Electro Explosive Devices: Functioning, Reliability, Hazards

Franklin Applied Physics, Inc.
Oaks, Pennsylvania, U.S.A.
www.franklinphysics.com

The Fat Lands of Egypt

Introduction

• Instructors:
  Beth Shimer, Jamie Stuart
• Daily Schedule
• Week Schedule
• Trainees
• Franklin Applied Physics, Inc.

John James Audubon
New Orleans 1830, 100 casualties

Test Strength of Materials

Other Government-Funded 19th Century Research
- Breakwaters, Telegraph
- USS Princeton, 1844

Twentieth Century
- Bombsights
- Fuzes
- EEDs – test operation, safety, reliability
- Symposia
- Protection from inadvertent firing
- Electrostatic discharge (ESD)
- Radio Frequency (RF) hazards
Definition of Explosion

Berthelot 1883:
“An explosion is the sudden expansion of gases into a volume much greater than their initial one, accompanied by noise and violent mechanical effects.”

Marcelin Pierre Eugène Berthelot
(1827-1907)

Berthelot Tomb

Physical Explosions
- Water suddenly vaporized
- No chemical reaction
- Mechanical bursting
- Destructive Effects
**Nuclear Explosions**

- Fission or Fusion
- Enormous quantities of heat suddenly released
- Rapid expansion of air
- Nearby material vaporized
- Radioactive elements not explosive
- Explosive trigger

**Atomic Demolition Munitions**

**Chemical Explosions**
Reaction Rate vs. Pressure

Electroexplosives:
Functioning, Reliability, and Hazards

The Explosive Train

Presented by Franklin Applied Physics, Inc.

EXPLOSIVES

- Nuisances
- British Definition
- Stability
- Sensitivity
- Safety and Reliability
- Effectiveness
- Convenience
Basic Terms

- Explosion
- Explosive
- Detonation
- Deflagration
- High explosive
- Low explosive
- Propellant
- Pyrotechnic
- Primary
- Secondary
- Booster

DDT

- Deflagration to Detonation Transition
  - Heat transfer
  - Gas products increase pressure
  - Increased reaction rate
  - Further increased pressure and heating
  - Pressure waves build up to shock waves
- DDT depends on confinement, particle size, surface area, packing density, charge diameter and length, heat transfer, thermochemical characteristics of the explosive

SDT

- Shock to Detonation Transition
  - Incident shock wave produces detonation immediately
- Efficient way to function insensitive secondary high explosives

Elements of a High Explosive Train
<table>
<thead>
<tr>
<th>Common device names</th>
<th>Safe &amp; Arm Device</th>
</tr>
</thead>
<tbody>
<tr>
<td>Igniter</td>
<td>Provision for interrupting propagation in case of accidental initiation of explosive train</td>
</tr>
<tr>
<td>First-fire</td>
<td>• Interposition</td>
</tr>
<tr>
<td>Initiator</td>
<td>• Rotation</td>
</tr>
<tr>
<td>Fuze</td>
<td>• Linear motion</td>
</tr>
<tr>
<td>Squib</td>
<td>• Disconnect power source</td>
</tr>
<tr>
<td>Primer</td>
<td></td>
</tr>
<tr>
<td>Detonator</td>
<td></td>
</tr>
<tr>
<td>Blasting cap</td>
<td></td>
</tr>
<tr>
<td>Detonating cord</td>
<td></td>
</tr>
<tr>
<td>Shock tube</td>
<td></td>
</tr>
<tr>
<td>Booster</td>
<td></td>
</tr>
<tr>
<td>Main charge</td>
<td></td>
</tr>
<tr>
<td>Output charge</td>
<td></td>
</tr>
<tr>
<td>Secondary charge</td>
<td></td>
</tr>
<tr>
<td>Base charge</td>
<td></td>
</tr>
<tr>
<td>Bursting charge</td>
<td></td>
</tr>
</tbody>
</table>

![Diagram of common device names](image1)

![Diagram of safe & arm device](image2)
Point-Impact Base-Detonating (PIBD) Artillery Shell

