discussed.

BASIC CIRCUIT THEORY OF OPERATION

The testing system is built around the decoupling characteristic of vacuum diodes in the capacitor charging circuit shown in figure 1. The diode under test is connected across a capacitor that is charged through a resistor and a vacuum diode in series. When the capacitor is charged to the breakdown voltage of the tube, the diode fires through a simulated load and the capacitor discharges through the diode until the voltage across it is too low to sustain the discharge, i.e., the tube quenches. The voltage at which breakdown occurs is monitored by another capacitor (reading capacitor) circuit in parallel with the firing capacitor but

decoupled from it by another vacuum diode. Auxiliary circuitry connected to the reading capacitor and the simulated load makes a simultaneous record of the breakdown voltage, energy transferred during breakdown, and transfer time.

The operating circuit is more complex, to provide flexibility in use and operation. Details are given in appendix A of this paper.

APPLICATION TO EXPLOSIVE COMPONENTS

The system described is essentially an energy transfer device with provisions for automatic monitoring of the test parameters. In the present investigation the energy was transferred to a resistor load, which simulated a detonator, through a cold cathode, which functioned as a switch.

The system is directly applicable to detonator study by simple modification of the test conditions.

1. The resistive detonator simulator can be replaced with the detonator itself.

2. The cold cathode diode can still be used as a transfer switch, if the particular application calls for it, or any other desired switching arrangement can be used.

3. The charging source can be varied to suit requirements.

   a. Cold Cathode as Switch

   The rate at which the voltage builds up on the firing capacitor can be controlled through the charging resistor, voltage of the charging source, and the magnitude of the standby voltage.

b. Switch Closure

The capacitors can be charged to the desired voltage, and the firing capacitor can then be connected to the detonator by manual switch closure. Switch closure can also be done automatically. The voltage on the reading capacitor is monitored by a voltage comparator which is arranged so that when the charging voltage reaches a preset value, the firing capacitor is dumped automatically into the detonator.

The automatic technique would be particularly useful in reliability studies. The voltage comparator can be programmed so that it automatically closes the firing circuit for preset increments of test voltage. The comparator can be programmed so that the detonators are automatically given a statistical (i.e., Bruceton) test. For automatic operation, the detonators can be fed into the testing circuit by means of a belt or hopper.

A method of adapting the system to the testing of explosive components is shown schematically in figure 2.

APPENDIX A—DETAILS OF AUTOMATIC TESTING SYSTEM

BASIC CONCEPT

Current from the charging source E charges the capacitors of the system through resistor R_c and the forward resistance of the vacuum diodes (fig. 1). The reading and firing capacitors are connected to a common point P through their vacuum diodes. When switch S is closed, the two capacitors are charged simultaneously. When the voltage on the capacitors reaches the breakdown voltage of the diode V_3 under test, diode V_3 breaks down and capacitor C_F discharges through it and its simulated series load R_2. The surge of current through the test diode and simulated load produces a voltage drop across the load, which is fed back into a control circuit that opens the charging switch S. When the switch S is opened, the charging source is disconnected from the test circuit, i.e., capacitors and associated equipment.

The reading capacitor, which was charged to the same voltage as the firing capacitor, is now isolated. It cannot discharge because of the high back resistance (10^{10} to 10^{11} ohms) of the vacuum diode, which decouples it from the firing capacitor that is discharging through the diode under test. The reading capacitor is connected to a firing voltage recording system which consists of a digital voltmeter and an electrometer, which acts effectively as a unity-gain impedance transformer with an input impedance of approximately 10^{13} ohms. (Isolation devices other than electrometers can be used, i.e., unity-gain operational amplifiers with

high input impedance, $> 10^{10}$ ohms.) This arrangement makes pos-
sible continuous monitoring of the voltage on the capacitor
without discharging it. When switch S opens, the vacuum-tube volt-
meter indicates the voltage at which the diode under test fired.
In the simplified circuit this event is indicated by the sudden
quiescent condition of the voltmeter indication. (Up to the point
of firing, the voltage indication increases in keeping with the
increase in voltage on the capacitors.) This firing voltage can
be recorded manually, or automatically with the help of appro-
priate circuitry that will be discussed later.

The energy fed to the load is measured with a thermocouple-
galvanometer arrangement connected across the load. (By means of
a photocell mounted on the galvanometer screen a GO/NO-GO indica-
tion can be printed on a tape.) The time during which this energy
is transferred is measured with an oscilloscope connected across
the load. The storage tube type of oscilloscope is well suited
for this type of measurement. It can be used for visual observa-
tion as well as for photographic recording.

OPERATING CIRCUIT

In the circuit shown in figure 3, provision is made for push-
button initiation of the measurement cycle with automatic printout
of the breakdown voltage together with automatic resetting of the
measuring system for testing the next tube. Energy transferred
and time for transfer are simultaneously observed visually or
photographically, photographic recording being automatic. In

addition, provision is made to calibrate the system against refer-
ence standards.

<div align="center">FIRING CIRCUIT</div>

General

The actual firing circuit differs from the basic concept in
that:

a. The capacitor assembly charging may be started from some
convenient preset value instead of from zero. This preset or
standby voltage will depend on test requirements. It provides a
stable starting point and makes possible a rapid rate of testing.

b. The reading capacitor is connected to the digital volt-
meter through a voltage coupler (electrometer or isolating oper-
ational amplifier with unity gain) to prevent discharge of the
capacitor. The reading capacitor is in the form of a capacitor
voltage divider. If the test voltages are too high (>100 v) for
direct coupling to the voltage coupler, the voltage divider is
adjusted so that the input to the voltage coupler is exactly
($\pm 0.1\%$) one-tenth the voltage appearing across the reading capac-
itors to make the system direct reading.

c. Provision is made for calibration of the firing circuit
against the reference voltage built into the digital voltmeter,
as well as against external references.

d. The loss of charge by the capacitors of the firing circuit
is minimized through the use of polystyrene, methyl methacrylate or
tetrafluoroethylene insulated switches and relays. The capacitors

of the firing circuit should have a polystyrene or electrically similar dielectric.

Operation

Standby Voltage

The initial charging voltage on the capacitors of the firing circuit is supplied by the d-c supply E'_s through the potentiometer E_s and the resistor voltage divider R_1, R_2 via switches S_1, S_2, and S_3. This arrangement effectively constitutes a form of d-c clamping circuit.

The initial charging voltage can range from zero to any specified value.

Capacitor Voltage Divider

The input range of the high-impedance voltage coupler used in the current work is only 20 v. Since test voltages in excess of this value are involved, a voltage adapter in the form of a voltage divider (C_3, C_4) is connected across the reading capacitor. Capacitor C_4 is chosen at some convenient value, and C_3 is chosen together with a trimmer so that the ratio $C_4/(C_3 + C_4) = 1/10$, to provide a 1/10 voltage attenuation across the input to the voltage coupler. The capacitance of the cable to the voltage coupler is included in the ratio. This provides a direct reading on the digital voltmeter of the voltage across the combination with the decimal point displaced by a factor of 10. Once this ratio has been established, the remaining capacitor is chosen so that the total of the capacitance in the recording branch of the circuit is equal ($\pm$ 10%) to that of the firing branch.

ENERGY TRANSFER

Theory

When the diode under test breaks down, the firing capac-
itor discharges through it and the detonator, which is simulated
by the resistance R_L in series with it. The firing capacitor
discharges until the voltage across it becomes too low to sustain
the diode in a conducting state, at which time the diode is quenched.
The energy dissipated in the load between the time of breakdown and
the time of quench is referred to as the energy transfer of the
diode. Mathematically this energy is given by the expression

$$W = \int_o^t \frac{E^2}{R_L} dt \text{ where E is the voltage across the load } R_L$$

at any instant of time t. In practice this measurement is made
with a thermocouple with resistance simulating the load R_L. This
circuit is not shown in figure 3.

The galvanometer is calibrated by discharging a reference
capacitor C charged to a voltage V through the thermocouple-gal-
vanometer system used in the energy-transfer test. The deflection
on the galvanometer is a measure of the energy transferred. Each
voltage to which the reference capacitor is charged corresponds
to a particular energy value, i.e., $W = \frac{CV^2}{2} \times 10^7$ ergs. For con-
venience the galvanometer scale is marked to read directly in ergs.
The reference capacitor is incorporated in the energy-transfer
circuit so that calibration can be checked periodically by a sim-
ple switching system. Calibration circuit is not shown in figure 3.

Automatic Record of Energy Transfer

In manual measurements of energy transfer, the galvanometer deflection in the system, described above, is observed and a record of the corresponding energy made in tabular form. This is carried out as a separate test independent of the breakdown voltage test. The recording of data can be automated in several ways.

In a photographic method, a camera is focussed on the scale of the galvanometer. The light beam is masked so that is appears as a lighted half-moon on the scale with the vertical edge set to the zero reference of the galvanometer. The shutter of the camera is opened and the diode is fired. The galvanometer deflects and the camera makes a continuous exposure of the deflection. The result of this is a picture consisting of a sharply defined white streak superimposed on the galvanometer scale. The edge of the streak represents the energy transferred, the value of which is read from the scale. In the experimental development of the automatic system, a Polaroid camera was used to check feasibility of the system. In production either 16-mm or 35-mm film can be used at a cost of less than one cent per diode.

A GO/NO-GO indication can be obtained by replacing the ground-glass scale of the galvanometer with a narrow, vertical-slit photoelectric pickup mounted in a position corresponding to the specification for minimum energy transfer. When the galvanometer deflects to this point, the photoelectric circuit is triggered to provide a go signal that can be audible, visual, or a command to the printer

in the form of a printout. (The printout will be incorporated
in the current system.) The printout of energy transfer will be
simultaneous with that of voltage breakdown. If a record of the
actual energy transferred is required, in addition to the GO/NO-GO
printout, a photograph (16 mm or 35 mm) can be made at the same
time that printout occurs.

A printout of energy transfer can also be obtained through the
use of circuitry that will automatically solve the equation
$W = \int_0^t \frac{E^2}{R_L} dt$. Essentially all that would be required is a squar-
ing circuit combined with an integrator. The instrumentation re-
quired is considerably more complex and costly than the thermocouple
approach. In addition, extended laboratory investigation may be
required to evaluate the significance of the intermittent nature
of the energy transfer-time characteristic with respect to the
magnitude of the energy transferred during breakdown in cases of
nonuniform discharge.

TRANSFER TIME

A measurement of the energy-transfer time -- the interval
during which the energy is transferred from the firing capacitor
to the load -- is obtained from an oscilloscope display of the
voltage drop across the load as a function of time.

Before the diode fires, the load is at ground potential
(except for negligible dark-current leakage in the diode). When
the diode breaks down, the voltage E_L across the load rises
rapidly and drops back to zero when the diode quenches. The inter-
val between initiation (0) and quench (Q) is the transfer time.

The pattern of the discharge generally approximates that of a capacitor discharging through a resistor, which in this case consists of the load (thermocouple) in series with the variable resistance of the diode. The pattern varies from tube to tube and frequently shows discontinuities of an erratic nature. The screen of the oscilloscope tube is calibrated to provide a direct measure of time in microseconds, on a GO/NO-GO basis.

The transfer time can be recorded on the tape simultaneously with the breakdown voltage and the energy transfer.

Several methods of doing this are available:

1. The observer reads the calibrated screen and presses a button, which locks a coded number on the printer wheel. This coded number is printed when the printout command is received by the printer. The button can be GO/NO-GO.

2. A photoelectric pickup can be mounted on the screen at a position corresponding to the specification time limit, to be actuated only if the diode fails to quench after the lapse of the specified time limit. Thus, if after the time limit the voltage on the load (point P) is greater than zero, the photographic system is pulsed to read NO-GO.

3. When the diode fires, a counter is started. After the specified time limit, the potential at point P is measured. If it is above ground, the counter is triggered and a NO-GO wheel is locked on the printer for printout on the tape. This pulse duration technique is inadvisable because of the uncertainties introduced by discontinuities in the energy-transfer pattern.

CALIBRATION

Calibration of the firing circuit consists in verifying that the voltage shown on the printout tape is the breakdown voltage of the tube under test. Both design and operating checks are involved. Design checks are used to verify the construction of the circuit. The operating checks are used in routine testing to assure proper operation of the system.

Capacitor Voltage Divider

The need for establishing the 1:10 ratio of the capacitor voltage divider was discussed previously. This ratio is set to a first approximation by measuring the capacitance of the components of the divider. The final or vernier adjustment is made by measuring voltage division with the digital voltmeter. This technique of setting capacitor ratios reduces to the adjustment of a trimmer capacitor until the correct voltage division is obtained. Conventional capacitor voltage-divider techniques are used The voltage across the reading capacitor may be read through an isolating electrometer or operational amplifier.

Input Voltage to Isolation Diodes

The charging system is effectively symmetrical (electrically) about P (fig. 3), the junction common to the two diodes. The anodes of the two diodes are at the same potential, and the two diodes are electrically equal with respect to effect on the firing voltage. The anode voltage is checked on each of the diodes with the digital voltmeter. The electrical equivalence of the diodes is checked by interchanging the diodes and applying a test voltage to the junction

point P. The forward resistance of the diodes is small compared with the charging resistance R_c, i.e., ohms compared with megohms. This results in a negligible effect on the rate of charging the capacitor of the system. On this basis, the diode V_2 could be eliminated. However, in addition to providing electrical symmetry, the use of two diodes provides additional decoupling between the reading and firing capacitor and reduces leakage paths for the firing capacitor.

Resistive Voltage Divider of Standby Voltage

The resistive voltage divider is adjusted to provide a voltage ratio of 1:10 ($\pm 0.1\%$) to match that of the capacitor voltage divider. Precision wire-wound resistors adjusted to 0.1 percent of specified value are commercially available. The voltage divider currently used consists of 45 kohms ± 0.1 percent and 5 kohms ± 0.1 percent in series across a variable voltage source to provide a variable standby voltage.

FLEXIBILITY OF OPERATION

The system can be used to check from one to three parameters of any type of two-terminal switching device in any combination. Devices can be screened for a particular parameter. It can be used to study the characteristics of voltage sources and loads.

EASE OF VOLTAGE READOUT

The capacitor-diode decoupling system provides a convenient, dependable way of obtaining data on transients, and to record function voltage with conventional equipment. Thus in tube breakdown

work, detailed visual observations of oscilloscope patterns can be made with the knowledge that a record of the test voltage is being made automatically. This is of considerable interest in the area of threshold voltage measurements, and in studies dealing with the stability of tube performance and the mechanism of the tube breakdown.

CONTROL OF RATE OF VOLTAGE BUILDUP

The RC charging method combined with the standby voltage technique provides a convenient and extremely flexible method for varying the rate of buildup of a test voltage. The voltage output E_c (voltage across the diode) is given by the equation

$$E_c = E_s + (E - E_s) (1 - e^{-t/RC})$$

where

E_s = standby voltage

E = source voltage

R = charging resistance

Thus three variables, each of which can be changed at will, can be used to control the charging rate. In addition, the standby voltage makes it possible to control the point at which a variable voltage is introduced.

This type of control is necessary in studies dealing with threshold breakdown voltage and in checking the response of a system to very slow charging rates, i.e., very long time delays.

BASIC CIRCUIT
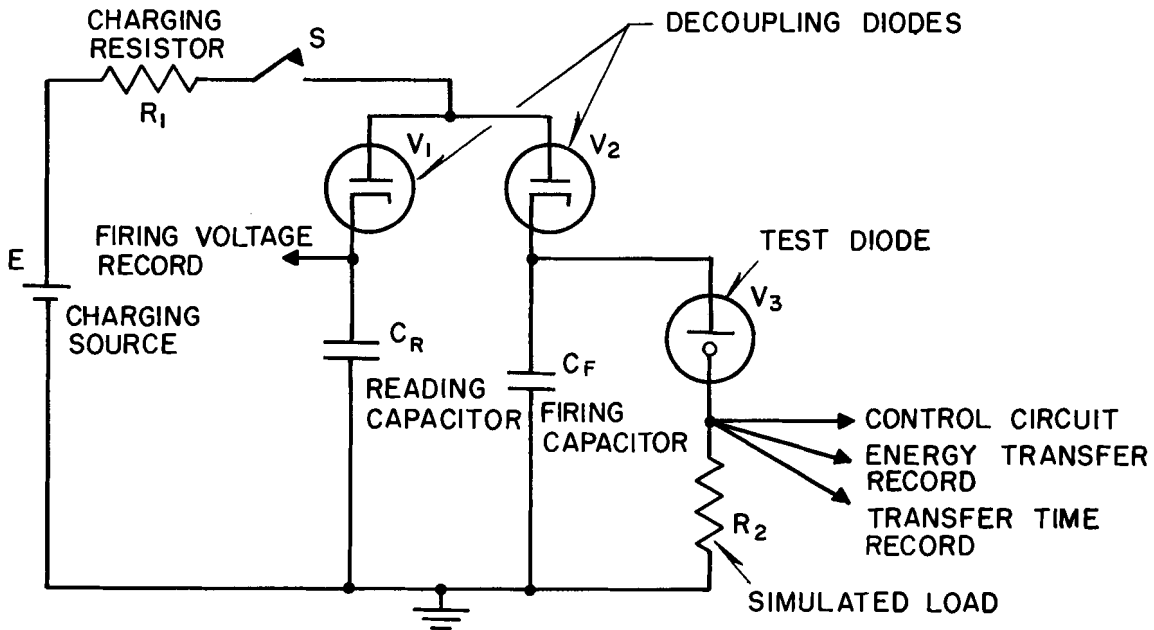
FIGURE 1

TESTER FOR EXPLOSIVE COMPONENTS
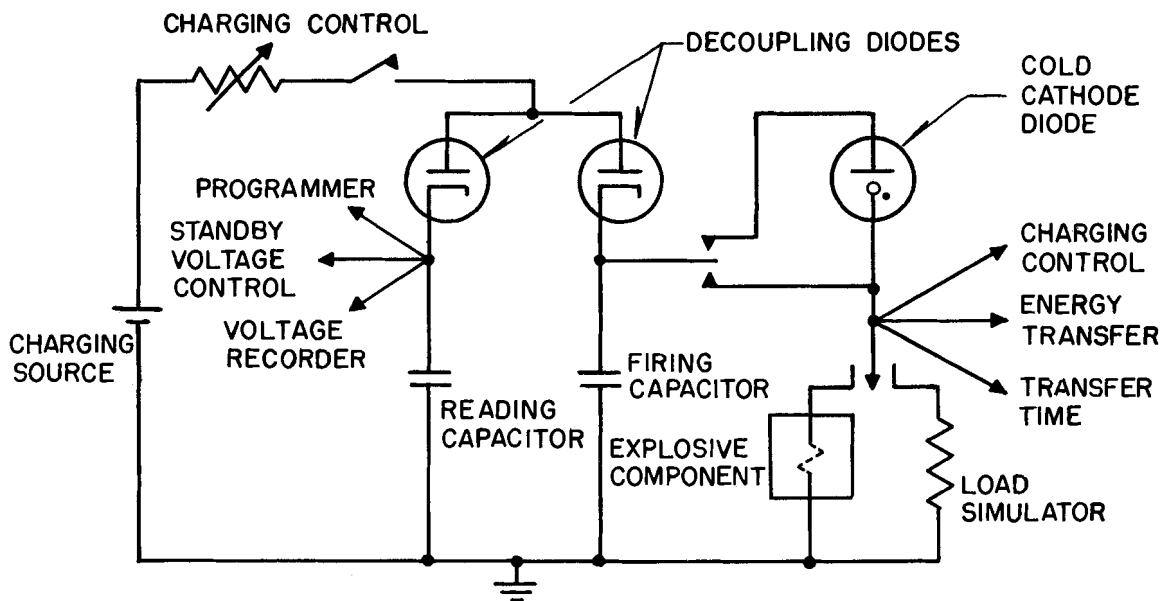
FIGURE 2

FIRING CIRCUIT
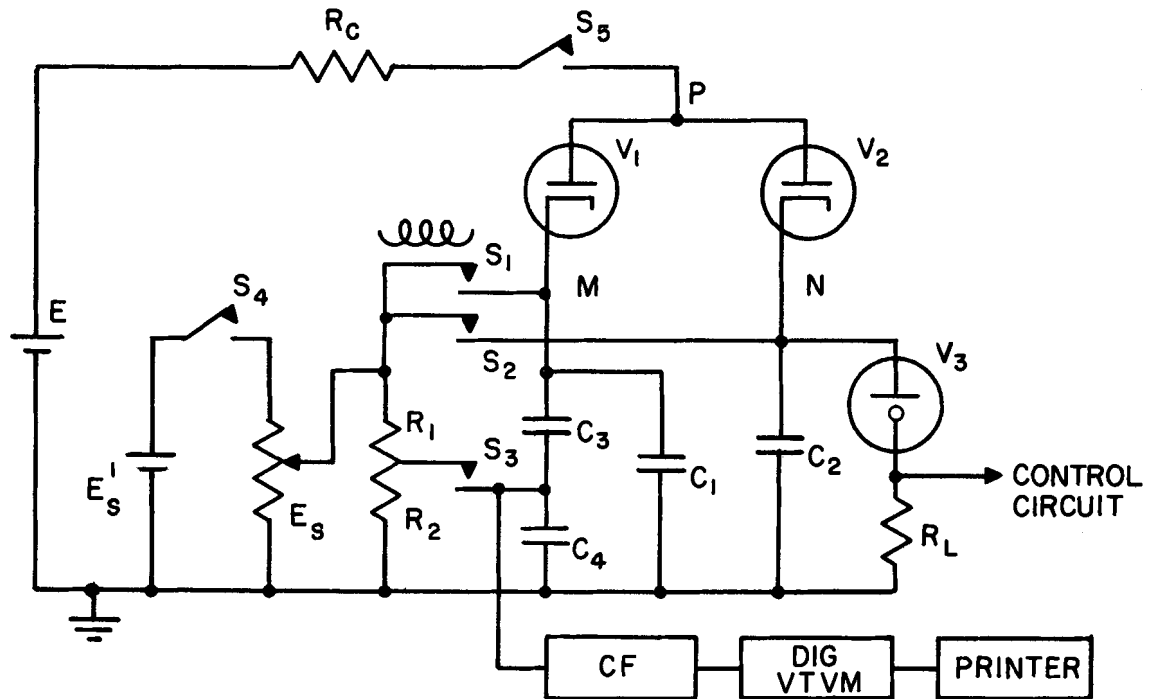
FIGURE 3

<u>Legend for Figure 3</u>

R_c = charging resistor

V_1, V_2 = isolation diodes (6AL5)

V_3 = test diode

C_1, C_3, C_4 = reading capacitors

C_2 = firing capacitor

R_1, R_2 = standby voltage divider

R_3 = standby voltage attenuator

E = charging voltage

E_s = standby voltage

E'_s = standby voltage source

S = charging switch

S_1, S_2, S_3 = contacts on standby voltage relay

S_4 = switch on standby power supply

R_L = load on test diode

CF = coupling circuit (electrometer, operational amplifier)

DIG - VTVM = digital voltmeter

14. A REVIEW OF EXPLOSIVE OUTPUT TESTING

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INTRODUCTION

Evaluating the output of explosives and explosive components is a natural part of explosive component development. Of the many characteristics of an explosive, the measurement of output is probably the most difficult. The difficulty is attributed to the extremely fast reaction time of explosives and their highly destructive nature. Parameters indicative of output are chemical energy content, explosion temperature, and pressure. However, to measure these latter parameters, which exist for short periods of time (microseconds), requires elaborate and sensitive instrumentation. To attempt to use such methods for quality control of production explosive components would be too expensive and impracticable. For these reasons output evaluation of components has been accomplished primarily by measuring the destructive or damage effect from explosives.

An example of this is the "Bent Nail Test" which was used some thirty years ago. Here we see a method used to measure output, improvised from need and lacking the scientific approach. Figure 1 illustrates this test. It consists of attaching the detonator to a four inch long (20d) wire finishing nail. Upon initiation of the detonator the nail is bent to some angle, dependent on the destructive

force of the detonator. For a given detonator and nail the angle is quite reproducible.

The exact mechanism of initiation of components in an explosive train is not entirely understood. Components are arranged in the "explosive train" starting with very sensitive components and leading up to the insensitive main charge. The ability to effect initiation transfer from one component to the next is not always a function of the damaging or destructive force associated with the component. Rather, it may be a combination of the temperature, shock pressure and fragments produced which determines whether or not the next component in the train will be initiated.

In the majority of output tests used today the vigor of an explosion is measured by the amount of damage caused to a surrounding material. In actuality the characteristic which is important is the ability of the explosive to initiate the next component in the explosive train. It does not necessarily follow that a correlation exists between the amount of damage caused in the test and the ability of the explosive device to initiate the next explosive component.

The various output tests in use today for military explosive components are:

      (a) Trauzl Lead Block
      (b) Sand Bomb
      (c) Lead Disc
      (d) Steel Dent
      (e) Gap Type Tests

There are other tests, more sophisticated, which measure such parameters as pressure, temperature and propagation velocity. However, they do not lend themselves to simplicity, nor is their exact correlation with ability to initiate other charges known. The data obtained in these tests is characteristic of the explosive but, not necessarily related to its ability to start initiation in another explosive. A description and evaluation of these tests are given below.

TRAUZL LEAD BLOCK

The Trauzl Block shown in Figure 2 measures the comparative disruptive power of explosives through the enlargement of a cavity in a lead block. Explosives under test are loaded into the cavity of the block and confined. After initiation the increased volume is compared with other explosives. The data or number generated gives a measure of the brisance and total energy content of the explosive. For comparison purposes the test is adequate. However, the energy necessary to cause the lead to flow need not be delivered at high pressure. The lead can flow also from either a high temperature or a low pressure of long duration. Since in most initiation transfers high pressures of approximately 2 to 30 kilobars are needed the test does not particularly correlate with the property of interest. While the test is easily run on explosives it is not particularly adaptable to devices such as primers and detonators.

SAND BOMB

The sand bomb test, which is widely used, consists of initiating the explosive device in sand. The apparatus for this test is shown in Figure 3. The explosive device is buried in sand of a known type and particle size and confined in a bomb. After initiation the sand is screened and the sand crushed by the explosive action is collected and weighed. The weight of sand crushed is a measure of the brisance of the explosive item. The inadequacy of this type of test to correlate brisance with effectiveness to cause ignition of another explosive has been forcibly demonstrated[1]. In an investigation of Mk 18 Torpedo failures low order action was observed in four out of fifteen trials. Mk 8 Mod 3 Detonators, which contained mercury fulminate base charges were a part of the explosive train. Sand tests indicated that the detonators were satisfactory. However, detonators from the same lot, when tested in a simulated torpedo mock-up gave low order actions. When these detonators were replaced with newly loaded detonators, high order actions were observed. Other detonators were artificially aged and tested in the sand bomb and explosive train mock-up. Good sand test results were obtained while low orders were observed in the mock-up. The problem was resolved by replacing the mercury fulminate base charge with lead azide. When the lead azide detonators were tested in the sand bomb, lower values than those obtained with fulminate detonators were observed yet,

lead azide which builds to detonation rapidly gave reliable
high order detonations while mercury fulminate gave low
order actions. A conclusion made from this investigation
was that no correlation exists between sand crushing ability
and ability to cause detonation.

LEAD DISC

Another widely used output test is the lead disc test.
This test consists of placing a lead disc approximately 1-1/4
inches in diameter and 1/8 inch thick on an anvil. The
explosive component is placed directly above the center of
the disc as shown in Figure 4. Upon initiation a hole is
blasted through the disc. The area of the hole is a measure
of brisance for the item. Experience has shown that the
position of the explosive device with respect to the lead
disc will affect the size of the hole obtained. That is,
a few thousandths of an inch separation between the lead
disc and explosive device can result in a significant difference
in hole diameter. Aside from the geometry effects, which
can be controlled, an example of non-correlation of this test
with ability to cause detonation is cited. The lead disc
test was used for output acceptance of the Mk 56 Mod 0
Detonator. This detonator was designed for use in the Mk 78
20 mm projectile fuze. During the development of the detonator,
high order initiation of the succeeding explosive components
in the fuze was obtained. The lead disc output data generated
at that same time was used as a criterion for acceptance of
the detonator. Subsequent production and output testing of the

detonator gave output results greater than those experienced
in development. However, when tested in the fuze, low
order initiations and duds occurred. The problem was found
to be associated with the different confinements afforded in
the test and in the fuze. Confined in the fuze the lower
output detonator built to a good detonation, while the
higher output one did not. Just as for the sand bomb test,
the inadequacy of the lead disc test was glaringly evident.

STEEL DENT

An easily performed test, which yields results which
correlate with the ability of a device to cause detonation,
is the steel dent test[3]. Figure 5 shows a typical test
arrangement for this experiment. The criterion of the test
is the depth of dent produced in the steel block. More
exactly it is the volume of the dent. For a given device,
however, the diameter of the dent is quite uniform and the
depth of dent (which is much simpler to measure) may be used.
The success of this test is due to the fact that steel has a
compressive strength of approximately 100,000 psi and does
not yield easily. In order to obtain measurable dents
shock pressures of about 7 kilobars are necessary. This
is in the range of pressures necessary to cause detonation
in high explosives and probably explains the success of
this test.

The work of Slie and Stresau has shown that for highly
confined columns of explosives, a near linear relationship

exists between the detonation velocity and depth of dent.
Figure 6 shows the depths of dent obtained with four high
explosives. Four explosive column diameters are plotted
versus the detonation velocity of the explosives, loaded
at the same density. The velocities used in this plot were
determined from velocity-density data from reference 3.

The above tests were conducted with the explosive
loaded in heavy walled brass tubes. However, when testing
explosive components, this type of confinement does not
always exist. The depth of dent is influenced by the manner
in which the component is confined[4]. Figure 7 shows the
effect of confinement and confining material on the Mk 63
Mod 0 Detonator. The depth of dent is plotted versus the
cavity diameter for three materials; steel, brass, and polystyrene.
The confining tube has a 0.5 inch length and 1.0 inch outside
diameter. The detonator has a 0.193 inch maximum diameter.
As the density of the confining material increases the depth
of dent increases. Also, as the cavity for a given material
increases the depth of dent decreases.

A closer look was taken at the effect of cavity diameter
on depth of dent. The item investigated was the Mk 70 Detonator
in a brass and polystyrene confinement. The plotted results
shown in Figures 8 and 9 show that an optimum cavity diameter
exists.

Although the steel dent test is superior to the other
output tests discussed, precautions must be taken. The

confinement, confining media, type of steel block and
hardness of block are some of the parameters affecting
the results[8]

GAP TYPE TESTS

The output of some components are tested by confining
the item in a geometry similar to its end application. The
next explosive component in the train is also included. The
criterion for acceptance is the initiation of the second
explosive component. However, to gain some confidence in
the test a penalty is imposed by increasing the gap between
the two components. Past experience has shown that in
establishing the gap to be used in such tests more than one
50% firing point was obtained.

NON-DETONATING EXPLOSIVE OUTPUT TESTS

Explosive components which contain non-detonating base
charges are usually referred to as Actuators, Drivers, Dimple
Motors and Bellows Motors. The device is usually designed
to perform some minimum amount of work. Consequently the
output tests applied measure some work function. Examples
of this are: compressing springs, shearing rods, and moving
a mass through some distance. In most cases these devices
do not initiate another explosive.

In addition to the work measurement type of test there
is a pressure bomb test. A simple explanation of its
operation is, the device is enclosed in a bomb of known volume.
Attached to the bomb is a fast responding gauge which can

sense pressure changes. The gauge is electronically coupled to an oscilloscope from which a pressure, time curve can be photographed. Figure 10 illustrates the test apparatus. This type of measurement can yield characteristic pressure build-up profiles, peak pressure, and total energy by integrating the area under the pressure time curve. It has proven to be quite useful in the selection of propellant type explosives for particular applications. Peak pressures, obtained by this method, are also used as a criterion for acceptance of devices.

SUMMARY

We have seen that most output tests for detonating materials rely on the measurement of damage as a criterion for output. The damage measured can be a result of low as well as high pressure effects. It is known that to effect detonation in high explosives, pressures of approximately 2 to 30 kilobars or more are necessary. Therefore it is possible to accept explosive devices which meet output requirements but will not function properly in an explosive train. For non-detonating devices, which perform some work function, the situation is better.

There is a need in both cases for tests which measure characteristics which are related to the intended use of the device. Measurement of characteristics such as velocity, temperature, pressure, heat flux, total energy, and total work are more significant. These parameters give a more scientific approach to output testing than existing tests. However, the exact mechanisms associated with the initiation of one explosive

item by another in a fixed geometry are not adequately known. Until more work is done to determine the governing mechanism, it is likely that output testing will follow the same approaches of the past.

REFERENCES

1. NAVORD Report 2932, "Investigation of Mk 18 Torpedo Failures", R. H. Stresau and L. E. Starr, 1953.

2. NAVORD Report 2422, "Small Scale Plate Dent Test for Confined Charges", W. M. Slie and R. Stresau, 1952.

3. OSRD 5611, "The Rate of Detonation of Various Explosive Compounds and Mixtures", Part II, M. D. Hurwitz.

4. NAVORD Report 3879, "Application of the Steel Plate Dent Test to the Quality Control of the Mk 63 Detonator", W. Slie and R. H. Stresau, 1954.

5. Contract No. N609215-3179, "Final Report on the Steel Plate Dent Test", W. L. Monson and T. J. Reid, 1955.
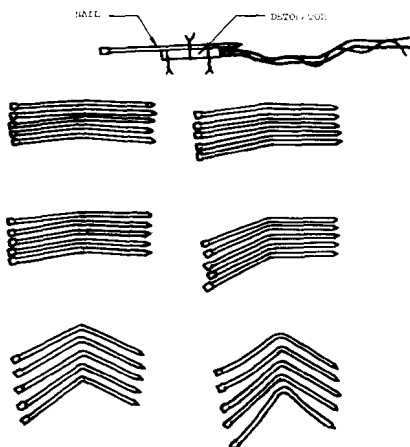
FIG. I

BENT NAIL TEST
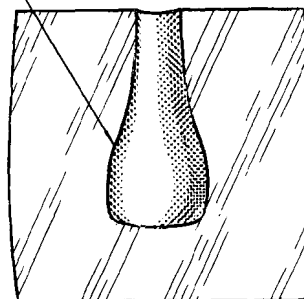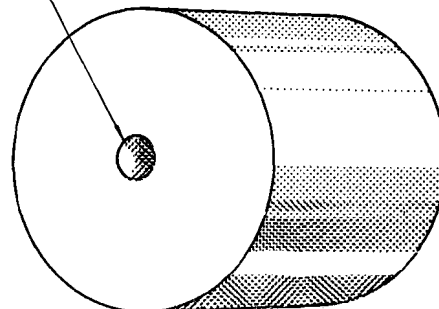
FIG. 2

TRAUZL LEAD-BLOCK TEST
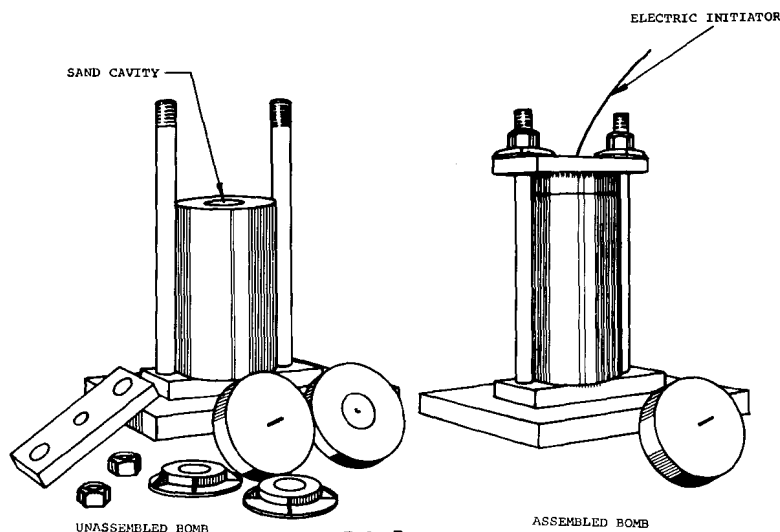
FIG. 3

SAND BOMB TEST
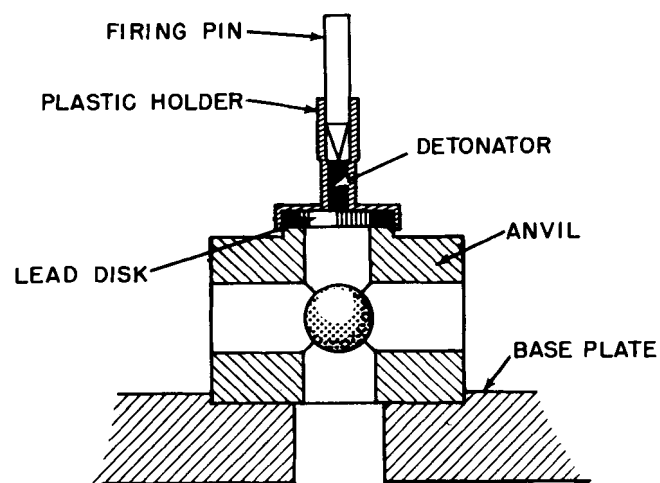
FIG. 4 LEAD DISK TEST
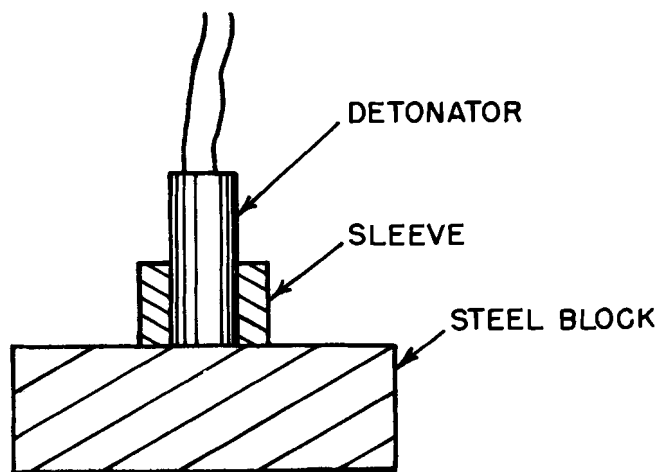
FIG. 5 STEEL DENT TEST
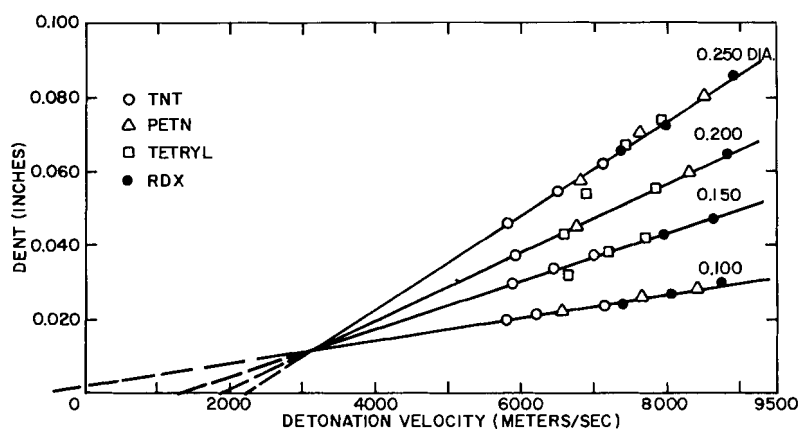
FIG. 6 DEPTH OF DENT IN STEEL BLOCK VS DETONATION VELOCITY

STEEL CONFINEMENT

BRASS CONFINEMENT

POLYSTYRENE CONFINEMENT

DEPTH OF DENT X 10³ INCHES

CAVITY DIAMETER (INCHES)
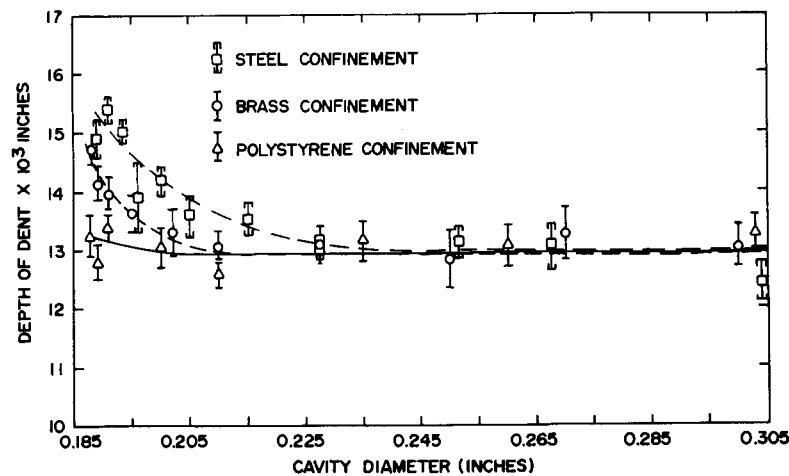
FIG. 7 EFFECT OF CONFINEMENT ON DEPTH OF DENT

AIR ONLY

FORCE FIT

MEAN DENT WITH NO CONFINEMENT -0″.0165

ID OF SPECIFICATION SLEEVE

MEAN DENT VALUES (MILS)

INSIDE DIAMETER OF CONFINING SLEEVE (INCH)
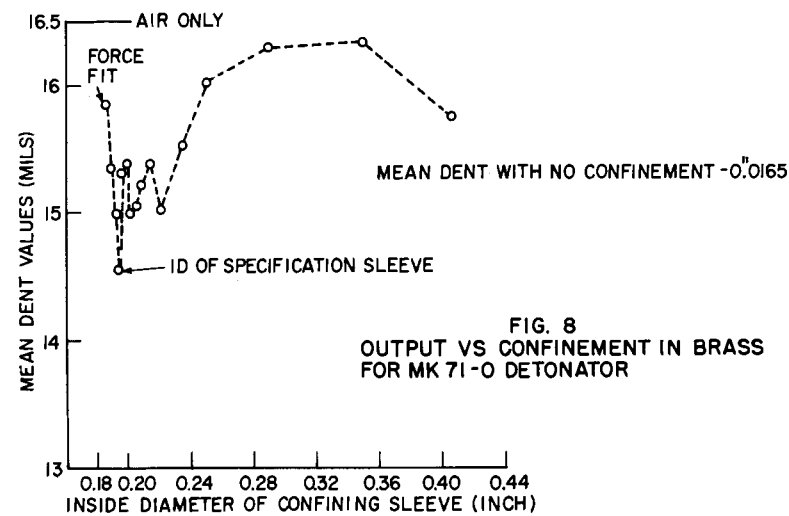
FIG. 8
OUTPUT VS CONFINEMENT IN BRASS
FOR MK 71-0 DETONATOR

AIR ONLY

FORCE FIT

MEAN DENT WITH NO
CONFINEMENT - 0.0165

ID OF SPECIFICATION SLEEVE

MEAN DENT VALUES (MILS)

INSIDE DIAMETER OF CONFINING SLEEVE (INCH)
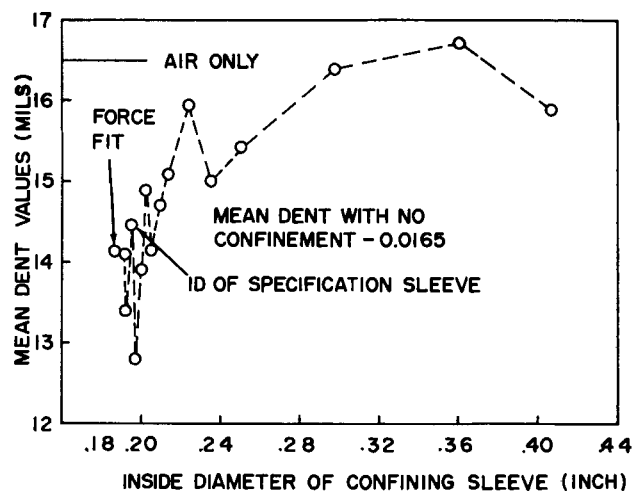
FIG. 9
OUTPUT VERSUS CONFINEMENT IN POLYSTYRENE
FOR THE MK 71-0 DETONATOR

CRO

CARRIER BRIDGE &
PREAMPLIFIER

FIRING CABLE

PRIMER BOMB ASS'Y

PRESSURE GAUGE
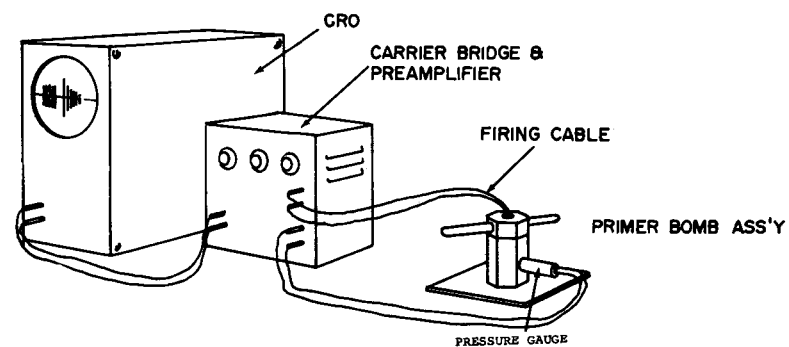
FIG. 10 PRIMER PRESSURE BOMB APPARATUS

14. DISCUSSION

In reply to a request for information on calibration of the steel dent and the basis for a decision on what depth of dent is acceptable, Mr. Menichelli said that a pressure of 7 kilobars will give a dent. The current devices deliver that much pressure. If further calibration is desired there is no ready answer.

Someone commented that Mr. Stresau has written some reports that may offer background for the dent test; the depth was related to detonation parameters.

Mr. Ayres of NOL pointed out that an explosive acceptor of known sensitivity can be used as a measure of output. A Bruceton type of test can be used to find the initiating capability of a device of unknown output.