Oil Well Perforating Gun

Shaped Charge Shells

M789 ammunition for 30-mm cannon
M789 Ammo

Electroexplosives: Functioning, Reliability, and Hazards

EED Construction

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Examples of Electroexplosive Devices

Complete EED
### Conductive Mix

![Conductive Mix Diagram]

### Characteristics of EEDs with Different Transducer Mechanisms

<table>
<thead>
<tr>
<th>TRANSDUCER MECHANISM</th>
<th>RESISTANCE RANGE (ohms)</th>
<th>SENSITIVITY RANGE (ergs)</th>
<th>FUNCTIONING TIME (micro sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot Wire</td>
<td>1 to 10</td>
<td>500 to 100,000</td>
<td>5 to 20,000</td>
</tr>
<tr>
<td>Conductive Mix</td>
<td>10 to 5,000,000</td>
<td>50 to 50,000</td>
<td>1 to 1,000</td>
</tr>
<tr>
<td>Carbon or Graphite</td>
<td>500 to 15,000</td>
<td>50 to 500</td>
<td>1 to 10</td>
</tr>
<tr>
<td>Exploding Bridgewire</td>
<td>0.0001 to 0.1</td>
<td>250,000 to 1,000,000</td>
<td>5 to 50</td>
</tr>
</tbody>
</table>

Source: Franklin Research Center

Note: We normally are opposed to expression of sensitivity in energy units; it is inconvenient here.
• Firing modes
  • pin-to-pin
  • pins-to-case
  • bridge-to-bridge
• Misfire
• Hangfire
• Dud

Detonators in Series

Time to Initiation and Bridgewire Break for Instantaneous Detonators

<table>
<thead>
<tr>
<th>Current (A)</th>
<th>Initiant (ms)</th>
<th>Bridgewire Break (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>17.5–25.5</td>
<td>12.0–45.0</td>
</tr>
<tr>
<td>1.0</td>
<td>9.5–11.5</td>
<td>10.0–12.0</td>
</tr>
<tr>
<td>1.5</td>
<td>6.4–7.5</td>
<td>7.8–9.5</td>
</tr>
<tr>
<td>2.0</td>
<td>4.4–5.3</td>
<td>6.5–9.5</td>
</tr>
<tr>
<td>3.0</td>
<td>3.9–4.3</td>
<td>2.8–4.0</td>
</tr>
<tr>
<td>4.0</td>
<td>0.8–1.0</td>
<td>1.0–2.0</td>
</tr>
</tbody>
</table>

Time to Initiation and Bridgewire Break for Delay Detonators

<table>
<thead>
<tr>
<th>Current (A)</th>
<th>Initiant (ms)</th>
<th>Bridgewire Break t₀ (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>17.5–25.5</td>
<td>12.0–45.0</td>
</tr>
<tr>
<td>1.0</td>
<td>9.5–11.5</td>
<td>10.0–12.0</td>
</tr>
<tr>
<td>1.5</td>
<td>6.4–7.5</td>
<td>7.8–9.5</td>
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<tr>
<td>2.0</td>
<td>4.4–5.3</td>
<td>6.5–9.5</td>
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<tr>
<td>3.0</td>
<td>3.9–4.3</td>
<td>2.8–4.0</td>
</tr>
<tr>
<td>4.0</td>
<td>0.8–1.0</td>
<td>1.0–2.0</td>
</tr>
</tbody>
</table>
Detonators in Parallel

NASA STANDARD INITIATOR, TYPE 1 (NSI-1)
- EPOXY WASHER
- END CLOSURE
- INSULATION DISC
- WELD WASHER
- LOCKWIRE HOLE (2 PLACES)
- WRENCHING SLOT (2 PLACES)
- INSTALLATION O-RING
- CONNECTOR O-RING
- ELECTRICAL CONTACT
- ELECTROSTATIC SPARK GAP
- SEALING DISK
- GLASS SEAL
- EPOXY FILLER
- INDEX KEYWAY (OPEN)
- INDEX KEYWAY (CLOSED)

Electric Match
- Pyrotechnic match-head composition
- Bridgewire
- Solder
- Insulator
- Conductors

Electronic Detonator with Microprocessor
Detonators with Toroids
Ferrite Filter in Header

Header with Capacitor
Electronic Detonator with Microprocessor
Apply the All-Fire Stimulus

- Know what it is for your EED
- Do not apply a lesser stimulus
- Do not exceed the all-fire stimulus by very much

Explosive $\implies$ Gaseous Products + Heat

Ignition Temperature

<p>| | |</p>
<table>
<thead>
<tr>
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</tbody>
</table>

Activation Energy

<table>
<thead>
<tr>
<th>Energy</th>
<th>Activation energy</th>
</tr>
</thead>
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<tr>
<td></td>
<td>Heat output</td>
</tr>
<tr>
<td></td>
<td>Reaction</td>
</tr>
</tbody>
</table>
Initiator Compositions

- Lead Azide, Silver Azide
- Lead Styphnate

Initiator Compositions

- Lead dinitroresorcinate (LDNR)
- Tetrazene

Primary Explosives

Point-Impact Base-Detonating (PIBD) Artillery Shell
EBW Firing Signature

Typical Bridge and Firing Characteristics

Energy versus Power

Energy versus Power Graph

Temperature vs Time Graph

Legend:
- 5 A
- 4 A
- 3 A

Time, Milliseconds

Temperature, deg C

Energy versus Power

EBW Firing Signature

Typical Bridge and Firing Characteristics

Energy versus Power

Energy versus Power Graph

Temperature vs Time Graph
Deposited Energy, Short Firing Time

\[ E = P \times t \]
\[ P = I^2 \times R \]
\[ E = I^2 \times R \times t \]

Long Firing Times

Firing Power

\[ P = I^2 \times R \]

AF & NF Current Versus Time
Blasting Machines
50-Cap and 30-Cap Size
For Claymore Mine

Capacitor Discharge
Blasting Machines

Wireless Blasting Machine
Don’t Use a Battery

• Supplies power without human intervention
• Illegal
• May have lost its charge
• Not suitable for high-resistance circuit

FIELD PROCEDURE

Field Procedure

• Keep shorted.
• Measure before connection.
• Connect with cap isolated and safe. Then move cap to charge.
• Carry in aluminum foil or ammo can.
• Shot line should be tight and twisted.
• Don’t patch shot-line through cables close to other lines.
• Keep shot line close to the ground – not over brush.
• Keep layout close to ground, with minimum area.
• Turn off radio transmitters.
• No mobile (vehicle-borne) transmitters in area.
• Eight-foot standoff distance for hand-held radio transmitter. The power limit is 4 to 5 watts.

Firing Many EEDs At Once

• In Parallel
• JATO units
• Disadvantage: High current
• Electronic detonators
• In Series
• Must be all the same type
• Time to function
• Time to break bridge wire
Electroexplosives: Functioning, Reliability, and Hazards

Devices, Actuators

Presented by Franklin Applied Physics, Inc.

Dimple Actuator

Bellows Actuator

Rotary Actuator
Gas generator, pressure cartridge

Automobile Air Bags

Aircraft Fire Suppression

Many uses in space shuttle
Pilot Ejection Systems

Explosive Switch
Corrugated Charge Holder in Vacuum, Before & After

Two Parallel Paths

Burst Heavy Conductor

Lower Arcs Clear
Upper Path Explosion

Final State

Summary

Firing System
EED Fires

Currents in Chassis

Isolation Resistor R

Inadvertent Ignition

- Improper fire command
- Improper use of battery
- Compromised isolation
- Galvanic cell
- Ground current
General Rule

• Be sure that any stimulus that may arise naturally, in the environment, is less than the explosive material's established no-fire level for that kind of stimulus.