Mr. Menichelli said that Mr. Taylor of Lake City Arsenal made a good point when he said that there is a need for a quick, cheap output test.

Mr. Tweed of AVCO mentioned a problem involving a donor charge, a barrier and an acceptor charge. He said that the acceptor charge detonated low order, and he wanted to measure output with a cheap test like the nail test. Mr. Menichelli suggested that the steel dent test might be used.

Mr. Stresau asked for a comment on one slide (Figure 6) that showed various lines pressing through a single point. Mr. Menichelli said that most of these data were on the right hand side of the graph. Something like two kilobars is required to give a measureable dent. Slides 6 and 7 were used to illustrate this discussion. All the data were taken at about 5800 meters per second or higher. These lines appear to be converging at a point. If steel dent tests are tried at less than 2 kilobars, there would be no dent, no data.

Mr. Stresau said that he had derived an equation that, in addition to involving hardness and other variables, showed the depth of dent divided by the charge radius to become a constant which he demonstrated on the blackboard.

Theory and reasons for possible deviation from the theory were given.

Mr. Dietrich of Atlas Chemical Industries added that output testing is necessary; and where one system is concerned, the results lead to valid conclusions. The existing tests serve as a production control on output.

Mr. Menichelli cautioned that some primary explosive cause effects that are difficult to explain.

Mr. Heinemann of Picatinny Arsenal, considering this review of explosive testing, spoke favorably of The Franklin Institute regarding their development of evaluation equipment for input sensitivity. He said that similar means are available for evaluating explosive output scientifically. The tests that he mentioned are not necessarily of the "quick and dirty" type but may include photographic apparatus and equipment necessary to evaluate explosive output similar to the initiator test sets designed at The Franklin Institute.

Mr. Menichelli said that these tests have not been forgotten, but that so far the numerical results have no correlation with ability to initiate secondary explosives.

Mr. Hannum of FIL suggested a practical way of calibrating the steel dent test for use in production testing if the initiator or donor is first proven to be able to detonate the acceptor. A donor charge of same diameter and density and about five diameters in length can be used as a reference for further output testing of the donor or initiator, by finding what depth of dent this makes in steel. Mr. Menichelli said that this sounded similar to the suggestion of Jim Ayres. He commented further that depth of dent is critically influenced by confinement.

Mr. Davis of Thiokol warned that orientation of the detonator with respect to the dent block is critical because of the side effects that can be produced. Mr. Menichelli agreed, saying that the cross section of the dent will often indicate the alignment, which has large effect on dent depth.

15. AN ADEQUATE INITIATOR DEVELOPMENT PROGRAM

Ruth E. Trezona

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The design and development of an initiator can be accomplished
in a matter of a few days or may require many months. For a detonator
to be used for system tests only, given a broad set of requirements
and no requirement for environmental testing,the detonators can be
assembled from components available, tested for a guesstimate of the
energy needed to fire and taken "up the hill" to be fired in the shell.
It works fine. Now the trouble begins. The users are in a hurry and
promise it will never be used except for local tests. They proceed
to have a large quantity made. The detonators do not work quite the
same; it seems that they didn't have "quite" the same bridge wire on
hand. You can guess what happens next. As fantastic as this story
sounds it has happened to us. Now let us back up and start again
just as we had to do for the group in a hurry. We will now make
haste slowly with an "adequate" program for developing an initiator.

If in the following program, aspects are not mentioned which are
important to your programs it may be because we, in our Artillery
group, are still earth bound and though interested in the exotic
space and underwater work, do not encounter the same problems.
The missile men for instance, who have tried to adopt some of our
old standard detonators in their items have found that the initiators

were not designed for the extremes of temperature, temperature cycling, reduced pressure and vibrations required of them. For the underwater group hermetic sealing of the initiators is important.

Which comes first – the fuze or the initiator? If the fuze comes first we may be given definite electrical power input requirements but allowed only space enough for a miniaturized initiator. If the initiator is developed first to a given set of physical and electrical requirements the development is straight forward – until – the time arrives for testing in the fuze.

Although theoretical knowledge of initiators is growing rapidly as witnessed here by the papers being presented we still also work on pre-conceived ideas and use the cut and try method until we meet our objectives mechanically, electrically and functionally.

The size and shape of initiators for conventional ammunition is generally limited and infact should be standardized. MIL-STD-320 "Terminology, Dimensions and Materials of Explosive Components for Use in Fuzes" should be complied with whenever possible. Using the standardized dimensions for new developments leads to the interchange-ability of the complete initiators their inert parts and tooling. The inert components for wirebridge initiators are fairly well established. They consist in our applications of drawn steel cups, glass-sealed headers (plug) or RF protected plugs and the bridgewire.

The explosive train consists of a primary explosive such as lead
styphnate and or lead azide and a secondary explosive such as,
RDX or PETN.

Design factors that affect the firing sensitivity are the
bridgewire material and dimensions; the primary explosive particle
shape and size, loaded density and contact with the bridge wire.

In addition to the usual electrical tests of the assembled
items including a test for static sensitivity it is wise to x-ray
them and eliminate those that appear defective before characterization
and environmental tests. I won't go into a discussion of the various
methods of determining statistically the all-fire and no-fire input
sensitivity of the item. We agree with those who do not use the
Bruceton staircase sensitivity test (except for finding the 50%
point) that the end points may not be too reliable. However, we
calculate the points usually the 99.9% and 0.1% with 90% confidence
and then fire a quantity at that point to establish a certain
reliability and confidence according to the number tested. For
example, values of N for zero (o) failures.

Reliability	Confidence	Level
	90%	95%
99% (1%)	230	299
99.3 (0.7%)	328	427
99.9 (0.1%)	2302	2995

Values are taken from Picatinny Arsenal SAAS Report No. 48 "Tables of Binomial Expansion for Statistical Reference Vol 2".

Since more power is required to fire at cold temperatures and less at hot temperatures, the all-fire point may be higher at -65°F and the no-fire point lower at +160°F than at ambient. Thus another valuable sensitivity check is to run Brucetons at the extreme temperatures. A statistically determined quantity should also be tested to confirm the all-fire at -65°F, and the no-fire at 160°F.

We receive Technical Data Sheets from Industries claiming to have items highly reliable with the degree of reliability determined by a Bruceton; any degree can be picked for calculations but I wonder if they checked the points by testing quantities at the input quoted.

Design factors affecting the output of the initiator are related to the density, quantity and confinement of the explosive which detonates. The initiator must be capable of detonating the next portion of the explosive train e.g., a lead or booster, thru barriers and across a gap. For artillery applications the fuze must also be safe against accidental firing of the lead when in the out-of-line position. Many methods have been used to measure the output of detonators, from the sand bomb test to shock velocity and detonation pressure measurements. Since it is too costly to

test the complete trains, the popular method of measuring output
indirectly is the steel dent test. The steel dent test is now a
standard test, MIL-STD-316 "Detonator Output Measurement by the
Steel Dent Test". An important factor to consider in the output
test is the external confinement of the initiator. Simulate fuze
confinement as closely as possible. Too much confinement may be
more misleading than too little. After it has been determined
that the new item fulfills or more than fulfills the specified
input and output requirement, the ruggedness of the design is
checked by subjecting groups (usually of 25) to cold functioning,
hot functioning, Jolt, Jumble, Temperature and Humidy cycle,
Transportation Vibration, Salt Spray, High Temperature Storage,
Low Temperature Storage, Water Immersion, 40 ft. drop and shock
test in air gun (10kg, 30kg, 100kg etc. depending on expected
acceleration in end item). When firing the conditioned items
information is obtained on time of firing and if possible the
output as determined by dent in steel.

Valuable information on designing initiators and conducting
the above tests can be found in MIL-STD-322 "Basic Evaluation
Test for Use in Development of Electrically Initiated Explosive
Components for Use in Fuzes" also in MIL-I-23659 (WEP) "Initiators,
Electric, Design and Evaluation of ".

What are some of the effects of the various environmental tests on the performance of loaded items? In high temperature storage or in cycling the bridgewire may be broken as a result of tension caused by thermal expansion; the functioning times may be longer due to expansion and then contraction of the explosive upon return to normal temperature causing separation from bridgewire. In low temperature tests the burning, initiation growth and propagation of the explosives can be retarded or prevented. For delay initiators it is especially important to run the cold-firing tests early in the development to determine the effect on propagation and delay time. In the impact tests Jolt, Jumble, Air Gun, Vibration, there may be structural damage of the inert parts or of the explosives. If the design is such that crumbled explosives can become lodged in crevices repeated impact or friction might result in initiation.

The program just outlined is based chiefly on "cut and try" and on an accumulation of experience in the initiator field. I would like to think , however, that a day will come when technical knowledge will advance to the stage that we can program our requirements for the computer and completely design the initiator on paper.

It is visualized that bridgewires of various materials, diameters and lengths will be evaluated for energy required to ignite various explosive compositions. From this evaluation, literature will be prepared which can be utilized in designing electric initiators. In addition, equipment capable of measuring the out put of various explosives under a series of conditions will be developed. An investigation, using this equipment, will be conducted and a report of all data prepared.

As a result of this work, it will be possible for a designer to select the bridgewire, explosives and container dimensions for an initiator simply by knowing the input and out put requirements. Once making this selection, prototypes can be assembled.

In addition, testing equipment which will be used for 100% non destructive inspection of electric initiators will insure that each item accepted will function reliably when used in its intended application.

There is a ditty that runs -

If all straight pins that have been lost

Should take a sudden notion

To rise and shine with all points up,

What a commotion!

To parody the ditty let us say -

    If all initiator data recorded and lost

    Should take a sudden notion

    To rise and feed into the computers

    What a commotion!

I don't want to leave you with the idea that all is commotion. Rugged and reliable items can be developed by careful designing based on the present state of the art and by thoroughly testing the design.

17. THE EFFECT OF COLD TEMPERATURE ON SENSITIVITY

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From time to time, it is of importance to the engineer to evaluate the performance of explosive items at extreme conditions. For instance, investigations pertaining to the performance of initiators are incomplete unless data are obtained at the extremes of temperature. Unfortunately, it is not always possible for the engineer to conduct his tests in climates having the desired temperature. Certainly, one would not expect the engineer to pick up and travel to Alaska whenever he has to conduct low temperature tests. Perhaps, for obvious reasons, the Eskimo engineer doesn't mind this inconvenience, but the government, because of increased incurred expenses, does. Thus, such a policy becomes unlikely, or is precluded altogether. As an alternative, an engineer must somehow simulate these tests by employing suitable conditioning chambers. It is possible to conduct firings in the conditioning chamber, thereby obtaining meaningful data, when initiators of low brissance are employed. However, powerful initiators are considerably destructive. Consequently, in order to prevent destruction of expensive equipment, the engineer is often forced to test outside the conditioning chamber. As a result of such practices, the data obtained lose their significance because the actual firing temperature is unknown.

Specifications have been written in which the procedures for conducting tests of this sort are outlined. For example, military

specification, MIL-S-45428A, requires testing the M2 Electric Squib in the following manner. The squibs are conditioned for a period of 16 hours at minus 65 plus or minus 5 degrees Fahrenheit. At the end of the conditioning time, one squib at a time is removed from the temperature chamber and fired within 2 minutes. The time interval between removal and fire is recorded.

It is believed that the results obtained from tests conducted in this manner are not indicative of firing at the actual cold temperature conditions. Because the squibs are removed from their cold environment and exposed to ambient conditions prior to fire, it may be assumed that they are actually tested at some higher temperature. Consequently, a study was initiated to evaluate and to determine the efficiency of such methods as have just been described.

Tests were conducted on M2 Squibs conditioned at -65°F in order to obtain a temperature-time relationship as the items warmed at room temperature. Because thermocouples were to be utilized in these tests, it was necessary that several be calibrated prior to performing the tests. This was accomplished in the following manner: the thermocouples were placed in the conditioning chamber at -65°F for 16 hours. Then the thermocouples were connected to a brush recorder and the voltage at -65°F obtained. The temperature in the chamber was lowered and the equilibrium voltage recorded. This technique was continued until sufficient data were obtained so that subsequently a graph could be plotted. This procedure was repeated on each thermocouple. The slide (Slide 1) shows a

typical temperature-voltage calibration curve obtained for one of the thermocouples. By means of such curves it was possible to accurately and expeditiously determine the temperature within the squibs. The M2 Squibs were prepared in accordance with the following scheme: The explosive charge and bridgewire were removed from the squib and a thermo- couple was installed so that when the explosive charge was "buttered in", the thermocouple was completely submerged in the charge. After drying at room temperature for 24 hours, the squibs were conditioned for 16 hours at -65°F. The squibs were removed from the conditioning box one at a time, and a temperature-time relationship was established at room tem- perature by means of a brush recorder. This next slide (Slide 2) shows the temperature-time relationship for one of the squibs as it warmed from -68°F at "0" time to about 75°F at time equal to 280 seconds. The curve shows that after an elapsed time of 120 seconds, the squibs warmed to about +45°F. As mentioned earlier, MIL-S-45428A stipulates that the squibs may be fired in up to 120 seconds after removal from the condition- ing chamber. Consequently, the squibs can be fired at a much higher temperature than the one we are interested in.

Tests were conducted to study the actual influence of temperature on the sensitivity of M2 Squibs. The Bruceton Test was employed for this purpose. A brief description of the Bruceton method of statistical analysis used in determining the sensitivity of explosives will be presented at this time for those of you who are not familiar with this technique. The procedure consists of testing explosive items at input energies which

differ by a fixed value. An input energy estimated for the 50% firing
reliability is used as the starting value. In the event the explosive
is actuated, the energy is lowered by a fixed amount. If the explosive
does not fire, the input energy is raised by this fixed interval. This
procedure insures that the majority of the testing occurs at the input
level at which half of the items tested explode. A suitable statistical
analysis was used to determine the input energies at the extremes or
99.9% and 0.1% firing reliabilities for a 90% confidence level, referred
to as the all-fire and no-fire points, respectively. For further details,
it is suggested that the report entitled <u>Statistical Analysis for a New
Procedure in Sensitivity Experiments</u> prepared by the Statistical
Research Group, Princeton University be consulted.

Three Bruceton constant current sensitivity tests **were** performed on
a single lot of M2 Squibs. The first was conducted at ambient temperature
(78°F). The second at -65°F and the third in accordance with MIL-S-45428A,
using the maximum allowable warmup time of two minutes.

The slide (Slide 3) shows a summary of the results obtained in the
3 tests. It can be seen, from a comparison of these results, that the
current calculated to obtain a 99.9% firing reliability at 90% confidence
level as well as for the 50% firing point is higher at -65°F than at
ambient temperature. These data show also that the current values for the
0.1% firing point at the 90% confidence level did not differ significantly
at these two temperatures. The results of the test performed in accordance
with MIL-S-45428A lie somewhere in between those of the other two tests,
with the exception of the current value for the estimated 0.1% fire with

90% confidence. This value is higher than either of the corresponding values for the other 2 tests. These results show that the data obtained in tests performed in accordance with military specifications of the kind mentioned earlier are not indicative of the conditions that are of primary concern. Resistance measurements on squibs immediately after removal from the -65°F atmosphere were considerably lower than the corresponding values obtained for these squibs about 2 minutes after removal. This was expected, because owing to the temperature rise within the wire bridges, a corresponding increase in reistance occurs. Consequently, it would be expected that these squibs would require less energy than those fired at -65°F and more than those fired at ambient temperature. The data presented in the previous slide supports this kind of reasoning.

For the reasons mentioned earlier, initiators with high output are not tested within the conditioning apparatus. Consequently, investigative effort was spent evaluating different insulating materials in an effort to determine their suitability for this application. One of these materials, called styrofoam, was found to satisfactorily insulate such large initiators as the M6 Blasting Cap. That is to say, the insulation maintained nearly test temperatures for a sufficient time and thus afforded the engineer with ample time to complete the test. The following describes the tests conducted on the M6 Blasting Cap to evaluate the styrofoam insulation.

M6 Blasting Caps were placed in 1 inch x 1 inch x 4 inch long styrofoam insulation and conditioned for 16 hours at -65°F. By means of

thermocouples, the temperature rise of the caps was measured as they warmed toward ambient temperature in a manner similar to that discussed earlier. The caps warmed from -65°F to -55°F in 120 seconds. After 60 seconds no noticeable change in temperature was observed.

The slide (Slide 4) shows a typical time-temperature relationship obtained for the M6 cap, contained in styrofoam insulation, as it warmed from -65°F toward ambient temperature. It should be observed that for the first minute or two, only a slight change in temperature is observed. However, after this short time lapse the curve appears to take the shape of the representative curve shown earlier (Slide 2) for the M2 Squib. The results just presented show that environmental conditions may nevertheless be maintained if insulating materials are used to contain the initiators. That is if the test can be conducted rapidly and efficently, reliable and meaningful data will be obtained.

Three Bruceton constant current sensitivity tests, similar to those pefformed on the M2 Squib, were conducted on the M6 Blasting Cap. The first test was performed at ambient temperature (78°F), the second at -40°F and the third conducted in the manner prescribed in MIL-S-45428A. Once again, in the last of the three tests mentioned, a maximum warmup time of two minutes was employed before actuating the caps.

The next slide (Slide 5) shows a summary of the results obtained in these three tests. A comparison of the results shown in the table points up what was stated earlier pertaining to the M2 Squib. It can be seen, as in the case of the M2 Squib, that the current estimated to obtain a

99.9% firing reliability at 90% confidence level as well as for the 50% firing point is higher at cold temperatures (-40°F in this case), than at ambient temperatures. These data show also that the current values estimated for the 0.1% firing point at the 90% confidence level did not differ at these two temperature conditions. As with the M2 Squib, the value for the means or 50% firing points for the M6 cap, lay somewhere in between the corresponding values obtained in the other two tests. Furthermore, the estimated current for the 0.1% fire at 90% confidence was higher in this test (Test 3) than the corresponding values calculated from the data in Tests 1 and 2. This result was likewise in order with that obtained in the test series conducted on the M2 Squibs. It should be noted that the calculated current for the 99.9% fire at 90% confidence was lower in Test 3 than the corresponding values obtained in Tests 1 and 2. This was not the same situation experienced in tests conducted on M2 Squibs. Observe also that the current range between the 99.9% point and 0.1% point at the 90% confidence level is narrow or the standard deviation, for this test is smaller than that in either of the other two. Now, Test 3 was conducted while the caps were in the process of warming toward ambient temperature. It could be that this unstable condition (brought about by rapid warming which possibly led to physical or transitional changes in the explosive charges and to thermal expansions and contractions which in turn could have produced thermal stresses) was responsible for the unusual data obtained in Test 3. In the corresponding test performed on the M2 Squib, more reasonable or expected results were obtained.

Because the squibs are more open or exposed than are the blasting caps,
it is conceivable that they warmed at a faster rate and thereby could
have reached a more stable state in a shorter time. A test to verify the
data obtained in Test 3 on the M6 cap is planned. This test, however, has
not been conducted as yet. A brief description of the test is in order,
and is as follows: one-hundred M6 caps will be conditioned at -40°F for
a minimum of 16 hours. Fifty will be removed and allowed to warm to
ambient temperature. After an arbitrarily imposed 24 hour period at
ambient temperature (to assure attainment of stable conditions), a Bruceton
constant current sensitivity test will be conducted. The other 50 will be
tested in accordance with MIL-S-45428A using the maximum allotted 2 minute
waiting period. A subsequent comparison of data obtained at ambient
temperature and in accordance with the military specification will be made.
This information will be furnished by Picatinny Arsenal to anyone interested
in the outcome of this investigation.

In conclusion, I would like to recommend that care be taken in conducting
initiator sensitivity and output tests at extreme temperatures to insure
that the initiator is maintained at the desired test temperature. Certain
insulating materials are adequate for this purpose. It may be even more
desirable to build barricades into conditioning equipment so that testing
in the chamber may be effected. Thank you

TIME VS TEMPERATURE RELATIONSHIP
FOR THE M2 ELECTRIC SQUIB.*

NOTE:
* THE M2 SQUIB WAS REMOVED FROM
COLD BOX AT -65°F AT "0" TIME.
THE GRAPH SHOWS THE RELATION
OF WARM-UP TEMPERATURE TO TIME
IN SECONDS.

Figure 2

TEMPERATURE VS VOLTAGE CURVE
OBTAINED IN CALIBRATION OF THERMOCOUPLE.*

NOTE:
* CALIBRATION AT TEMPERATURE
POINTS DESIGNATED ON GRAPHS

Figure 1

TIME VS TEMPERATURE RELATIONSHIP FOR THE M6 BLASTING CAP.*

NOTE:
*THE M6 CAP(CONTAINED IN STYROFOAM INSULATION) WAS REMOVED FROM THE COLD BOX AT -65°F AT "0" TIME.
THE GRAPH SHOWS THE RELATION OF WARM UP TEMPERATURE TO TIME.

Figure 4

SUMMARY OF 3 BRUCETON CONSTANT CURRENT SENSIVITY TESTS CONDUCTED ON THE M2 SQUIB

TEST NUMBER	RELIABILITY		
	99.9% (MILLIAMPERES)	50% (MILLIAMPERES)	0.1% (MILLIAMPERES)
1 (A.T.)*	510.5	407.1	324.6
2 (-65°F)	611.8	445.4	324.2
3 (SPEC)**	538.8	430.0	343.2

NOTE:
* A.T. AMBIENT TEMPERATURE (78°F)
** THE TEST WAS CONDUCTED IN ACCORDANCE WITH MIL-S-45428A

Figure 3

SUMMARY OF BRUCETON CONSTANT CURRENT SENSITIVITY TESTS CONDUCTED ON THE M6 BLASTING CAP

TEST NUMBER	RELIABILITY		
	99.9% (MILLIAMPERES)	50% (MILLIAMPERES)	0.1% (MILLIAMPERES)
1 (A.T.)*	627	524	438
2 (-40°F)**	753	574	438
3 (SPEC)***	597	542	491

NOTE:
* A.T. AMBIENT TEMPERATURE (78°F)
** THE M6 CAPS WERE FIRED IN STYROFOAM INSULATION AT AMBIENT TEMPERATURE
*** THE TEST WAS CONDUCTED IN ACCORDANCE WITH MIL-S-45428A

Figure 5

For Discussion Refer to Classified Supplement
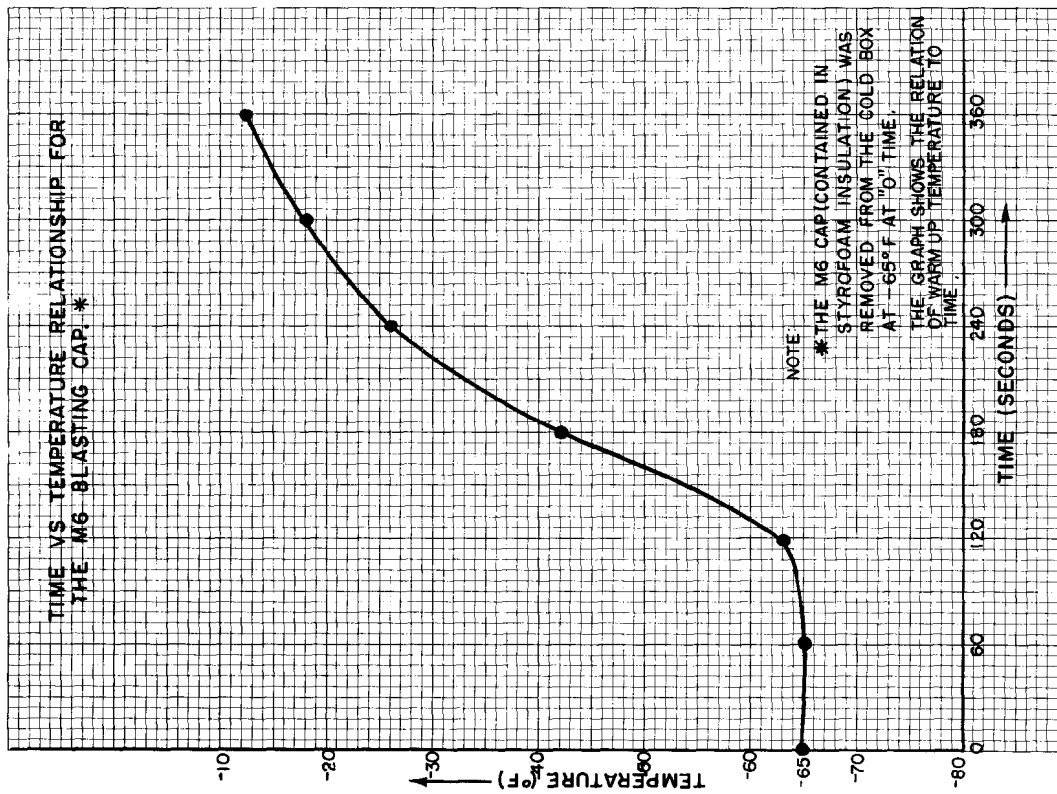
18. HIGH SPEED PHOTOGRAPHY APPLICABLE TO THE DEVELOPMENT OF ELECTROEXPLOSIVE DEVICES

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INTRODUCTION

Wider application of high speed photography to the design and development of electric initiators can often serve as a basis for better understanding their fundamental operational principles. Both smear and framing camera techniques have been used for many years to study high explosive and detonation phenomena. Sophisticated methods have been developed by investigators in these fields[1,2]. Investigators of primary explosives, however, have made much less use of high speed photography, and especially of the smear camera. Bowden[3] has spread sensitive explosives on glass or mica-plates and used the smear camera to study their growth of explosion. Roth[4] has used the smear camera to study the transition from burning to detonation in cellulose acetate tubes. Also, it was encouraging to note that two papers[5,6] were presented at the 1960 Electric Initiator Symposium in which the employment of smear camera photography was reported. High speed photographic techniques used at the NOL(WO) to study initiators and initiating

explosives are described in this paper in the hope that
more extensive use of high speed photography to these
study areas will be stimulated.

SMEAR CAMERA TECHNIQUES

Fundamentally, a smear camera is a continuous writing
instrument which in its simplest sense gives a time-distance
record. The camera uses a rotating mirror as shown in
Figure 1, or a rotating drum. The slit of the camera is
aligned to observe the desired event which must be luminous.
The rotating mirror or drum sweeps the image across the
film giving a time-position record of the light emitted.

GROWTH OF EXPLOSION FROM BRIDGEWIRE

Information on the growth of explosion can be extremely
helpful in understanding the mechanisms leading to detonation.
The test arrangement which we have used to study growth of
explosion from a bridgewire is shown in Figure 2. A wire
is mounted at the transparent plastic-explosive interface.
The slit of a smear camera is then aligned perpendicularly
to the wire. This arrangement will give a time distance
record of the growth of explosion to both sides of the
bridgewire along the surface of the explosive in contact
with the plastic. Figure 3 shows typical records taken
with this arrangement. In these records three types of
lead azide are compared for growth of explosion at a
density of 3.25 g/cm^3. For the records shown, it was found

that RD-1333 lead azide exhibits a very short accelerating

build up to final detonation velocity, milled PVA lead azide

goes directly into full detonation velocity, and milled

dextrinated lead azide has a short duration low velocity

regime. The final velocities at a density of 3.25 g/cm^3

were 3850 meters/sec for RD-1333, 3720 meters/sec for

milled PVA, and 3280 meters/sec for the milled dextrinated.

Time-distance curves can be plotted from the photographs as

shown in Figure 4. The numerical constants needed for the

transfer from the smear record to a graph must first be

determined. These constants will depend upon the magnifica-

tion of the object and the sweep speed of the camera. By

taking the slope or first derivative at various points of

the time distance curve, one can obtain the velocity of the

propagation. This can be pursued one step further by taking

the derivative of a time-velocity or distance velocity curve

and obtaining the acceleration or deceleration of the

reaction at any point.

GROWTH OF EXPLOSION AND INTERFACE TRANSFER IN A COLUMN

Explosive reactions in cylindrical columns are of direct

interest to electric initiator designers who generally load

their explosives in this form. A technique which we have

used to observe the growth of explosion in a hemicylindrical

column is shown in Figure 5. The bridgewire is mounted at

the bottom of the explosive column at the plastic-explosive

interface. This fixture is presently being used to study

ignition transfer from a column of normal lead styphnate

to one of dextrinated lead azide. A typical record is

shown in Figure 6. The loading pressure in this case was

20,000 psi for both explosives. At the interface a build up

in the lead azide is observed. A steady state detonation

starts about 1.4 mm (0.056 inch) above the interface.

Irregular retonation waves into the lead styphnate have

also been observed. Simultaneously with the formation of

the steady state detonation, a retonation wave may form

which travels backwards to the origin of initiation.

Retonation indicates that the lead styphnate had previously

only partially reacted. Unfortunately, we have so far not

obtained as much detail as we'd like to have. Burning

normal lead styphnate does not emit light of sufficient

intensity to register on the film. Methods to improve the

luminosity involve some compromise. The addition of finely

powdered aluminum to the styphnate increases the luminosity,

but decreases the burning rate. Widening of the camera slit

and use of a slower sweep speed increase the film exposure

time, but the accuracy of the record is decreased.

SHOCK WAVES FROM EXPLODING WIRES

Another technique as shown in Figure 7 is employed to

observe the normally non-luminous shock wave from an

exploding wire. This method was developed by Bennett[7] at

the Aberdeen Proving Ground. A mirror is placed 7 to 10 cm. in back of the wire. The wire explosion is backlighted by its own reflection when the mirror is normal to the optical axis. The shock wave refracts the light resulting in an image of the shock wave on the film. Figure 8 shows the type of photograph taken. Both the highly luminous plasma and shock wave expansion can be examined. From this shock wave expansion one can calculate the energy release per unit wire length by means of the Taylor-Lin[8] equation.

PROPAGATION IN A METAL CLAD CHARGE

Events that are normally non-luminous need an auxiliary light source. For example an exploding wire may be used as shown in Figure 9 to illuminate the disintegration of a No. 6 commercial blasting cap. The blasting cap surface is made highly reflective by covering it tightly with a thin aluminized plastic film. The light from the exploding wire is reflected onto the blasting cap by a half silvered mirror placed 45° to the optical axis. The mirror also permits camera observation of the blasting cap. As the cup disintegrates, light is no longer reflected to the lens by the disintegrated portion of the cup, thus permitting the propagation to be followed. The type of photograph obtained is shown in Figure 10. The arrival of the shock wave at the surface of the blasting cap can first be seen from the change in light intensity. This is followed by the disintegration of the metal cup.

FRAMING CAMERA TECHNIQUES

SIMULTANEITY TESTING - High speed framing cameras such as the Beckman & Whitley Model 189 are used fairly extensively to measure detonator simultaneity. Figure 11 shows selected frames of an explosion sequence taken at a framing rate of 1,000,000 frames/second. The simultaneity of initiation of two lengths of Primacord by a special detonator was being checked. Exploding wires behind two lenses were used to backlight the event.

GENERAL INFORMATION - Slower framing cameras (1000 to 10,000 frames/second) are often useful for obtaining information on specific problems. One problem this type of camera recently helped resolve was the difference in time dispersion between lots of obturated 1.5 second delay actuators as made in production. Loading tests, hardware inspection, pyrotechnic inspection, and moisture analyses all failed to give any clues for the difference in delay time dispersion. However, when the delays were initiated under water before a framing camera the camera revealed that lots exhibiting higher dispersions always had a very much greater gas leakage through the bakelite initiator plug than those lots which had consistent times. A typical record is shown in Figure 12. The photographs showed in addition that the gas leak was between the bakelite and metal inserts, a heretofore unsuspected trouble spot. With this information remedial action was possible.

SUMMARY

The techniques described are fairly simple and have been very useful in interpreting explosive events at the NOL(WO). Wider application of high speed photography can be very helpful in electric initiator designs and should be more fully exploited.

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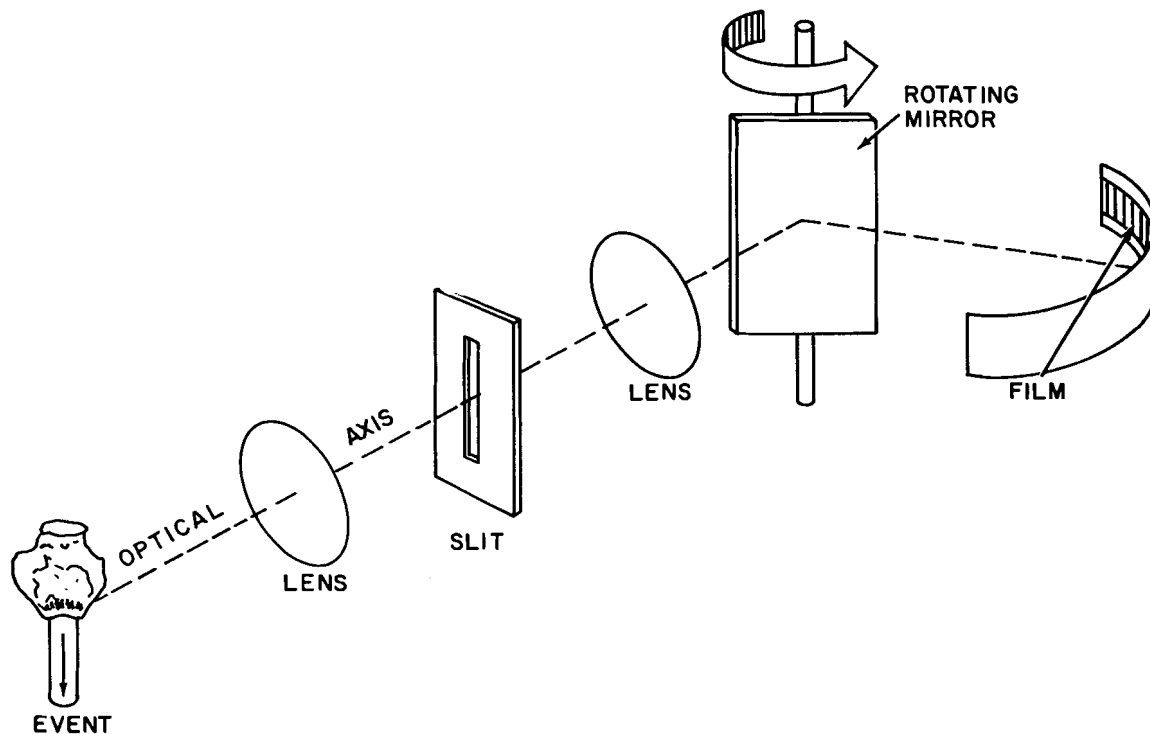
FIG.1 ROTATING MIRROR SMEAR CAMERA COMPONENT ARRANGEMENT

FIG.2 TEST ARRANGEMENT TO OBSERVE GROWTH OF
EXPLOSION FROM BRIDGEWIRE

MILLED PVA   RD 1333   MILLED DEXTRINATED

0123
MICROSECONDS

DENSITY=3.25g/cm³

FIG. 3 SMEAR RECORDS OF GROWTH OF EXPLOSION OF LEAD AZIDES

FIG. 4 DISTANCE, VELOCITY, AND ACCELERATION CURVES

FIG. 5 TEST ARRANGEMENT TO OBSERVE GROWTH
OF EXPLOSION AND INTERFACE TRANSFER
IN EXPLOSIVE COLUMN
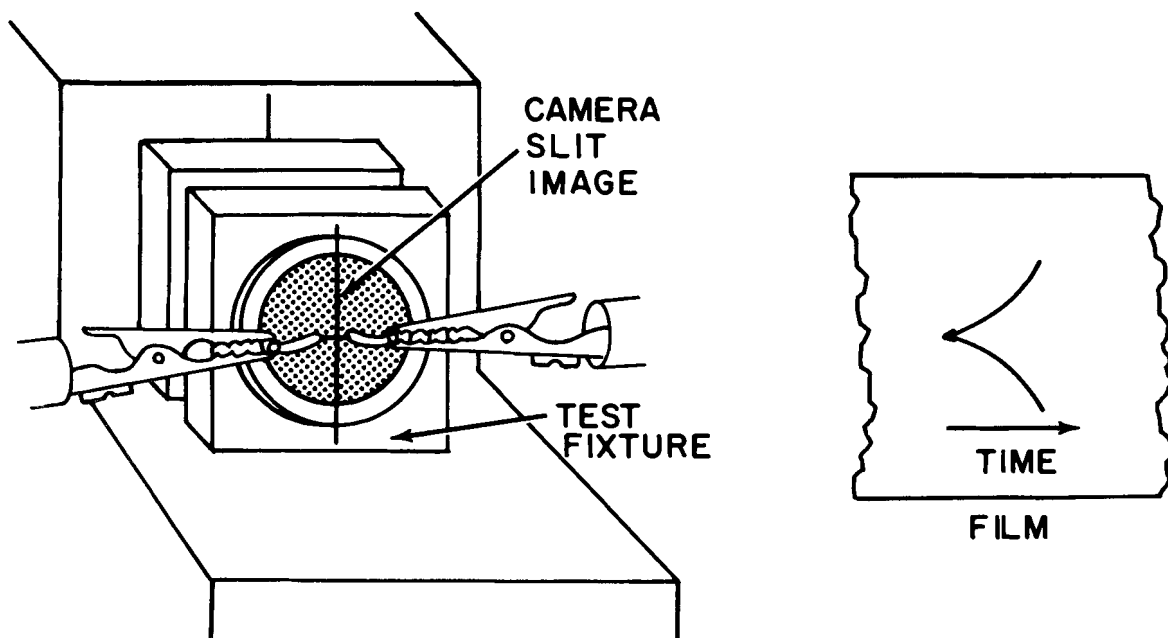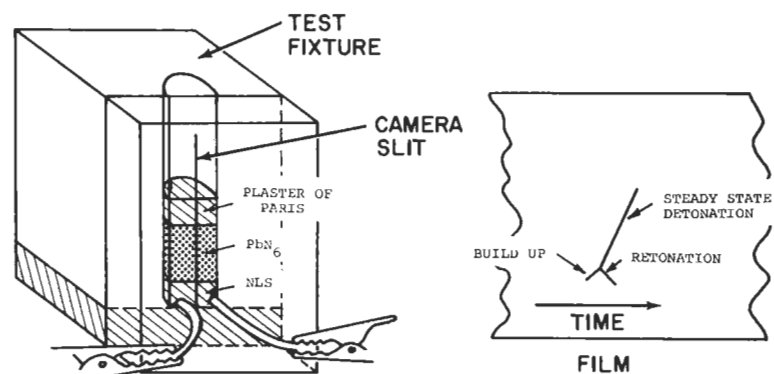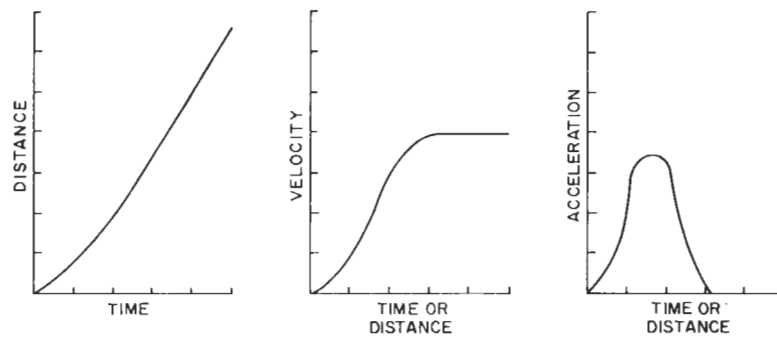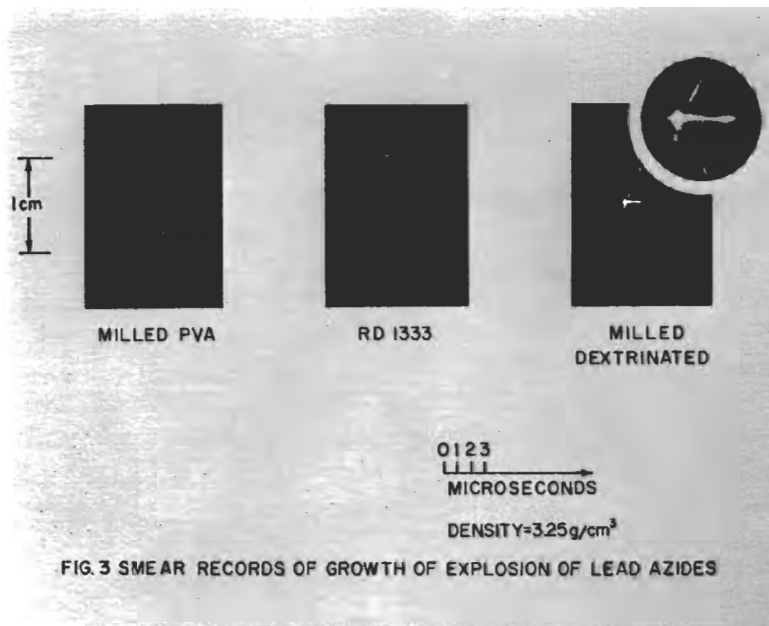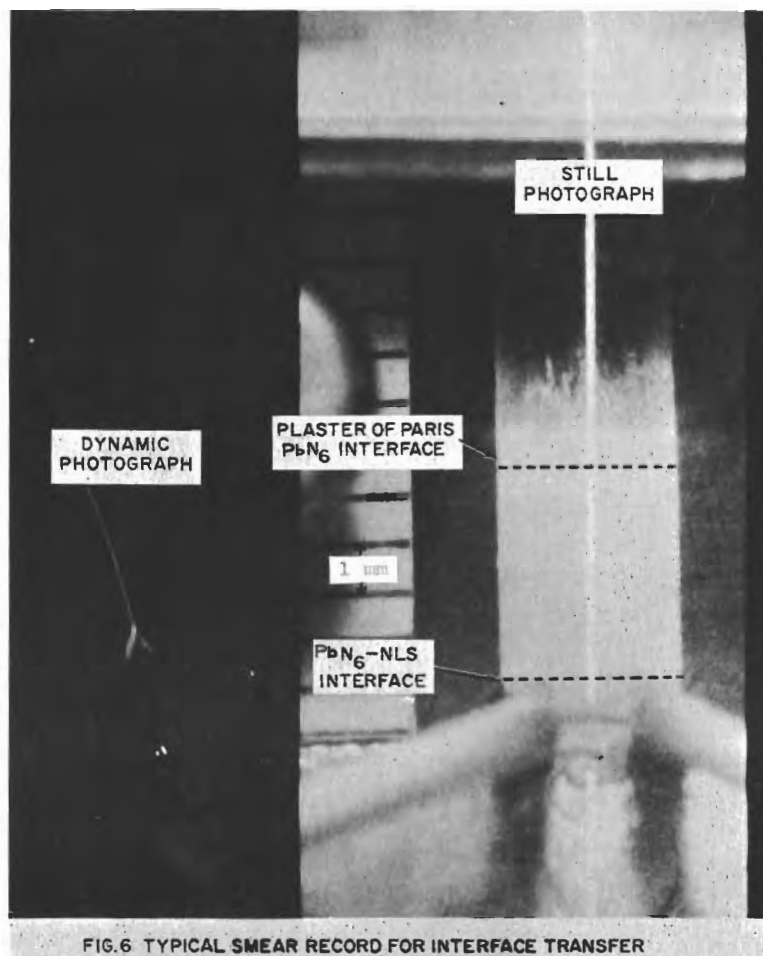
FIG.6 TYPICAL SMEAR RECORD FOR INTERFACE TRANSFER

STILL PHOTOGRAPH

DYNAMIC PHOTOGRAPH

PLASTER OF PARIS PbN_6 INTERFACE

1 mm

PbN_6-NLS INTERFACE

FRONT SILVERED MIRROR

CAMERA SLIT

8 CM.

WIRE

TIME

FILM

OPTICAL AXIS OF SMEAR CAMERA
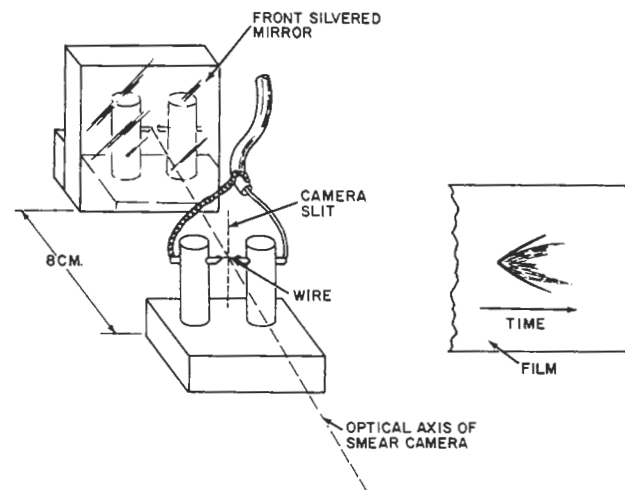
FIG.7 TEST ARRANGEMENT TO OBSERVE SHOCK WAVE FROM EXPLODING WIRE