Firing Signal at Wrong Time

• Examples:
  • End of shot-line out of sight
  • Setback closes impact switch
  • Software error
• Solutions

Principles of Safety

• Keep the leadwires of your electric igniter short-circuited together, and isolated, until you are ready to fire.
• Make all electrical connections before you arm the system, i.e. before you insert the igniter into the rocket motor.
• Clear all unnecessary people away before you arm the system
T23E1 Detonator

Rocket Sled Accident
October 9, 2008

Rocket in Airplane

Proper Test Procedure
Accident Set-Up

Galvanic Currents

- Dissimilar metals in contact
- Conductive material or liquid touching dissimilar metals
- Sea water, urine, etc. in contact with metal
- These form an unintended chemical electric battery, and can fire an EED!
- Precaution: always keep EED circuit isolated from metal objects

Galvanic Cell in Earth

Ideal Detonator Array
Potential Difference in Ground

Leakage Current, Multiple Sources

Grounds for Trouble

System Grounds
Galvanic Cell

Lessons to Learn from this Story

• Keep EED leadwires twisted together, until you connect them to the shot-line.
• Do not ground EED leadwires
• Do not ground any part of EED firing circuit
• Do not ground the shot-line
• Keep ends of shot-line twisted together, until you are ready to fire.

Ground Currents

• Faulty electric motor, for example. Short to frame.
• Buried metallic conductors
• Exposed pipes
• Frame of metal building
• Precaution: keep the entire EED circuit isolated from ground, at all times, whenever possible.
Means of Obtaining Static Charge

- rubbing and friction
- contact and separation
- conduction
- induction
- spark or corona from another charged object
- particle contact – blowing dust, snow, etc.

Nature of personnel ESD sparks

ESD in EEDs

- Spark discharge through bridgewire
- Spark discharge pins-to-case
- Spark from person
- Spark from equipment
ESD Safety procedures
(some may not be applicable)

- Grounding
- Avoid plastics
- Non-static clothing – cotton, linen, leather
- Non-static equipment
- High humidity
- Avoid contact and separation processes
- Shielding
- Static insensitive EEDs

Test Circuit

High-voltage probe

Ball switch
Automated Ball Switch

Electroexplosives: Functioning, Reliability, and Hazards

Lightning

Thundercloud
- Temperature difference top to bottom up to 100°F (55°C)
- High winds
- Small particles ionized
- 100 million volts top to bottom

Thundercloud with earth image
Timing of lightning processes

- Stepped leaders form ionized path from cloud to ground -- 20-30 milliseconds
- Return streamer (return stroke) -- large current for ~ 0.1 millisecond
- Process may repeat several times
- First stroke is usually largest
- May have long-duration continuing current
Range of Resistivity Values for Several Types of Soils

- **Soil Composition**
- **Resistivity (Ohm-cm)**

<table>
<thead>
<tr>
<th>Soil Composition</th>
<th>Resistivity (Ohm-cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sea Water</td>
<td>100-200</td>
</tr>
<tr>
<td>Marsh</td>
<td>200-300</td>
</tr>
<tr>
<td>Clay</td>
<td>300-16,000</td>
</tr>
<tr>
<td>Clay, mixed with Sand and Gravel</td>
<td>1,000-135,000</td>
</tr>
<tr>
<td>Chalk</td>
<td>6,000-40,000</td>
</tr>
<tr>
<td>Shale</td>
<td>10,000-50,000</td>
</tr>
<tr>
<td>Sand</td>
<td>9,000-80,000</td>
</tr>
<tr>
<td>Sand and Gravel</td>
<td>30,000-500,000</td>
</tr>
<tr>
<td>Rock – Normal Crystalline</td>
<td>5,000,000-10,000,000</td>
</tr>
</tbody>
</table>
Protection Zone – Probability of Strike < .001

Extended Protection Zone with Grounded Poles and Wire
ESD Accidents

ηλεκτρον, "electron"
Greek for amber

Mounting the T23E1

Self-Propelled Gun
Gun Mechanism

Breech

Slide Safe & Arm

Firing Lines Coming Out
Phalanx CIWS

Search Radar
Trackig Radar
6 - 20mm gun barrels
Ammmunition drum > 800+ rounds

Friction on Insulating Layer

Spark Voltage on Oscilloscope

Separate Ground Connections for Gun and Electric Primer
Schematic Diagram Showing Ground Connections

Oscilloscope Connection

Solution That Worked

2-Pin Mount for Primer
General Solution
A New Safety Rule

- ESD is unavoidable wherever there is motion.
- Don’t ground initiator leadwires.
- Always short-circuit the EED leadwires together, at the same place.

AN UNUSUAL ACCIDENT RE-CREATED

James G. Stuart
Franklin Applied Physics, Inc.

In Air & On Ground

Chaco Hut
Throwing Out Coil of Leadwires

This Man’s First Mistake
- He made ballistic connection before electrical connection.
- We should always make electrical connection before ballistic connection.

Accident Causes Considered
- AC power lines
- Radio frequency (RF) power
- High-pressure air line nearby
- Sympathetic detonation from another blast
- Electrostatic discharge (ESD)

ESD Apparatus to Test Detonator
Electric Detonator

High Explosive Charge with Tape

Thundercloud with Earth Image

Charge Separation on Detonator Parts
Recommendations

- Make electrical connection before ballistic connection.
- Do not use electric detonators when thunderclouds are overhead.
- Use only electric detonators that are ESD-insensitive.
- Do not throw electric detonator leadwires up into the air.
- Unroll electric detonator leadwires along the ground.
Demonstrate Explosion

Safely Knotted Leadwires

Wrapped Leadwires – Not Recommended!
Taped Leadwires – Don't Use Plastic Tape!

Plastic Tape

Accident Sudbury, Ontario Plastic Tape with Detonating Cord

Friction Tape
Don’t Wrap Leads Around Shock Tube!

Lessons Learned

- The pins-to-case firing mode can be particularly sensitive to electrostatic discharge.
- Do not use plastic tape on detonators.
- Do not wind the plastic-insulated leads of detonators around anything.
- Any kind of motion can produce electrostatic charge separation. Use a ground straps.

Perforating Gun ESD Accident

Inside Perforating Gun
Possible Causes Investigated

Use only detonators that tests have shown to be insensitive to ESD.

Defective Cap, ESD-Sensitive

ESD Booster-Cap
Factors Affecting RF Safety

Output from Pulse-Modulated Transmitter

\[ \overline{P} = \left( \frac{T}{\tau} \right) P \]

Thermal Stacking

Metal Shielding
Protecting an EED

Resonant Cavity

Quality Factor $Q$

$$Q = \omega \frac{(\text{StoredEnergy})}{(\text{PowerLoss})}$$

$$Q = \frac{\mu}{\mu} \left( \frac{V}{5\delta} \right) \times \text{Geometrical Factor}$$

Pineville, Kentucky
RFID SYSTEMS
- ACTIVE TAG

PASSIVE TAG

Package with Tag and Detonator
Electric Detonator

<table>
<thead>
<tr>
<th>Radio Band</th>
<th>Wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>125 kHz</td>
<td>2.4 km</td>
</tr>
<tr>
<td>148 kHz</td>
<td>2.0 km</td>
</tr>
<tr>
<td>13.6 MHz</td>
<td>22 m</td>
</tr>
<tr>
<td>433 MHz</td>
<td>69 cm</td>
</tr>
<tr>
<td>900 MHz</td>
<td>33 cm</td>
</tr>
<tr>
<td>2.4 GHz</td>
<td>12 cm</td>
</tr>
</tbody>
</table>

Magnetic Coupling

Reader with Loop Antenna
Field Wire is Better

EM Radiation
Maxwell’s Equations

\[ \nabla \cdot \vec{D} = 4 \pi \rho \]

\[ \nabla \times \vec{H} = \frac{4 \pi}{c} \vec{J} + \frac{1}{c} \frac{\partial \vec{D}}{\partial t} \]

\[ \nabla \times \vec{E} + \frac{1}{c} \frac{\partial \vec{B}}{\partial t} = 0 \]

\[ \nabla \cdot \vec{B} = 0 \]

Induction & Radiation Fields

- Wavelength \( \lambda = c/f \)
- Frequency is \( f \), in sec\(^{-1}\)
- Speed of light is \( c = 3.0 \times 10^{10} \) cm sec\(^{-1}\)
- Induction field predominates for distances less than \( \lambda \). Currents and voltages go back and forth.
- Radiation field predominates for greater distances. Energy goes out to infinity.