CAMERA SLIT

WIRE

DISTANCE – CM

2

1

0

0 2 4 6
MICROSECONDS
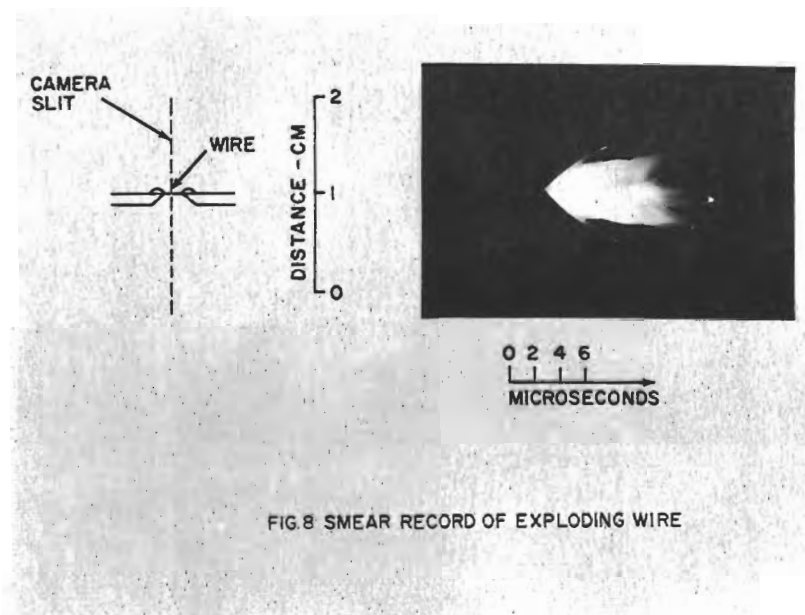
FIG.8 SMEAR RECORD OF EXPLODING WIRE
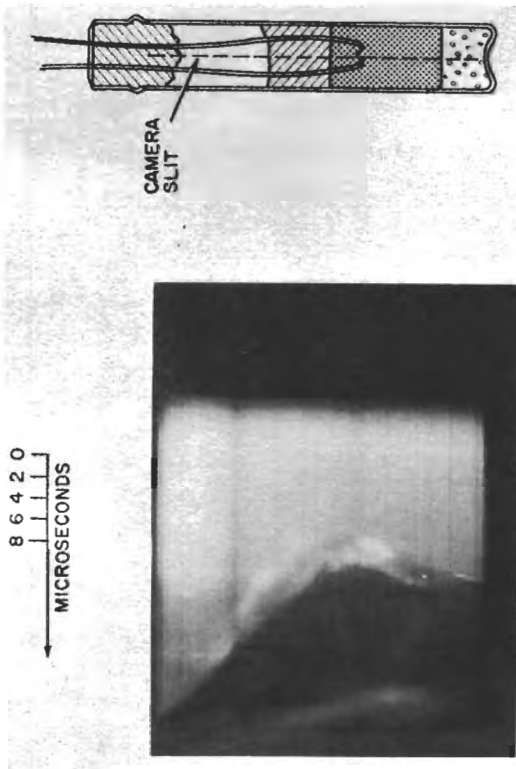
FIG. 10 SMEAR RECORD OF BLASTING CAP DISINTEGRATION
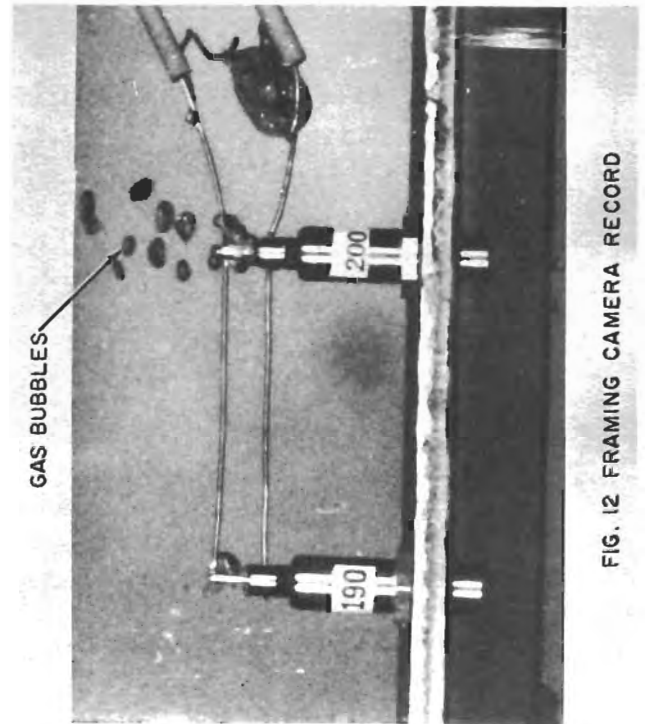
FIG. 12 FRAMING CAMERA RECORD
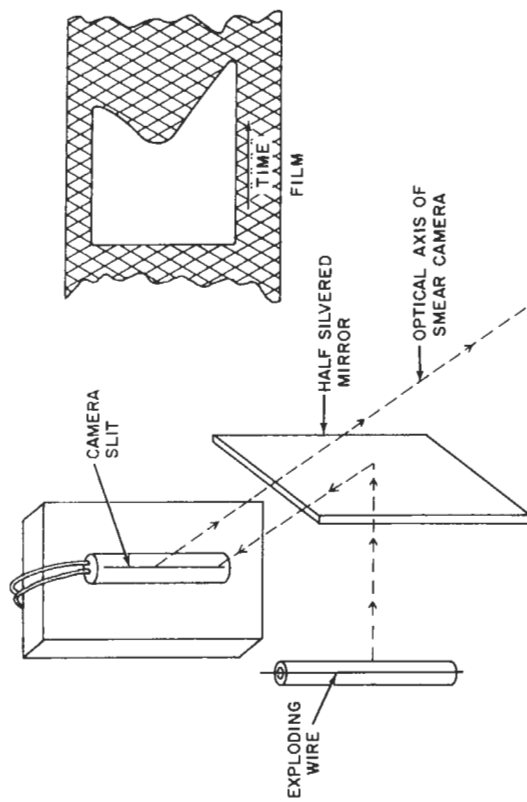
FIG. 9 TEST ARRANGEMENT TO OBSERVE DISINTEGRATION OF BLASTING CAP
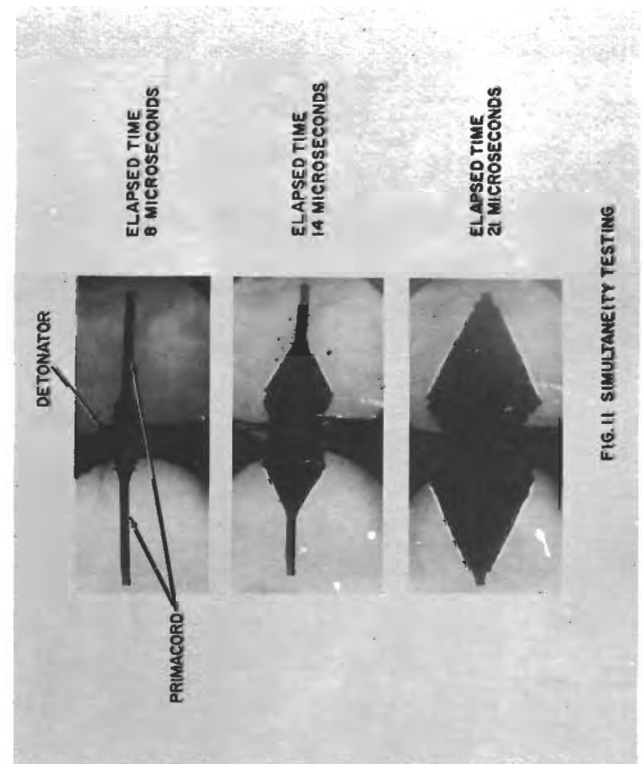
FIG. 11 SIMULTANEITY TESTING

18. DISCUSSION

Mr. Smith of NOL, Corona, suggested the use of color film on some of this work. Mr. Leopold replied that the camera requires extremely fast film. Polaroid 3000 (ASA speed of 3000) is currently in use. Color films with top ASA ratings of between 200 and 400 are probably not fast enough.

19. INSTRUMENTATION FOR THE TESTING OF ELECTRIC INITIATORS

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In the past decade electrically initiated explosive devices have become extremely important in missile and space applications. The evaluation of these devices in the design, development and production stages and the means by which evaluation tests are accomplished are critical in conveying information from one organization to another or, for that matter from one person to another. The means by which an electric initiator is characterized including the statistical test plan and the instrumentation must consider the use, the user, and the developer.

We believe that the user should have variational information on a device that is characteristically quantal (go, no go). In transforming the quantal response of explosive devices into variational information, many items must be tested by one of many available test plans (1,2,3). Each of these plans may have particular advantage in a given set of circumstances but it is not necessary to elaborate on this subject now. No matter which of the test plans is used, the measures of central tendency and dispersion--the reliability and confidence--are an expression of the performance of the test equipment as well as of the device being tested. Unfortunately these cannot usually be separated once the test has been made. We cannot say that so much of the stimulus went into system losses and the rest fired the device. There is a need to develop and fully evaluate items of test equipment for electric initiators before they are placed into service. Further, there is a need to be assured of continued reliability in performance as the equipment ages.

In order to understand the need for test equipment, we will review briefly the characteristics of the items to be tested. Until recently, the static or simple dc resistance of the device was the only non-destructive electrical test that could be applied to electric initiators. Recent advances in the dynamic properties of this measurement have opened new possibilities in non-destructive testing. These are discussed elsewhere[4],[5]. Static resistance must be measured with a current that will have no appreciable influence on subsequent firing characteristics of the device under test. In a test set it is essential that the measuring current for determining static resistance be kept down to a level which will leave unaffected any initiator that may be tested on the equipment. This means a very low current indeed for some devices.

In measuring sensitivity of electric initiators, the type of initiator being tested and its ultimate application are both of importance. There are a number of different types of electric initiators available today and probably many new hybrids in the development stages. The usual devices include the hot wire or conventional bridgewire, the carbon bridge, the spark gap and the conductive mix types. These ordinarily contain primary explosives. Some of the more recently developed explosive initiators contain only secondary explosives. These include some of the exploding bridgewire devices and some that have conductive mixes.

The nature of the pulse applied to each of these initiators will obviously vary. Different types of initiators have different applications. One cannot expect the Army to supply each anti-tank round with an exploding bridgewire device and associated power supply at a cost perhaps 100 times that of a carbon bridge detonator and ferro-electric wafer. On the other hand there are other applications where there is a definite need for the features of an exploding wire device.

Just as there is a need for different types of electroexplosive initiators there is a need for different types of power sources to actuate them and a need for different types of input for their evaluation. As a general rule, the sensitivity of carbon bridges initiators is evaluated using a capacitor discharge. Capacitor discharge tests have been proven of value in comparing evaluation data in field problems with information that is published on the performance of initiators in the Electric Initiator Handbook[6]

Capacitor discharge testing is also of value in determining the sensitivity of the more sensitive of the wire bridge initiators. Initiators of high sensitivity must be used in applications where the space occupied by the device and its power source must be kept as low as possible. It follows that the device is usually assembled with special safety precautions into a system that is inherently a safe one. This usually means that the subassembly of which the initiator is part is a completely enclosed system, free from the effects of static electricity and of the possibility of ignition or damage by radio frequency energy. Indeed, there is a definite need for sensitive electric initiators.

Wire bridge devices are more suited to testing by constant current impulse than by any other means. They are tested either by the application of a step function of current or by a timed pulse. In any case it is possible to observe the voltage drop across the initiator under test and to obtain information on energy, power, and voltage during the pulse. Once this information has been obtained, it is possible to make predictions of the performance of these devices from almost any type of power source that can be described electrically and mathematically[7].

Spark gap and conductive mix initiators, while potentially important in some applications, are not as popular as the conventional hot-wire devices. The spark gap is usually tested and fired from capacitor discharges and the conductive mix is excited from almost any source that can be imagined. Both are characterized by radical resistance changes in the process of functioning.

Exploding bridgewire (EBW) devices are relatively new in the ordnance field; the full impact of these devices has not yet been felt. Presently there is a trend toward a systems approach on these devices in which the EBW is purchased with the power source and custom-fitted to a weapon. This approach seems sound, but without proper safeguards it could result in very high cost, particularly in the determination of quality and reliability. Independent evaluation of the power source and the explosive device appears to be one approach to reasonable expenditures in systems evaluation.

Many weapon designers, initiator developers and manufacturers in both government and industry have been faced with the problem of evaluating electric initiators. Often there are problems involved in performance of a prototype system or subsystem that can be traced directly to a lack of quality or uniformity in the instrumentation used for the evaluation of the initiator in the system. We may suppose that some of this trouble can be eliminated if some of the problems and their solutions are understood. For this reason we are presenting some of the information on instrumentation that we have accumulated in twelve years of designing and developing equipment, and also putting it to use for evaluation.

Let us begin with the problems that are common to most initiator testing. The first measurement is usually bridge resistance. In order to measure resistance we must pass some current through the bridge circuit of the initiator under test. In the usual case there is a need to limit the current to a safe value. It is not sufficient that the device remains uninitiated; safe current is, from a testing point of view, one which

leaves the device unaltered in any respect. Actually, the chemical reaction that is hastened by the application of heat to the explosive is accentuated by even the slightest rise of temperature in the bridge circuit. If a part of the chemical contained in the initiation region of the initiator undergoes any kind of reaction then the EED under test is no longer the same device; subsequent test results may not necessarily apply to the device in its original condition. We must exercise caution to use very low currents for measuring resistance and the implication is never to waste time retesting an item exposed to bridge current unless the magnitude of exposure is proven safe. The safe value of current for each specific type of initiator may be determined by a series of tests that classify the characteristics of the device. This has been done for a number of specific classes of initiators, like the wire bridge, to the extent that we are satisfied with the application of a current of 1 milliampere for resistance measurements.

Similarly, the carbon bridge, if properly manufactured, will tolerate a current on the order of 10 microamperes[8]. Tolerance limits have not been established for many of the conductive mix initiators, although our experience indicates that it is advisable to use as low a current as is possible. Exploding wire types of initiators are also not fully described in this sense although currents smaller than those required to fuse the bridgewire should certainly be used. We generally specify a current that is high enough to give the required resolution of resistance measurement and low enough so that the bridgewire remains well below the fusing point.

Two means of measuring resistance have been found satisfactory. These are shown in Figure 1. The first method (Fig. 1A) used a conventional Wheatstone bridge with a current-limiting a resistor in series with a battery power supply. The current limiting resistor is changeable according to the type of initiator under test, so that the current is appropriate. The necessarily low current means that the indicating galvanometer must be

sensitive. In the second or voltage drop, method (Fig. 1B) the current through the device under test is kept constant, and the voltage across the device is amplified by a precision amplifier whose output is fed to a digital voltmeter that presents the resistance of the initiator digitally.

Following the resistance check, the electroexplosive device is usually exposed to an input stimulus. If the test is for acceptance, the exposure level is generally specified and all firing is executed at one input level. If sensitivity is being checked, the input stimulus is varied according to one of the test plans referenced earlier. Where input conditions are described in terms of more than one variable, all but one of the variables are held constant.

The three main types of test equipment for electric initiators are capacitor discharge, constant current and constant voltage. Simplified versions of these test circuits are shown in Figure 2.

The need for the capacitor discharge test becomes evident if one considers the energy level at which the initiator fires. Theoretically only that energy available on the capacitor is allowed to enter the input terminals of the initiator. In reality, it has been found that the input energy alone is not a good criterion for judging the performance of an initiator. If both capacitance and voltage are specified, then the capacitor discharge test has more meaning. Certain regions of the log-capacitance vs log-voltage curve for some initiators are linear and do exhibit the correct slope to be of constant energy response.

There are losses to be reckoned with in any test set; these become of major importance in capacitor discharge test sets. Previous papers presented on this subject list in detail some of the problems associated with capacitor discharges testing[9]. Some of the more important parameters that must be considered, as contributing to capacitor quality, are dissipation factor, dielectric hysteresis, voltage breakdown, and leakage resistance. Dielectric materials that have been found to be suitable for initiator testing include Teflon, polystyrene, and Mylar.

In testing initiators, there have been differences in results when capacitors with different dielectric materials were used, which shows the need for care in specifying and recording the exact conditions of every test.

Another important factor in capacitor discharge equipment is the leakage resistance of the circuit. This becomes of critical importance if the time lapse between disconnection of the power source and the connection of the detonator is long or variable. The switch or relay in the firing line must not bounce or degrade with repeated use. The stray capacitance on the firing line end of the equipment introduces losses that can be important, particularly when the value of firing capacitance is low. The attachment of auxiliary equipment including that for safety, resistance and functioning time introduces stray capacitance and shunt resistance to the extent that a compromise is required between loss parameters and ease of use of the equipment.

The problems associated with constant current testing are different from those of the capacitor discharge test. First, a means of obtaining a constant current is needed. Some evaluators have advocated that a resistance the same as that of the initiator be placed in a circuit that is essentially a constant voltage source. At the time of the test, the initiator is switched into the place of the resistor. This test method is acceptable if the resistance of the initiator does not change with the application of power. There are but a few initiators in existence that are thus characterized; most that we have evaluated change by a factor of from two to four in the process of being excited. It can be concluded that this approach does not yield a constant current test. Electronic regulation has been considered for providing constant current. The main problem here is that it takes a relatively long time for the regulators to take hold. We have found that a relatively high voltage, high current power supply fitted with series current limiting resistors offers one of the better means of testing a wire bridge device, as is shown in Figure 2B.

The switch used in supplying the current to the device under test can be a mercury relay, preferably one that has mercury to mercury contact if a step function of current is desired. There is also the probability that a pulse of controlled application time is desired.

Solid state devices have been used to obtain rectangular pulses for which the conduction time can be controlled[10]. The leakage current involved in these devices is usually in the microampere region which makes them adequately isolating for use as a switch in testing wire bridge and conductive mix initiators. The switching current that these devices are presently capable of handling reaches into the hundred-ampere region. Our experience has been that pulses as short as 100 microseconds can be delivered with reliable performance, by the use of a silicon controlled rectifier (SCR) switch. Transistors that are now in production appear to offer many advantages as switching devices for timed current applications to initiators. For initiator testing with pulses less than 100 microseconds, we have found that a pulse-forming network and thyratron offer a reasonably shaped and reproducible pulse. The lower limit in time nor has the upper limit in magnitude of the applied pulse (currently on the order of 16 amperes for conventional wire bridged devices) have not been approached to date.

Constant voltage tests are conducted in a manner similar to the constant current tests with a circuit similar to that shown in Figure 2C. The power source is usually a rugged device capable of delivering a hundred or more amperes. The switch is a mercury relay or a suitable solid state device. So far, constant voltage testing has been limited to devices that have relatively high resistance and that are relatively sensitive. It is important that the power source have good voltage regulation from no-load to the maximum load expected from the initiators which may be tested. Transients from the power source in any of the test sets are not desirable for they tend to complicate evaluation of the initiator and lead to misunderstandings where data are compared. Inductive resistors are one of the greatest offenders in producing transients.

The exploding bridgewire device is found in the realm of capacitor discharge testing. The circuit requirements are so different for this type of testing that volumes of material have been written concerning circuits and responses. The prime requirement for repeated testing is that the equipment stay the same. One of the weak points of early EBW firing circuits was the switching device. Some gap switches that have been in use are reported to have had a life of some 30 shots, after which performance degraded to the point that the switch rather than the detonator was being evaluated. This is obviously undesirable in any test set. Though these switches have been improved, we have solved the problem in a different way. We use a General Electric 7171 Ignitron that is capable of standing off 10,000 volts, and conducting current with a magnitude as high as 35,000 amperes for a few microseconds. This type of device has been in use for the application of pulses to EBW devices for a period of about three years. During that time several thousand pulses have been applied to various devices without any measurable degradation of performance.

The capacitor used in EBW circuits must be carefully selected for very low internal inductance and resistance. High quality capacitors for use in EBW circuits are available from a number of well-known suppliers that will build capacitors to any reasonable specification.

Transmission lines present a problem in testing EBW devices. Maximum power or energy is delivered to the device when the transmission line matches the load. In most practical situations where the line is very short, there is no great line-impedance effect upon energy transfer. The difference in characteristic impedance is nevertheless measurable. Low impedance lines are not plentiful commercially. Recently some low inductance, low impedance lines have been advertised, but no information is available on these lines in connection with testing EBW devices.

Knowledge of the functioning time of most initiators is important, because it permits the quality and applicability of a device to be determined for a specific task. Furthermore, it serves as a check on the dispersion of the lot of items being tested. We have defined functioning time as the time lapse between application of an electrical impulse to the input of the initiator and the flash of light from the initiator. We obtain functioning time by detecting the light output of the initiator with a photomultiplier circuit. Many other methods of indicating that the initiator has functioned such as ionization gaps, sound, free surface velocity, and break contacts have been used by others. We have used a 10 megacycle timer as an indicator that permits sensing of the leading edge of the input signal as a start pulse and receives the output of the photomultiplier as a stop pulse. In practice there is little difference in functioning time measurements of detonating devices by the photo-multiplier method and the ionization gap method if done properly. In any case some care must be exercised in setting up the equipment. The photo-multiplier method of determining functioning time permits one to check the accuracy of the equipment without the need for firing detonators. This may be done using small pilot lamps in place of the initiator. This check is more difficult in the other methods mentioned. Furthermore, the ease and efficiency of using this method for determining a time mark at functioning has not been surpassed. No modifications or fittings are required on or in the vicinity of the initiator being tested and there is no need for changing hardware after each shot.

If the job of running all of the tests in the laboratory is not to fall to the designer of the equipment, some means of integrating the equipment into a practical and convenient unit is required. Even though the equipment is well integrated, the operator must have a high degree of technical skill to cope with normal, everyday problems that arise in initiator testing; but with integrated equipment the task of testing becomes more routine. It will also be found that the results of repeated tests become more meaningful. A "firing-benefit" of the integrated

instrument approach to initiator testing is the virtual elimination of instrument-snatching. The non-integrated test set up is subject to light hearted pilferage by others in a laboratory. It appears that this is to be expected when the equipment is left in unsightly and loosely-organized assembly. This is far less true if equipment is supplied in a rack, neatly assembled and lettered. The equipment tends to stay in a package, to the substantial benefit of all concerned. Circuit changes or apparently minor modifications may be introduced unknowingly or wrongly be considered insignificant when equipment is changed repeatedly.

We have constructed a number of test sets of the different types that are discussed briefly in this paper. The first one that we undertook to construct was for our own use here, when the evaluation and characterizatio of electric initiators was first assigned us as a task. We went through the throes of designing and evaluating this test set the hard way. Most of the components that we originally selected were eventually replaced. Under the sponsorship of Picatinny Arsenal we constructed 11 of the final models of this instrument that we called The Franklin Institute Laboratories Initiator Test Set (FILITS) Model 2. Model 1 could not even be transported across the laboratory without the need for minor repair. Figure 3 is a photograph of the model 2 equipment. Many of these capacitor discharge test sets are still in use. Unlike the present situation, the cry at that time was for more and more sensitive initiators. Units, tens, and hundreds of ergs was the sensitivity range discussed at the first Electric Detonator Symposium[11].

Missile circuitry and the possibility of inadvertent firing caused a restoration of interest in less sensitive devices, which still prevails. Some combination capacitor-discharge and constant-current test sets were designed for Lockheed Aircraft for use on the Polaris program[12]. An example of one of these is shown in Figure 4.

Pulse testing under constant excitation was also of great interest to the Army at this time. As a result The Franklin Institute Universal Pulser (FILUP)[13] was designed. Three of these units were constructed. One was supplied to Picatinny Arsenal which sponsored the development of the equipment, one went to White Sands Missile Range and one remains at The Franklin Institute. This equipment is shown in Figure 5. It contains all of the equipment and instruments necessary to make resistance, functioning time and sensitivity measurements on electric initiators from constant current and constant voltage rectangular pulses. In addition, it features digital readout of current and voltage. An oscilloscope is built in to provide for the examination of waveforms in the equipment and on the initiator as tests are being made.

Two types of generators are used to provide pulses ranging from 1 microsecond to several minutes. Current is available up to about 40 amperes and voltages up to 800 volts. There are limitations on both current and voltage with the load resistance of the device under test. More detailed characteristics of the FILUP are available from the references cited. This equipment is presently the work horse of our evaluation program. It is well suited for testing the one-ampere, one-watt devices that are so much discussed today.

A device for testing exploding bridgewire detonators[14] is shown in Figure 6. This equipment was designed to be used with the FILUP or with measuring equipment external to the instrumentation shown in this photograph. A precision power source is used here with an upper limit of 3000 volts. The firing switch in this circuit is unique, we believe for the evaluation of EBW devices. This equipment is quite earth bound rather than airborne, and for that reason we have place in it a ground-based switch (which was mentioned earlier) that is known as a General Electric 7171 Ignitron. This switch will control 10,000 volts, and conduct 35,000 amperes for a few microseconds if it needs to. This is not the best feature of the switch, however. The one we have in our

laboratories has been fired thousands of times and we are unable to detect any appreciable change in performance when waveforms are checked across a resistive load. This stable operating characteristic is highly necessary to the continuing operation of a test set. Special capacitors having very low inductance are used. They are selected by a very heavy switch; values of capacitance are 1, 2 and 10 microfarads and they are rated at 6000 volts.

A coaxial current shunt is built into the equipment so that the current waveform of the device under test can be observed with an oscilloscope for each shot. Sync pulses and monitor jacks are provided in the rear. In addition the equipment has been interlocked for safe operation.

Recently, the FILITS has been revamped to provide more convenient and precise capacitor discharge testing of electroexplosive devices. This latest piece of test equipment is shown in Figure 7 and is called FILITS 3[15]. It provides for the digital indication of bridge resistance ranging from a few hundreths of an ohm to 15,000 ohms. This is accomplished with measuring currents of ten microamperes in the case of sensitive devices. One milliampere is used on low resistance devices that are less sensitive. The circuit shown in Figure 1B is the one used to measure resistance. This circuit is easily adjusted, it is fast to use, and operator error is inherently low by virtue of the digital presentation.

Selection of the firing capacitor is accomplished simply. All of the available capacitors are mounted behind a panel with connectors from each capacitor to one terminal of a two-conductor female receptacle on the face of the panel. One of the firing circuit leads is common to all the capacitors; the other is common to the receptacles. Placing a two-pronged jumper plug into one of the clearly marked receptacles connects the chosen capacitor into the circuit. The interlock switch provided on the swing-down portion of the capacitor selector panel provides safety for the operator; the charged capacitor can deliver a painful or harmful shock.

This interlock disconnects the source of power and discharges the firing capacitor circuit. A space position is provided on the capacitor bank so that the user may connect any capacitor he desires into the circuit.

The chosen capacitor is charged by à precision power supply that is adjustable to units of volts with an upper limit of 1000 volts. Not completely satisfied with this, we have made provision for dividing this voltage by ten or by 100. The reasons for this is evident to those who have made tests on well-made, sensitive detonators. Adjustment to hundreths of volts is sometimes desirable. Just to be sure that this excellent power supply stays this way, the digital voltmeter is left connected to the power supply side of the firing relay. The potential on the capacitor is known up to the instant of firing.

Functioning time measurements are made using a 10-megacycle EPUT and timer. This instrument indicates functioning time to the nearest tenth of a microsecond, and sometimes readings of this precision are necessary. The leading edge of the capacitor discharge pulse is used to start the counter, and in the case of detonators and squibs, the flash output of the device is used to produce a stop signal.

New concepts have been introduced into the initiator field recently that have opened a need for experimental assessment of initiator response to repeated pulses. There is a need to prevent radio frequency energy or pulsed telemetry current from affecting performance. The need for the information is evident if one examines and compares existing RF sensitivity data for continuous wave (CW) and pulsed radar. The total energy or average power required to affect a device is often less in the case of pulsed energy than it is for CW. There are mathematical and physical explanations for the apparently greater sensitivity and some experimental data on a few types of these devices[16].

The task of evaluating initiator sensitivity to repeated pulses has in most cases been complicated by the addition of an RF component included in the pulse envelope. The need to eliminate the RF and obtain a clearer picture of pulsed performance instigated the development of a repetitive pulse generator.

Such an instrument has recently been developed for the application of constant current pulses to wire bridge initiators. The natural evolution of the generator is from a radar pulse modulator, and that is where we began. We found that a conventional pulse modulator when suddenly connected to a load gave a response similar to that shown in Figure 8. Note that the amplitude decays rapidly at an exponential rate upon application of successive pulses. If adjustment is made using a dummy load, the first few pulses and the assessment of initiator input are always higher than the steady state amplitude. Several ineffective schemes were designed to eliminate this problem; the power supply and associated equipment were never quite good enough.

We finally arrived at the circuit that is depicted in Figure 9. The regulation of the pulser becomes of minor importance in the circuit because the output is transferred from a dummy circuit to the initiator circuit without the pulser being "aware" that it has been switched. Desired pulse conditions, repetition rate, pulse width and amplitude, are set by viewing conditions with the dummy circuit in use. In this state, pulses from the pulse repetition rate generator are discharging the pulse forming network into the dummy load.

At the desired time and for a desired interval, governed by the output of the gate, the pulses are switched into the initiator. The result is exposure of the initiator to a train of precisely controlled pulses. Present limitations on this device are Pulse Repetition Frequency (PRF)-20 to 2500 PPS: Pulse width-1 to 10 microseconds; Amplitude-up to 20 amperes; Application time 1 millisecond minimum. The range of most of these characteristics can be expanded by the use of more refined components. This equipment, known as FILREP, is shown in Figure 10.

Table 1

OPERATIONAL CHARACTERISTICS OF FRANKLIN INSTITUTE INITIATOR TEST EQUIPMENT

Equipment Name	Nature of Stimulus	Operating Ranges		Other Features and Functions
		Capacity or Time	Amplitude	
FILITS 2	Capacitor Discharge	0.0001 to 1 MFD	to 1000 volts	Resistance, Functioning Time
FILITS 3	Capacitor Discharge	0.001 to 16 MFD	to 1000 volts	Resistance, Functioning Time
FILUP	Rectangular Pulse	1 microsec or longer	to 40 amperes to 800 volts	Resistance, Functioning Time
Lockheed Tester	Capacitor Discharge Rectangular Pulse	to 100 MFD 7 millisec or longer	to 1000 volts to 10 amperes to 160 volts	Resistance, Functioning Time, Flame Length
FILREP	Repeated Rectangular Pulses	1 to 10 microsec trains	to 20 amperes to 2000 volts	Controlled Application Time
EBW Tester	Capacitor Discharges	1,2,10 MFD	to 3000 volts	Current shunt Monitor jacks
Static Safety Tester	Capacitor Discharges	500 MMFD	to 25,000 volts	

All of these instruments cover a wide range of precisely controlled input stimuli. Output characteristics are summarized in Table 1. They are evaluation tools, but just a little more than that. They are special tools for specialized craftsmen in a specialized field. The need for the results that these tools can produce is great. A common language in electric initiator technology is being generated by their use daily. New information is being produced and disseminated on initiator sensitivity, performance and quality. This information we feel is valid and correct from an instrument point of view. Results could be reproduced from day to day, month to month and year to year. This is after all the real objective of evaluation instrumentation. Further, the results can be applied to practical problems concerning initiator use including safety and reliability. To these problems there can be no compromise answers.

We have a long way to go before we can say all instrumentation problems with electric initiators are solved. New problems are continually arising, and some turn out to be very perplexing indeed.

People are thinking, developing, testing and creating new initiating devices faster than the old ones can be fully evaluated. As in most other technology understanding improves existing devices and opens new domains that in themselves contain a host of new problems to be solved. This process can only improve the performance, reliability and efficiency of the weapons and spacecraft that need initiators to perform their function.

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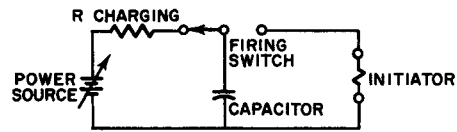
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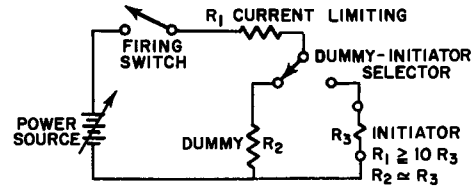
(B) CONSTANT CURRENT
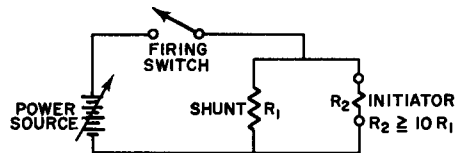
(C) CONSTANT VOLTAGE

FIG. 2. SIMPLIFIED FIRING CIRCUITS FOR
ELECTRIC INITIATOR TESTING
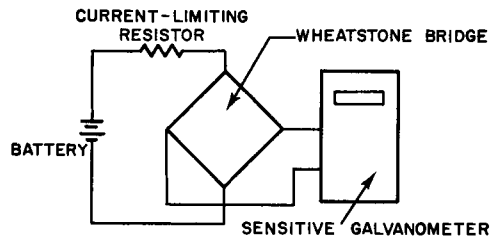
(A) CURRENT LIMITED BRIDGE
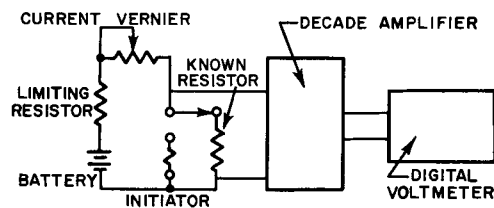
(B) POTENTIAL AT CONSTANT CURRENT

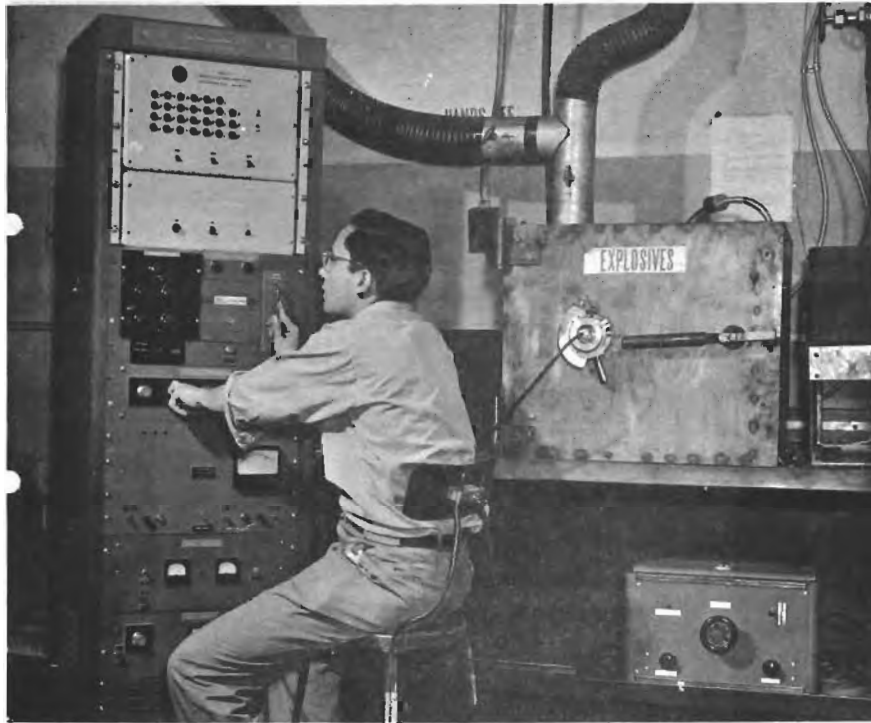FIG. I. TWO PROVEN METHODS OF MEASURING
INITIATOR RESISTANCE

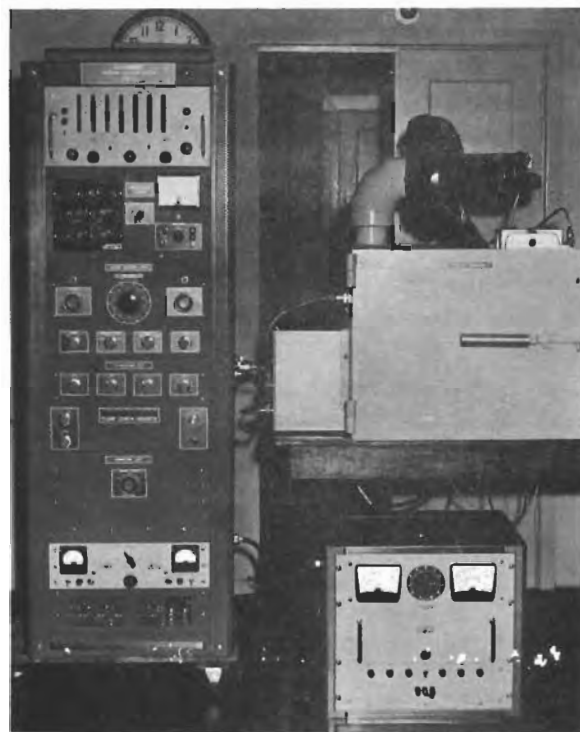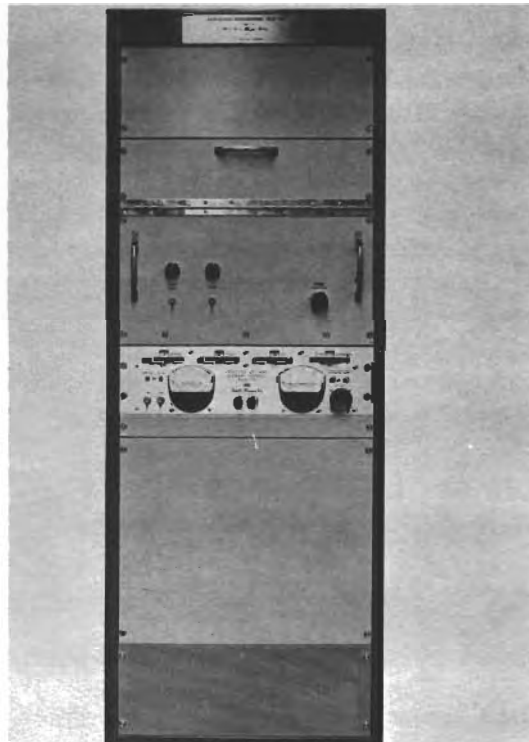FIG. 3. FRANKLIN INSTITUTE LABORATORIES INITIATOR TEST SET-FILITS 2

FIG. 4. LOCKHEED UNIVERSAL INITIATOR TESTER

FIG. 5. FRANKLIN INSTITUTE LABORATORIES UNIVERSAL PULSER - FILUP
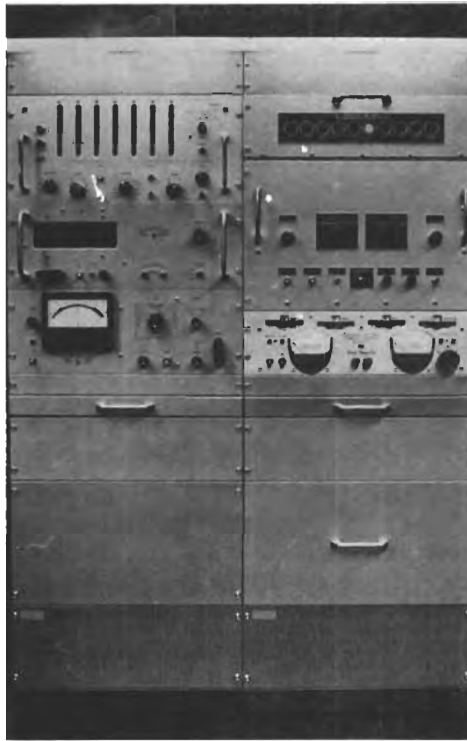

FIG. 6. EXPLODING BRIDGEWIRE TEST SET

FIG. 7. FRANKLIN INSTITUTE LABORATORIES
INITIATOR TEST SET-FILITS 3
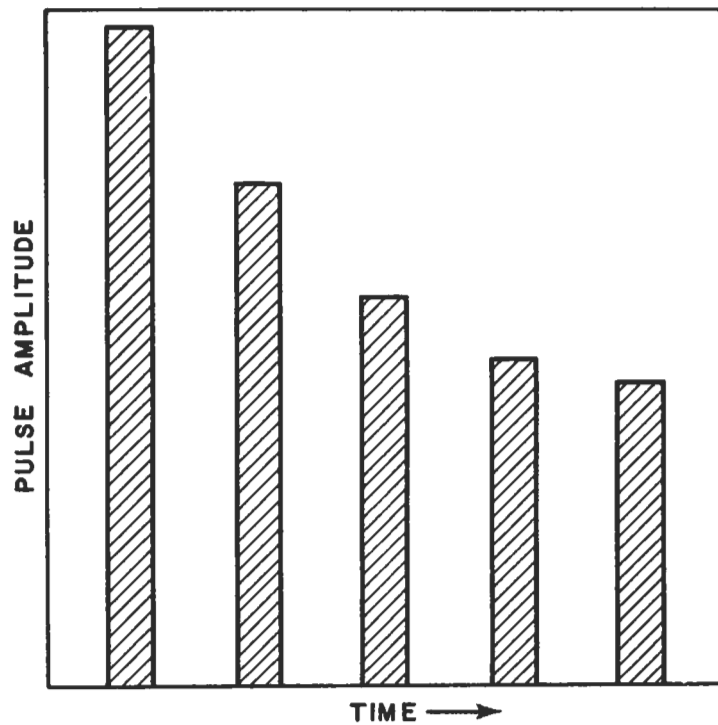
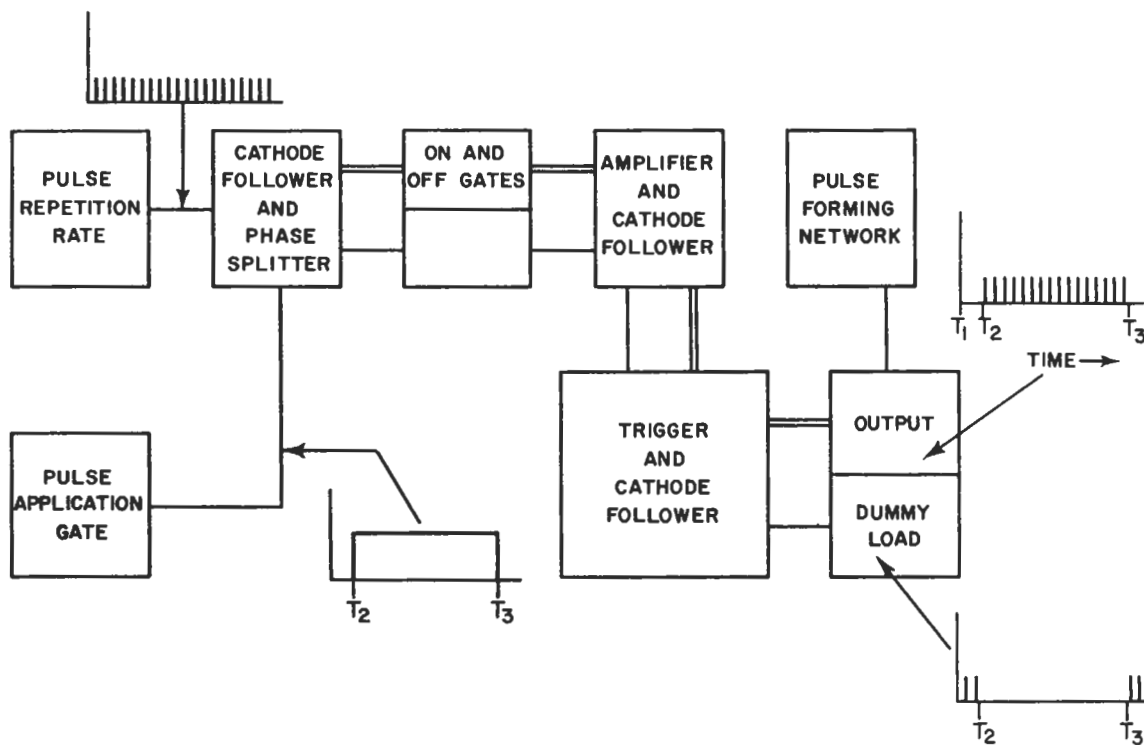FIG. 8. VARIATION IN PULSE AMPLITUDE FROM
CONVENTIONAL PULSE GENERATOR

FIG. 9. BLOCK DIAGRAM OF PRECISION-AMPLITUDE REPETITIVE PULSE GENERATOR
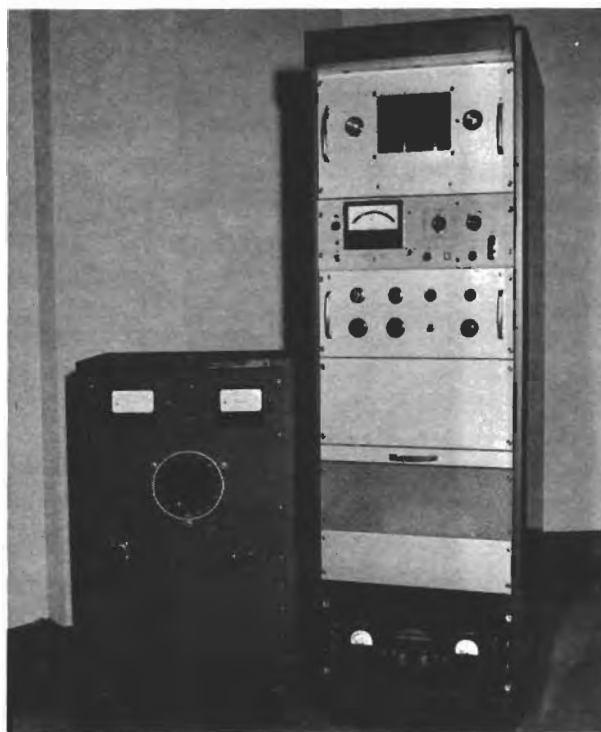

FIG. 10. FRANKLIN INSTITUTE LABORATORIES
REPETITIVE PULSER

19. DISCUSSION

Mr. Hauser of the Air Force Aeronautical Systems Division said that a statement was made that there is a need for data concerning the response of EEDs to electrical pulses. He stated further that he had spent time recently searching for literature on this subject. He asked if any information was being published on this or if there were references available on this to help in the assessment of hazards. Mr. Davey suggested searching the proceedings of the recent HERO Congress, which contain information on pulsing. He also mentioned a paper on this subject which was presented at the last Electric Initiator Symposium. The author of the paper was Mr. Kabik and others at NOL, White Oak. This paper is a theoretical treatment of the response of initiators to transient pulses. The references in the paper are also helpful. Mr. Kabik added that there will be another paper on this subject by Dr. Rosenthal, later in the program.