Plane Wave Solutions

\[ \vec{E}(\vec{x}, t) = \vec{\varepsilon}_1 \vec{E}_0 e^{i(\vec{k} \cdot \vec{x} - \omega t)} \]

\[ \vec{B}(\vec{x}, t) = \vec{\varepsilon}_2 \vec{B}_0 e^{i(\vec{k} \cdot \vec{x} - \omega t)} \]

\[ \vec{\varepsilon}_2 = \frac{\vec{k} \times \vec{\varepsilon}_1}{k} \]

\[ B_0 = \sqrt{\mu \varepsilon} E_0 \]

\[ E \]

\[ H \]

\[ \frac{1 \text{ statvolt/cm}}{1 \text{ oersted}} = \frac{3.0 \times 10^4 V/m}{\left( \frac{1}{4 \pi} \right) \times 10^3 \text{ ampere-turn/m}} = 377 \Omega \]

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Maximum Allowed Levels

<table>
<thead>
<tr>
<th>Frequency Range</th>
<th>Unrestricted Electric Field (V/m)</th>
<th>Unrestricted Magnetic Field (rms Amp-turn)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MHz</td>
<td>Midi</td>
<td></td>
</tr>
<tr>
<td>0.01 to 2</td>
<td>70</td>
<td>0.19</td>
</tr>
<tr>
<td>2 to 30</td>
<td>200</td>
<td>0.53</td>
</tr>
<tr>
<td>30 to 150</td>
<td>90</td>
<td>0.24</td>
</tr>
<tr>
<td>150 to 225</td>
<td>90</td>
<td>0.24</td>
</tr>
<tr>
<td>etc.</td>
<td></td>
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</tr>
</tbody>
</table>

Radiation from Isotropic Source

\[ S = \frac{P}{4 \pi r^2} \]

Radiation from Anisotropic Source

\[ S = G \frac{P}{4 \pi r^2} \]

RF Pickup in EED Absorbed Power-Safety Margin

\[ P_r = S A r \]

\[ \frac{P_{NF}}{S A} \]
RF Power Pickup

\[ P_r = P \frac{G_i G_r \lambda^2}{16 \pi^2 R^2} \]

\[ P_r = P \frac{G_i}{4 \pi R^2} A_r \]

Half Wave Dipole and Aperture

\[ P = \frac{P_r G A}{4 \pi R^2} \]

\[ A = \frac{\pi}{4} d^2 \]

Safe Distance

Fundamental Expression

\[ P_r = \frac{P_i G_i A_e}{4 \pi r^2} \]

\[ r = \sqrt{\left(\frac{P_i}{P_r}\right) \frac{G_i}{4\pi A_e}} \]

RF Effects
Plane Reflectors

Absorbed Power (Gaussian)

\[ P_r = S A_r \]

\[ P_r = \frac{c}{8\pi} |E_0|^2 A_r \]

Absorbed Power, MKS

\[ P_r = S A_r \]

\[ P_r = \frac{E^2}{R} A_r \]

Transmitting Tower near EED
Direct and Reflected Waves

Reflection Coefficient

\[ E_{TOT} = E + E_{REFL} \]
\[ E_{TOT} = E \left(1 + \rho\right) \]
\[ -1 \leq \rho \leq 1 \]

Incorporate Reflection (Gaussian)

\[ A = \left(1 + \rho\right)^2 A_{FS} \]
\[ P_r = \frac{c}{8\pi} |E_o|^2 A \]
\[ P_r = \frac{c}{8\pi} |E_o|^2 \left(1 + \rho\right)^2 A_{FS} \]