In reply to a question by Mr. Digney of du Pont, Mr. Davey said that a 1P22 photomultiplier was used to sense the initiator flash. Response time of the photomultiplier is of the order of 10^{-13} seconds. Times of interest are only 10^{-6} to 10^{-7} seconds. The photomultiplier tube is not usually the limiting factor in the response, but rather the light output from the initiator. The biggest problem is in assuring that adequate light is available. Sensitivity of the counter is a problem too. It is necessary that both start and stop sensitivity settings are correct.

ABSTRACTS

21. <u>Low Energy, Secondary Explosive Detonator</u>   Robert L. Wagner

A mechanically insensitive, low energy activated detonator is being
developed for conventional ammunition fuzing. This paper presents the
progress and problems in reproducibility and reliability of such a
detonator.

22. <u>The Physics and Statistics of the Electrical</u>   J. W. Martin
    <u>Initiation Process in Conducting Composition Systems (U)</u>

The variations in electrical resistance and sensitivity of conducting
composition and carbon bridge initiators are studied by means of random
rectangular arrays of resistances. The mechanism of hot spot formation is
studied together with means of energy transfer to the explosive components.
Deductions are given concerning threshold sensitivity and conditions are
given for obtaining firing intervals of a few microseconds.

23. <u>Bridgewire Diameter Design Considerations for an</u>   Harold S. Leopold
    <u>EBW Initiator</u>

The effect of wire diameter on the vigor with which a wire explodes from a
high energy input and the subsequent initiation of PETN surrounding the
wire was investigated. The wire with the most vigorous explosion is not
necessarily the most efficient for effecting detonation. The diameter
of the wire can be chosen so as to favor time reproducibility, reliability
of effecting detonations, or vigor of the bridgewire explosion.

24. <u>Electrothermal Characterization of Electroexplosive</u>   L. A. Rosenthal
    <u>Devices</u>

The basic theory used to describe the electrothermal properties of an EED
is reviewed. Several instruments and techniques capable of providing
such measurements are presented. Various sources of errors and problems
are discussed. Results are presented to indicate the type of measurements
possible. Areas of future application are examined.

25. <u>Sensitivity Predictions Using Nondestructive</u>   Michael G. Kelly
    <u>Techniques (U)</u>   Raymond G. Amicone

It is shown that a non-destructive measurement of initial resistance and
bridgewire power sensitivity may be used to make accurate predictions of
the firing sensitivity of a given EED. The equipment, the measuring
technique, and the associated theory are discussed as are some of the
more practical applications of non-destructive EED testing.

26. <u>Shock Initiation Through a Barrier</u>   Edward L. Miller

The initiation of one explosive component by another explosive component
through a barrier without penetration of the barrier has been accomplished.
The use of such a system in a rocket motor has been successfully demonstrated.

27. A Proposed Mechanism for Shock Initiation of Low-   L. B. Seely
       Density Granular Explosives

Stagnation, a process in which shock-driven material from explosive grains
at one level in a charge is brought to rest against grains in the
succeeding level, produces hot spots responsible for the first stage in
shock initiation of granular charges. It explains a number of puzzling
shock-sensitivity phenomena, some of which are reviewed.

28. Bruceton Tests: Results of A Computer Study on   J. W. Martin
       Small Sample Accuracy   Mrs. J. Saunders

The staircase sensitivity test of Dixon and Mood, also called the Bruceton
test, has been simulated on an electronic computer which generates a known
sample mean and standard deviation. Using the results equivalent to 200,000
firings the accuracy of tests on samples of 25 to 100 items is assessed.
For samples of 100 items the adequacy of large sample theory is confirmed but
for smaller samples large corrections are necessary for the standard
deviations and the confidence limits are wider. The related "run-down" test
is discussed in an Appendix and suggestions are made concerning the best
test spacing and grouping. The run-down test is compared to the Bruceton
test.

29. Initiation Parameters (U)   Z. V. Harvalik

Thermal and nonthermal parameters to accomplish initiation of explosives is
discussed. The significance of these parameters in establishing a mode of
initiation is elaborated in conjunction with energy interactions with
metastable compounds. An attempt is made to define the sensitivity of an
explosive.

21. LOW ENERGY, SECONDARY EXPLOSIVE, DETONATOR

R. L. Wagner

A. L. Maynard

T. G. Blake

Picatinny Arsenal, Dover, New Jersey
Hanley Industries, Inc., St. Louis, Missouri

INTRODUCTION

The desirability of an electric initiator containing only secondary
explosives with its resultant mechanical insensitivity has been discussed in
a number of papers given previously at these electric initiator symposia.
Such an initiator, one that can be activated from compact power sources
such as Lucky crystals, (eliminating the bulky power sources required for
Exploding Bridge Wires) could advance the state-of-the-art of conventional
ammunition fuze design.

This paper presents the progress and some of the problems in
achieving reproducibility and reliability of this initiator.

BACKGROUND

Approximately six years ago the Diamond Ordnance Fuze Laboratory
initiated a project through a contract with the American Cyanamid Company
to investigate the feasibility of developing an electric detonator which con-
tained explosive materials no more impact sensitive than PETN. In addition
to this work, various investigators, E. I. du Pont de Nemours Co., Inc. and
Armour Research Foundation in the United States and The Royal Armament
Research and Development Establishment in the United Kingdom, have worked
on this problem. Results of the work by these people established design

parameters for achieving burning to detonation in a secondary high explosive such as PETN and RDX.

One of the more important aspects in the design of such a detonator is its activation by a relatively low energy electrical power supply. The primary objective of work in this connection is to activate the burning in an initiator with a capacitor discharge of 10,000 ergs at 1,000 volts. The limited energy requirement imposed segregates this development from the exploding bridge wire type initiators.

In pursuing this objective, Hanley Industries, Inc., St. Louis, Missouri has been engaged by Picatinny Arsenal under Contract No. DA-23-072-ORD-1575 to study the design parameters affecting the sensitivity of a low energy electric detonator of the burning-to-detonation type. This paper presents the results obtained by Hanley Industries, Inc.

HARDWARE AND ASSEMBLING

Most of this discussion will center around the conductive mix itself. However, considerable effort went into the design, testing and selection of hardware, and the optimization of techniques for assembly.

The parameters in loading and assembling which were studied included insulating material, length of gap, consolidation pressure, column lengths and column diameters. The design of detonator hardware which resulted from these studies is shown in slide No. 1.

One of the important considerations in the design, as you might well guess, is confinement. Aside from the parameters which influence confinement in every initiator such as column diameter, length, wall thickness, etc., there are a few unique areas within the detonator where small variations in confinement significantly affect sensitivity. Mostly

these are related to assembly operations.

During consolidation of the conductive mix the confines include the metal walls of the column into which the mix is being pressed, the metal column bottom against which the mix is being pressed and the surface of the circular insulating film which divides the conductive mix column. The insulating film area is the point where the confinement may vary during consolidation.

Experiments have shown that an incomplete or otherwise inferior bond line around the perimeter of this circular spark gap can result either in total malfunction or a decrease in sensitivity. The low energy discharge across the gap will physically push the mix out of the gap area if an avenue is available rather than initiating it. The result is usually a malfunction showing an open circuit and traces of conductive mix pushed between the insulating film and one or both of the brass electrodes.

Data which illustrates this is shown on slide No. 2. Sensitivity of detonators in which the bonds were deliberately broken is compared with detonators which were assembled carefully so that the bond was not disturbed.

All the items were loaded using a conductive mix which had never failed at 10,000 ergs under normal conditions. Results of this experiment show that only 60% of the initiators having disrupted bonds fired at 10,000 ergs.

Another place where care must be taken to prevent variation in confinement is in the torque load applied to the hardware assembly after loading. The initiator sub-assembly is confined finally by the application of 17 - 20 ft. lbs. torque. This is the maximum that can be applied in this system without damage to the metal parts.

A reduction in this load results in decreased sensitivity. Slide No. shows the results of omitting the torquing operation on ten (10) initiators loaded using a conductive mix that normally would be expected to function at 10,000 ergs. The percentage of fires decreased to less than 85%.

There is one more place where confinement is not controlled strictly by dimensions and that is in the mechanical back-up provided by the explosive loaded next to the conductive mix charge. This confinement is largely influenced by the density of the charge. The effect of loading pressure of this charge on sensitivity or propagation of the conductive mix charge has not been studied extensively. Some testing was conducted which indicated the effect of omitting the charge below the conductive mix.

Slide No. 4 shows the effect of reduced confinement below the conductive mix charge. The conductive mix used in this test was one which fires consistently at 10,000 ergs in normal detonators. With the downstream explosive charge omitted the percentage fires decreased to less than 90%.

Although no specific data exists to prove conclusively that increasing the consolidation pressure of the explosive below the conductive mix charge significantly affects sensitivity, there is a feeling on the part of the investigators that it may. There have been enough happenings during the program which seem to indicate a trend. One case in point which admittedly is insignificant if considered by itself is a test where the 50% firing point was elevated to the 60% point when consolidation pressure was raised from 8,000 p.s.i. to 12,000 p.s.i. These results are shown on slide No. 5. A portion of the work going on at the present time is directed toward studying this more thoroughly.

THE CONDUCTIVE MIX

Sporadic success has been obtained with sub-sieve RDX/acetylene black mixes. Of more than fifty (50) mixes prepared with these ingredients only three exhibited ignition characteristics indicating that a detonator meeting the 10,000 erg design requirement was possible.

In over three hundred (300) tests utilizing one of the three sensitive mixes there have been no failures with a firing energy of between 9,000 and 10,000 ergs.

A reproducible process for making the RDX/acetylene black conductive mix of this sensitivity has been elusive. Batches of mix made using identical processing perform differently. Considerable effort has been expended in attempting to characterize those parameters most influencing the final sensitivity of the mix, and in defining the physical properties of a good mix.

The parameters which have been studied most are ingredient percentages and mixing methods.

The results of this work have been disappointing in that we were unable to define a process which would produce a mix which would give reproducible results on a batch to batch basis. Even when materials from the same lot were used and the mixes were made side by side, results were not consistent. Great pains were taken to control temperature, mixing time, equipment and even who would be the individual assigned to prepare the mix. During this period of preparing and evaluating many batches of mix it appeared that uniformity of coating the RDX was perhaps more influential than mere proportions of the ingredients.

In line with this indication a conductive material which had good dispersion and coating properties was used. An extremely fine graphite with a particle size of less than one micron suspended in a butylene glycol and manufactured by the Joseph Dixon Crucibles Company as No. 78-24 Colloidal Graphite, has given encouraging results.

Seven (7) consecutive mixes have been processed by one method using this material and sub-sieve RDX and the results, based on limited tests indicate that all are equal to or slightly higher in sensitivity than the best previous mix using other materials. Slide No. 6 shows the results of these tests.

The pre-mixed ingredients included 85% sub-sieve RDX and 15% colloidal graphite (dry basis) in 700 cc. distilled water.

A procedure was adopted which included ball mill mixing for twelve (12) hours with a Fisher Scientific No. 8-382 milling jar and 88, 3/4" diameter by 3/4" long ceramic milling cylinders. The mill turned at 20 to 21 rpm.

After removal from the milling jar, the mixes were placed in transparent glass containers and allowed to settle for a minimum of four hours. The RDX settled, taking with it that graphite which had become attached to it. Most of the remainder of the unattached graphite remained in suspension and was removed along with the liquid by decantation.

The results of the seven consecutive mixes processed in this manner indicate that a conductive mix of the desired sensitivity can be produced and reproduced.

In addition to these ball milled mixes, four batches mixed in a Waring

Blender have given similar results. Slide No. 7 shows the results of one which is typical of the group.

The blender was a Waring Model 700B. Ingredient percentages were again 85/15 (dry basis) but because of the smaller mixing container only approximately 300 cc. of distilled water was used.

Mixing times ranged from one-half hour to two hours with the variation apparently not affecting the sensitivity.

In a further step toward simplification of mixing, a mix was made in which the mix ingredients were mixed together in a beaker by slurrying for just a few minutes. In this case the explosive used was from a fifty pound production batch of primer grade RDX purchased from E. I. du Pont de Nemours, Inc. as Lot No. 7-5. The mix performed very well, all tests firing without failure with as little as 2,500 ergs. Slide No. 8 shows the results of this test.

CONCLUSIONS

Having defined the materials and some of the parameters involved in the successful production and reproduction of acceptable low energy initiators, optimizing the geometry of the initiator seems to be in order.

The present initiator assembly has been chiefly a test vehicle in which a number of characteristics could be easily varied. It was designed without respect to size or weight limits.

To be of a practical size or shape, much of the external mass would be removed since the initiator would no longer need to be as rugged or adjustable and not at all re-usable.

A miniaturized version of this initiator has been incorporated into an M51 fuze and fired successfully when a piezoelectric ceramic placed in the nose of the fuze was crushed by a six foot drop of the fuze. This particular version was 1/4" diameter by 1/2" long. The following slides show the fuze in action. Slide No. 9 shows the test set up. Slide No. 10 shows the fuze in mid-air. Slide No. 11 shows the fuze exploding.

We have come a long way with this development. There were times when it appeared that the design goals might not be achieved. We feel, however, that there is yet much to be done. There are still many questions unanswered. For example, although it is possible to reproduce results now using a particular conductive material, we do not fully understand why. Work will continue to study the properties of the materials separately and when mixed. Included in the program are light microscope and electron-microscope studies of the materials. Also of interest may be the polarity characteristics of the conductive material and surface oxygen.

It is hoped that the future will bring application in new initiator design work of the burning-to-detonation principals studied.
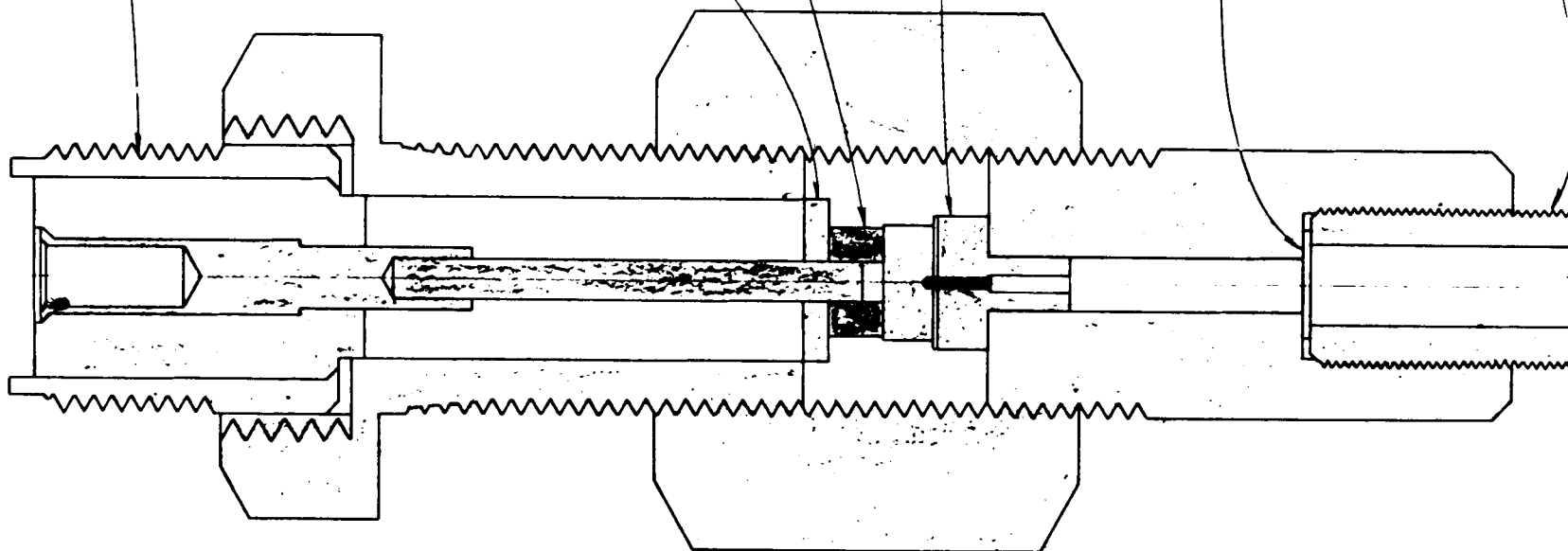
INITIATOR
RETAINER

CONTACT
INSULATOR

CONTACT

INITIATOR
SUB-ASSEMBLY

DIAPHRAGM

DIAPHRAGM
RETAINER

INITIATOR ASSEMBLY

MECHANICALLY INSENSITIVE ELECTRIC DETONATOR

HANLEY INDUSTRIES, INC
ST. LOUIS, MO.

SLIDE NO. 2

EFFECT OF BROKEN BOND ON FUNCTIONING

	No. Tested	No. Fired	No. Failed
Normal Detonators	10	10	0
Detonators With Broken Bonds	10	6	4

Detonators Contained Conductive Mix HA 10D
Firing Energy 10,000 ergs (1000 VDC .002 μf capacitor)

SLIDE NO. 3

EFFECT OF TORQUE IN FINAL ASSEMBLY

	No. Tested	No. Fired	No. Failed
Normal Detonators Torque 17-20 # lbs	10	10	0
Detonators No Torque	15	7	3

Detonators Contained Conductive Mix HA 10D
Firing Energy 10,000 ergs (1000 VDC .002 μf capacitor)

SLIDE NO. 4

EFFECT OF DECREASE OF CONSOLIDATION PRESSURE ON EXPLOSIVE CHARGE NEXT TO THE CONDUCTIVE MIX

Explosive Charge Next To Conductive Mix	No. Tested	No. Fired	No. Failed
8,000 psi (Normal)	15	15	0
Explosive Omitted	15	13	2

Detonators Contained Conductive Mix HA 10D
Firing Energy 10,000 ergs (1000 VDC .002 μf capacitor)

SLIDE NO. 5

EFFECT OF INCREASE OF CONSOLIDATION PRESSURE ON EXPLOSIVE CHARGE NEXT TO THE CONDUCTIVE MIX

Explosive Charge Next To Conductive Mix	No. Tested	No. Fired	No. Failed
8,000 psi (Normal)	10	5	5
12,000 psi	15	9	6

Detonators Contained Conductive Mix HA 42
Firing Energy 10,000 ergs (1000 VDC .002 μf capacitor)

SLIDE NO. 6

CONDUCTIVE MIX SUBSIEVE RDX AND DIXON 78-24 COLLOIDAL GRAPHITE BLENDED IN BALL MILL

Conductive Mix Number

Energy, Ergs	HA-57		HA-58		HA-59		HA-60		HA-61		HA-62		HA-63	
	Fired	Failed	Fired	Failed	Fired	Failed	Fired	Failed	Fired	Failed	Fired	Failed	Fired	Failed
10,000	5	0	5	0	5	0	5	0	5	0	5	0	5	0
7,500	5	0	4	1	5	0	5	0	5	0	5	0	4	1
5,000	5	0	3	2	4	1	4	1	5	0	4	1	4	1
2, 500	4	1	2	3	5	0	1	4	5	0	1	4	3	2

SLIDE NO. 7

CONDUCTIVE MIX - SUBSIEVE RDX AND DIXON 78-24
COLLOIDAL GRAPHITE BLENDED IN A WARING BLENDER

Sample No.	Firing Energy (ergs)	Fired	Failed
1	10,000	x	
2	10,000	x	
3	10,000	x	
5	10,000	x	
6	7,500	x	
7	7,500	x	
8	7,500	x	
9	7,500	x	
10	7,500	x	
11	5,000	x	
12	5,000	x	
13	5,000	x	
14	5,000	x	
15	5,000	x	
16	2,500	x	
17	2,500	x	
18	2,500	x	
19	2,500	x	
20	2,500	x	

SLIDE NO. 8

COMMERCIALLY AVAILABLE PRIMER GRADE RDX WITH AN
AVERAGE 60 MICRON PARTICLE SIZE WAS THE EXPLOSIVE
INGREDIENT AND DIXON 78-24 COLLOIDAL GRAPHITE
HAND SLURRIED IN A BEAKER

Sample No.	Firing Energy (ergs)	Fired	Failed
1	10,000	x	
2	10,000	x	
3	10,000	x	
4	10,000	x	
5	10,000	x	
6	7,500	x	
7	7,500	x	
8	7,500	x	
9	7,500	x	
10	7,500	x	
11	5,000	x	
12	5,000	x	
13	5,000	x	
14	5,000	x	
15	5,000	x	
16	2,500	x	
17	2,500	x	
18	2,500	x	
19	2,500	x	
20	2,500	x	

23. BRIDGEWIRE DIAMETER DESIGN CONSIDERATIONS FOR AN EBW INITIATOR

Howard S. Leopold

U. S. Naval Ordnance Laboratory
White Oak, Silver Spring, Maryland

INTRODUCTION

Factors governing the choice of the bridgewire dimensions of an EBW (exploding bridgewire) initiator are much more complicated than those for conventional hot wire items. Compounding the difficulty is the small amount of literature available on this aspect of EBW design. One of the many decisions confronting the designer of an EBW initiator is the choice of the bridgewire diameter. Preliminary work has been done on this problem at NOL/WO and may be of help to EBW designers. Some of the effects of varying the bridgewire diameter on the wire explosion and subsequent growth of explosion in PETN surrounding the wire are given in this paper.

ELECTRICAL CIRCUITRY

The firing circuit used in this study is shown in Figure 1. A GL-7964 triggered spark gap tube was used as the switching device. Circuit dimensions were kept as small as possible consistent with the necessity for testing in an explosive firing chamber. The firing circuit had the following parameters:

$$C = 0.97 \text{ microfarad}$$

$$L = 0.58 \text{ microhenry}$$

$$R = 0.35 \text{ ohm}$$

$$V_o = 2000 \text{ volts}$$

The circuitry was typical in that many EBW firing units in use consist of a 1 microfarad capacitor charged to 2000 volts.

EXPERIMENTAL METHODS

The outputs of platinum bridgewires ranging in diameter from 0.0005 to 0.005 inch were determined. A photographic technique used by Bennett[1] was employed to observe the shock wave from and the plasma expansion of the wire. The wire was mounted in a holder as shown in Figure 2. The slit of a smear camera was aligned perpendicularly to the wire. The reflected image of the wire explosion provides backlighting for the event. Unfortunately, only the upper portion of the wire explosion trace was usable. Reflections set in almost immediately in the lower portions because of the short length (0.050 inch) of bridgewire.

The growth of explosion in the PETN surrounding the wire was observed in a test fixture as shown in Figure 3. The transparent plastic permitted camera observation of the bridgewire at the explosive-plastic interface. The slit of a smear camera was aligned perpendicularly to the bridgewire between the contact pins. The smear record thus showed the growth of explosion along the surface of the test explosive in contact with the transparent plastic.

Concurrent with the smear camera records, oscillograms were obtained of the current and voltage waveforms. The voltage was corrected for the inductive component. Resistance, power, and energy values were then calculated.

EXPERIMENTAL RESULTS

Let us first take a look at how various diameter platinum wires of the same length behave in the experimental circuit. Figure 4 shows an idealized* current-time trace. Superimposed on the trace are the points where the various diameter wires explode. As is to be expected, the time to wire explosion is in the order of increasing diameter. An examination of the oscillograms shows that the 0.0005, 0.001, 0.0015, and 0.002 inch diameter wires explode on successively higher levels of the first current pulse. The 0.003 inch diameter wire explodes just after the first current peak. The 0.004 and 0.005 inch diameter wires do not receive enough energy to completely vaporize by the time current ceases to flow after two or three half cycles.

Nash and Olsen[2] have shown that there is a close to linear relationship between the cross sectional area of the wire and the time to burst at constant initial voltage. Our results plotted in Figure 5 confirm this relationship up to the 0.003 inch diameter with the same slight curvature as shown by Nash and Olsen. A definite deviation is noticed with the larger diameter wires which received insufficient energy to completely vaporize.

Let us now look at a typical smear photograph showing the growth of explosion in PETN. Figure 6 is such a photograph.

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*This is idealized because each diameter wire would produce a trace somewhat different from the traces for other diameter wires. This occurs because of the differences in wire resistance and minor changes in wire inductance.

The PETN was at a density of 1.0 g/cm^3. This is 56.5% of theoretical maximum density. We find that the PETN is apparently initiated at the time of the wire burst. There follows a period of accelerating burning during which there are simultaneous electrical and chemical energy contributions to the reaction. A detonation wave becomes discernible approximately 1 mm from the bridgewire in less than 1 microsecond after the wire burst. Reflected shock waves from the steel containing ring are also apparent. Once detonation commences no more electrical energy is needed to sustain the chemical reaction. Thus the time interval (in which we are interested) is the time to burst plus approximately 1 microsecond. In hundreds of shots conducted with platinum wires we have never observed an instance where detonation develops at a later period or is caused by a secondary electrical pulse.

The photographic observations of the bare wires have been examined and plotted as shown in Figure 7 to show the shock wave and plasma expansions as functions of time. The curves are plotted over the maximum time interval of observation, or up to a maximum of 2 microseconds. The vigor of the wire explosion, as measured by the radial expansion from the time of wire burst, shows that an optimum wire diameter exists. From the two plots in Figure 7 it can be seen that for the circuit conditions the 0.003 inch diameter wire gave the most vigorous output, closely followed by the 0.002 and 0.0015 inch diameter wires.

The existence of an optimum diameter can be rationalized
on the basis that very thin wires are poorly matched to the
firing circuit. They explode in short times using little
of the available stored energy. If the wire diameter is too
large, it will not absorb sufficient energy to cause vaporization.
This occurs even though the stored energy is sufficient to
completely vaporize the wire. If it is hypothesized that the
vigor of the wire explosion is directly related to the ability
of the wire to effect detonation, then a 0.003 inch diameter
wire should be optimum for the circuit parameters employed.
Each wire's ability to effect detonation should decrease as
the vigor of the wire explosion decreases. This was tested
in the following manner. A series of test shots was run to
reveal the optimum wire diameter for detonation of PETN by
gradually decreasing the sensitivity of the PETN around the
wire. This was done by increasing the density of the PETN.
This method eliminated any change in the electrical parameters.
The results are shown in Table 1. Whereas the vigor of the
wire explosion was observed to be in the following decreasing
order:

1) 0.003 inch diameter wire
2) 0.002 "   "   "
3) 0.0015 "   "   "
4) 0.001 "   "   "

The ability to effect detonation by the wires was found to
be in the order:

1) 0.002 inch diameter wire

2) 0.0015 "   "   "

3) 0.003 "   "   "

4) 0.001 "   "   "

The bare wire with the most vigorous shock output is not
the best for effecting detonation when surrounded by explosive.
An examination of the oscillograms showed that the current
pulse dropped off rapidly with the 0.003 inch diameter wire
when exploded in contact with PETN. See Figure 8. Wires
less than 0.003 inch in diameter retain the resurge. It
appears that energy of electrical origin in the interval
just after the wire burst can be beneficial in effecting detonation.

Energy deposition to time of wire burst, energy deposition
during the microsecond interval after burst, and the total
energy deposition did not correlate with the ability of the
wire to effect detonation. This can be seen from Figure 9.
Neither energy density nor average power showed a correlation.
The average power and peak power are shown in Figure 10. Peak
power does correlate with the ability to effect detonation.
Peak power occurs almost concurrently with the peak voltage
and may indicate the most important period of electrical
energy deposition.

It was also noticed that the best time reproducibility
is obtained when the wire explodes on the initial portion of
the current pulse. The length of the block rectangle in Figure
5 indicates the time spread observed for each wire size.

SUMMARY

Work is continuing to find the factors that determine the growth to explosion of PETN. Wire length and wire material studies are currently adding new insights which will be reported on in the future.

In conclusion, with the circuit parameters used relatively thin and relatively large diameter platinum wires are unable to effect detonation in PETN. The intermediate diameter sizes that effect detonation should be chosen so as to explode on the portion of the current pulse to give the desired effect. This is illustrated in Figure 11. If time reproducibility is the main consideration, the wire should explode in region A with enough of a safety factor to insure detonation. If general functioning reliability is the main consideration, region B should be chosen. If maximum wire output is desired (i.e., to break diaphragms, etc.) region C should be chosen.

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TABLE 1

Effect of Wire Diameter

Wire Diameter (inch)	Density of PETN (g/cm³)																	
	0.7		0.8		0.9		1.0		1.1		1.125		1.15		1.175		1.2	
	D	L	D	L	D	L	D	L	D	L	D	L	D	L	D	L	D	L
0.005	0	3	0	2	0	2	0	2										
0.001			2	0	2	0	2	0	0	2								
0.0015			2	0	2	0	2	0	2	0	3	1	3	3	0	2	0	2
0.002			2	0	2	0	2	0	2	0	4	0	5	1	0	2	0	2
0.003			2	0	2	0	2	0	2	0	3	1	0	6	0	2	0	2
0.004			0	2	0	2	0	2										
0.005			0	2	0	2	0	2										

D = Detonation

L = Low order
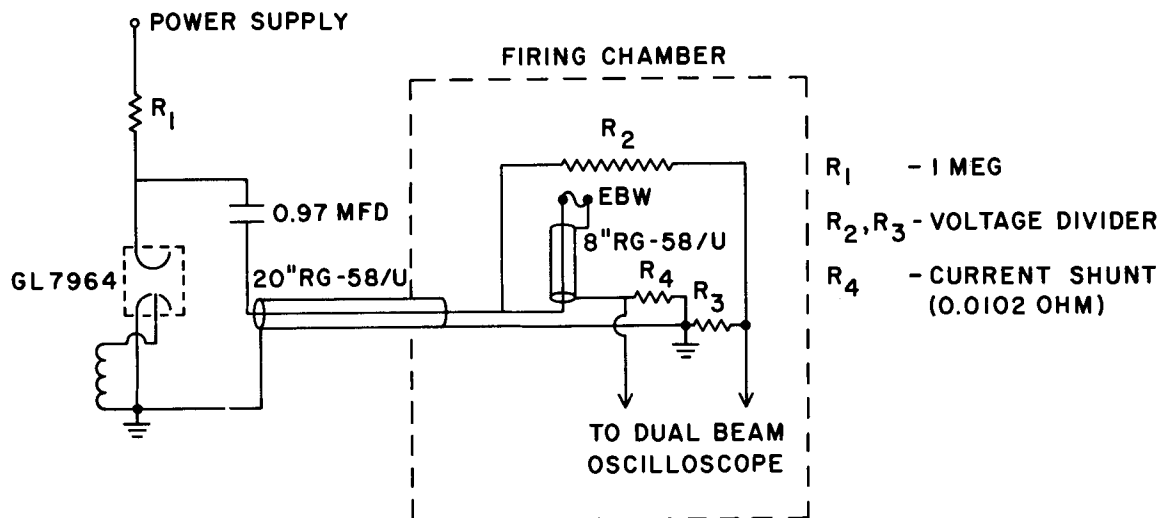
FIG. I TEST CIRCUIT
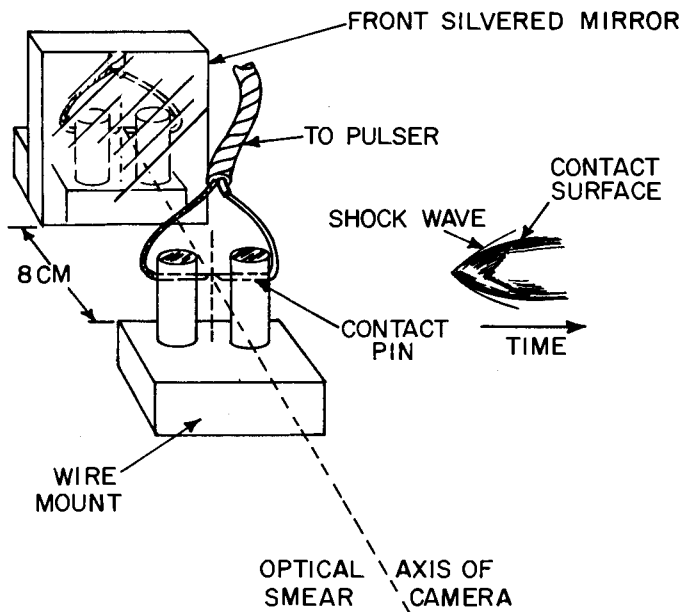
FIG. 2 TEST ARRANGEMENT
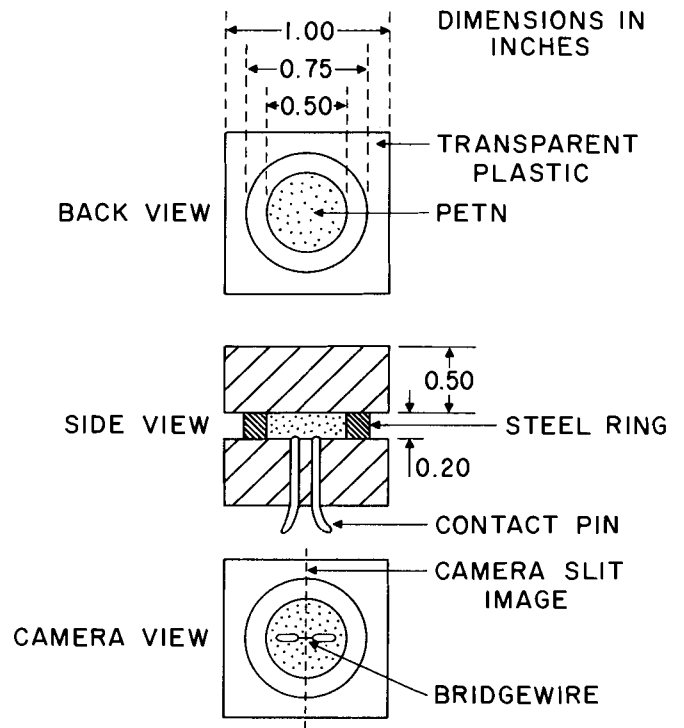
FIG. 3 TEST FIXTURE
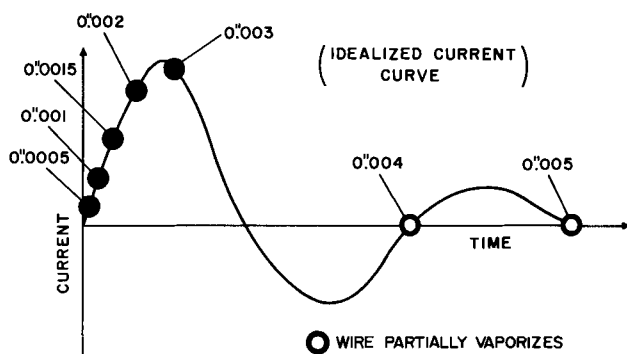
FIG. 4 EXPLOSION LOCI OF VARIOUS DIAMETER WIRES
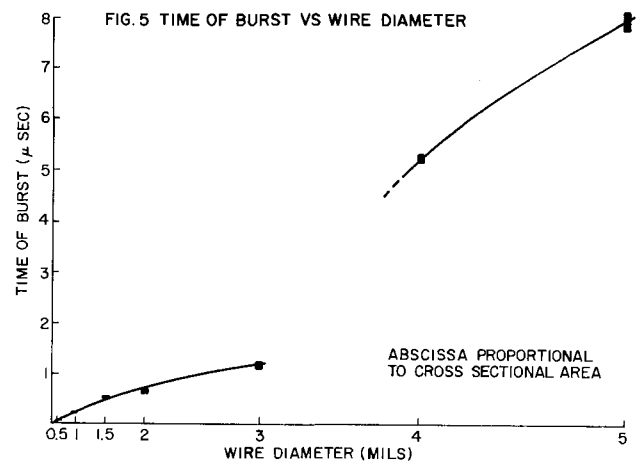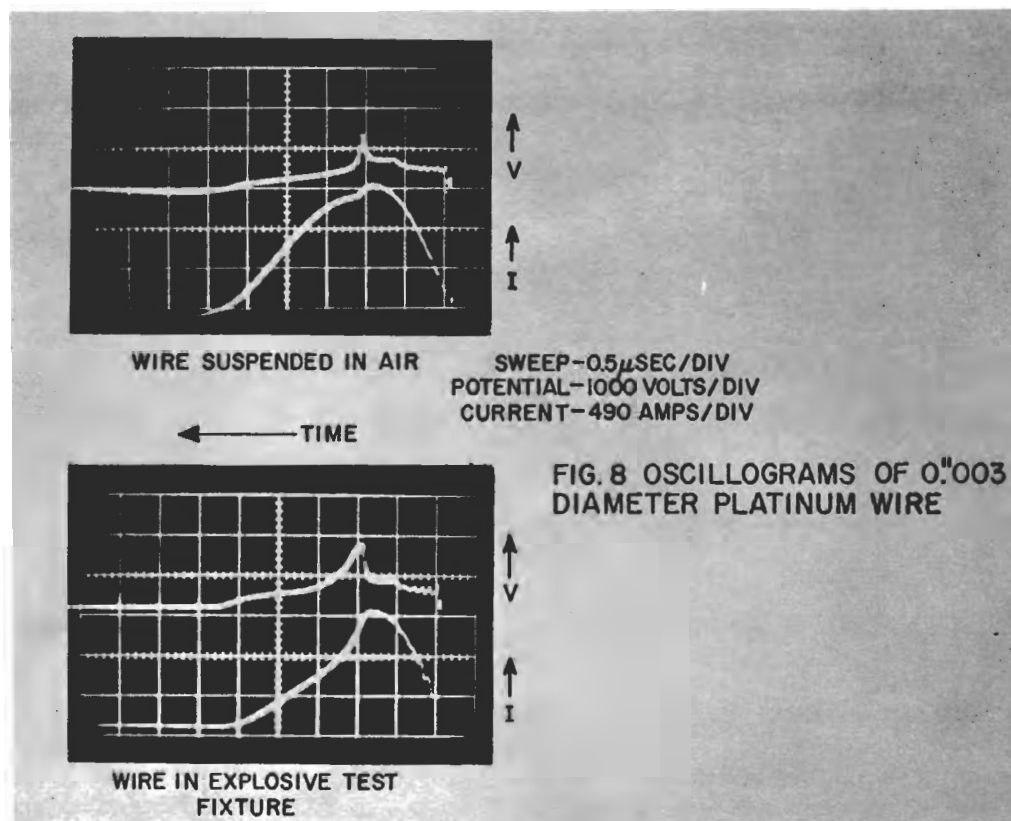

FIG. 5 TIME OF BURST VS WIRE DIAMETER

FIG. 6 GROWTH OF EXPLOSION IN PETN
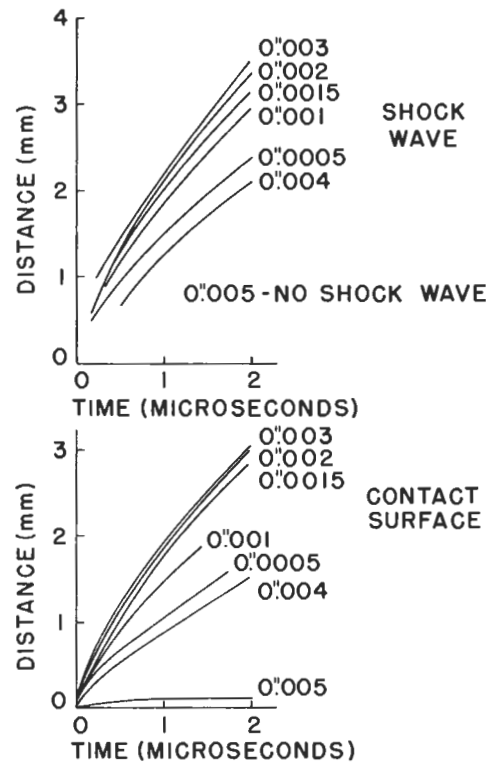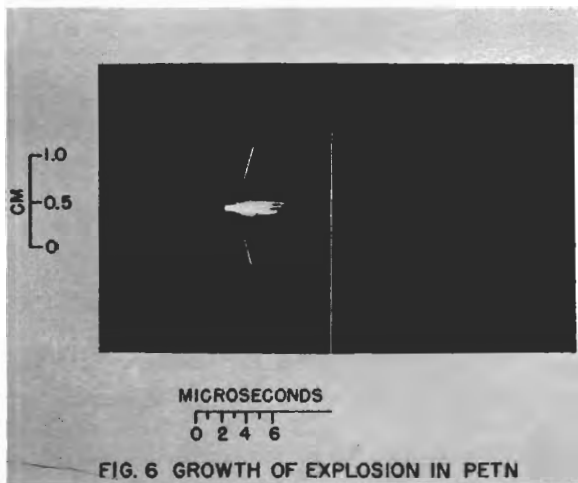
FIG. 7 PHOTOGRAPHIC OUTPUT COMPARISON

WIRE SUSPENDED IN AIR

WIRE IN EXPLOSIVE TEST FIXTURE

SWEEP—0.5 μSEC/DIV
POTENTIAL—1000 VOLTS/DIV
CURRENT—490 AMPS/DIV

FIG. 8 OSCILLOGRAMS OF 0".003 DIAMETER PLATINUM WIRE
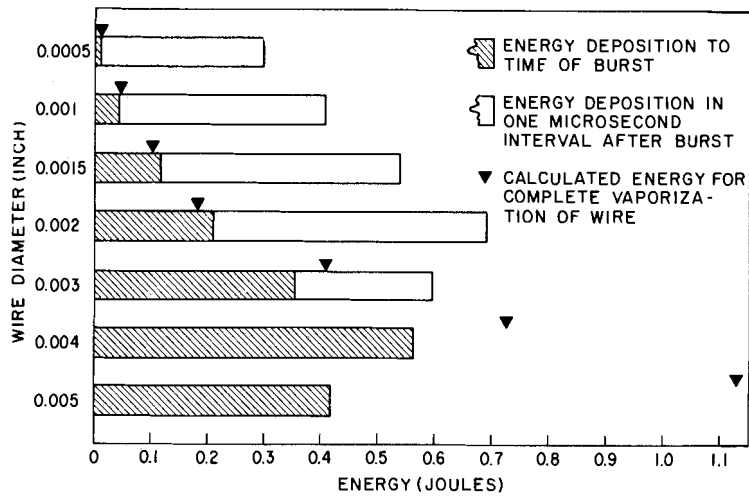
FIG. 9 ENERGY DEPOSITION
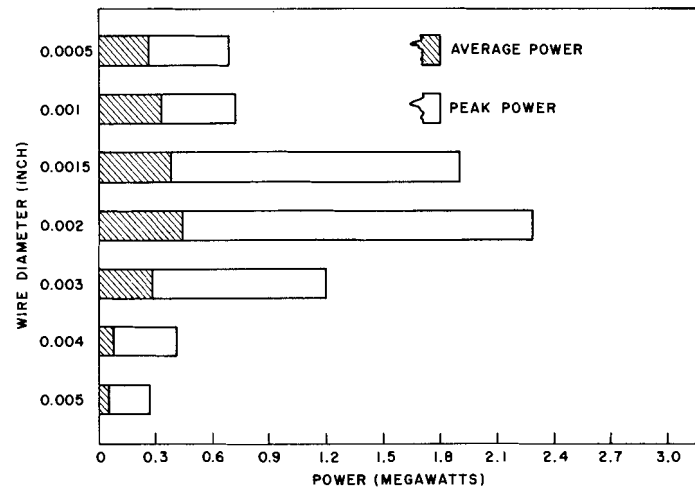
FIG. 10 PEAK AND AVERAGE POWER

A — OPTIMUM TIME REPRODUCIBILITY
B — OPTIMUM FUNCTIONING RELIABILITY
C — OPTIMUM WIRE OUTPUT
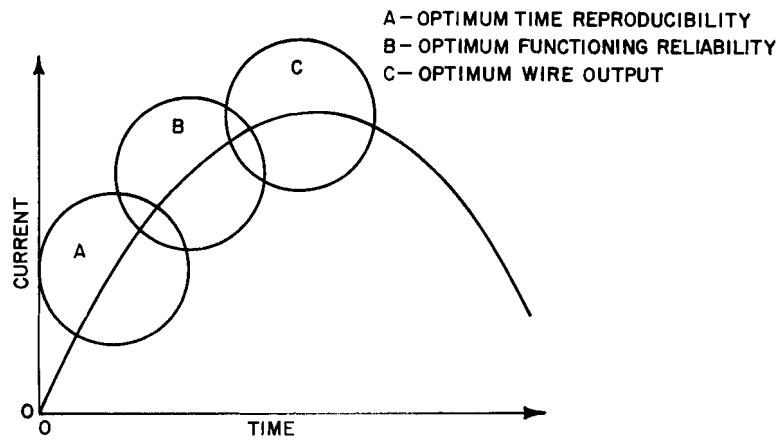
FIG. II REGIONS OF WIRE EXPLOSION

Mr. Cameron of Douglas Aircraft asked if these studies were run only on platinum wire. Mr. Leopold said that this was true for the studies of diameter, but current work is being done with other materials. He continued that initially there was no idea of what wire material was best. Solderability and relative inertness, in addition to thermal dynamic properties, were considerations in the choice of a wire material.

Mr. Sealy of Los Alamos asked how the velocity in the burning phase compared to sound velocity. Mr. Leopold said that they had tried to determine this. The sound velocity in these non-homogeneous materials, half PETN and half air, was not known. Initial burning measures 700 or 800 meters per second and close to 5000 meters per second at detonation.

Mr. Forbess of GLA gathered that the electronics were held constant through this entire program. He asked if there was any information on the effect of rise time or rate on this subject. Mr. Leopold indicated that some of the early studies were concerned with inductance and resistance. He indicated further that it is desirable to get as high a rise rate as possible. This has to do with the "pinch effect" in the wire. The greater the current density the higher the pinch effect.

Mr. Forbess asked if Mr. Leopold believed there was no limit to rise time as far as improving performance is concerned. Mr. Leopold said that if the device has a limit, he didn't believe it could be achieved with conventional firing circuits. If super-refined circuitry is used, such as that mentioned by Mr. Stresau, then there may be an optimum.

Mr. Forbess asked if a current magnitude had been approached at which less desirable results were obtained. Mr. Leopold answered that within the limits of the circuitry, the maximum current available was found to be best. Mr. Forbess then mentioned that there was no control of the time of wire break. Mr. Leopold agreed, saying that any additional resistance or inductance inserted in the firing line decreased the ability to effect detonation.

Mr. Forbess asked if there was any information relating the frequency of the discharge to the quality of the results. Mr. Leopold said only relative to the inductance available, that ranged from 6 to 13

microhenries. He said that any decrease in frequency which is indicative
of increased inductance over this range would be harmful.

Mr. Moses of Holex asked if any card-gap sensitivity tests
had been performed on low density PETN. Mr. Leopold said he hadn't made
any such tests. Around ten different types of build-up or decay have been
observed for detonation produced by the bridgewire. These will be
explained in reports but no work has been done with air gaps nor has any
mechanical sensitivity test been performed.

Mr. Fisher of Aerojet asked for a comment on the use of ribbon
as opposed to the cylindrical wire that was used. Mr. Leopold expressed
his view that energy density would be lost and that this would be harmful.
If there is abundant input energy available, he saw no reason why a ribbon
wouldn't work.

Mr. Hauser of Aeronautical Systems Division commented that there
is a discontinuity in the coaxial cable feeding the EED. He asked if
results might be biased by the discontinuity because of the effect on the
waveform slope, and if any work had been done with other coupling circuits.
Mr. Leopold answered that he had not yet examined the transmission line
effects. Energy calculations are made from the input to the wire or as
near to the wire as possible.

24. ELECTROTHERMAL CHARACTERIZATION OF ELECTRO-EXPLOSIVE DEVICES

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INTRODUCTION

The performance of an electro-explosive device is related to the efficiencies of conversion of electrical energy into heat in the bridgewire and heat transmission from the wire to the explosive in intimate contact with it. Many aspects of this electrothermal conversion process can be characterized by electrical measurements made at the device input terminals. Providing the bridgewire can be used as its own resistance thermometer, the temperature rise and the response time of the bridgewire can be evaluated. The object of such electro-thermal characterizations is to make meaningful measurements which can be used to evaluate overall EED performance.

PRINCIPLE CONCEPTS

Consider the simplest single time constant model to describe this electrothermal process. Power $P(t)$ is put into an EED and results in a temperature rise (θ) of the wire (and the explosive in contact with it) according to

$$C_p \frac{d\theta}{dt} + \gamma\theta = P(t) \qquad \#1$$

In this expression "C_p" is the heat capacity (watt-sec/°C) of a lumped composite system. Heat loss is represented by "γ" which is expressed in watt/°C and includes all

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possible paths. In the assumption of this simple lumped model, these two parameters essentially describe the electro-thermal conversion process. Thermal response is described by a time constant $\tau = C_p/\gamma$. The right hand of equation #1 is the forcing function, power, which will be some time function.

In order to obtain the parameters C_p and γ, simple power functions are applied to the EED[1]. By solving equation #1, we anticipate the temperature rise solution $\theta(t)$. Experimental techniques provide a physical solution from which C_p and γ can be extracted in light of the solutions developed. Cases will arise where the simple model fails to completely, or with sufficient detail, confirm the experimental observations. These problems will be described later. If the experiment fits the proposed model then C_p and γ are clearly defined for this lumped equivalent and are the sought after characterizations of the EED.

Consider the application of a current step function (I) to the EED. Now $P(t) = I^2 R$ but R is related to the temperature rise θ. A solution to equation #1 results in

$$\theta = \frac{I^2 R}{\gamma'} \left[1 - e^{-\gamma' t/C_p} \right] \qquad . \qquad \text{#2}$$

This is a simple exponential rise as shown in figure 1. Note that a modified heat loss factor

$$\gamma' = \gamma - I^2 R\alpha$$

results due to thermal feedback. Because the unit heats up and increases its resistance, there is a further grabbing

of power. The term "α" is the temperature coefficient of resistivity at the starting or reference temperature.

It is apparent that the final temperature achieved in figure 1 (θ_{ms}) is

$$\theta_{ms} = I^2 R/\gamma \qquad \#2a$$

from which γ can be evaluated. The slope of this curve at the origin is

$$d\theta/dt\Big]_{t=0} = I^2 R/C_p \qquad \#2b$$

from which C_p can be resolved.

If the step function is reduced to a narrow pulse as shown in figure 2 then power is put into the device adiabatically and by examining the cooling curve from an initial temperature θ_0, the time constant can be readily determined. If the cooling follows

$$\theta = \theta_0 e^{-t/\tau} \qquad \#3$$

then the simple model is confirmed. The peak temperature excursion is related to the energy (E) in the input burst according to

$$\theta_0 = E/C_p \qquad \#3a$$

where

$$E = \int_0^t I^2 R \, dt$$

The developing of a convenient experimental procedure for getting C_p and γ is the instrumentation aspect of these characterization studies. If the model proposed is an accurate representation, then the solution of equation #1

for known waveforms will yield the desired parameters.
When the model fails to describe the actual performance
then although C_p and γ can be individually measured, they
have less meaning. The instrumentation techniques will
be described.

INSTRUMENTATION TECHNIQUES

In the previously cited solution of the power equation
the temperature rise "θ" must be measured external to the
device. Providing the bridgewire has a moderate α, then
the resistance change can be used instead. Actually a
monitoring current must be passed through the device since
voltage changes corresponding to resistance – temperature
changes will be sensed. This relationship is

$$R_\theta = R(1+\alpha\theta)$$

where R_θ is the resistance, for a temperature change θ,
from the reference resistance level R. For a change

$$R_\theta - R = \Delta R = \alpha R\theta \quad .$$

The factor $\alpha R(=M)$ appears repeatedly in many solutions and
is a basic parameter of the bridgewire[9].

Two transient testing techniques have been developed
based on the previously cited solution to the electrothermal
equations. These are shown in figure 3. It is desirable
to avoid photographic evaluation techniques where possible.

An impulse or cooling curve, testing technique is shown
in 3(A). A current burst (I_a) in the form of a half-sine
wave dumps energy into an EED in an adiabatic manner. By

passing a trickle current (I_t) through the device a negative

going exponential (V_s) is observed. The discharge pulse (I_a)

is also passed through an RC circuit which generates a

positive going exponential (V_1) as shown. This RC circuit

has an adjustable time constant. A scope is employed to

observe the cancellation of these two exponentials. Since the

RC circuit is calibrated, the time constant can be measured

directly at cancellation. By measuring the amplitude of the

cooling curve (V_s) and relating it to the energy input, C_p

can be determined. A perfect cancellation of the two generated

exponentials would support the concept of a single time

constant model.

A second transient testing technique employs a square

wave driven bridge circuit shown in figure (3B). Based on

the previously cited example of step function response, the

voltage drop across an EED when driven by a constant current

I is sketched in figure (4B). There is an initial step and

an exponential rise due to heating. The resistance increases

by R_B due to heating and an electrical equivalent for this

performance can be constructed. It is only good for the

heating portion of the cycle since the thermal energy stored

cannot be reflected as an electrical equivalent. The bridge

shown can match the components R_s, R_3, and C_3 to the electro-

thermal model. In turn, Y and T can be extracted at balance

for the EED under test. Here again it is possible in many

cases to get good balance conditions as evidence of a single

time constant. The square wave must be of sufficient duration so that equilibrium conditions are reached. By making R (Fig 3B) large compared to the EED resistance, the constant current testing mode is employed.

These transient tests are described in another publication[4]. In cancelling out exponentials, as in both these techniques, the existence of other time constants sometimes becomes apparent. For example, a dominant time constant can be removed leaving a smaller, superimposed, response. Three time constants have been observed at times. A fast response is generally associated with heat flow along the wire and the wire surface. A longer time constant is related to the explosive perhaps in a cylindrical zone about the wire. A much longer time constant is associated with heat diffusion into the ambient plug and environment. For a Mark 1 Squib these time constants could be typically 1ms, 5ms, and 500ms. If the long time constant is ignored then a model as shown in figure 4A could be proposed for certain units. This considerably complicates the analysis and interpretation. Both time constants can be dependent on the intimacy of the explosive contact with the bridgewire to different degrees. The impulse testing accentuates the fast time constants since the response is essentially the derivative of the square wave response. However, one can establish a composite time constant which is actually the dominant time constant and show that it is most representative of the importance of the explosive surrounding the wire.

It is not necessary to use only one instrumentation procedure for characterization. For example, C_p can be determined by dumping any known energy burst adiabatically into the EED and measuring the resistance change and relating it via α to C_p. Then γ can be determined by steady-state techniques; for example, the temperature rise at equilibrium for a current step. There has been fairly good correlation in all transient type measurements.

Another recently developed technique for electrothermal measurements is based on the solution of equation #1 when the input is a sinusoidal driving current[5]. An EED will thermally lag the cyclic power fluctuations by some phase angle (β). Thus the resistance is a double frequency variation at some lagging angle. In the presence of the fundamental current, a third harmonic is generated which is uniquely related to the electrothermal characteristics of the EED. By measuring the phase angle lag of the third harmonic as well as its amplitude, γ and τ are readily evaluated. The instrument developed has been designated a phase shift bridge[6]. Figure 5 shows the bridge circuit and some of the defining equations . The typical third harmonic Lissajous figure for a balanced condition is included.

The bridge is a normal A.C. line frequency bridge which at balance will leave a residual third harmonic error voltage (V). The resistor R_1 is selected to drive the EED with a sinusoidal constant current. An auxiliary phase shift lagging

network provides a calibrated phase lagging voltage for the horizontal (H) scope display. A unique closed figure corresponds to the desired balance condition.

This new method, although less accurate in resolution than transient techniques, provides several advantages. It is very rapid and insensitive to lead length and circuit inductance. Devices with small temperature coefficients can be measured since the third harmonic detection results in high signal/noise resolution capabilities. The useful range is limited by the line supply frequency, although power oscillators can be used. Measurements are made as a dynamic oscillation about a thermally stable elevated temperature. Although C_p determinations compare very well with transient measurements, the values of γ are consistently higher. There is correlation however. In a dynamic measurement we sense and favor the fast time constants which results in a high effective γ. Study and evaluation of this measurement technique is continuing.

Another valuable instrument for static resistance measurements is the self-balancing bridge as shown in figure 6. It consists of a tuned high gain amplifier and a positive feedback bridge circuit. If initially the bridge is at or close to balance then the circuit will not oscillate. When unbalanced the oscillation amplitude will build up until heating in the EED restores the bridge to near balance in the presence of oscillation. This self-balance action keeps the bridge at near balance for any oscillation state. The

break-in point of oscillation can be used for resistance
measurements at no power dissipation. By placing the EED
in a temperature programmed box, accurate resistance temperature
curves can be obtained by repeatedly establishing the break-in
condition. As another aspect, by setting the self-balancing
bridge into oscillation and setting the EED into a hot box,
the change (decrease) in self-balancing power is related to
temperature environment yielding γ as $\Delta P/\Delta\theta$.

The aforementioned measurement techniques with variations
and extensions have been applied in characterization studies.

Where the simple thermal models are applicable good
results can be obtained limited by experimental errors.
The largest source of error is in the determination of α
which enters all calculations. Since the temperature
coefficient is the only means of reading information out of
the EED, variations in α can seriously mask electrothermal
measurements. It has been observed that a given group of
EED's made under carefully controlled conditions does not have a
broad distribution in its characteristics. It takes
extremely careful measurements to resolve differences in
units which are close to begin with. In addition to α
variations, the device resistance and current flow during testing
must be carefully measured since they enter most equations
as the square and cube respectively. An accurate determination
of $\alpha R = M$ offers a convenience in many measurements. A poorly
welded or soldered bridgewire joint can introduce errors. Solder

wetting the wire can upset the α value.

MEASUREMENTS

Dramatic evidence of these electrothermal measurements results when the bare wire measurements are compared to loaded measurements. For example, the bare bridgewire of a Mark 114 Primer yielded the following data by the electro-thermal phase shift bridge

Environment	Resistance (ohms)	τ (ms)	Heat Loss γ ($\mu w/°C$)	Heat Cap (C_p) ($\mu w\text{-}sec/°C$)
Air	4.25	4.2	70	0.294
Ethyl Acetate	4.15	1.6	318	0.510
Water	4.11	0.98	1220	1.200
Lacquer (Dry)	4.11	0.73	1270	0.930

There is a great sensitivity of C_p, γ and τ to the surrounding medium.

By transient testing techniques the following was observed for a Mark 1 Squib

	τ	γ ($\mu w/°C$)	C_p ($\mu w\text{-}sec/°C$)
Unloaded	14.0 ms	180	2.5
Loaded	4.6 ms	618	2.84

The above are typical measurements that can be performed on the instruments indicated. In general loading an EED will increase the heat capacity (C_p) slightly and the heat loss

(γ) significantly. The time constant always goes down
with loading.

A less dramatic, but perhaps more useful application
of these characterization measurements, is in the quality
control of manufactured EED's. Identical units should yield
identical measurements if the experimental accuracy is not
a factor.

Figures 7, 8, and 9 are histograms describing the heat
loss factor (γ) for a manufactured lot of EED's[7]. A sharp
distribution would be indicative of close measurement and
manufacturing tolerances. Sports and defective units can
be readily determined. The electrothermal phase shift bridge
was used for these tests and individual α variations were
not considered. At a sacrifice of resolving power the phase
shift bridge is rapid in operation and requires a minimum
of operator interpretation.

When a series of Mark 1 Squibs was evaluated on both
the phase shift bridge and earlier transient testing
instruments a correlation was observed. However as previously
indicated the phase shift bridge measures a dynamic γ which is
larger than γ determined by transient measurements.

APPLICATIONS

In addition to the quality control aspect of electro-
thermal characterizations other areas of application exist.
Earlier work showed that the behavior of the EED to periodic

waveforms could be explained using the simple single time constant model[8]. Knowing the thermal parameters of the bridgewire system it is possible to compute the wire temperature rise and the conditions for initiation of the explosive around the bridgewire. It is obvious that the response to an electrical power waveform is a thermal transient problem.

One challenging area is that of sorting devices based on indicated electrothermal measurements. The electrothermal parameters should be related to the intimacy of thermal contact between the explosive and the wire. Consider the possibility of sorting devices on the basis of "γ". The heat loss factor is important primarily where heat losses are significant, for example, in steady state modes of firing. For constant current firing, a figure of merit which closely describes the firing mode can be selected. For the case cited the maximum temperature reached for any current (I) is

$$\theta_m = \frac{I^2 R}{\gamma - I^2 R \alpha}$$

Therefore if θ_m is considered a figure of merit and computed for each EED then the largest θ_m would correspond to the EED exhibiting the greatest temperature rise for the assumed current.

Results of sorting using this procedure are indicated below[9].

Functioning Point	High Figure of Merit	Low Figure of Merit
95%	274 ma	282 ma
50%	267 ma	277 ma
5%	259 ma	272 ma
No. of Units	51	30

These groups were loaded Mark 1 Squibs separated on the basis of the figure of merit. The γ determinations were made by transient techniques. There is a clear separation obtained although it is not large. Actually these units should be very similar in characteristic and performance. Essentially this is a sorting imposed on a selected high quality group of EED's. If large manufactured lots are exposed to this type of selection, then "cleaner" separations could be expected.

If the units were to be fired by fast short bursts then sorting should be on the basis of C_p. Theoretically each waveform should have its own figure of merit. In practice constant current or capacitor-discharge firing need only be considered. Work is continuing in this area and the value of such sorting is apparent.

Electrothermal characterization is extending our insight and understanding of the behavior, performance, and reliability of electro-explosive devices.

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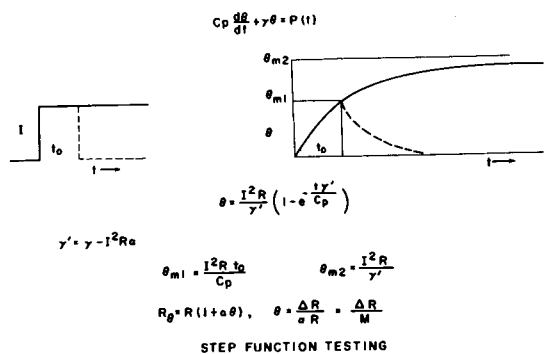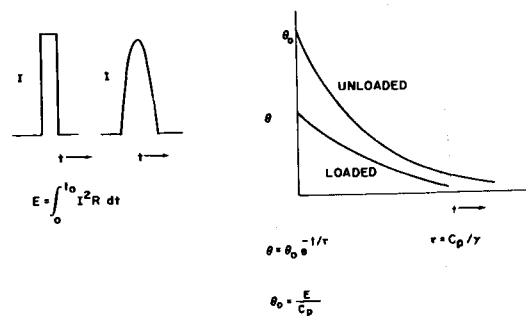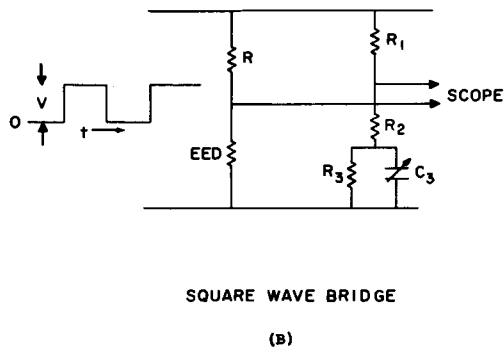   White Oak.

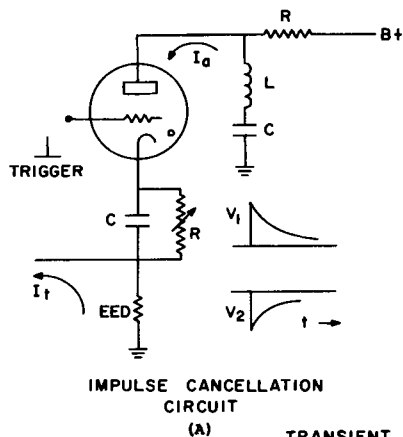$$C_p \frac{d\theta}{dt} + \gamma\theta = P(t)$$

$$\theta = \frac{I^2 R}{\gamma'}\left(1 - e^{-\frac{t\gamma'}{C_p}}\right)$$

$$\gamma' = \gamma - I^2 R_a$$

$$\theta_{m1} = \frac{I^2 R \, t_0}{C_p} \qquad \theta_{m2} = \frac{I^2 R}{\gamma'}$$

$$R_\theta = R(1 + a\theta), \qquad \theta = \frac{\Delta R}{a R} = \frac{\Delta R}{M}$$

STEP FUNCTION TESTING

Figure 1

$$E = \int_0^{t_0} I^2 R \, dt$$

$$\theta = \theta_0 \, e^{-t/\tau} \qquad \tau = C_p/\gamma$$

$$\theta_0 = \frac{E}{C_p}$$

IMPULSE TESTING

Figure 2

IMPULSE CANCELLATION CIRCUIT
(A)

SQUARE WAVE BRIDGE
(B)

TRANSIENT TESTING TECHNIQUES

Figure 3

$$\theta = \theta_m (1 - A e^{-at} - B e^{-bt})$$

ELECTRO-THERMAL ANALOG
(A)
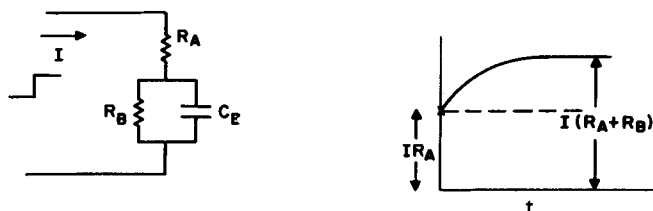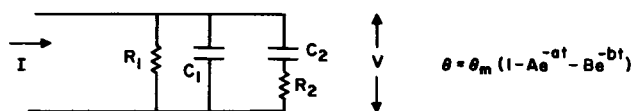
ELECTRICAL EQUIVALENT CIRCUIT
(B)

Figure 4

$$R = R_1 \, R_4 / R_X \qquad \gamma = \frac{I_m^3 \, R_a^2}{2 \, V_3 \, \sqrt{1 + \tan^2\beta}}$$

$$\beta = 3\theta$$
$$\tan\beta = 2\omega\tau$$

ELECTRO-THERMAL PHASE SHIFT BRIDGE
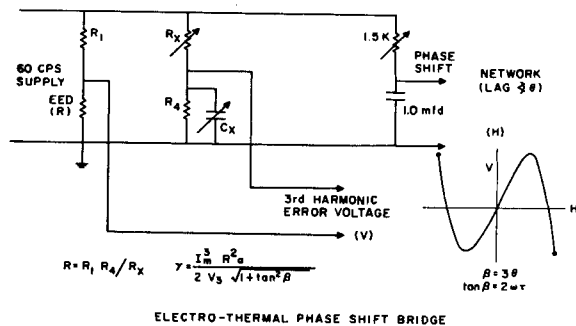
Figure 5

24-15

24. DISCUSSION

Upon request by Mr. Hauser of Aeronautical Systems Division, Mr. Rosenthal identified a paper concerning thermal stacking from radar pulses. It was by Kabik, Solem and Rosenthal; and entitled "Response of Electroexplosive Devices to Transient Electrical Pulses". (Naval Ordnance Laboratory Technical Report 61-20, 17 April 1961).

26. SHOCK INITIATION THROUGH A BARRIER

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The use of barriers in explosive trains is quite common. They normally exist because the construction of the device is such that a barrier is present. However, in some cases, a barrier is introduced in order to aid in propagation of the explosive train. This may be in the "burning to detonation" type devices or for the purpose of shaping the detonation wave. Regardless of "why" barriers exist, they are usually disrupted, fragmented, broken or severely damaged when the train is exploded. This is normally necessitated by the fact that transfer of detonation from one component to another is usually easier if the barrier is penetrated.

The transfer of detonation through a barrier without destroying or penetrating the barrier has never been fully investigated. It can be visualized that such a system would be advantageous where a build-up of gases is required such as in a rocket motor.

In the early part of 1963 the Initiator Section of Picatinny Arsenal was requested to study the feasibility of using the shock transfer method of initiation in a rocket motor. In order to utilize this system it was necessary to determine what, if any, explosives could be initiated by the shock transfer method. An investigation was conducted which revealed that several explosives, ranging from

the very sensitive NOL #130 primer composition to PETN could be initiated

by the shock transfer method provided the conditions were satisfactory.

Barriers between 0.060 inch and 0.115 inch thick were used successfully.

During this investigation it was determined that in order to success-

fully initiate the less sensitive explosives (ie PETN) through a barrier

it was necessary to have them in intimate contact with the barrier material.

This may not be true for the more sensitive explosives such as lead azide

and primer compositions.

The fact that bare explosives could be initiated through a barrier did

not necessarily mean that explosive components would be initiated. It was

therefore necessary to investigate this possibility. Tests were conducted

in which explosive components were substituted for the bare explosives used

previously. During this investigation a series of approximately 60 tests

were conducted using a test set-up as shown on slide #1. As may be seen

from the slide, the donor component was an electrically initiated detonator.

The charge weights in this item were varied in an effort to determine the

range over which successful initiation would take place. The steel barrier

employed ranged from 0.060 inch thick to 0.115 inch thick. The ultimate

thickness was 0.100 inch. I would like to point out that although aluminum

cylinders were used for the initial tests, steel was substituted early in

the program. Furthermore, the receptor component was held next to the

barrier by counter sinking a hole of precise depth to make the component

flush with the top of the steel cylinder.

Upon completion of these tests, the results were closely evaluated and the following conclusions were reached.

a. The charge weight of both the donor and receptor have a definite bearing on the performance of the train. This was evidenced by the fact that when a charge of 90 milligrams of PETN was used as either the base charge in the donor component or as the receptor component and the other charge was only 40 milligrams of PETN there would be considerable damage to the barrier. This damage could easily result in barrier penetration. It was apparent that the two charges must be reasonably in balance. As an example of this, a charge of 90 milligrams of PETN in the donor component easily initiated a charge of 70 milligrams of PETN in the receptor component with limited damage to the barrier. The test components used for these tests were 0.147 inch in diameter.

b. The pressure at which the charge is pressed in the receptor charge will determine the reliability of initiation by the donor charge. Tests conducted on receptors containing PETN pressed at 10,000 pounds per square inch (psi) resulted in an occasional failure (ie the receptor component was not initiated by the donor component). However, when the pressure was increased to 15,000 psi the receptor component functioned reliably.

During the tests just outlined it was noted that the damage to the steel sleeves was very minute. This immediately created the question "Is the receptor component being initiated low order or high order"? In order to determine the order of detonation it was necessary to first be sure that we could produce a definite high order detonation.

In an effort to accomplish this, an M55 stab detonator containing 19 milligrams of PETN as the base charge and lead azide RD1333 and NOL #130 as the other charges was placed in the test fixture in place of the receptor component. It was felt that the NOL #130 would definitely be initiated high order since it is a very sensitive explosive composition. Upon initiation of the donor component the receptor component was initiated. Upon examination of the steel cylinder which contained the M55 detonator it was noted that the hole had been expanded to approximately two times its original diameter. Test fixtures used for housing the receptor components revealed a very little expansion of the hole.

At this point in the investigation it was decided to conduct tests, using the shock transfer method, in a simulated rocket motor test fixture. A portion of this fixture is shown in Slide #2. The donor component contained a charge of 78 milligrams of PETN pressed at 10,000 psi. The receptor component contained a charge of 50 milligrams of PETN pressed at 15,000 psi. The black powder charge consisted of 660 milligrams loose loaded. The barrier for these tests was 0.100 inch thick steel.

The fixture was placed in the simulated rocket motor with propellant. Upon initiating the donor component the entire train functioned satisfactorily. This test was conducted using both a receptor component in one case and an M55 stab detonator in the other. This was done in order to determine what effect the order of detonation would have on the performance of the motor. Based upon the limited tests conducted, it appeared that the order of detonation would not adversely affect the rocket motor performance.

Common sense tells us that a high order and low order detonation cannot act identically on a succeeding explosive or pyrotechnic composition. Therefore, it must be assumed that the order of detonation can determine the performance of the rocket motor. It is apparent then, that some form of control must be maintained over the receptor charge to insure satisfactory and reliable functioning. It is therefore recommended that anyone planning to utilize the shock transfer method of initiation invest both time and money in further characterizing the effects of shock transfer initiation.
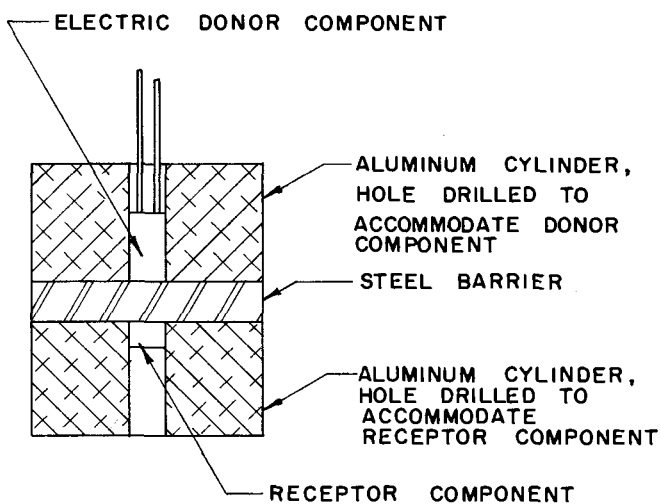
ELECTRIC DONOR COMPONENT

ALUMINUM CYLINDER, HOLE DRILLED TO ACCOMMODATE DONOR COMPONENT

STEEL BARRIER

ALUMINUM CYLINDER, HOLE DRILLED TO ACCOMMODATE RECEPTOR COMPONENT

RECEPTOR COMPONENT

Figure 1

DISC, STEEL, TYPE 4340

BODY

DONOR COMPONENT FIG. 12

.102-.004

ADAPTER NUT

O'RING

ADAPTER

BLACK POWDER

RECEPTOR COMPONENT FIG. 13

Figure 2

26-5
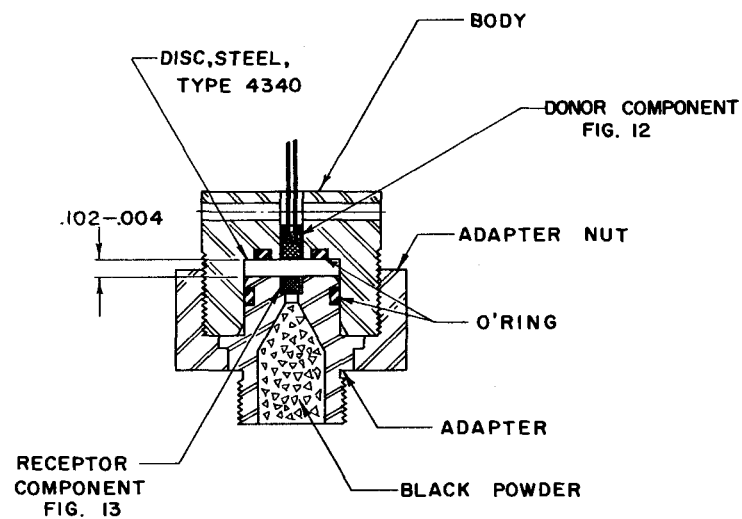
27. A PROPOSED MECHANISM FOR SHOCK INITIATION OF LOW-DENSITY GRANULAR EXPLOSIVES[*]

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INTRODUCTION

Initiation of homogeneous explosives. The mechanism of shock initiation
in homogeneous explosives was elucidated by Campbell et al[1]. Briefly,
initiation occurs in this way: The shock heats the explosive by com-
pression; the hot explosive reacts homogeneously; detonation begins in
the region first heated, namely, where the shock first entered the ex-
plosive; a detonation sweeps through the shocked explosive at a velocity
characteristic of the compressed moving material; the detonation breaks
through the shock front producing in the unshocked explosive an over-
driven detonation which soon decays into a normal stable detonation.
Mader[2] showed by machine calculations that all the measured features of
this mechanism could be predicted quantitatively from the measured or
reasonably assumed constants needed for the kinetics and hydrodynamics
of the explosive involved. Experiments also showed that discrete in-
homogeneities in mainly homogeneous bodies of explosives produced local
points of initiation[1]. Sites of initiation were induced down-stream
from the inhomogeneities and within the homogeneous part of the explosive.
The presence of these hydrodynamic hot-spots permits initiation by shock

1. A. W. Campbell, W. C. Davis, and J. R. Travis, Phys. Fluids 4, 498 (1961).
2. C. L. Mader, Phys. Fluids 6, 375 (1963).

* Work performed under the auspices of the U. S. Atomic Energy Commission.

interaction when the pressure in the parent shock is noticeably lower than that required to initiate the same explosive if truly homogeneous. Evans, Harlow, and Meixner[3] showed that intensification of shock heating is to be expected down-stream of inhomogeneities. They calculated temperatures for the case of a vacuum bubble in nitromethane and found high temperatures in the liquid just beyond where the bubble had collapsed. Assuming hot-spots of this type, Mader[2] calculated the resultant hydrodynamic disturbances, and showed that the calculated critical size of hot-spots which would just produce detonation agreed with the critical size of the inhomogeneities found by experiment. Campbell[4] and co-workers have investigated several solid explosives above 75% crystal density. They demonstrated that nitromethane, if packed with carborundum particles, shows the initiation characteristics of an imperfect solid rather than the characteristics of a homogeneous explosive, which nitromethane usually exhibits. The cumulative results of all these investigations form a quite satisfactory picture of the initiation of homogeneous condensed explosives. The extension to imperfect homogeneous explosives may be expected to apply very well to practical secondary explosives in the high density region.

Granular explosives. Shock initiation of low-density granular explosives has not been treated as completely as has that of high-density explosives. In granular explosives at low densities the inhomogeneities, instead of being occasionally present in a continuous body of explosive, become the main feature of the charge. In fact, the explosive is no longer the

3. M. W. Evans, F. H. Harlow, and B. D. Meixner, Phys. Fluids 5, 651 (1962).
4. A. W. Campbell, W. C. Davis, J. B. Ramsay, and J. R. Travis, Phys. Fluids 4, 511 (1961).

continuous matrix; the granules of explosive may rather be considered as discrete bodies in a continuous matrix of air. Under these circumstances it is not clear that principles from the homogeneous or almost-homogeneous regimes can be applied.

Grain-burning theory. Our investigation of the shock initiation of granular explosives has been carried out with reference to ideas advanced by Kistiakowsky[5] about twenty years ago. It had been shown by MacDougall and Jacobs[6] that high explosives can be made to deflagrate in a controlable fashion at quite high pressures. On this basis it was proposed that in a detonation each grain of a granular explosive deflagrates under the high pressure and temperature induced by the shock associated with the detonation wave. Thus in a full strength detonation the grains are completely consumed by this surface reaction soon enough to support the wave. These ideas were first proposed as a mechanism for the transition to detonation from deflagration, making use of the idea of "precursor shocks" resulting from high flow velocities in violent deflagrations[7]. They were also proposed for the mechanism by which explosives detonate by mechanical impact. Bowden[8] and his co-workers had shown the importance of hot-spots in initiation by impact, and had demonstrated three ways in which such hot-spots could be formed: (1) heating by friction, (2) heating by rapid viscous flow, and (3) heating by adiabatic compression of gas bubbles.

5. G. B. Kistiakowsky, Third Symposium on Combustion, Flame and Explosion Phenomena, (Williams and Wilkins, Baltimore 1949), p. 560. These ideas were developed by Kistiakowsky and his colleagues in the early 1940s.
6. Science in World War II. Chemistry volume (Little, Brown, and Co., 1948) p. 64.
7. A. R. Ubbelohde in Third Symposium on Combustion, Flame and Explosion Phenomena (Williams and Wilkins, Baltimore 1949), p. 570.
8. F. P. Bowden and A. D. Yoffe, Initiation and Growth of Explosion in Liquids and Solids, (Cambridge Univ. Press, 1952), p. 2.

The growth of deflagration would be a second stage resulting from any of these ignition methods.

If it is true that surface burning takes place in a detonation wave in granular explosives, then the first problem in explaining how a pure shock initiates a granular explosive is the problem of explaining how the grain surfaces can be ignited. In a granular charge the component to be most strongly heated by shock compression will be the most compressible one, namely, the interstitial gas. It is quite plausible that this hot gas should ignite the surfaces of the grains since it surrounds them on all sides. Thus the grain-burning theory leads to a picture of the detonation process very different from the one which must obtain in a homogeneous explosive.

EXPERIMENTS ON GRANULAR EXPLOSIVES

Effect of interstitial gas on sensitivity. The easiest point to test concerning the initiation of granular explosives is the question of the mode of ignition. Does the compressed interstitial gas provide the ignition mechanism? Cachia and Whitbread[9] evacuated some small-gap-test PETN receptor charges to a pressure less than 10^{-4} torr, and found no change in sensitivity. In these experiments the amount of gas in the interstices was reduced by a factor of at least 10^6. If the interstitial gas were playing an important part in ignition such complete removal would be expected to have an effect. It is possible that on removal of the gas another means of ignition would present itself, but this precise substitution with no perturbation of the overall process must be regarded as unlikely.

9. G. P. Cachia and E. G. Whitbread, Proc. Roy. Soc. (London) A246, 268 (1958).

The temperature reached by shock-compressed gas in the interstices of a granular pressing depends markedly on the nature of the gas. Reynolds and Seely[10] have calculated the temperatures achieved by shock processes in argon and methane, and found a temperature differential between the two gases of thousands of degrees over a wide range of shock strengths. Seay and Seely[11] reported shock initiation experiments on wedges of PETN which showed no effect on the distance to detonation of substituting either argon or methane for air as the interstitial gas. This is shown in Fig. 1.

It has, of course, been pointed out that the production of high temperature in the gas is not alone enough to accomplish ignition; sufficient heat must be transferred to the solid grain surface to raise its temperature high enough to start deflagration. Thus the differences in heat transfer coefficients for various gases must be considered. Roughly compensating differences in the heat transfer coefficients of some gases have been found[12,13], but it seems unreasonable to expect that the wide variety of temperatures achieved by different gases should be compensated exactly in every case. From the experiments with various gases, the only reasonable conclusion is that the interstitial gas is not involved in determining the shock sensitivity of granular explosives. The experiment of Cachia and Whitbread[9] and also one of Seay and Seely[11], in which the charges to be initiated were evacuated, seem to avoid this difficulty since in these cases the amount of energy in the compressed gas is cut down almost to the vanishing point. From the vacuum experiments

10. C. E. Reynolds and L. B. Seely, Nature, 199, 341 (1963).
11. G. E. Seay and L. B. Seely, J. Appl. Phys. 32, 1092 (1961).
12. G. J. Bryan and E. C. Noonan, Proc. Roy. Soc. (London) A246, 167 (1958).
13. J. I. Evans and A. M. Yuill, Proc. Roy. Soc. (London) A246, 176 (1958).

it can be concluded that the gas is not responsible for ignition of the grain-burning reaction. Influenced by this, one may question the existence of grain burning itself, but rejection of the interstitial gas as the ignition agent does not logically require this.

The light from granular explosives. With the gas plainly in the interstices, and a strong shock running through the pressing, it is hard to see how the gas can avoid being compressed. If compressed, the gas must become hot to a degree depending on its hydrodynamic and thermodynamic properties. Yet there is no evidence from the sensitivity behavior of the explosive that the hot gas is there; at least, it cannot be playing the crucial role in ignition that has sometimes been assigned to it. It therefore seemed appropriate to look for other evidence concerning the state of the interstitial gas in granular explosives, and this was the occasion for a study of the light emitted by a full strength detonation wave.

The nature of the light given off by detonating granular explosives is demonstrated in Fig. 2. The structure of the four charges is shown in the diagram in the upper part of the figure. They were initiated by Primacord from a common booster. The images of the ends of these charges were focused on the slit of a rotating mirror camera (RMC) as shown. The resulting RMC picture is reproduced at the bottom of the figure. The first trace on the right is a record typical of many granular explosives over a wide range of densities. The other three charges differed in the position of a light shield which covered half the cross section of the charge at each of three levels. The effect of these shields on the light observed enables one to identify the position of origin of the various light signals. Between the camera and second charge from the right a

very thin steel sheet was placed over half the charge as shown in the
diagram. From this it may be seen that light at the bottom of the record,
that is, at late times, comes from the shock wave in the air. On the
surface of the third charge a thin layer of lead was evaporated. The
very brilliant flash of light is seen to occur just before the shock came
through the lead on the crystal surfaces. Finally, the lead was evaporated
on a surface pressed 0.8 mm below the end of the charge holder and the
charge completed with a thin second pressing at the proper density. From
this it can be seen that the light appearing earliest in time is emitted
by the detonation front and scattered through the portion of the charge
not yet traversed by the wave. The so-called detonation light arises
from within the charge and is quite bright. From the intensity relative
to the air shock it would be possible to believe it arises from the inter-
stitial air.

However, let us compare the intensities of detonation light when
various gases are present in the interstices. In Fig. 3 is a diagram
of four HMX charges fired in a similar manner to those in Fig. 2 but
containing argon, air, CO_2, and CH_4. Note that the intensity of the
shock light at the extreme bottom of the RMC picture varies from gas to
gas in about the way expected from calculations of shock temperatures.
Half of the argon-filled charge has been shielded with an ND 1 filter
(transmits 10%) because of the extreme brilliance of the argon shock
light. Comparison of the shock light in the argon-filled case with
that of the other gases is difficult because of its brilliance. From
the negative it can be estimated that the shock in argon is 50 times as
bright as in air. Detonation light cannot be distinguished in the argon-
filled charge because of the brilliance of the free-running argon shock.

For the other gases it can be seen that detonation light has the same intensity regardless of the nature of the gas. Figure 4 shows four additional gases. From these pictures we conclude that there is something bright and presumably hot within a granular explosive charge, but it is not to be accounted for by compression of the interstitial gas.

In Fig. 5 are shown traces from charges of PETN pressed to different percentages of crystal density as indicated by the percentages written above the traces. It will be seen from the RMC traces that the total amount of detonation light becomes less as the pressing density increases. We believe this indicates that detonation light arises in the interstices.

In Fig. 6 are RMC traces of detonations emerging from three PETN charges pressed at a density 75% of that of the crystal. The particle sizes in the three cases are quite different. For the very fine PETN, it will be noticed that the detonation light is a smooth line. For the coarse PETN the light is broken up into patches which are dispersed in space and time. We believe this indicates again that the individual interstices are causing the light.

In Fig. 7 is shown another RMC picture of some very large PETN grains. In this picture the individual grains can be identified and it can be established that the light flashes do not correspond to the features of the front faces of the crystals. We believe that they are related to the spaces behind these crystals. The flashes therefore indicate the positions of those interstices, and also show some effect of the properties of the rear faces of the front-row crystals.

In Fig. 8 are shown RMC traces from granular RDX charges, one in air at normal pressure and the other at a pressure of a few microns.

This degree of vacuum is sufficient to demonstrate the point to be made

here. Other experiments have been run in which the pressure was certainly

below 10^{-4} torr, but the fore-pump vacuum in this shot produces a film

that is about the same as a truly high-vacuum shot. Although the light

from the free-running shock is practically reduced to zero in the case

of the evacuated shot, the intensity of the detonation light is unchanged.

In all of the photographs presented so far detonation light is extremely

bright. It is quite impossible for the small amount of residual gas in

the evacuated charge to radiate at this total output. The only material

available is the explosive itself. We have therefore proposed that part

of the material of which the explosive is made, undoubtedly more dissociated

and more ionized than it is under Chapman-Jouguet conditions in the deto-

nation, is the source of detonation light.

MECHANISM FOR DETONATION LIGHT

Experimental demonstration. The mechanism by which part of the explosive

products can be brought to a sufficiently high temperature to explain

detonation light has been arrived at by a combination of experiment and

theory. It was possible to design a one-dimensional experiment using

single crystals of sufficiently large dimensions to be able to see that

a strong light signal is generated when the explosion products from one

crystal expand and then collide with another solid crystal. The arrange-

ment for this large-scale experiment in simplified geometry is indicated

by the diagram in Fig. 9, and the resulting RMC film is shown there in

register with the diagram. In this experiment the interstitial gas has

been evacuated from the space between the crystals since at this scale

for the interstice, the gas would be an important source of light and

could obscure what we wish to observe. On the basis of this sort of

picture we have come to the conclusion that the high temperature material responsible for detonation light is produced by the process of stagnation occurring in the detonation products.

Description of stagnation. Consideration of the process of stagnation reveals it to be particularly well adapted to the production of high temperature. At the start of the expansion the entire first crystal can be thought of as gaseous detonation products at Chapman-Jouguet conditions. The temperature is appreciable, but only high enough to be photographed with some difficulty. The gas also contains potential energy in two forms; as pressure, and as interatomic repulsion, since the density is above that of the original crystal. When the detonation front reaches the face of the crystal the expansion starts immediately. Theory tells us that the pressure drops to zero at the extreme front of the expansion, $p_e \rightarrow o$, and that density and temperature do likewise, $\rho_e \rightarrow 0$, and $T_e \rightarrow 0$. In the limit at the front, the material is traveling at "escape velocity", and the various other forms of energy have been converted completely to the kinetic form. Back of the front the conversion to kinetic energy is progressively less complete. When this fast-moving material strikes the solid grain ahead it is, for the very first material, completely mismatched. As a result the velocity is dropped to zero and a large fraction of the energy is randomized. The stagnated material forms a shock front running against the incoming material and in the limit, that is for the very first material, the strength of the shock is infinite as gaged by the pressure ratio. The temperature of the recompressed material must be calculated for such a shock. The process is an excellent way of producing high temperature.

To make these ideas more concrete let us consider the one-dimensional case with the help of the x-t diagram in Fig. 10. The expansion part of

the process can be considered in terms of the theory of characteristics. We will assume that the detonation products can be treated as a polytropic gas with $\gamma = 3$ in which case the theory of characteristics becomes particularly simple[14]. The leading characteristic is a straight line whose slope is equal to the escape velocity. Characteristics farther back in the flow have slopes equal to the sum of the particle velocity plus the speed of sound at each point. Thus under these assumptions the solution of the expansion flow is fairly simple.

The method of characteristics must be abandoned in order to be able to treat the shock wave advancing into the expanding products; differential equations no longer apply, and the recompression is not an isentropic process. If we retain our assumption that the gas is polytropic, we can say that for a strong shock the temperature ratio across the shock is proportional to the pressure ratio, or

$$\frac{T_R}{T_e} \propto \frac{P_R}{P_e}$$

where the subscript R refers to the reflection and subscript e to the expansion. The relation between the temperature in the detonation T_D and that in the reflection T_R thus depends on the state variables in the expanded gas, the highest temperature being reached by the first material to be stagnated. Later gas, flowing into the shock at higher pressure reaches a lower temperature depending on its position in the expansion.

14. J. O. Hirschfelder, C. F. Curtiss, and R. B. Bird, Molecular Theory of Gases and Liquids, (Wiley, New York 1954) p. 740.

The expansion velocity into a vacuum for a polytropic gas starting from rest is

$$u_e = \frac{2c_D}{\gamma-1} \, ,$$

where c_D is the sound speed in the detonation.

With a starting particle motion in the detonation u_D, this becomes

$$u_e = \frac{2c_D}{\gamma-1} + u_D \, ,$$

which, since $\gamma = 3$, simplifies to

$$u_e = c_D + u_D \, .$$

Thus the time t_t required for the material to cross the distance L between the crystals is

$$t_t = \frac{L}{c_D + u_D}$$

The equations describing the flow can then be expanded* in terms of a parameter W which is given by

$$W = \frac{t - t_t}{t_t} \, ,$$

with t being the time measured from the start of the expansion. The resulting linearized expressions can be expected to be valid over a period about one-tenth as long as the transit time; that is for

$$W < 1/10$$

* Carried out for another purpose by B. Kent Harrison, LASL.