Incorporate Reflection (mks)

\[ A = \left(1 + \rho\right)^2 A_{FS} \]
\[ P_r = \frac{E^2}{R} A \]
\[ P_r = \frac{E^2}{R} \left(1 + \rho\right)^2 A_{FS} \]
Earth’s Surface

Refraction at Earth’s Surface

Refraction at Interface

\[
\frac{\sin \alpha}{\sin \beta} = \sqrt{\frac{\varepsilon'}{\varepsilon}}
\]

\[
E_{TOT} = E + E'
\]

\[
E_{TOT} = E \left(1 + \gamma \right)
\]

\[
\gamma = -\frac{\sin(\alpha - \beta)}{\sin(\alpha + \beta)}
\]

Far-Distance Approximation

for \( r \geq 2h \),

\[
\gamma = \left(\frac{h}{r} - 1\right)
\]

\[
E_{TOT} = E \left(\frac{h}{r}\right)
\]

\[
A = \left(\frac{h}{r}\right)^2 A_{\beta}
\]
Loss Resistance

Wire Dimensions and Resistance

\[ R = \frac{L}{\sigma A} \]

Metal Conductivity

Skin Depth
Gaussian
\[ \delta = \frac{c}{\sqrt{2\pi \mu \omega \sigma}} \]
mks
\[ \delta = \sqrt{\frac{2}{\omega \mu \sigma}} \]

Skin Depth in Various Metals

<table>
<thead>
<tr>
<th>Copper</th>
<th>Iron</th>
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</thead>
<tbody>
<tr>
<td>c 3.00E+10</td>
<td>3.00E+10 cm/sec</td>
</tr>
<tr>
<td>\mu 1</td>
<td>1</td>
</tr>
<tr>
<td>f 5.40E+05</td>
<td>5.40E+05 1/sec</td>
</tr>
<tr>
<td>\omega 3.39E+06</td>
<td>3.39E+06 1/sec</td>
</tr>
<tr>
<td>\sigma 5.20E+17</td>
<td>8.80E+16 1/sec</td>
</tr>
<tr>
<td>\delta 9.01E-03</td>
<td>2.19E-02 cm</td>
</tr>
<tr>
<td>\delta 3.5E-03</td>
<td>8.6E-03 inch</td>
</tr>
</tbody>
</table>

Loss Resistance in Round Wire (Gaussian Units)
\[ R_L = \frac{L}{\sigma A} = \frac{L}{\sigma 2\pi \delta} = \frac{L}{\sigma 2\pi r} \sqrt{\frac{2\pi \mu \omega \sigma}{\sigma}} \]

Loss Resistance in Round Wire (mks units)
\[ R_L = \frac{L}{\sigma A} = \frac{L}{\sigma 2\pi \delta} = \frac{L}{\sigma 2\pi r} \sqrt{\frac{\omega \mu \sigma}{2}} = \frac{L}{rc} \sqrt{\frac{\mu}{\sigma}} \]
Reduced Aperture

\[ A_e = \frac{R}{R+R_L} A_{fs} \]

Matching Section

Loss in Matching Section (Gaussian units)

\[ L = \frac{\lambda}{2} \]
\[ R_L = \frac{1}{2}\left(\frac{\mu}{\sigma}\right) \]
\[ A_e = \frac{R}{R+R_L} A_o \]
\[ A_s = \frac{R}{R + \frac{1}{2}\left(\frac{\mu}{\sigma}\right)} A_o \]

Loss in Matching Section (mks units)

\[ L = \frac{\lambda}{2} \]
\[ R_L = \frac{c}{2r_e \sqrt{4\pi f \sigma}} \]
\[ A_e = \frac{R}{R + R_L} A_o \]
\[ A_s = \frac{R}{R + \frac{c}{2r_e \sqrt{4\pi f \sigma}}} A_o \]
Mechanical Aperture

Antenna Types
- EED as Dipole
- Monopole
- Vertical Antenna
- Short Dipole
- Half-Wave Dipole
- EED Pins
- Long Straight Wire
- Small Loop
- Geometrical Pattern
- Multiple Sources