The ratio of the temperature in the stagnated region to the temperature in the detonation is, for $\gamma = 3$,

$$\frac{T_R}{T_D} \approx 2\left(1 + \frac{u_D}{c_D}\right)^2 (1 - W)$$

where u_D is the particle velocity in the detonation, and c_D is the sound velocity in the detonation.

This expression is useful, even though it is not clear what values for u_D and c_D are appropriate to the other assumptions of the calculations*. Taking the values u_D = 2 mm/μsec. and c_D = 5 mm/μsec. which are approximately correct for solid explosives at crystal density (but not proper for a perfect gas) the ratio becomes

$$\frac{T_R}{T_D} \approx 4 (1 - W)$$

which predicts a temperature four times the detonation temperature for the very first material to stagnate, with linearly (because of the dropping of higher terms) decreasing temperature as the stagnation proceeds. This same treatment predicts an average density of a few tenths of a gram per cubic centimeter for the stagnated material at W = 0.1.

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* We are indebted to Dr. Ian C. Skidmore, United Kingdom Atomic Weapons Establishment, for making available to us a simple development indicating that for the first material T_R = 5.3 T_D.

It was first shown that the interstitial gas in a pressing of granular explosive is not involved in the initiation of detonation in that pressing. Then it was shown that detonation light did not arise from the interstitial gas. Now it has been proposed that this very bright light, which is nearly always present in the detonation of granular explosives, arises by a process of stagnation in the products of detonation.* The calculations that have been made show that there is a rise of temperature in the combined expansion-stagnation process. The specific temperatures reached in real detonation products are in considerable doubt because the limiting factor is undoubtedly ionization and no detailed calculation involving ionization has been attempted. A reasonable guess for the temperature is thought to be about $10,000°K$. The density will be a few tenths of a gram per cubic centimeter. This material stagnated against an explosive grain constitutes a very effective hot-spot. As we have so far expounded stagnation, however, it concerns full-strength detonations. The problem remaining is to present the evidence for the same sort of mechanism during the process of shock initiation.

* It might be mentioned parenthetically that we now have the problem of explaining why, in most cases, we see no evidence of the compressed interstitial gas. It seems reasonable to propose that the gas, although very hot, is very "thin" in the optical sense, and therefore does not emit much radiation. It is not appropriate to discuss this further here.

Initiation light in tetryl. The relationship of detonation light to the initiation process can be studied by means of the wedge technique. This technique has been explained in detail elsewhere.[11,15] In Fig. 11* is shown a RMC picture of a bare wedge of tetryl illuminated with an argon flash. The progress of the initiating shock can be followed because the surface of the wedge ceases to reflect light into the camera when the shock emerges. When the wave has gone over to full strength detonation, bright detonation light can be seen. A certain amount of such light can be seen before full detonation velocity is reached. In Fig. 12 is shown a photograph of a similar wedge but without the auxiliary argon light. Every effort was made to collect all the light possible from the wedge. In this picture it can be clearly seen that the first appearance of light comes early in the acceleration of the shock. As the wave builds up toward detonation the intensity of the light also increases, culminating in detonation light. This close association of the light with the initiation process has suggested that there is a functional connection between the two. Initiation light shows all of the peculiar characteristics of detonation light, and in fact, is believed to be the result of the same sort of process as that which gives rise to detonation light.

The fact that the initiating shock is at first dark should be interpreted in light of the detection limit of the camera, estimated no lower than 3500°C. At this stage of the evidence we can note that if a stagnation process exists all along the course of the initiating shock, it is entirely reasonable that weak stagnations in the unaccelerated

15. T. E. Holland, A. W. Campbell, and M. E. Malin, J. Appl. Phys. 28, 1217 (1957).

* This work was performed by I. E. Lindstrom.

shock should not be detected by the camera. If this were the case these "dark" hot-spots would nevertheless be hot enough to be very reactive chemically and could be responsible for the observed acceleration of the wave. The crucial part of the initiation process is the time when the shock first enters the charge, and at that time the shock must be essentially nonreactive. This immediately raises the question as to whether a stagnation process can be legitimately postulated for shocks in inert materials.

Light from shocked inerts. Figure 13 shows a record from a Comp B-3 charge which contained along its length sections of granular sodium chloride. The entire assembly was submerged in water to suppress air shock light. The sequence of the sections of the charge is shown in the sketch at the bottom of the figure. This sort of experiment was used by Paterson[16] in Scotland to indicate that chemical reaction was not necessary to produce the same sort of light as detonation light. It can be seen that the shock light from the sodium chloride is much brighter than the light from the Comp B-3, the important feature being the porosity of the salt. Blackburn and Seely[17] used the methane and the two open gas chambers to show that the light does not arise from the interstitial gas. It can be seen on the negative from which this print was made that the light from the air-filled sodium chloride bed is actually somewhat brighter than from the methane-filled bed. This has been noticed for several inerts when strong shocks are used. The important point to be made here is that for any gas there is at least a certain amount of light emitted by the particle bed and this minimum

16. S. Paterson, Nature, 167, 479 (1951).
17. J. H. Blackburn and L. B. Seely, Nature, 194, 370 (1962).

is extremely bright. The light observed for the methane-filled particle bed is probably close to the minimum for the conditions in this experiment.

Figure 14 is a RMC picture of two charges of sodium chloride, one of which has been evacuated to less than 10^{-4} torr. The presence of light of undiminished intensity after 99.99998% of the air has been removed, is strong evidence that the air is not responsible for the production of shock light in the charge. Instead it seems clear that hot sodium chloride is emitting the light. It is suspected that stagnation is the mechanism by which a small part of the sodium chloride can become sufficiently hot.

In Fig. 15 shock light is recorded from granular beds of sodium chloride, sugar and sand. In our experiments all transparent or translucent materials produced this light when a particle bed was shocked. In Fig. 16 are shown pressings of large-particle-size ammonium sulfate filled with argon (on the left) and methane(on the right) shocked with waves of three different pressures. The material from which the pressings were shocked was Lucite in all cases. The match to the pressings was quite good, there being only a few kilobars difference between the pressure in the Lucite and in the pressings. It will be noticed that as the shock strength is lowered the luminosity in the argon-filled and methane-filled charges becomes more nearly equal.

Restrictions on the production of shock light. An extremely brilliant light is produced by shocks in beds of granular inerts. In almost every respect, this light shows the same characteristics as does detonation light (effect of density, particle size, vacuum, etc.), the one exception being that the light output is somewhat increased by interstitial gases that become very hot on compression. But for all such charges interest is centered in explaining the very bright minimum of light intensity that

is observed even with the coolest interstitial gas and also with a good
vacuum.

In the case of detonation light the plane wave experiment with two
single crystals of PETN was crucial in establishing the mechanism of
light production. It can be reasoned beforehand that a similar experi-
ment in simplified geometry with inert crystals will be unsuccessful.
It was actually tried with two plates of glass and an evacuated space
between them. The way in which the free surface of the first piece of
glass will move is well-known; namely with twice the particle velocity
of the shock. Because the glass is a solid it will move practically as
one piece. In contrast to detonation products, its density will not
approach zero. On colliding with the second piece of glass it will be
only slightly mismatched and the particle velocity will be reduced
almost exactly to its value in the original shock. The shock will be
reconstituted in the second piece of glass. The temperatures that
could be produced by such a process in the first piece of glass can be
estimated fairly accurately[18] and certainly lie far below the detection
limit of our camera.

However, a slight variant of the two-plate-plane-wave experiment
did produce light, and this result is believed to indicate clearly
what conditions are necessary for stagnation light in inert materials.
In this experiment a triangular-shaped trough was cut in the front
face of the first plate and the experiment otherwise left as described
before. The effect of this triangular cut was to perturb the plane
wave and produce an interaction when the sides of the cut met. This

18. J. M. Walsh and R. H. Christian, Phys. Rev., 97, 1544 (1955).

produces an example of the so-called cavity effect[19]. Judging from target patterns and flash x-ray pictures resulting from glass-lined cavity charges, the glass in this experiment can be expected to travel across the evacuated space as a fine spray. The RMC photograph resulting from this experiment is shown in Fig. 17. There it can be seen that light was produced opposite the notch at the surface of the prism of glass. Thus we come to some understanding of how it is possible to observe very brilliant shock light in pressings of granular inerts and at the same time is not possible to observe any light in a simplified plane wave experiment. Shock irregularities are necessary for the production of light; the inert material must be broken up by the interactions so that it will be mismatched with the solid material with which it collides. Of course, in a pressing, with random orientation of irregularly-shaped particles such interactions will be provided in great variety.

Stagnation theory of shock initiation. The proposed mechanism of shock initiation, then, involves stagnation occurring among the grains of an explosive pressing. When it first enters the assembly of grains the shock behaves about as it would on entering an assembly of inert particles. The shock pressure in the grains can in some cases be as little as 1/50 that necessary to start homogeneous reaction. The shocks are randomly oriented within the grains. On leaving the grain surfaces, the shocks cause the material to move off, and because the surfaces are randomly oriented to each other, this material interacts in various ways, producing jets in some cases. The projected material, which

19. G. Birkhoff, D. P. MacDougall, E. M. Pugh, and G. I. Taylor, J. Appl. Phys., 19, 563 (1948).

apparently must be broken up and must act hydrodynamically rather than as particles, collides with the surface directly ahead. Depending on the nature and orientation of that surface, the jetted material stagnates to a greater or less degree. The actual conditions, both of the original jetting and the final stagnation, are difficult to calculate. The variety of these conditions reflects the random orientation of the surfaces in the pressing. However assuming that one could calculate a sort of "standard" situation (for instance, a two-dimensional triangular cavity charge with a 45° apex angle whose jet collides with a plane surface at right angles to the jet axis) one could then be sure of finding stagnation hot-spots with a wide variety of temperatures, some few hotter than the standard, and no doubt many at lower temperatures.

Stagnation hot-spots are no doubt similar to other sorts of hot-spots except that they are not isotropic. The hottest material lies directly against the surface of the solid explosive particle and the temperature behind this falls as the distance to the surface increases. Heat transfer to the surface directly ahead would be rather efficient because of the density and turbulence. At the edges of the hot-spot the explosive surface of the grain against which stagnation takes place can be ignited by the spread of surface burning. From the rear increasingly colder material at higher density flows toward the hot area. The life of the hot-spot must be controlled by the same sort of factors that have been found to control the life of isotropic hot-spots. Heat conduction and hydrodynamic effects will tend to cool them; the rate of reaction of the inflowing material and the rate of spreading of the deflagration along the surface will tend to keep the hot-spots in existence. The question as to whether a given marginal hot-spot can start a reaction that will

eventually build up sufficiently so that energy can be supplied to the original shock must depend on the size of the hot-spot among other factors. Large hot-spots will grow, small ones will die out.

Disproof of the interstitial gas as the ignition agent would not necessarily dispose of grain-burning. It is also true that if stagnation is adopted as the ignition mechanism, grain-burning need not be adopted. However it seems reasonable that, because of the position of the hot material, grain burning should start from stagnation hot-spots. Evidence on this point may be obtained from other data on rates of growth to detonation under various conditions. The performance of sensitive granular secondary explosives suggests that grain-burning does occur. On the other hand it is certainly possible that other modes of reaction occur in other explosives--primary explosives, for instance.

INITIATION BEHAVIOR IN GRANULAR SECONDARY EXPLOSIVES

The existence of stagnation hot-spots is supported mainly by experiments on detonation light and shock light. The fact that shock sensitivity of granular explosives does not depend on the interstitial gas adds support over against the proposal for ignition by the interstitial gas, but actually there are other possible ways of generating hot-spots which can be altered in one respect or another so that they will explain all the well-established facts about explosives initiation. However it is not easy to explain shock light, detonation light, and initiation light without stagnation.

One set of circumstances in shock initiation of granular explosives might result in the ignition stage of the process being the critical one. This would mean that the question of whether the stagnation hot-spot could grow or not would determine whether the explosive detonated. The

chances for growth of the hot-spot would depend on the size of the interstitial spaces. This in turn depends at a given density on the size of the particles. We thus come to the conclusion that when the initial growth of the hot-spots is in question a granular explosive composed of large particles would be more sensitive than the same explosive composed of small particles. This will be quite surprising to those used to thinking in terms of the grain-burning theory. However, it is not a prediction exclusively associated with stagnation. Other theories can be adjusted to yield the same result: hydrodynamic hot-spots within the grains would act in the same way; and some assumptions concerning the heat transfer from compressed interstitial gas will yield the same result[20]. Under other circumstances with the same explosive, or perhaps under any circumstances that can be achieved in practice with certain explosives, the rate of growth to detonation may be the critical factor determining whether the explosive will detonate or not. In such cases the initiation behavior will be as predicted by grain-burning. The explosive will be more sensitive when the particle size is small than when the particle size is large. Practical determination of the sensitivity will require a charge several diameters long. Initiation behavior of this type can not be observed in an experiment that can be validly described as plane-wave or one-dimensional.

<u>Gap test results for tetryl.</u> Gap tests have a poor reputation as sources of fundamental information since so many puzzling gap test results have been left unexplained. It is believed, however, that with care gap tests can produce valid data over a wide variety of conditions.

20. A. Maček, Private communication (1963).

Results[21] from a 1-5/8" diameter gap test are shown in Fig. 18 for two particle sizes of tetryl. The thickness of the Lucite attenuator is plotted against the density. This system has been calibrated for pressure by free-surface measurements, and the results could be quoted as pressure in the tetryl. For present purposes the Lucite thickness is adequate. Notice that the finer material requires a thinner attenuator, that is, is harder to initiate than the coarse material. This is interpreted to mean that the life of the stagnation hot-spots is the critical question determining the sensitivity of tetryl in these tests.

By way of an example of the puzzling nature of gap test results observe the data[21] from the small-scale gap test on the same two samples of tetryl shown in Fig. 19. This small-scale test uses a 1/2-inch diameter acceptor charge. The variation of the sensitivity of the large particle-size tetryl with density is perplexing and quite different from the sensitivity given by the large-scale test. In general it is not satisfactory to use this large a particle size in the small-scale test, apparently because the growth to detonation becomes the critical stage of the overall initiation process for some densities, whereas in the large-scale test the ignition stage is critical under all conditions.

This is confirmed by the nature of the results for the large particle size at densities of 1.3 gm cm^{-3} and below in the small-scale test. In this region the dents in the witness blocks that are used to identify detonation are smaller than normal. Usually an acceptor charge length of one diameter will give as good results as any longer charge

21. J. O. Johnson, Private communication, report in preparation.

length, and will produce a sharp transition as the attenuator thickness is decreased, from no dent at all indicating failure, to a full size dent representing detonation. For densities of 1.3 gm cm^{-3} and below, however, a sharp transition can be obtained only by using charge lengths greater than three diameters. Thus the detonation requires a long run for growth. Apparently failure is being determined by the processes postulated for the grain-burning theory. The size of the tetryl particles apparently guarantees adequate stagnation hot-spots in the initial stage of the process, but the low surface area available for subsequent grain-burning makes this latter the critical process in the small-scale geometry.

Gap test results on PETN. The sensitivity of PETN is sufficiently great that particle-size samples we have tried behave reasonably in the small-scale gap test. In Fig. 20 are shown results[21] on two particle sizes of PETN. The value at 1.75 gm cm^{-3} was obtained by Urizar[22]. Note that the smaller particle size material is less sensitive than the larger. Also note that very close to crystal density the sensitivity becomes very noticeably less. At this same density the light from stagnation is very much reduced (Fig. 5). Interesting possibilities for additional work include the determination of particle size effects and rate of growth to detonation at this density.

In Fig. 21 the attenuator thickness (in the small-scale gap test) for 50% fire are plotted[23] against the specific surface of a variety of PETN samples all at a density of 0.95 gm cm^{-3}. The larger the surface (finer PETN grains), the less sensitive the PETN to shock initiation.

22. M. J. Urizar, Private communication.
23. R. H. Dinegar, R. H. Rochester, and M. S. Millican, Explosivstoffe, in press (1963).

It has been indicated that after ignition by stagnation, grain-burning is a likely mechanism for spreading of the reaction. In Fig. 22 are shown some data[24] which are consistent with this proposal. The time from the entrance of the initiating shock into the acceptor until the emergence of the detonation from the end of the acceptor has been plotted as ordinate against the attenuator thickness as abscissa for two particle sizes of PETN. Although the transit times depend on the strength of the initiating shock, the curve for the fine PETN lies lowest. This means that the time required for the growth of the shock to detonation is less for the larger specific surface, in agreement with the proposal that grain-burning is the mechanism for reaction. We are reporting here total times whereas what we would like to obtain are rates of growth or better yet rates of reaction. Here is a place for further experimentation by more elaborate methods.

Attention should be drawn to the fact that these tests illustrate the association of lower sensitivity with more rapid growth to full-speed detonation. Information to date indicates that this is not at all rare among reasonably sensitive secondary explosives. This is quite definitely not the association to be expected on the basis of the old grain-burning theory. Recognition of this situation can be of great aid in the design of explosive devices.

In Fig. 23 are plotted some preliminary small-scale gap-test results[25] for PETN samples thoroughly wet with water*. All the samples

24. R. H. Dinegar, R. H. Rochester, and M. S. Millican, ACS Symp. on Detonation, September 1963.
25. R. H. Dinegar, et al, Private communication.

* This sort of experiment was suggested by Professor F. P. Bowden of Cambridge University in September 1960.

are of course less sensitive than the corresponding dry samples. However, the fine samples are now more sensitive than the large--the slope of the curve has changed sign. It is believed that the mode of ignition, and perhaps also the mode of reaction, has changed. The introduction of a material as dense and incompressible as water in the interstices would be expected to prevent stagnation. One of the possibilities for initiation might be by means of hydrodynamic hot-spots within the grains. If this is so the rate of build-up to detonation might also be different, since surface burning would probably not be involved in the water-filled charge. Further measurements on this type of system are in progress.

CONCLUSION

Stagnation has been proposed as a hydrodynamic mechanism for production of detonation light. Through a study of the light from shocked beds of inert particles and the association of light similar to detonation light with the process of shock initiation in tetryl,we have been led to postulate stagnation hot-spots as the ignition mechanism for shock initiation of granular explosives. Because the stagnation hot-spots occur against the surface of the down-stream grains, it is proposed tentatively that growth to detonation (as distinct from ignition) is controlled by the rate of reaction of the surface of the grains.

ACKNOWLEDGEMENTS
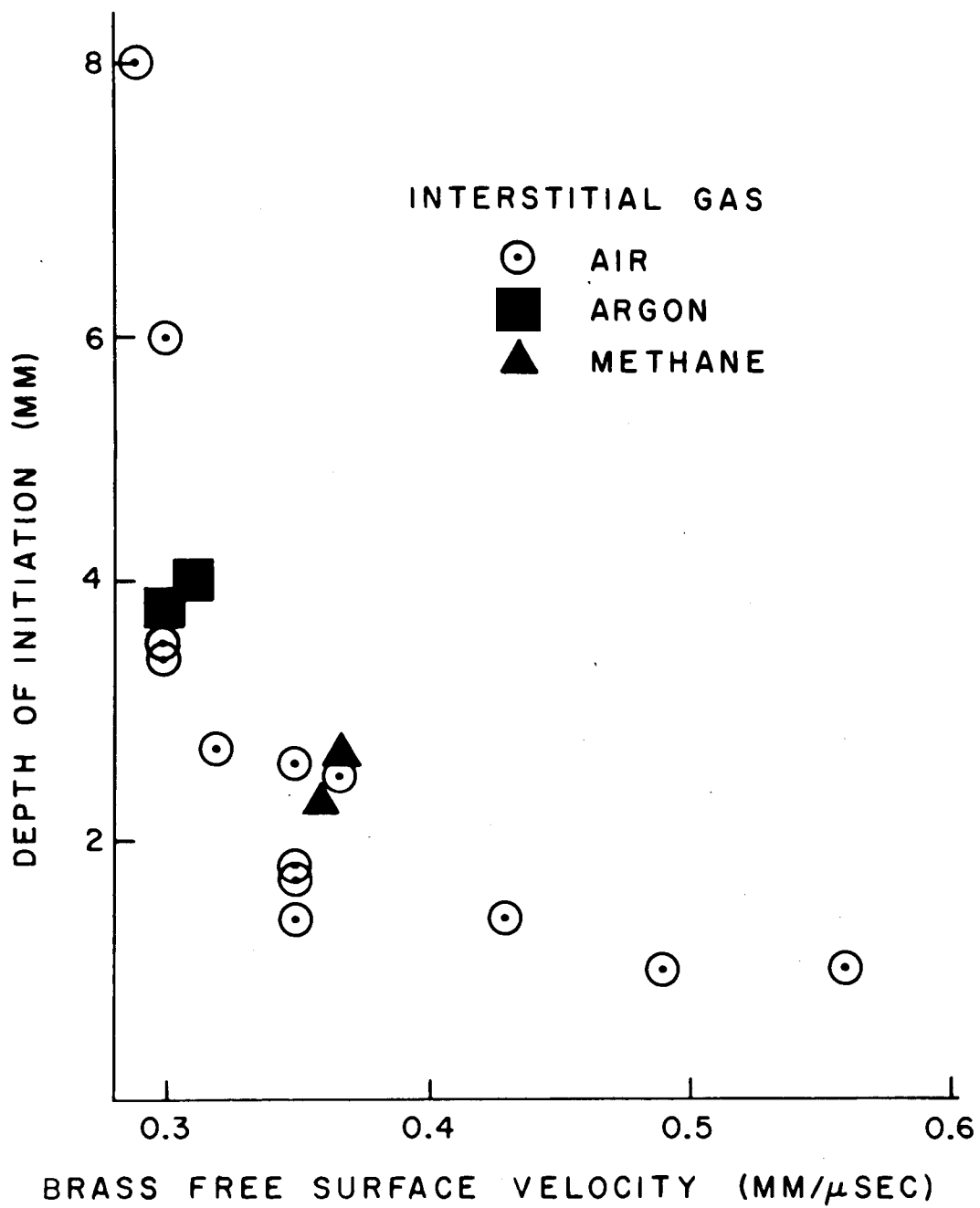
Fig. 1 Depth of initiation vs brass free surface velocity (a measure of shock pressure) for PETN at density 1.0 g cm^{-3}. Data are from plane wave wedge experiments described in reference 11.
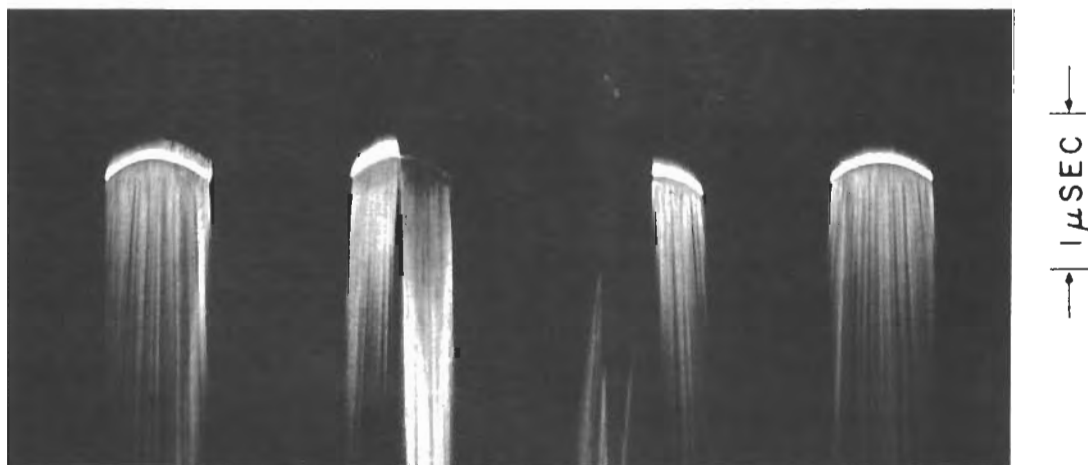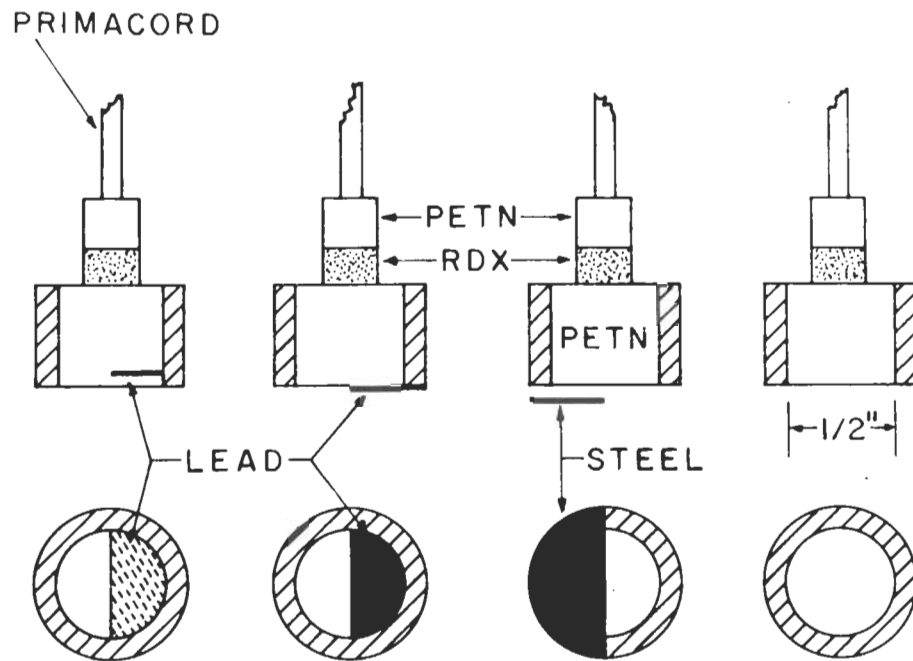
Fig. 2 Rotating mirror camera (RMC) traces of detonation waves emerging from pressings of PETN at 50% of crystal density. Light shields were placed as shown to demonstrate the position of origin of the light signals.
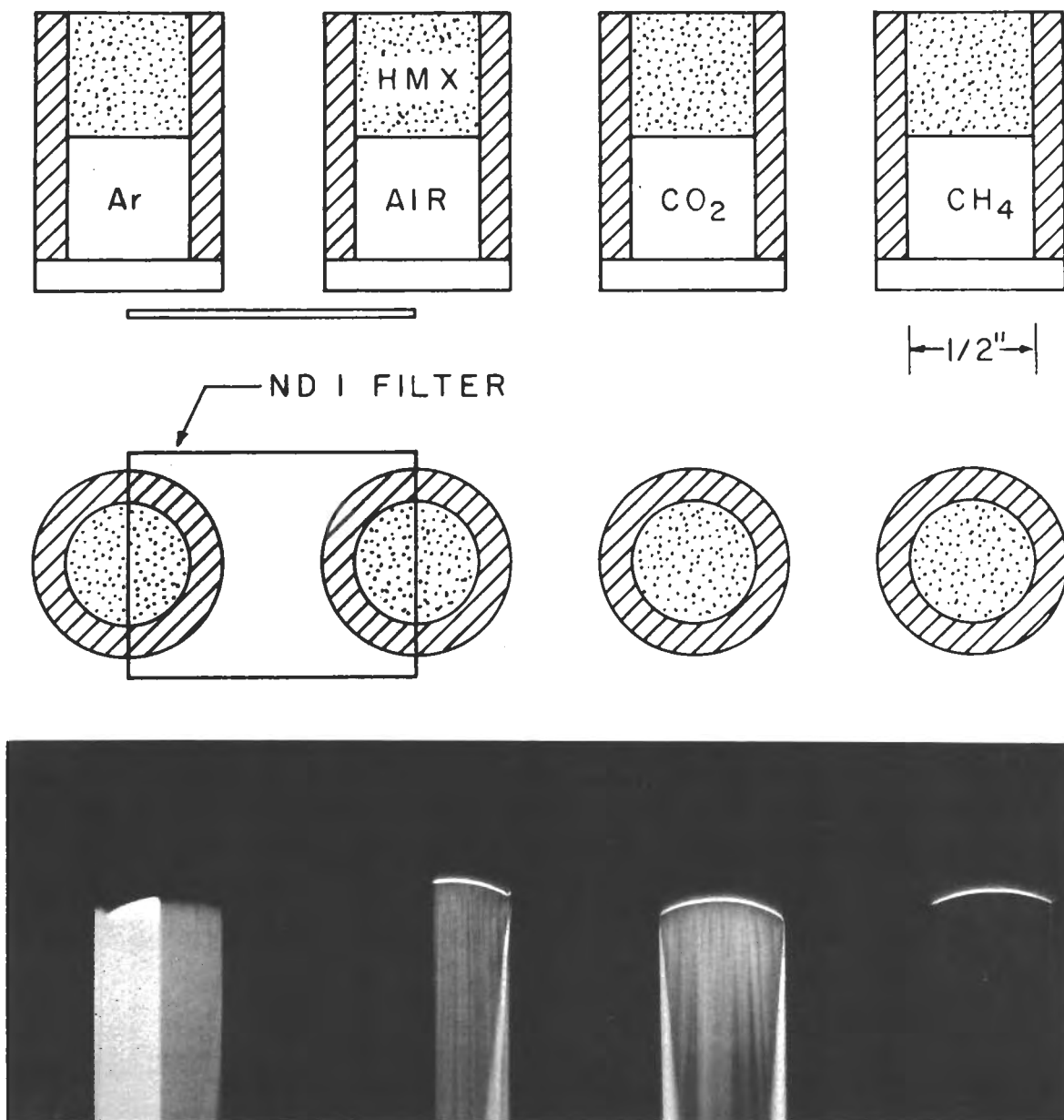
Fig. 3 RMC traces of detonations emerging from HMX charges pressed at 75% crystal density. Various gases surrounded and interpenetrated the explosive charges as labeled.
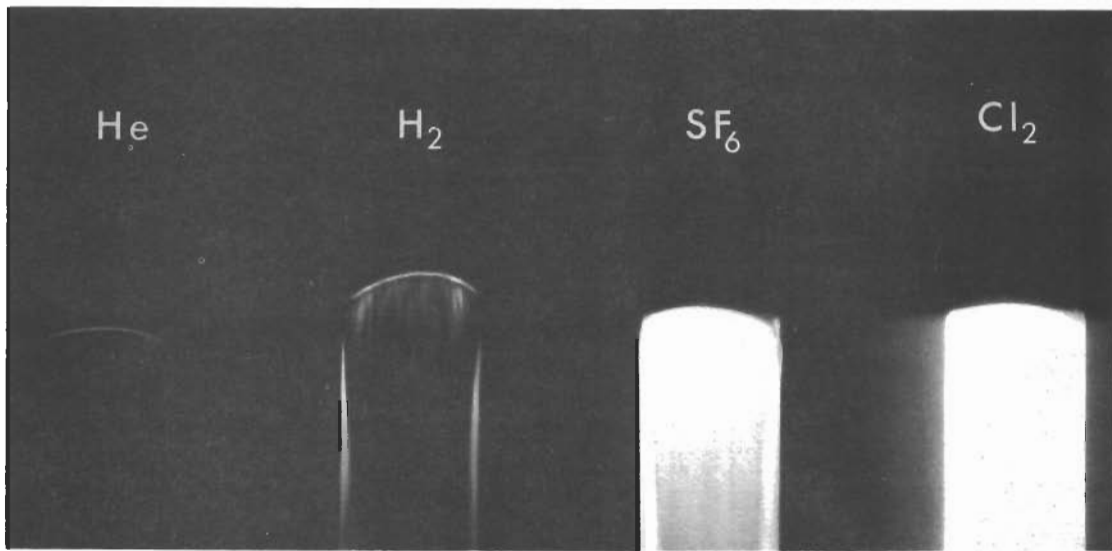
Fig. 4 HMX charges similar to those in Fig. 3 with additional gases.
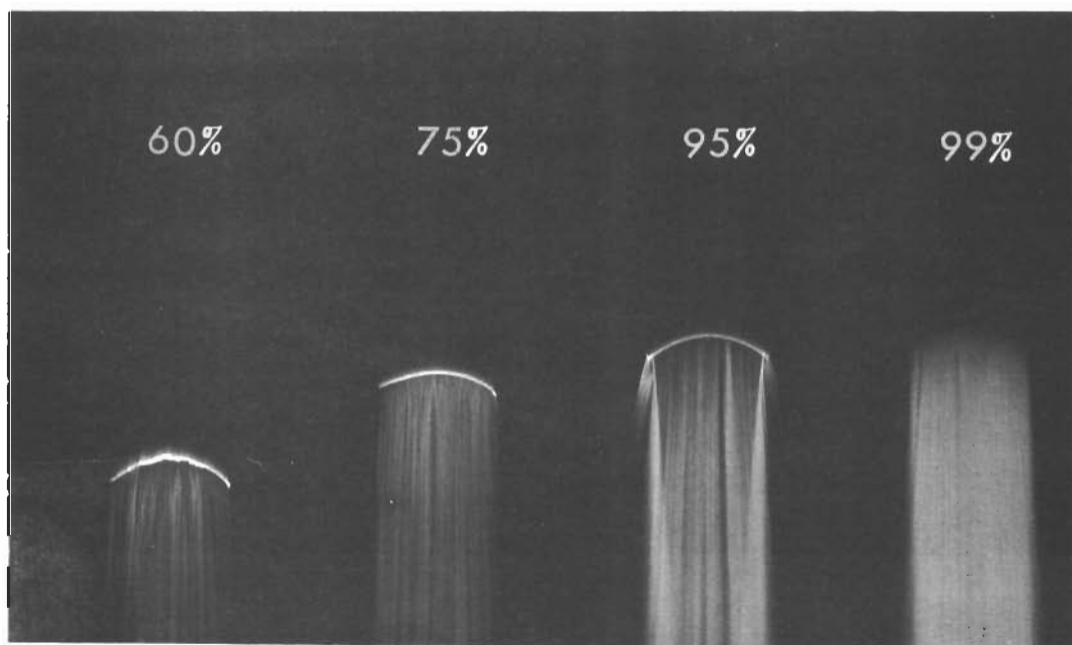
Fig. 5 RMC traces of detonations emerging from the end of PETN charges pressed to the indicated percentages of crystal density.
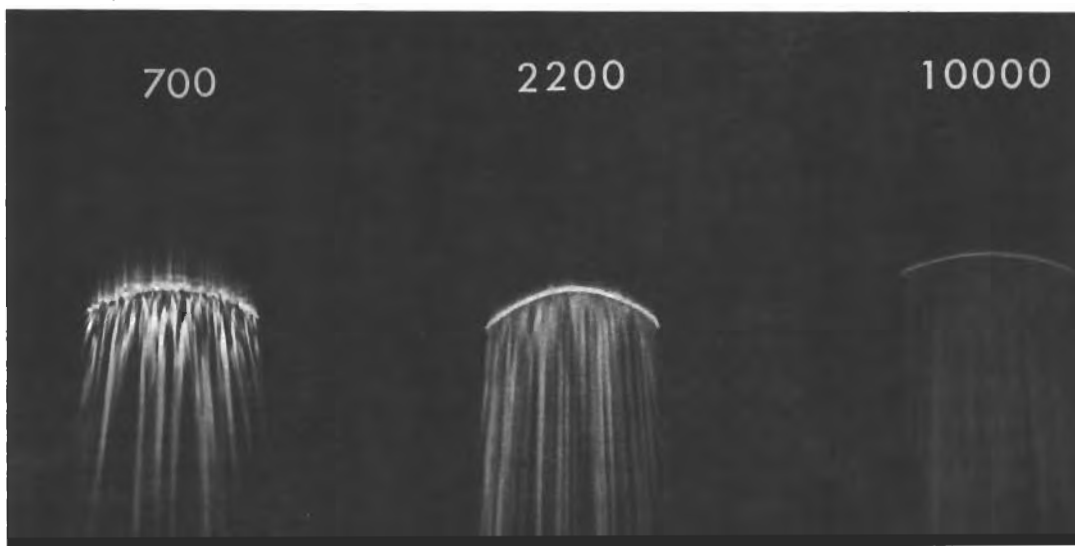
Fig. 6. The effect of particle size on detonation light. Numbers above traces are specific surfaces of PETN samples in cm^2 g^{-1}.

Fig. 8 RMC trace of detonations emerging from charges of RDX at 60% of crystal density. The charge on the left is at 580 torr while that at right is at a few microns.
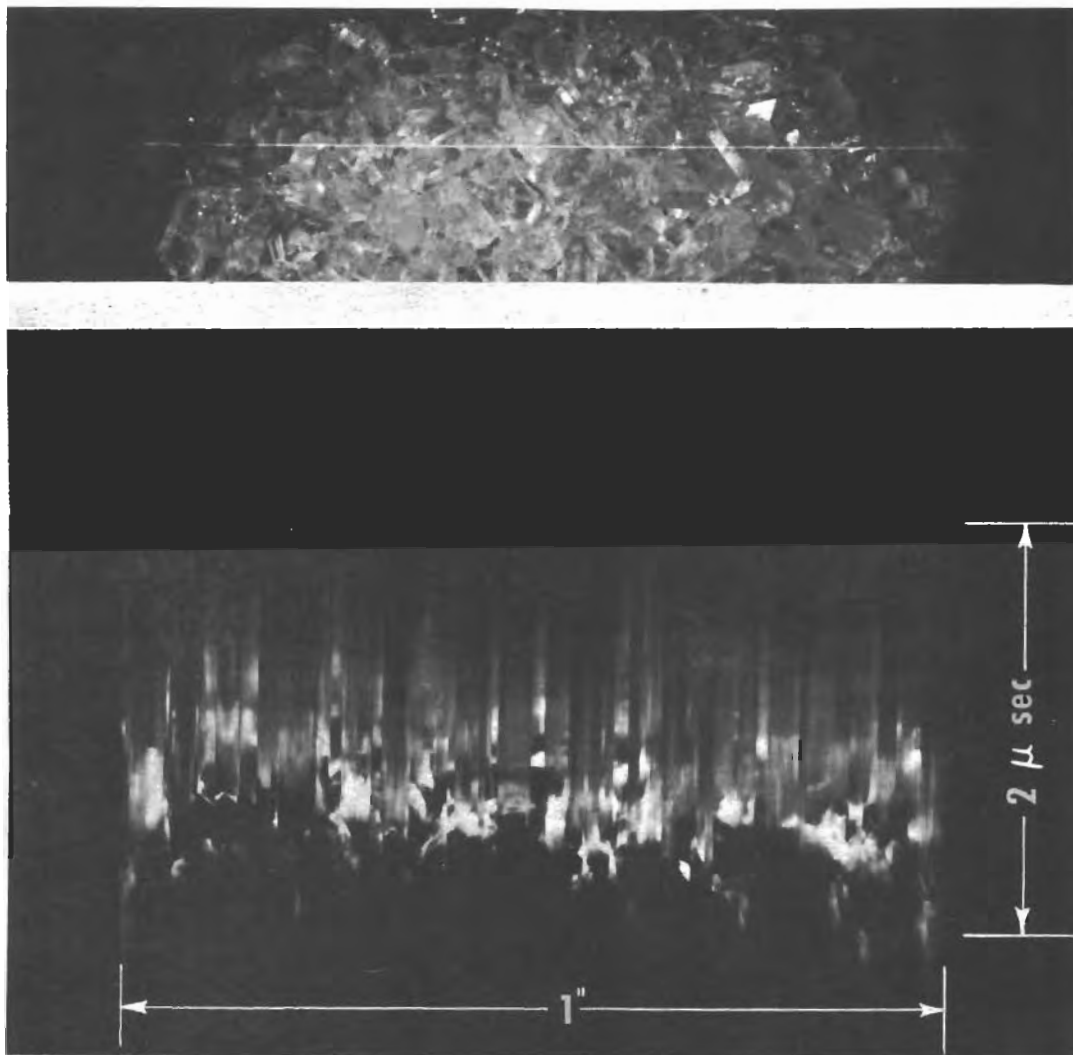
Fig. 7 RMC trace of a detonation wave emerging from a bed of very large PETN crystals at pour density.
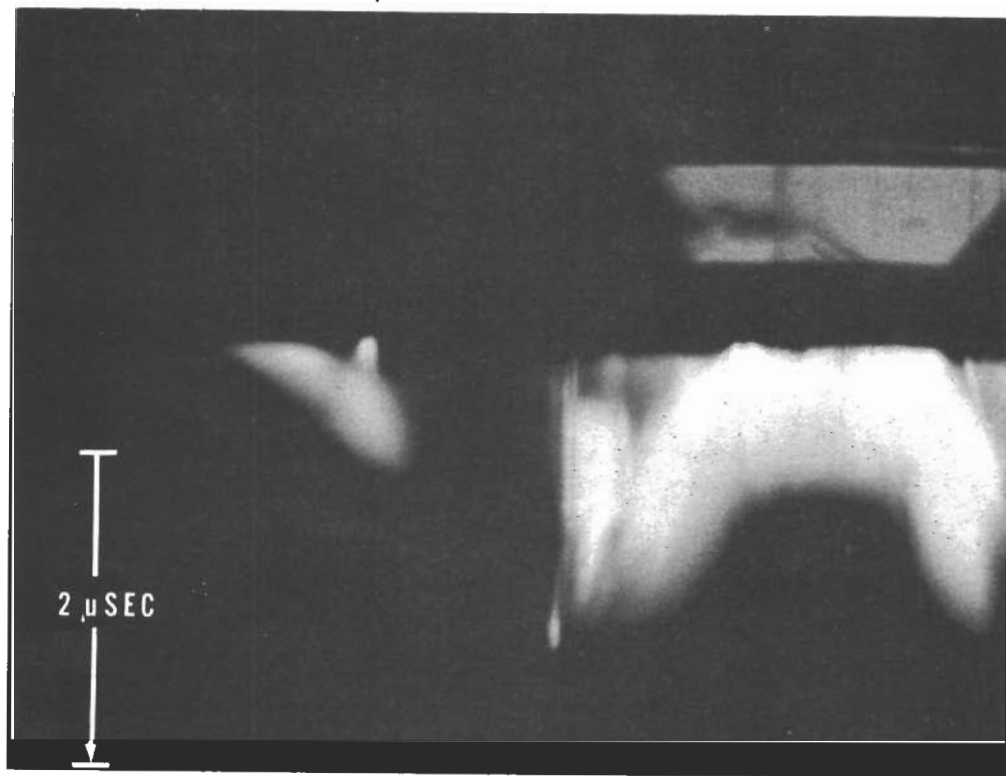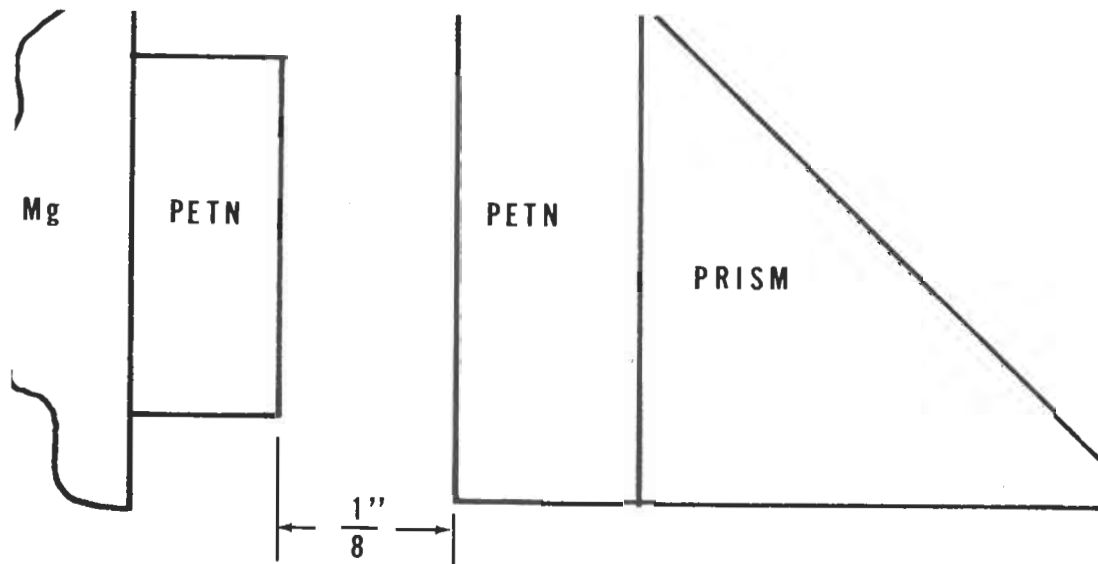
Fig. 9 A plane wave experiment with two large PETN crystals with an evacuated space between them. The view in the RMC photograph at the left is from the side and at the right is end-on through the PETN crystals. Light from the detonation in the PETN crystal is more intense on the right because of a clearer optical path through the crystals in that direction.
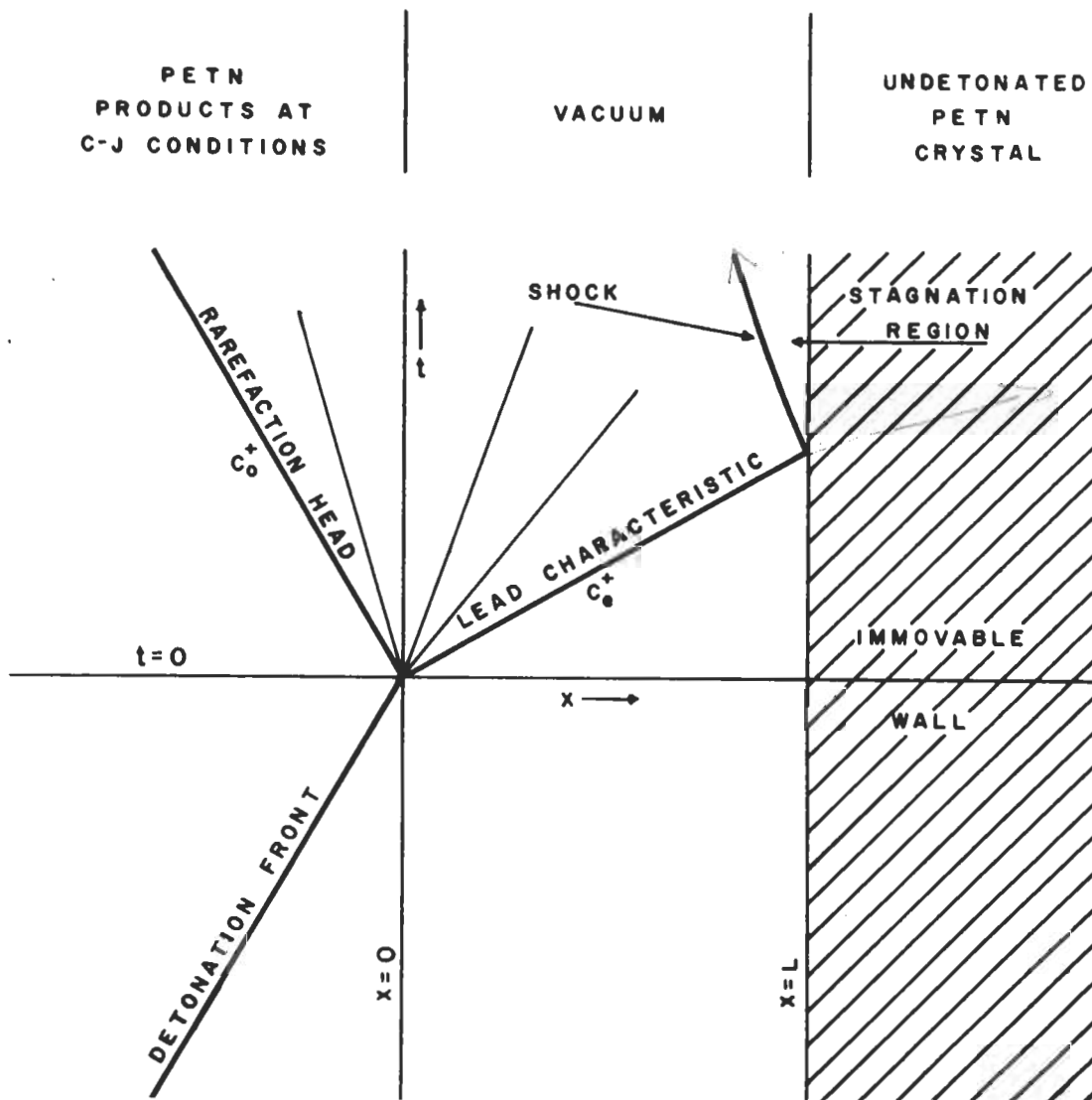
Fig. 10 An x-t diagram of a plane detonation wave arriving at the surface of one plane PETN crystal, the detonation products expanding across an evacuated space, and colliding with an immovable wall.

TETRYL

← 2 inches →

REFLECTED
ARGON FLASH
LIGHT

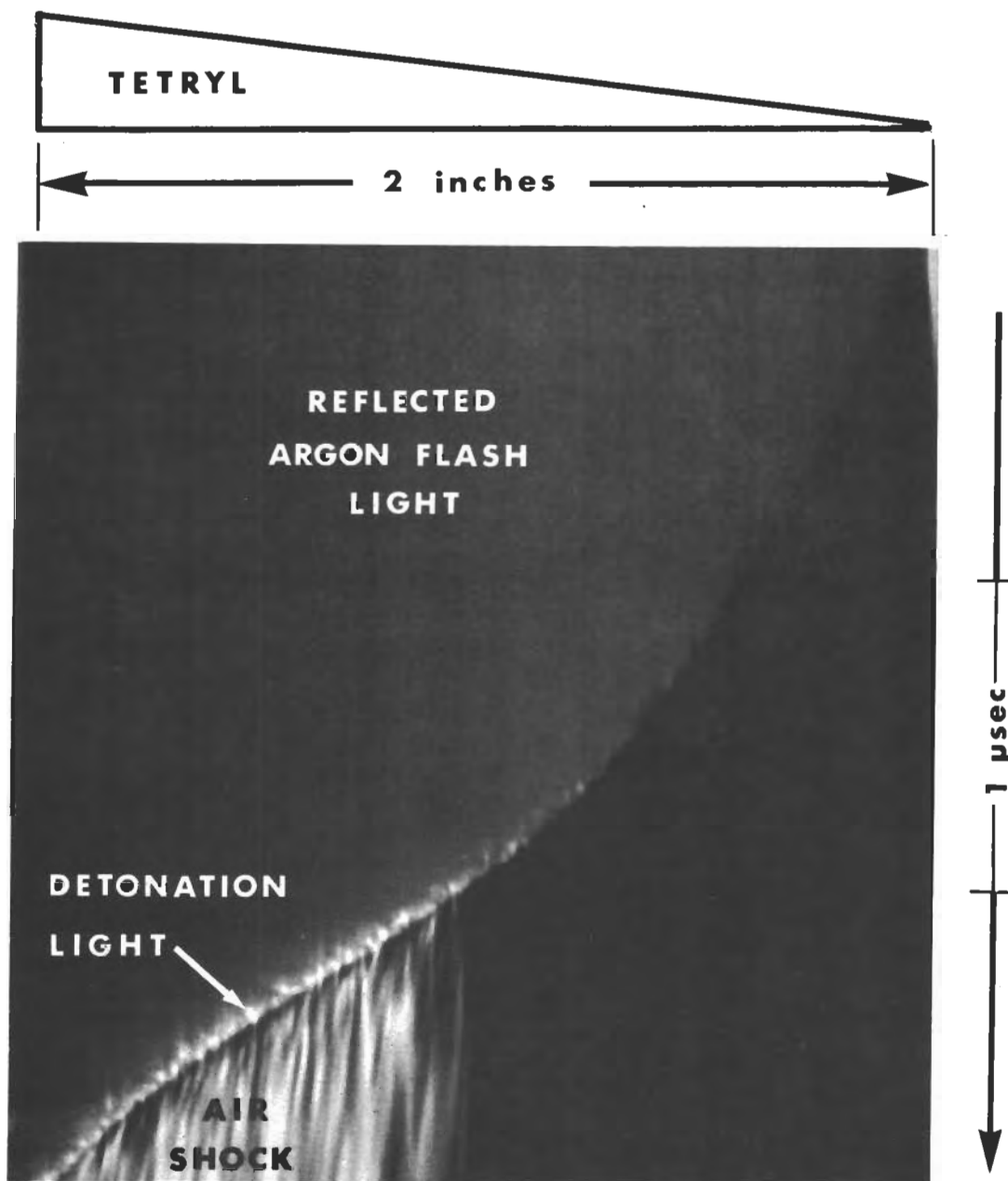DETONATION
LIGHT

AIR
SHOCK

1 μsec

Fig. 11   RMC trace showing the progress of a shock through a wedge of coarse tetryl with eventual build-up to detonation.   The density of the explosive was 1.3 g cm^{-3}.
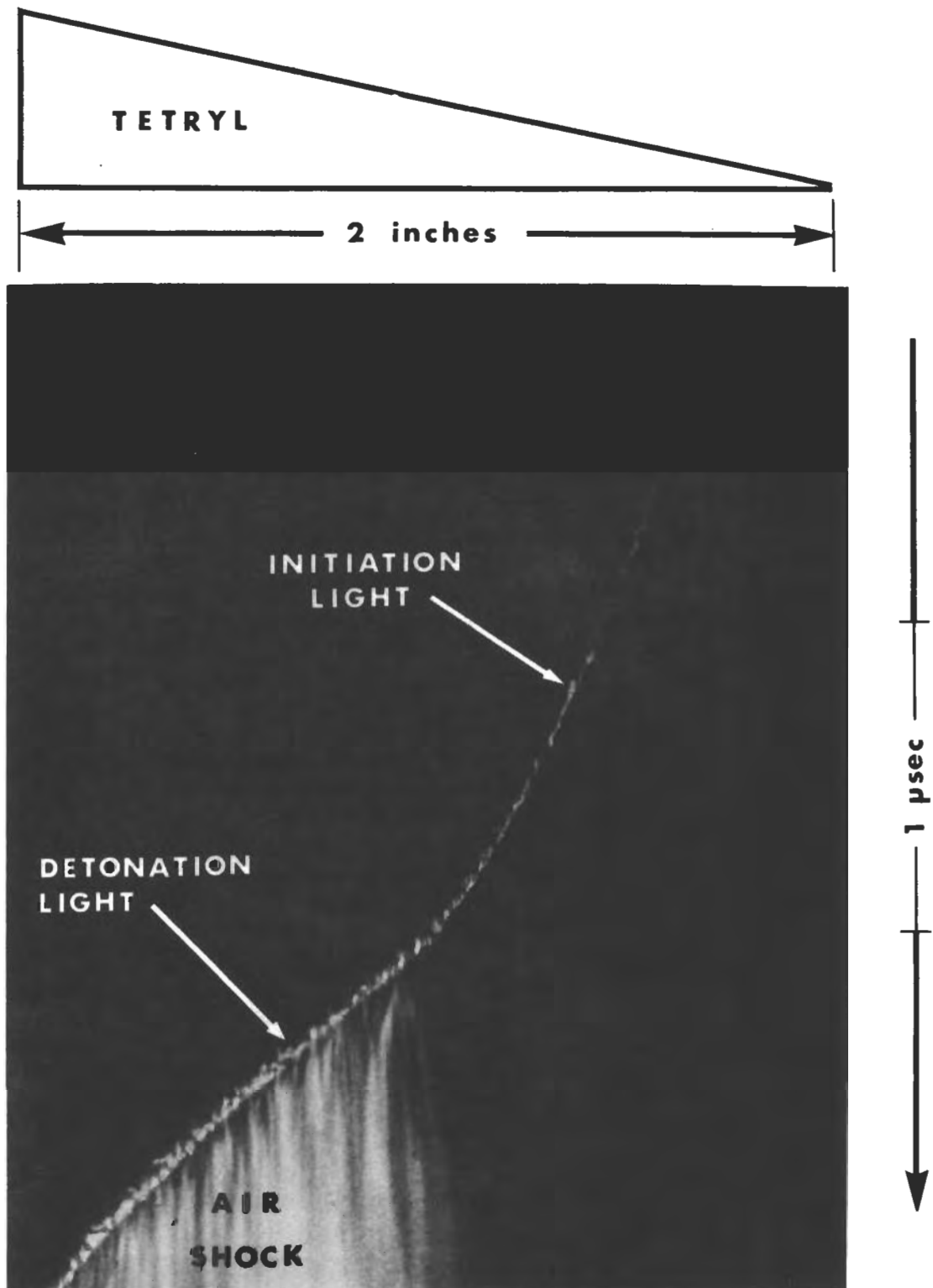
Fig. 12 A charge similar to that in Fig. 11 viewed without the argon flash. This print required retouching so that it could be reproduced by offset printing. Film prints of a similar shot are available.
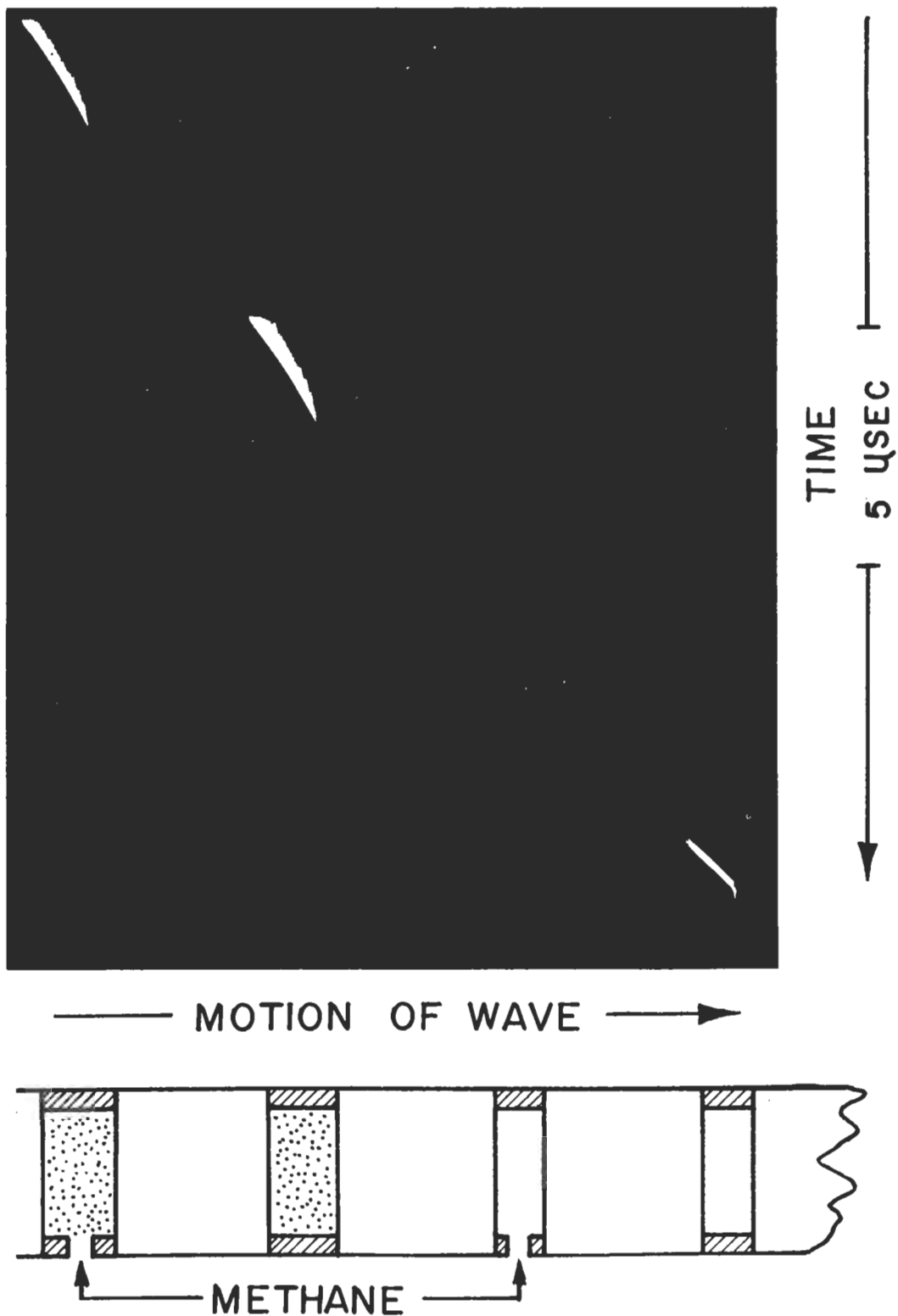
Fig. 13 Side-on RMC photograph of a Comp B-3 charge containing sections of NaCl. Shaded areas, Comp B-3; dotted areas, granular NaCl; white areas, open spaces; lined areas, Lucite tubing. The entire arrangement was immersed in water.
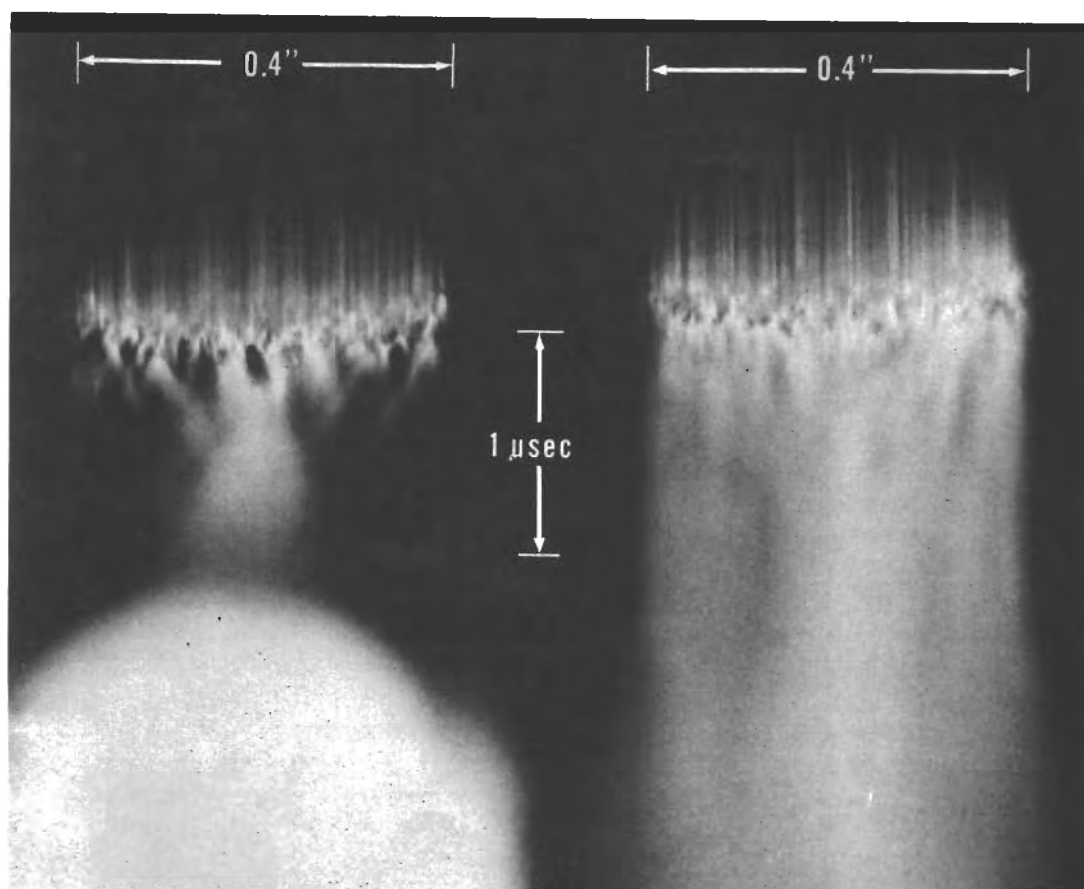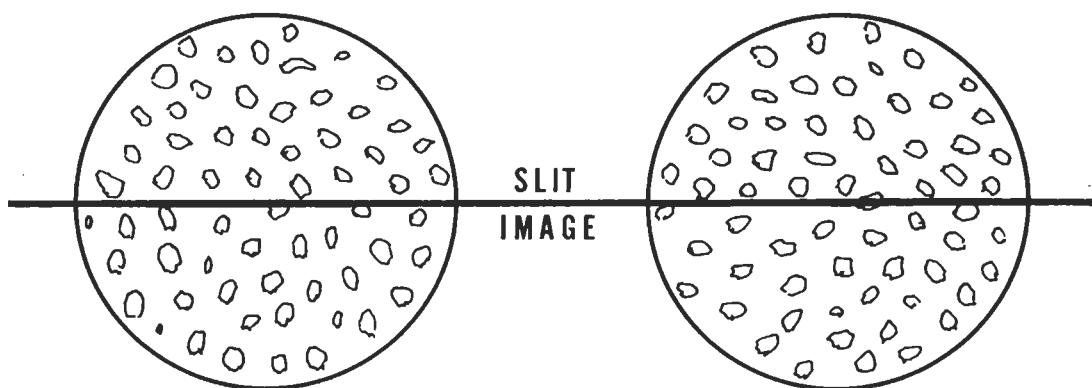
Fig. 14 RMC traces of strong shocks emerging from two beds of
NaCl. Bed at left at less than 0.1 µ pressure; at right 580 torr.
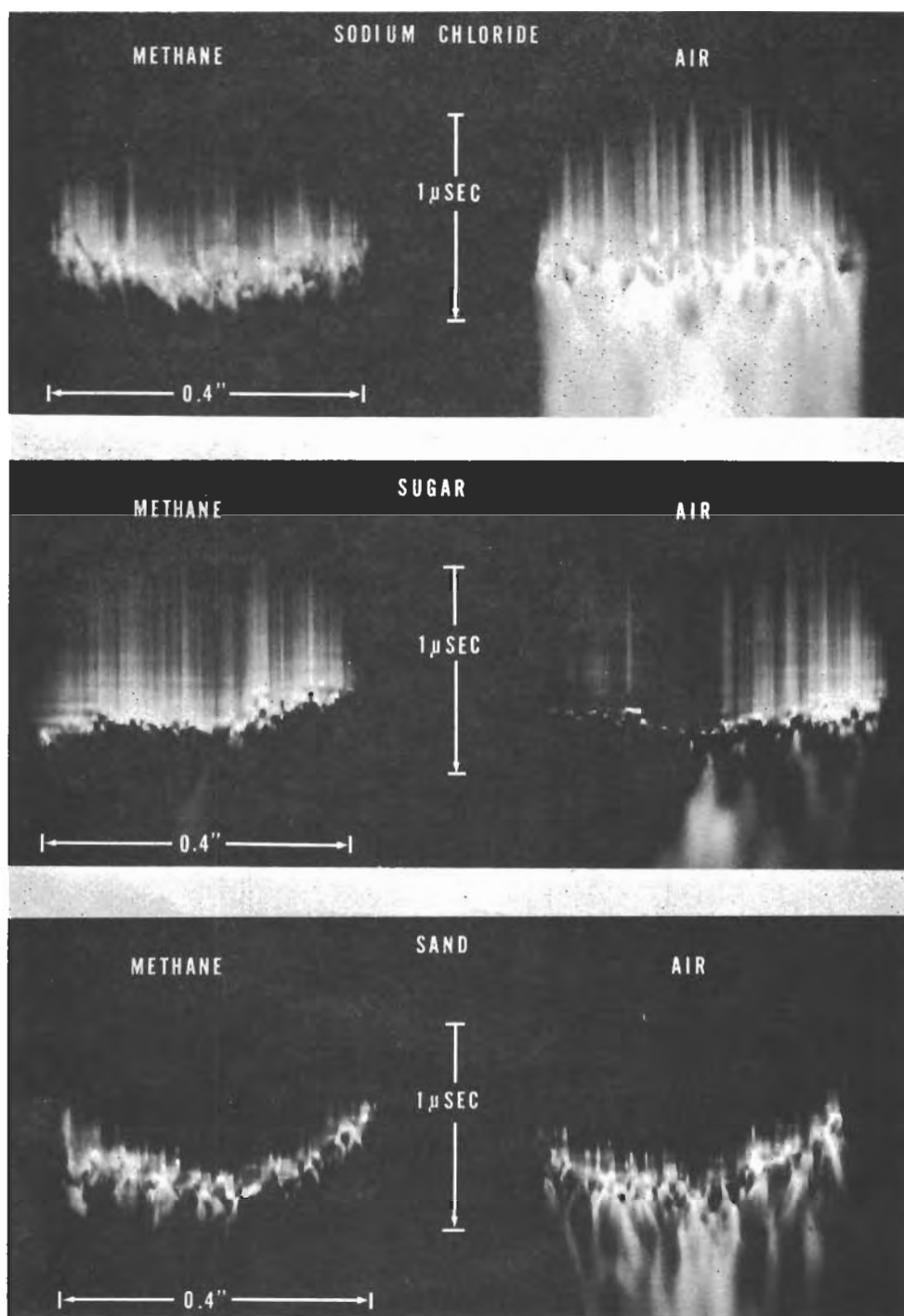
Fig. 15. RMC traces of strong shocks emerging from beds of NaCl, sugar, and sand in methane (left) and air (right).
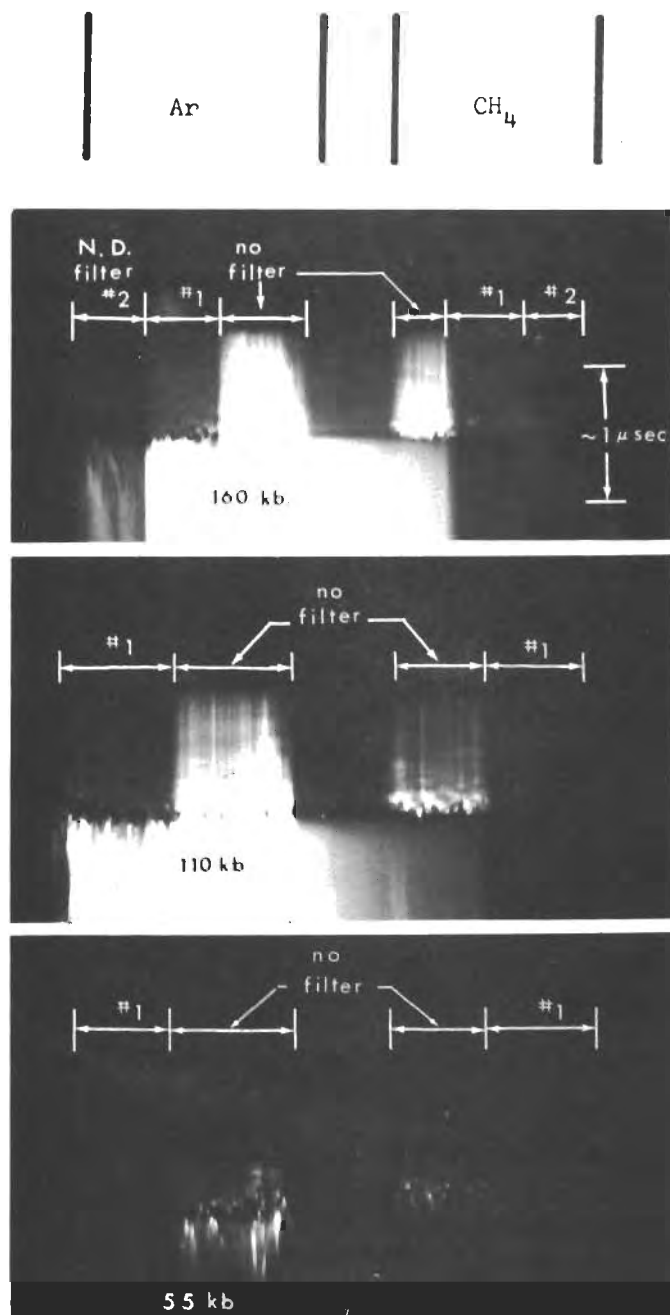
Fig. 16 Shocks of three different pressures emerging from the
end of ammonium sulfate pressings into atmospheres of methane and argon.
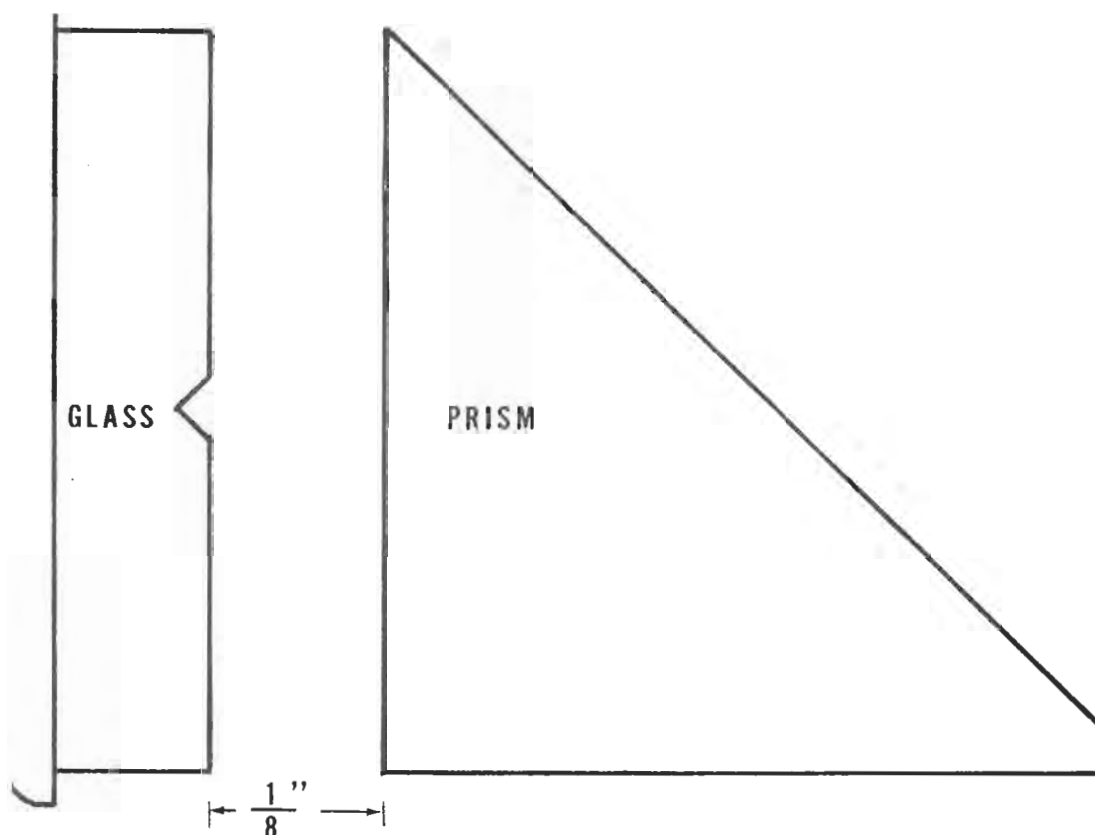
Fig. 17 RMC photograph viewing plane shock traveling from left to right through the assembly shown above. The space between the glass plate and the prism was evacuated. The burst of light seen on the prism face is opposite the triangular groove in the glass plate.
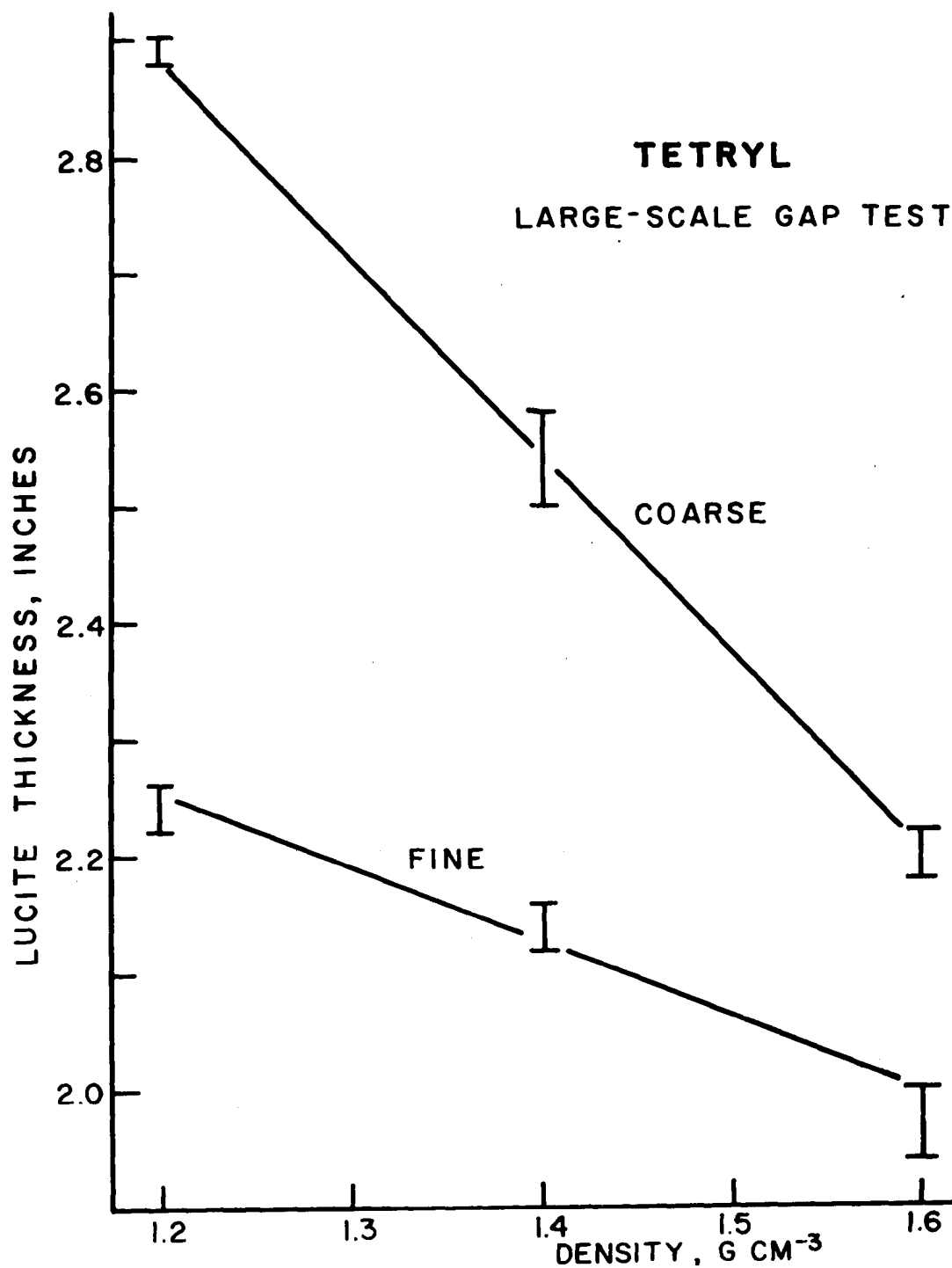
Fig. 18 Large-scale gap test results on tetryl. The coarse sample consisted of particles about .4 mm in diameter (specific surface, 600 cm^2 g^{-1}). The fine sample was ball-milled to a specific surface of 4800 cm^2 g^{-1}. Specific surfaces were measured by a permeameter.
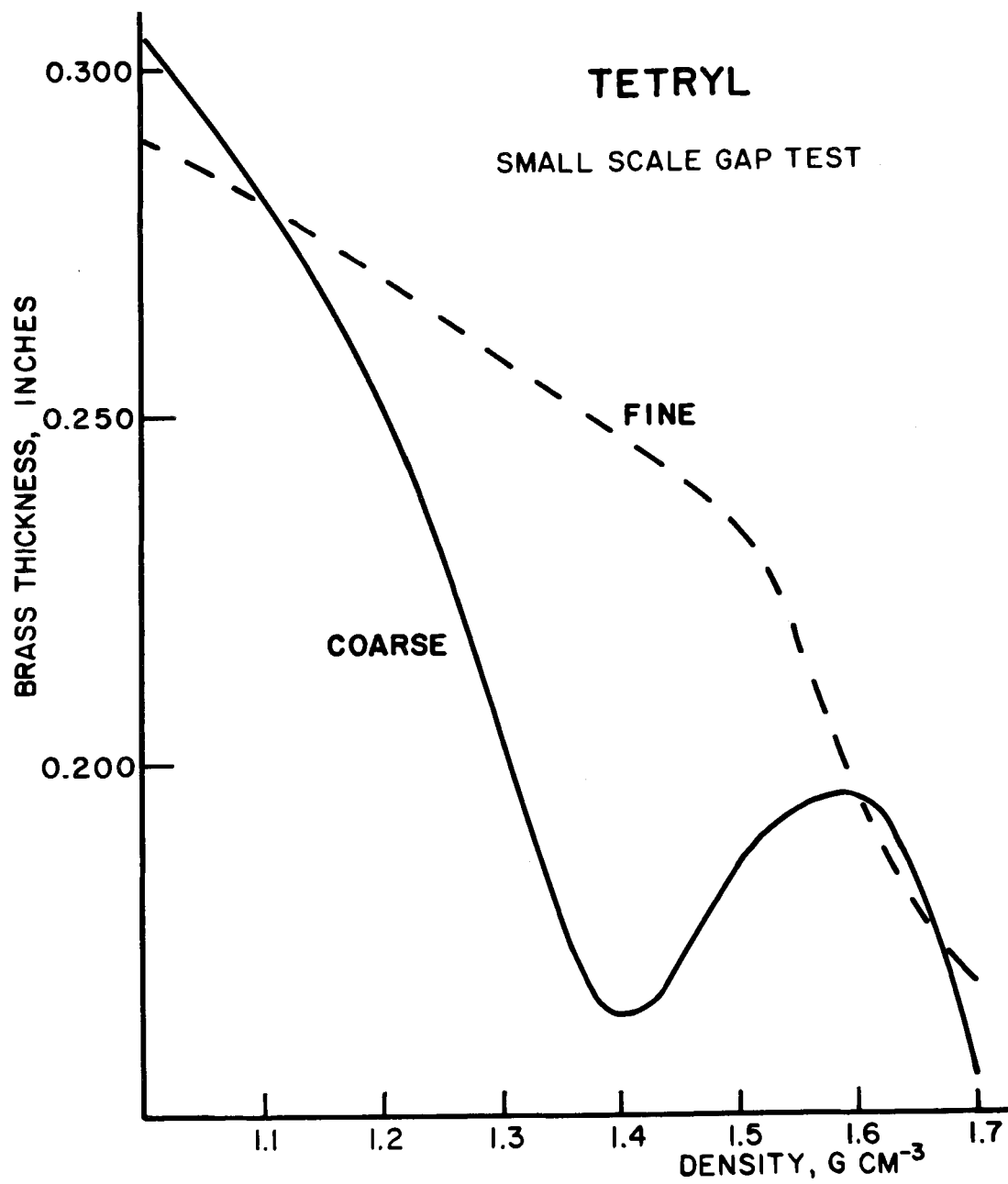
Fig. 19 Small-scale gap test results on the same type of tetryl as that described for Fig. 18.
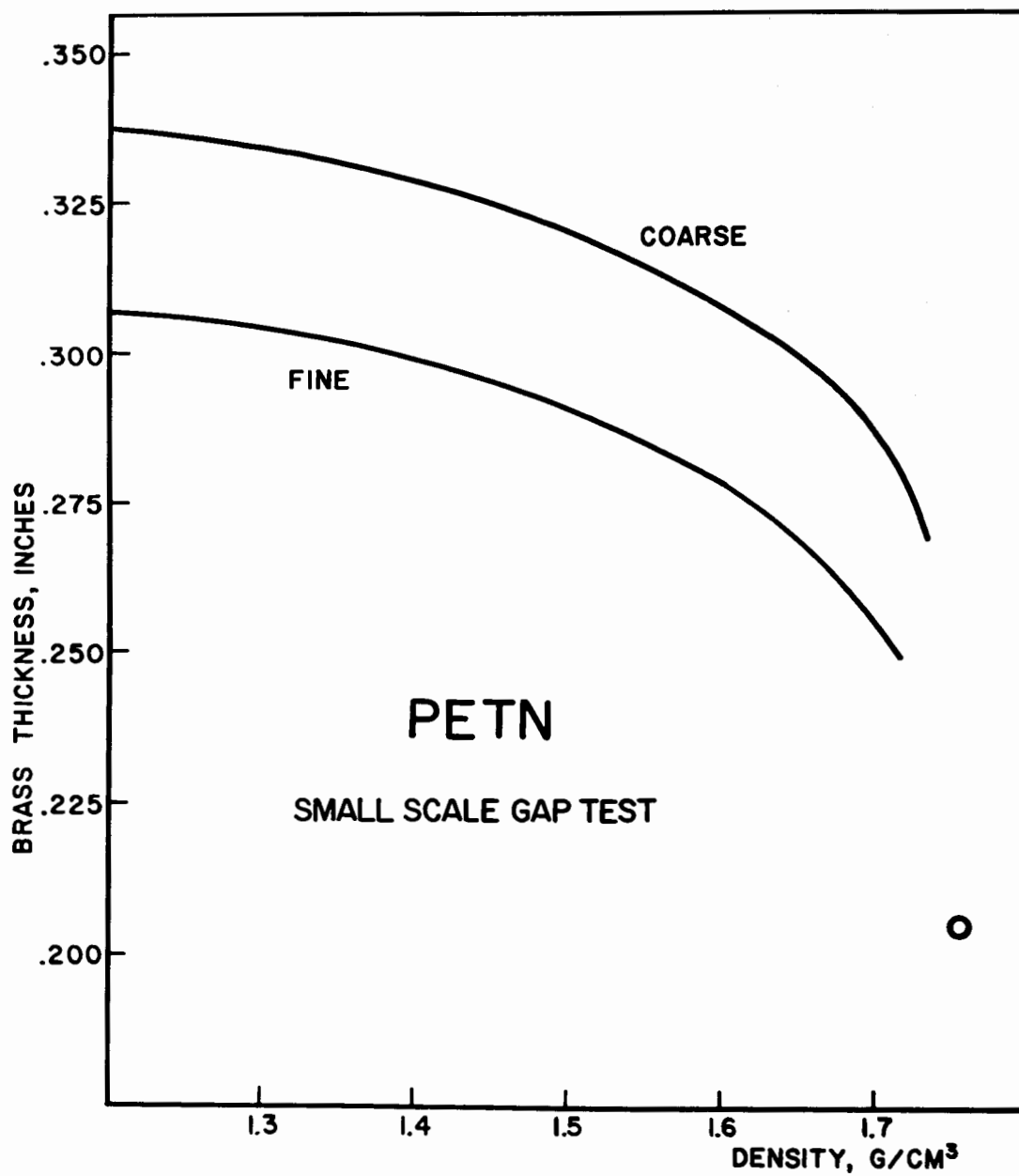
Fig. 20 Small-scale gap test results on two samples of PETN. The coarse sample had a specific surface of about 3500 cm^2 g^{-1}. The fine sample was ball-milled to about 10,000 cm^2 g^{-1}.
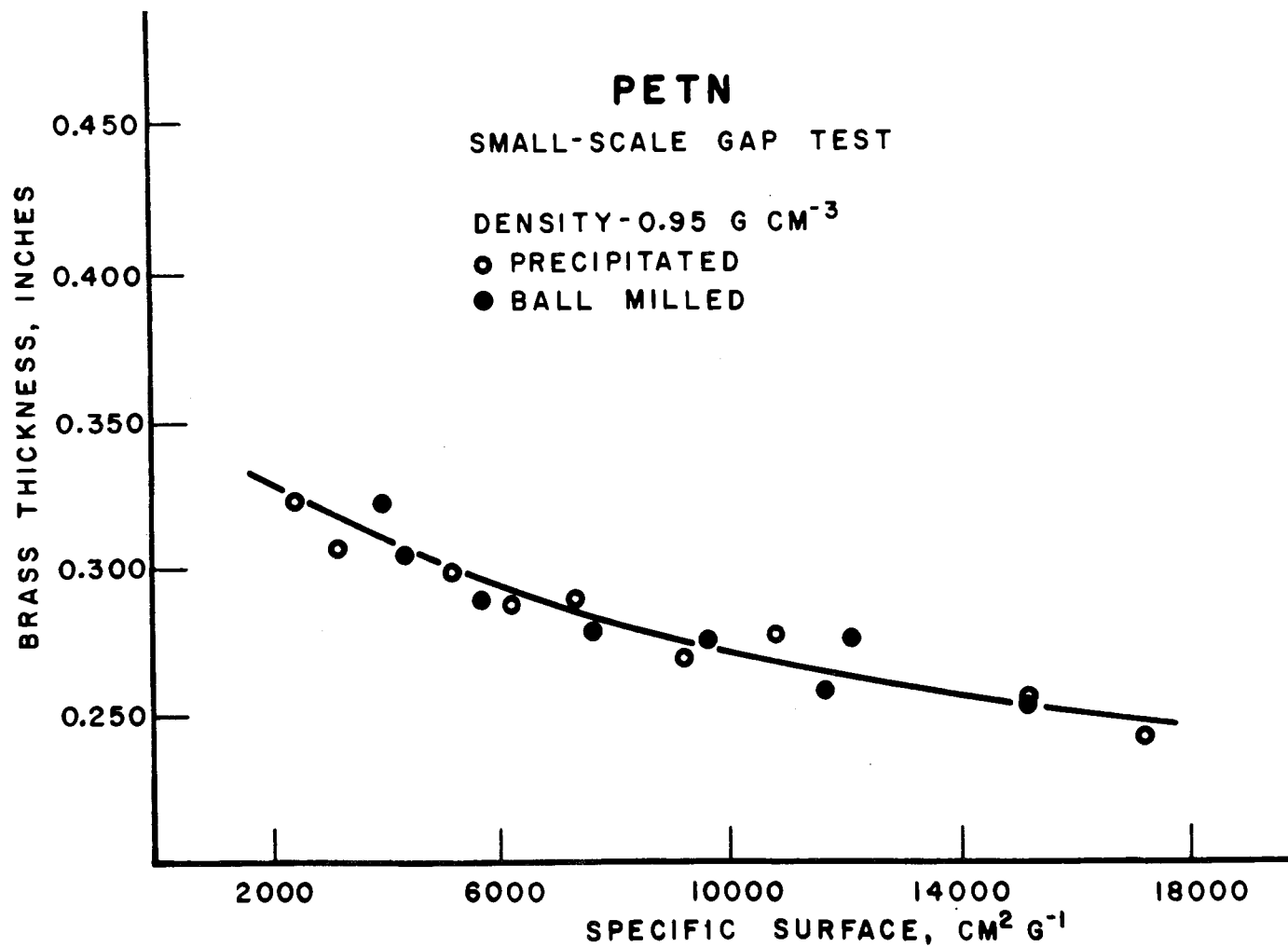
Fig. 21 Small-scale gap test results for samples of PETN of various specific surfaces.
Some samples were prepared by special methods of precipitation, others by ball-milling.
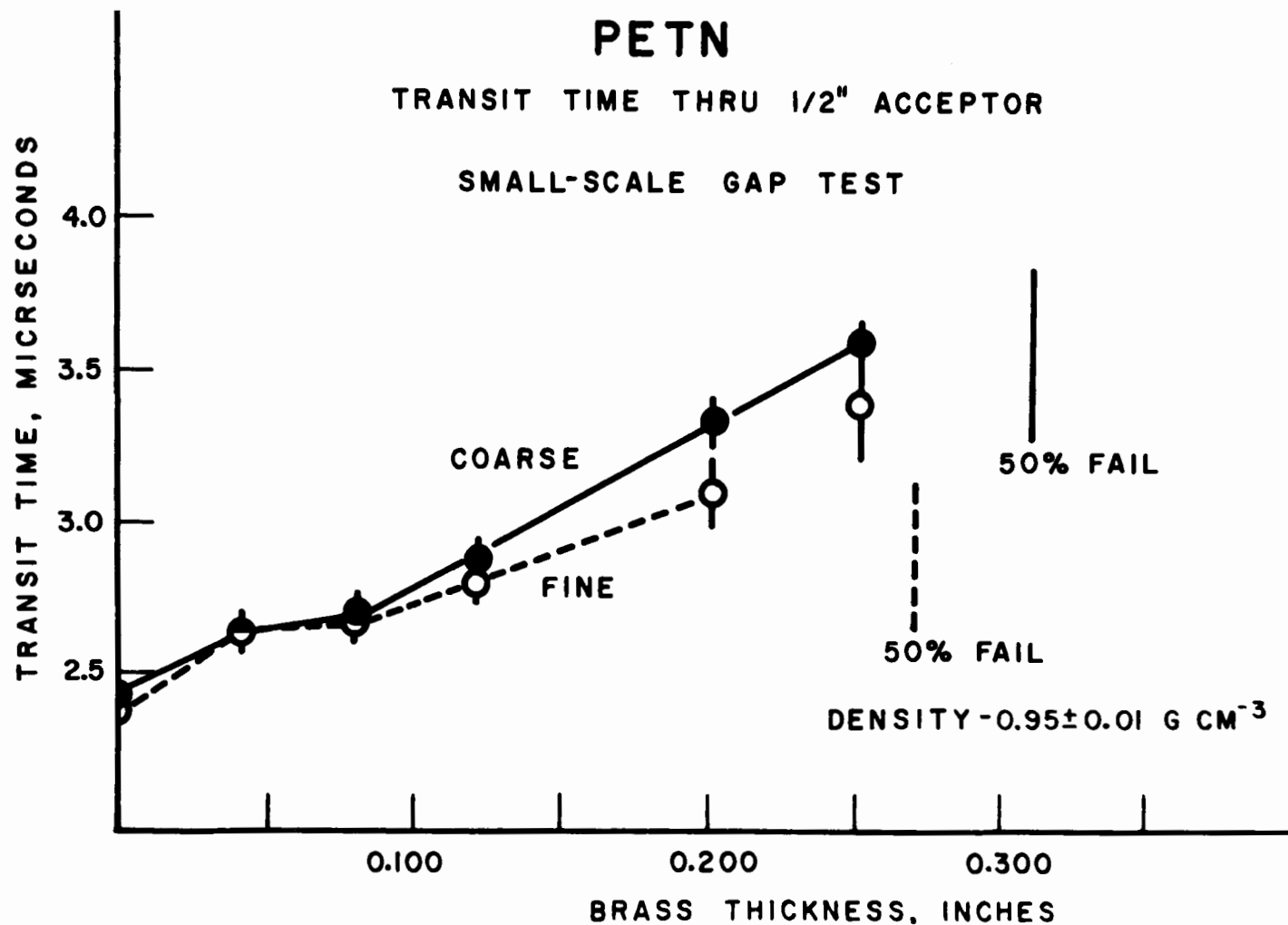
Fig. 22 The transit time through the acceptor in the small-scale gap test as a function of the brass attenuator thickness. The coarse material had a specific surface of 3900 cm^2 g^{-1} while that of the fine material measured 11,500 cm^2 g-1.
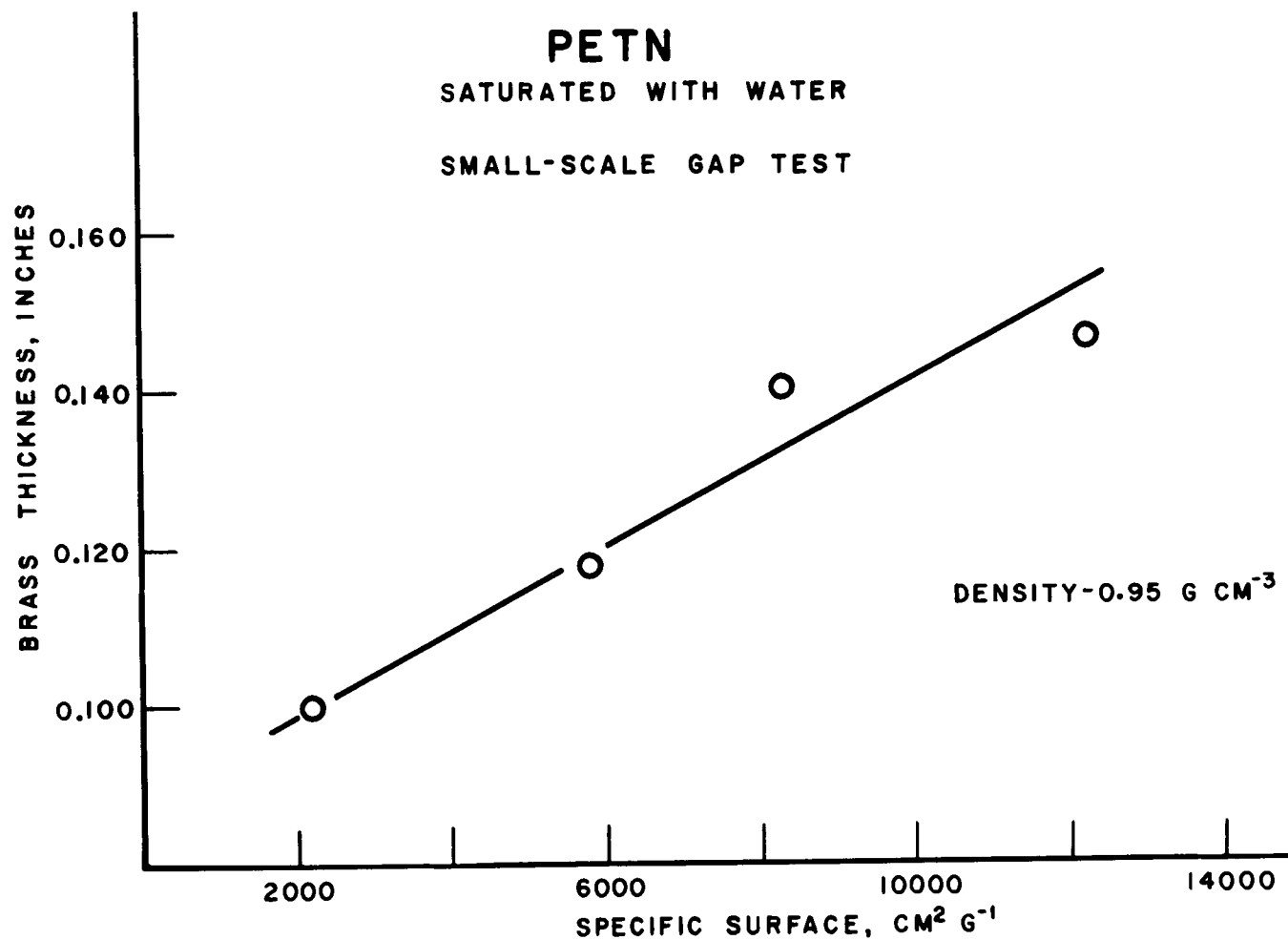
Fig. 23 Small-scale gap test results on water-saturated PETN samples of four different specific surfaces (measured on the dry PETN). The precision of the two points at high specific surface is poor—about ±10%.

27. DISCUSSION

Mr. Weintraub asked if any experiments were run using nitroglycerine. He also wondered if the impurities in PETN, for example, would show some effect. Mr. Seely said he hadn't performed such experiments, and added that nitroglycerine is a homogeneous explosive for which the story has been completely developed by Campbell, Davis, Travis, Ramsey and their associates. Bowden's results were for impact tests, and he showed that bubbles can be source-points of initiation. One must distinguish between results of impact, which extend over a relatively prolonged period, and shock initiation, which happens during the passage of the first shock.

In response to a question regarding publication, Mr. Seely said that the material in this paper will come out first in the proceedings of this Symposium. Some fragments have been published at the American Chemical Society Symposium on Detonation, by Denninger, Rochester and Millikin, this fall.

Someone interested in this subject said that they were using twinning as an indication of pressure. Someone else then mentioned that Picatinny Arsenal was doing some work with gas-free nitroglycerine that was less sensitive. In fact, there was some difficulty in initiating these gas free explosives. Mr. Seely said that this brings up the subject of initiation by hot spots. The group mentioned above (Campbell, et al) put bubbles in liquid explosives, and tungsten and other materials in solid explosives. These other foreign materials in solids were found to be just as good as bubbles in liquids, in inducing initiation. This is due to perturbation of the shock; that is, it puts a irregularity in the shock-wave, and as it passes, a hot spot is induced beyond the inhomogeneity. The point is that homogeneous explosives can be initiated with the aid of inhomogeneities at noticeable lower pressures.

In considering explosive sensitivity in terms of loading density, the charge can be pressed to crystal density. In this condition the explosive is homogeneous and without interstices, and the stagnation process is less efficient. Where the cross-over came, Mr. Seely did not know. He supposed that the bubble mechanism or hydrodynamic hot spot came in between. Mr. Parker of Librascope asked if the interstices were filled with anything but water. Mr. Seely said that a silicon rubber material,

similar in consistency to rubber, or to the du Pont plastic sheet, was used. Results were identical to the water-filled charges when they were done right. There was one exception, and this is being investigated. It may be impossible to wet all of the surfaces of the explosive grains with the silicone material, resulting in poor incorporation. In other words, stagnation is not eliminated.

Mr. Simmons added a note of thanks to Mr. Ted Hannum and adjourned the symposium.

28. BRUCETON TESTS - RESULTS OF A COMPUTER STUDY ON SMALL SAMPLE ACCURACY

J. W. Martin

Mrs. J. Saunders

R.A.R.D.E. - Fort Halstead - England

1. Introduction

The Bruceton test is one of the most widely used in the measurement of the response of explosive devices subjected to possible means of initiation. Thus, to quote some typical examples, it is used to assess the response of electric igniters to electrical impulses, the sensitivity of explosives to falling weights, and the effect of air gaps on the passage of detonation.

The test undoubtedly also has applications outside the explosive field and is suitable for the estimation of the mean and standard deviation of samples when absolute measurements may not be made, because such a measurement would change the properties of the sample. Thus an explosive sample that did not detonate under a given falling weight would no longer be representative of the original. The same would be true of steel bars in impact tests or of insects treated with test insecticides.

Popularity of the test is almost certainly due to the ease with which a sequence is followed which enables properties at and around the 50% event point to be found and the ease with which the associated numerical calculations are carried out (in contrast to many alternative statistical procedures).

Though the test is widely used and its theory well established (Ref. 1) the theory is based upon large samples and a minimum sample size of 200 is recommended. The test is, however, widely used both in the U.K. and in America, on much smaller samples often as low as 25 and seldom over 50. In this report the effect of small sample size is examined by means of large numbers of tests simulated on a digital computer (i.e. using the Monte Carlo approach as is usual in instances where a theoretical solution is not easily obtained).

2. The Bruceton test sequence

Firstly, a trial is made at a level where the chances of explosion or non explosion are expected to be approximately equal. If explosion occurs, a test is made at a lower stimulus; if no explosion occurs, the next highest level is tried. In this way, at a series of test heights, the experimenter records a sequence of the following type, 0 representing failure and X an explosion:-

Stimulus level

i								number fired, n	n_i	n_i^2
3	X				X	X		3	9	27
2	X	X	X	0	0	X	X	4	8	16
1	0		X	0	X	0	0	2	2	2
0			0	0				0	0	0
								$\sum n$	$\sum n_i$	$\sum n_i^2$

etc

The increments of stimulus level are chosen to be equal, and of the order of $\frac{1}{4}$ to 2 standard deviations apart. (It is sometimes necessary to carry out some transformation to ensure that the expected response follows a near normal distribution; for example, logarithms of heights of fall of weights on to explosives and logarithms of voltages in the case of electric igniters).

The mean is estimated from

$$m = x_0 + d\left(\frac{\Sigma ni}{\Sigma n} - \frac{1}{2}\right)$$

and the standard deviation from

$$= 1.620d\left(\frac{\Sigma n.\Sigma ni^2 - (\Sigma ni)^2}{(\Sigma n)^2} + 0.029\right)$$

where x_0 = stimulus at which the line of all failures occurs

d = interval between stimuli

The mean and standard deviation may thus be calculated in a few minutes. The simplicity is one of the attractions of the test. It can also be seen that observations are concentrated around the 50% explosion points so that in any test sequence nearly half, within close limits, will be explosions.

3. Computer simulation

A standard procedure for the generation of "random" numbers on the RARDE computer is to take a 39 binary digit number, multiply by $5^{17} \times 2^{-38}$ delete the more significant half and to take the remainder, after shifting the decimal point, as a random number. This procedure gives, a rectangular distribution between 0 and +1. To make numbers that follow a normal distribution it is only necessary to sum these numbers in as few as fours, making use of the central limit theorem.

The normally distributed random numbers are then tested in sequence with a series of test heights, in the usual Bruceton procedure – an explosion being recorded if the test height was larger than the number and a failure if smaller. The test height is then changed accordingly and the next number tested. Finally the O's and X's at each level are collated and the mean and standard deviation calculated by the Bruceton procedure.

At the same time, as a check on the sample of numbers, the actual mean and standard deviation, calculated numerically, were also obtained.

4. The system variables

For a given sample the Bruceton test is completely specified by:-

1) Position of test heights relative to mean

2) Step size between the testing stimulus levels

3) Number of objects to be tested.

The test heights were made 1) with the mean coincident with a test height

2) with the mean midway between test heights

3) with the mean quarterway between test heights

The step size was made $\frac{1}{4}$, $\frac{1}{2}$, 1, 2 standard deviations, and sample sizes of 25 and 100 were examined.

5. Results

The results are given in two forms, namely histograms figures 1 - 4 and tables 1 and 2. These may be summarised as follows:

a) Position of mean relative to test height

This, had little effect either for samples of 25 or 100 at any spacing of the test grid. In figures 1 and 2, the histograms show little difference down any column. Tables 1 and 2 show no effect on the average Bruceton means, standard deviations or their standard errors.

b) Effect of interval between test heights

Very little difference appears between the results for test intervals $\frac{1}{4}$, $\frac{1}{2}$ or 1 s.d. apart. At 2 s.d.'s however, the result for each trial can lie only at discreet values, with no possible values in between. The histogram appears as separate blocks. This is because most of the tests take place at two levels and the occasional X or 0 outside these levels has an overriding effect on the numerical result. Depending on whether, say, two X's or three appear at the highest level, the answer, numerically has one of two values, widely spaced (because of the large test interval) and with no possible values in between. Even so, however, the outlines of the histogram have a near normal distribution.

o) Effect of sample size

With 100 items the test gives estimates of mean (Fig. 1) distributed closely in accordance with theory, with the important exception of a few rare results lying outside the curves where the expectation is negligible. This supports the opinion often held by users of the Bruceton test that the confidence limits can be misleading. It appears from the computer tests, that while a 5% confidence limit can be applied without one being grossly misled, lower percentage confidence limits need to be used with great caution. Standard deviations are estimated with much less precision and confidence limits given by large sample theory can be very misleading. Fig. 3.

With 25 items per test, the estimates of mean are widely distributed (Fig. 2) and the occurrence of estimates outside the expected distribution is apparent.

The standard deviations, Fig. 4 are markedly non normal, being skewed so as to under-estimate the standard deviation. The mode of the estimate is approximately as follows:

Table 3   (sample size 25)

Interval size true standard deviations	$\frac{1}{4}$	$\frac{1}{2}$	1	2
Ratio of most likely estimate of s.d. to true s.d.	0.55	0.65	0.75	1.0

Tables 1 and 2 give the average values of standard deviation for samples of 25 and 100 items and Table 4 extends this to intermediate values. The carpet graph of figure 5 shows how the underestimation of the standard deviation is affected by test height spacing and sample size. This correction is appropriate if results of many trials are pooled.

The precision of a standard deviation estimate from a single sample of 25 is so poor that it is of little value. Table 3, however, should be consulted to show the most likely factor to be applied as a correction.

6.   Comparison with exact measurements

It is useful to compare the accuracy of estimates where a 'go' or 'no-go' test of the Bruceton type is used, with the case where non destructive measurements may be made. For example, the weights of propellant charges can be found without recourse to tests of the Bruce-ton type and a table of exact weights found can be used to estimate the standard deviation exactly for the sample.

The question arises, how does the accuracy of the estimated average weights (and spread about the average) compare with that found by the Bruceton process? This is answered by the following table where N is the total number of objects available for test and o is the standard deviation of the factor measured.

Approximate expression for standard error of:	Bruceton Process	Continuous Process
Mean	$\simeq \sigma / \sqrt{\dfrac{N}{2}}$	$\sigma / \sqrt{N}$
s.d.	$\simeq \sigma \sqrt{\dfrac{N}{2}}$	$\sigma \sqrt{2N}$

(The factors G and H used in ref. 1 have been taken as unity, their approximate value. In the case of standard deviations, however, this is very approximate and the standard error can easily be larger).

It can be seen that the Bruceton type test requires twice as many items to estimate a mean with given precision and four times (at least) as many to estimate a standard deviation.

This is a helpful concept for comparison with averaging continuous measurements. It is important to point out, however that this is not a criticism of the Bruceton test since when measurements must necessarily be destructive, there is no possibility of using the continuous process.

7.   Conclusions

The Bruceton method of analysis has been simulated using results equivalent to 150,000 firings. Large sample theory gives a good agreement with the spread of means with samples of 100 but with samples of 25, the spreads are excessive.

With standard deviations the spreads are very large and with a sample of 25 there is a tendency to underestimate, particularly when small intervals are used between test heights.

The opinion of experimenters that the Bruceton test gives a good mean but a relatively poor standard deviation is confirmed and numerical values can now be given to qualify this statement. The histograms of this report give an approximate basis for estimating the confidence limits.

8. Suggestions for further work

The Monte Carlo method of analysis as used here, should also be applied to the so called "run down" system where batches of items are tested at various levels. Like the Bruceton, this procedure is used as a simplified "probit" analysis. A knowledge of the accuracy of the tests and the cost in loss of efficiency in comparison with full probit analysis is required. This, together with the Bruceton method, covers the principal systems available when destructive measurements must be made. The optimum test height spacing for estimation of a good standard deviation is a matter of general interest and importance.

Some preliminary results of work proceeding along these lines are given in Appendix 2.

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1. Dixon and Mood (1948)
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TABLE I

Mean value of Bruceton mean	$\frac{1}{4}$	$\frac{1}{2}$	1	2
Mean at test height — 0	-.0019	-.0053	+.0029	+.0002
$\frac{1}{4}$	-.0053	+.0115	-.0025	+.0043
Mean midway between test heights — $\frac{1}{2}$	+.0070	+.0525	+.0086	+.00197

Standard error of Bruceton mean	$\frac{1}{4}$	$\frac{1}{2}$	1	2
0	.0629	.0734	.0682	.0835
$\frac{1}{4}$	.0589	.0659	.1181	.0762
$\frac{1}{2}$	.0622	.0841	.0705	.0810

Interval between test heights (s.d's)

Mean value of Bruceton s.d.	$\frac{1}{4}$	$\frac{1}{2}$	1	2
Mean at test height — 0	.4834	.5082	.5049	.5108
$\frac{1}{4}$	.4521	.4888	.4845	.4916
Mean midway between test heights — $\frac{1}{2}$	.4620	.4966	.4915	.5072

Standard error of Bruceton mean			
.1092	.1016	.0962	.0668
.1409	.1214	.1595	.0985
.1385	.1295	.0996	.0999

Summary of results using 100 trials of 100 items with true mean = 0 and standard deviation = $\frac{1}{2}$.

TABLE II

Mean value of Bruceton mean

| | Interval between test heights (s.d's) | | | |
	1/4	1/2	1	2
Mean at test height — 0	.0068	.0152	.0340	.0087
Mean midway between test heights — 1/4	.0107	+.0390	+.0163	+.0054
1/2	.0207	−.0321	+.0199	.0102

Standard error of Bruceton mean

| Interval between test heights (s.d's) | | | |
1/4	1/2	1	2
.1079	.1221	.1151	.1635
.1091	.1268	.1248	.1613
.1254	.1200	.1538	.1478

Mean value of Bruceton s.d.

	1/4	1/2	1	2
Mean at test height — 0	.2745	.4258	.4479	.5034
Mean midway between test heights — 1/4	.3073	.3721	.4471	.4892
1/2	.3430	.3917	.4523	.4887

Standard error of Bruceton s.d.

1/4	1/2	1	2
.1838	.2443	.1746	.1481
.1418	.1710	.1931	.1858
.1751	.2115	.1864	.2036

Summary of results using 100 trials of 25 items with true mean = 0 and standard deviation = $\frac{1}{2}$.
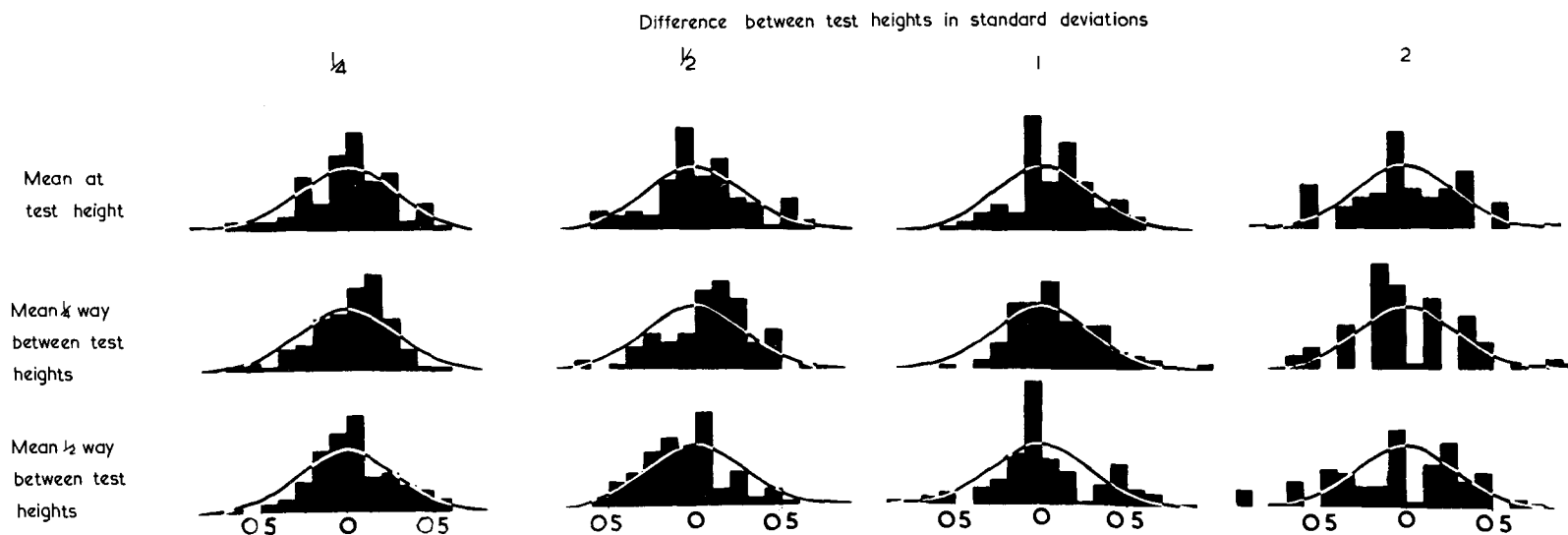
Difference between test heights in standard deviations

FIG. I   SPECTRUM OF BRUCETON MEANS. EACH HISTOGRAM GIVES THE RESULT OF
100 TRIALS OF 25 ITEMS. THE X AXIS SHOWS THE ERROR IN THE MEAN,
MEASURED IN TERMS OF 'TRUE' STANDARD DEVIATIONS.

Difference between test heights in standard deviations

FIG. 2 SPECTRUM OF BRUCETON MEANS. EACH HISTOGRAM GIVES THE RESULT OF
100 TRIALS OF 100 ITEMS. THE X AXIS SHOWS THE ERROR IN THE MEAN,
MEASURED IN TERMS OF TRUE STANDARD DEVIATIONS.

Difference between test heights in standard deviations

¼   ½   1   2

Mean at
test height

Mean ¼ way
between test
heights

Mean ½ way
between test
heights

0·5   1·0   1·5   0·5   1·0   1·5   0·5   1·0   1·5   0·5   1·0   1·5

FIG. 3   SPECTRUM OF STANDARD DEVIATIONS. EACH HISTOGRAM GIVES THE RESULT
OF 100 TRIALS OF 25 ITEMS. THE X AXIS SHOWS THE RATIO OF "FOUND" TO
"TRUE" STANDARD DEVIATION.

Difference between test heights in standard deviations
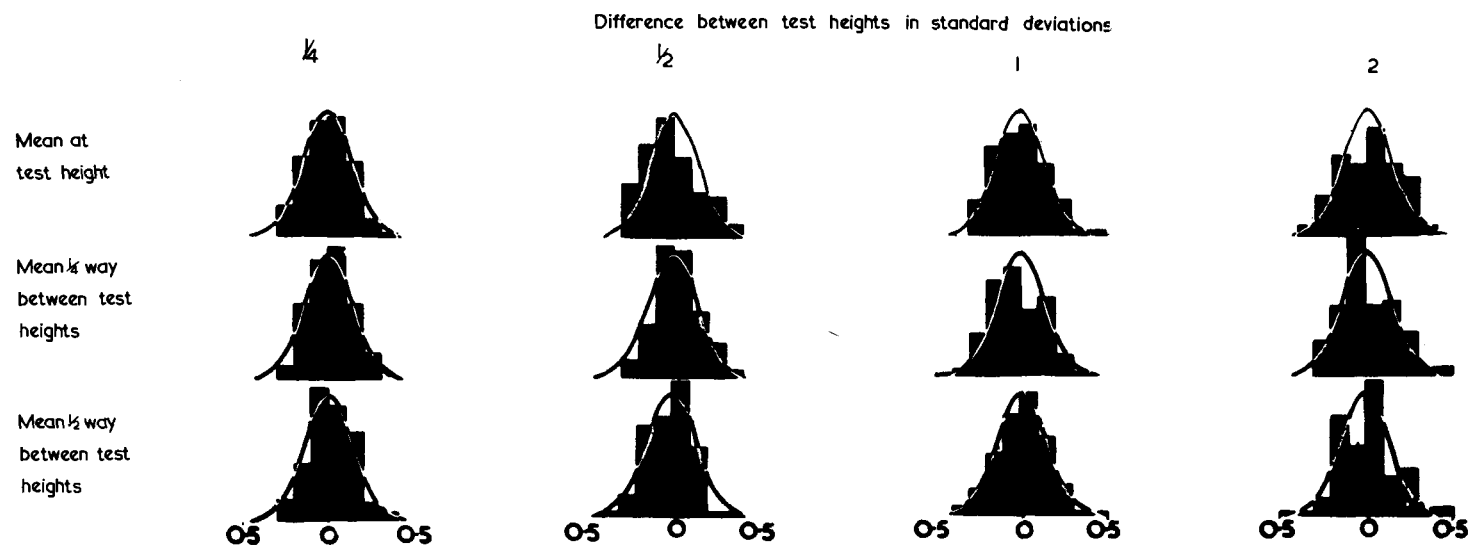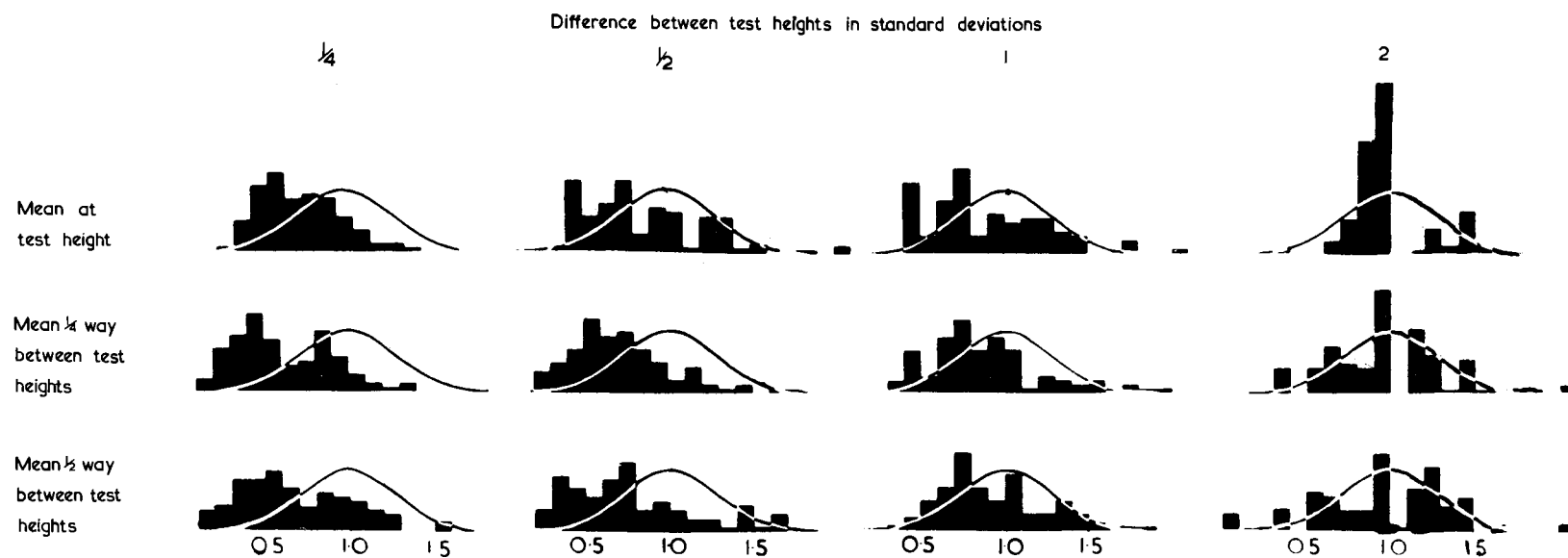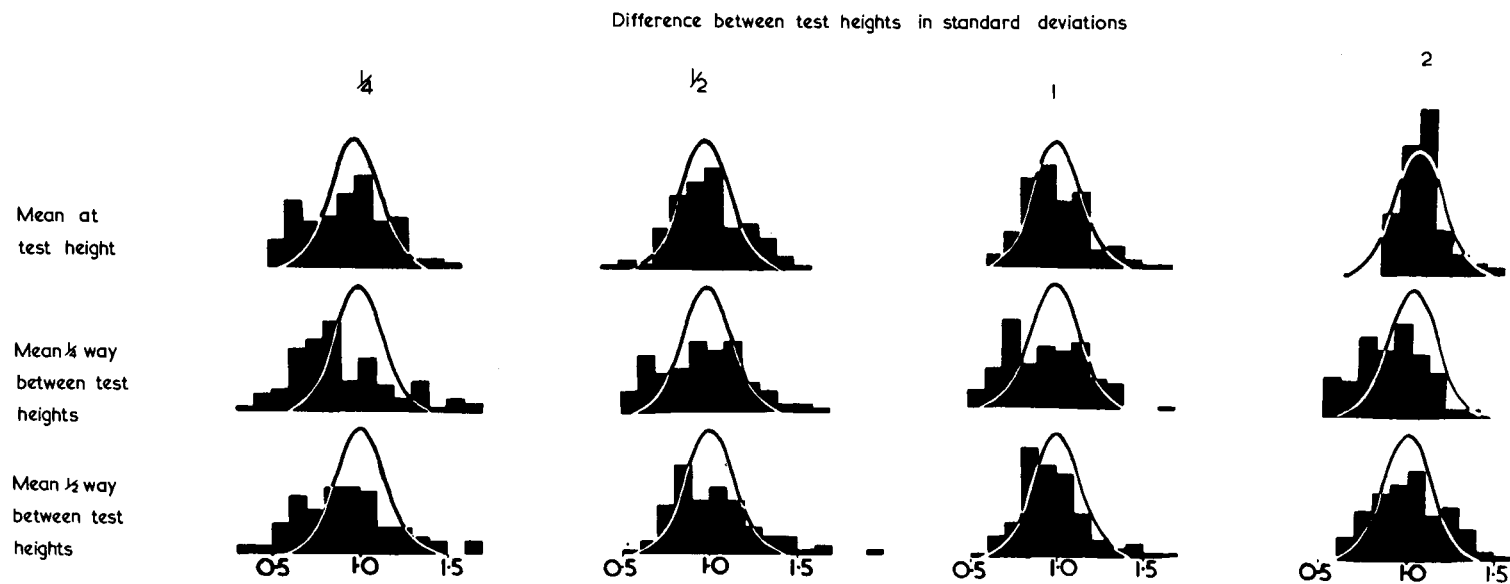
FIG. 4   SPECTRUM OF STANDARD DEVIATIONS. EACH HISTOGRAM GIVES THE RESULT
OF 100 TRIALS OF 100 ITEMS. THE X AXIS SHOWS THE RATIO OF 'FOUND' TO
'TRUE' STANDARD DEVIATION.
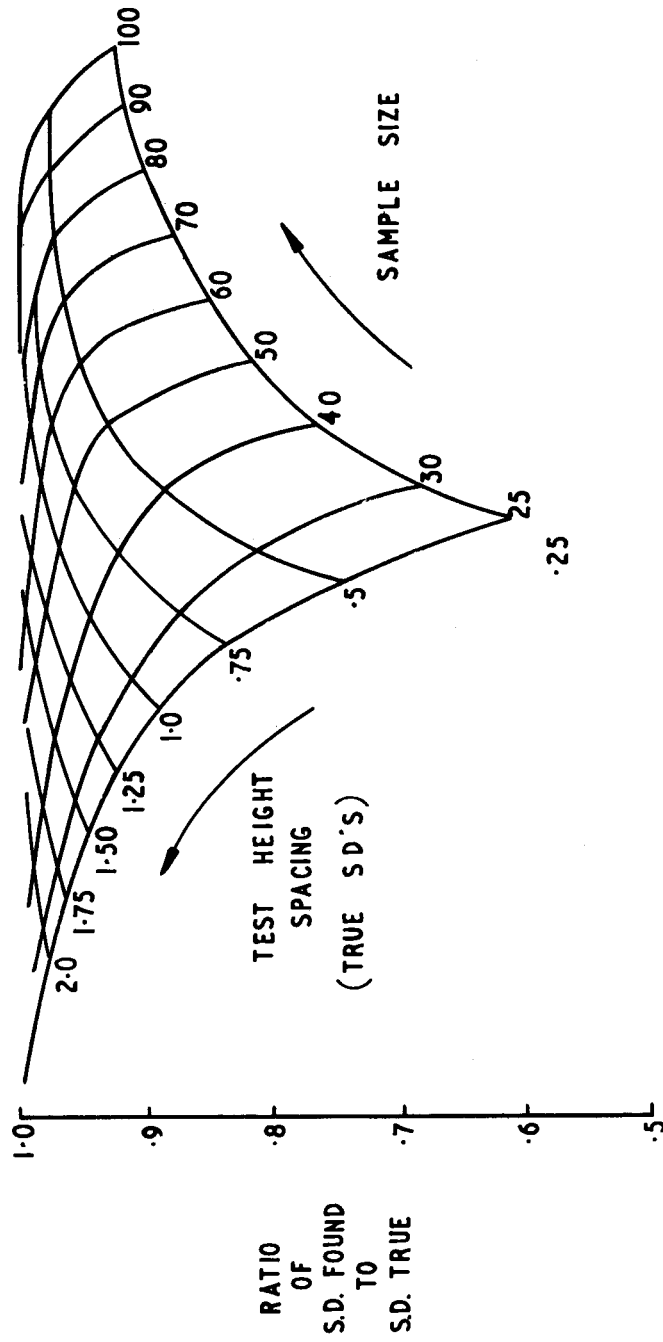
FIG. 5   EFFECT OF SAMPLE SIZE AND STEP SIZE ON UNDERESTIMATION OF THE STANDARD DEVIATION

Tests on Large Sample Theory

To test the distribution of random numbers provided by the Amos computer a large sample Bruceton test was applied. The results of 100 runs of 1000 numbers are given:-

	Found	Theory
Bruceton mean	0.0021	0.0000
Standard error	0.0204	.0224 (G=1.01)
Bruceton s.d.	0.5031	0.5000
Standard error	0.0303	0.0309 (H=1.38)

The values of mean and s.d. were also calculated directly, the results being:-

	Found	Theory
Mean	.0008	.0000
Standard error of mean	.0161	.0158
Standard deviation	.5002	.5000
Standard error of s.d.	.0105	.0120

These calculations provided a satisfactory check on large sample Bruceton theory and computer random number distribution.

Appendix II

Run down tests

In these, the groups of items are tested at various stimulus levels and plots are made of percentage response against stimulus level. On probability graph paper the sigmoid curve is transformed to straight lines. This gives a rapid method for the estimation of mean and s.d., which may be further analysed more accurately by the method of least squares or to the best possible advantage by Probit analysis (Ref.2).

Two features of run down tests are of interest and users of the tests repeatedly ask the questions:-

1. Is the run down, using graphical analysis, as efficient as the Bruceton Procedure.

2. What is the optimum choice of test heights and optimum division of the sample into sub-groups.

A limited amount of work has been carried out to obtain approximate answers to these questions again using the Monte Carlo Method. The variables involved were:-

1. The number of items available.

2. The spacings between test stimuli.

3. The choice between two large groups and various arrangements of larger numbers of smaller groups.

It was decided to limit the tests to 60 items for the purposes of this paper since:-

(a) Less than 60 items are hardly suitable for run down tests.

(b) Largely because of (a) a test of about 60 items is a popular choice.

(o) 60 factorises conveniently into 2 x 30, 3 x 20, 4 x 15, 5 x 12, 6 x 10, thus enabling the group size to be made a convenient variable with a fixed number of items available for test.

It was also decided that groups should be equisized and equispaced on the normal stimulus scale. It is unlikely that this is an optimum arrangement, but it appears that these factors are not very critical and the optimisation is not a sharp one.

The computer simulation consisted of the generation of 60 normally distributed random numbers of mean zero and standard deviation of one half and the division of these numbers into smaller groups. These groups were then tested to find the percentage that did not exceed the chosen stimulus levels and the % response as stimulus deduced.

Ref.2, page 221 may be used to deduce that efficiencies as high as 70% may be obtained for means.

The percentage response was then converted to the probability co-ordinates and a least squares line fitted that represented the graphical fitting on probability paper. Any responses of 0 or 100% were rejected since these give points at infinity and cannot be plotted. (In Probit analysis these points are included but they have very low weighting).

The mean and standard deviation deduced by the simulated experiment were then available for analysis.

Efficiency

As with the Bruceton tests it is useful to introduce the concept of efficiency using the properties of "continuous" data as a yardstick. The standard error for mean and standard deviation are given approximately by:-

$$\text{s.e. mean} = \frac{\sigma}{\sqrt{N}}$$

$$\text{and} \quad \text{s.e. s.d.} = \frac{\sigma}{\sqrt{2N}}$$

so that given the standard error and σ we may calculate N and compare this with the number of items in the sample, i.e. the efficiency is $\frac{100N}{n}$ %, reaching 100% in the "continuous" case.

No difficulty arises in instances where the means and s.d.'s are normally distributed since the standard error may be deduced directly. Difficulty does arise in the case of non-normally distributed data since effective values of the standard error may be deduced for say the 5% and 1% points of the distribution of means or s.d.'s. For these cases the ±5% points are 3.29 s.e.'s apart and the 1% points are 4.65 s.e.'s apart.

Results

The pattern of the results shows that the distributions of means and s.d.'s are non-normal. There is a centre range of results which are near normal with a double ended departure from normality which gives unduly high and unduly low estimates. The departure from normality is probably because when 0 and 100% responses are obtained the sample is out discontinuously by one group.

Tables A2(i) and A2(ii) gives values for the mean and s.d. which were obtained in less than and more than 1% and 5% of occasions. As only 100 trials were done at each condition the 1% points are not very accurate but taking the tables as a whole the trends may be deduced.

The presence of a + in the table indicates that within a run of 100 trials, one or more gave all 0 or 100% response, i.e. a catastrophic result.

Effect of group size

Splitting the sample into two groups only appears undesirable since there is a greater risk of all 100% or 0% response. Splitting between 3 and 5 groups appears to be the best with an optimum at 4 to 5. The larger number would be preferred in practice because it gives the experimenter greater control as the experiment proceeds in smaller steps.

Having a large number of groups of few items is unsatisfactory since the resolution becomes coarsely graded.

Spacing between the groups

Means are determined with reasonable efficiency if the total coverage is between 1 and 3 s.d.'s. Two s.d.'s is probably the approximate optimum.

Standard deviations are poorly determined with 1 s.d. total spread. The optimum is again at 2 s.d.'s. If the spread is increased to 3 s.d.'s there becomes a strong chance of all 0% and 100% response, particularly for small numbers of large groups.

Comparison with the Bruceton test

The efficiency is lower than the Bruceton test both for means and standard deviations. No doubt some of this difference could be recovered if weighted values were used as in Probit analysis. However, bearing in mind the labour involved in the calculations, this procedure does not compete with the Bruceton test. It is sometimes claimed that the run down test has the advantage that any departure from normality is detected. With small samples this is most unlikely to be the case: with larger samples it is, however, a point to be considered. It should be remembered, however, that the results of a large Bruceton test may be given graphical treatment in the same way as run down tests and the normality can be checked by using the χ^2 test included in the "less read" section of the Dixon and Mood report. It is also impracticable to make predictions concerning chances of one in hundreds on the basis of small samples.

Conclusions

For the type of experiment where control of a known product is being monitored by run down tests, the sample should be split into four groups spaced equally over a range of two to three standard deviations about the mean, aiming at responses of 90%, 70%, 30%, 10% or thereabouts.

Run down tests using graphical analysis are, however, less efficient than Bruceton tests and possess no advantage over them. Numerical analysis raises the efficiency, but is much more time consuming. Even the Bruceton test is, however, by comparison with non-destructive testing, inefficient particularly for the determination of standard deviations. Most effective analysis of either test can be carried out by means of Probit analysis and this is well worthwhile if expensive experiments are being carried out.

Table A2(i)

Values of upper and lower 5% points from 100 trials on samples from a population of zero mean and standard deviation equal to ½.

Values for mean

Arrangement of groups	½	1	1½	2	2½	3	3½	4	Total spread of test heights in s.d.'s
2 x 30	-.374 .172	-.135 .156		+		+		+	
3 x 20		-.251 .169		-.173 .182		+		+	
4 x 15	-.260 .338	-.178 .150	-.155 .192	-.194 .170	-.240 .200	-.224 .210		+	
5 x 12		-.305 .170		-.179 .153		-.164 .259		+	
6 x 10		-.170 .309		-.208 .180		-.312 .164		+	

Values for s.d.'s

Arrangement of groups	½	1	1½	2	2½	3	3½	4	Total spread of test heights in s.d.'s
2 x 30	.179 1.943	.336 1.137		+		+		+	
3 x 20		.301 1.981		.342 .834		+		+	
4 x 15	-.827 4.990	.283 1.565	.305 .909	.347 1.015	.392 .810	.342 .971		+	
5 x 12		.236 1.981		.377 .955		.388 1.033		+	
6 x 10		.247 1.797		.351 1.036		.392 1.067		+	

Martin and Saunders 19

Table A2(ii)

Values of upper and lower 1% points from 100 trials on samples from a population of zero mean and standard deviation equal to ½.

Values for means

Arrangement of groups	½	1	1½	2	2½	3	3½	4	Total spread of test heights in s.d.'s
2 x 30	-.557 .373	-.345 .250		+		+		+	
3 x 20		-.434 .289		-.279 .930		+		+	
4 x 15	-4.632 .842	-.528 .729	-.276 .226	-.418 .561	-.520 .434	-.595 .624		+	
5 x 12		-.774 .654		-.255 .208		-.319 .466		+	
6 x 10		-1.081 8.437		-.292 .236		-.463 .450		+	

Values for s.d.'s

Arrangement of groups	½	1	1½	2	2½	3	3½	4	Total spread of test heights in s.d.'s
2 x 30	-1.977 1.977	.249 1.992		+		+		+	
3 x 20		.292		.305 1.378		+		+	
4 x 15	-13.23	.224 2.05	.279	.331	.318 .969	.213 1.855		+	
5 x 12		.168 7.049		.2939 1.409		.217 1.363		+	
6 x 10		-11.056 5.924		.2291 1.921		.299 1.996		+	

Martin and Saunders   20

Efficiencies of determination of means derived from $\pm 5\%$ points

Grouping / Total spread of test heights	½	1	1½	2	2½	3	3½	4
2 x 30	15.1	53.3		+		+		+
3 x 20		25.6		35.8		+		+
4 x 15	12.6	41.9		34.0		23.9		+
5 x 12		20.0		40.9		25.2		+
6 x 10		19.7		30.0		19.9		+

Efficiencies of determination of s.d.'s derived from $\pm 5\%$ points

Grouping / Total spread of test heights	½	1	1½	2	2½	3	3½	4
2 x 30	0.72	3.52		+		+		+
3 x 20		0.80		9.32		+		+
4 x 15	.067	1.37	6.18	5.05	12.91	5.69		+
5 x 12		0.749		6.75		6.42		+
6 x 10		0.939		4.81		6.55		+

NOTE   A   "-" represents an attempt to obtain a value but with an incidence of all 0% - 100% response.

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