Dipole Antenna

Equivalent Antennas

A

B

C

D
Vertical Whip Antenna

Half-Wave Dipole Works Best

\[ \ell = \lambda / 2 \]

\[ \lambda = \frac{c}{f} \]

\[ f = \frac{c}{2 \ell} \]

Half-Wave Dipole Formulae

\[ G = 1.65 \]

\[ A = \frac{\lambda^2 G}{4\pi} \]

\[ A = 1.65 \frac{\ell^2}{\pi} \]

Incorporate Other Effects

\[ A_r = \frac{G\lambda^2}{4\pi} \frac{R}{R_i + R} \left( 1 + \rho \right)^2 \left( 1 + \gamma \right)^2 \]

\[ A_c = \frac{1.65c^2}{4\pi f^2} \frac{R}{R + \frac{1}{2r_0} \sqrt{\frac{\mu}{f \sigma}}} \left( 1 + \rho \right)^2 \left( 1 + \gamma \right)^2 \]
Gain & Radiation Resistance of Short Dipole

\[ G_M = \frac{3}{2} \]

\[ P = \frac{I_0^2 (k d)^2}{12 c} \]

\[ P = \frac{1}{2} I_0^2 R \]

\[ R = \frac{d^2 f^2}{6 c^3} \]

EED Pins – Circular Aperture, or Worst Case Half Wave Dipole

Current Zones in Long Dipole

Gain & Effective Aperture of Small Loop

\[ G_M = \frac{3}{2} \]

\[ A_e = 4 \pi^2 \frac{A^2}{\lambda^2} \left( \frac{4 \pi}{c} \right) \frac{R}{(R + R_L)^2} \]
Longer Wires

Maximum Gain of Wire Antennas

Maximum Gain for Given Wire Length

\[ G = 1.5 + 0.1322 \left( \frac{\ell}{\lambda} \right) + 0.0775 \left( \frac{\ell}{\lambda} \right)^2 \]

\[ A = \frac{\hat{\lambda} G}{4\pi} \]

\[ \hat{\lambda} = \frac{c}{f} \]

\[ A = \frac{1}{4\pi} \left[ 1.3 \left( \frac{c}{f} \right)^2 + 0.1322 \left( \frac{c}{f} \right) + 0.0775 \ell^2 \right] \]

Multiple RF Sources

\[ I = I_1 \sin \omega_1 t + I_2 \sin \omega_2 t + \ldots \]

\[ P = \overline{I^2} R \]

\[ P = \frac{1}{2} I_1^2 R + \frac{1}{2} I_2^2 R + \ldots \]

\[ P = P_1 + P_2 + \ldots \]
Aperture of Short Dipole

\[
G_M = \frac{3/2}{(A_m)M} = \frac{\lambda^2}{4\pi} \\
A = \frac{3}{2} \frac{\lambda^2}{4\pi}
\]

Effective Aperture of Half-Wave Dipole

\[
A_e = \frac{3}{2} \frac{\lambda^2}{4\pi} \frac{R_R}{R_L} \\
A_e = \frac{d^2}{16\pi c R_L}
\]

Small Loop with Skin-Effect Loss

\[
A_s = 4\pi^2 \frac{A^2}{\lambda^2} \left( \frac{4\pi}{c} \right) \left( \frac{R}{R + R_L} \right)^2 \\
R_L = \frac{\ell}{r_0 c} \sqrt{\frac{\mu f}{\sigma}} \\
A_s = 4\pi^2 \frac{A^2}{\lambda^2} \left( \frac{4\pi}{c} \right) \left( \frac{R}{R + \ell \sqrt{\frac{\mu f}{\sigma}}} \right)^2
\]

Small Loop with Skin-Depth Loss and Reflection

\[
A_s = (1 + \rho) 4\pi^2 \frac{A^2}{\lambda^2} \left( \frac{4\pi}{c} \right) \left( \frac{R}{R + \ell \sqrt{\frac{\mu f}{\sigma}}} \right)^2
\]
Blasting Wire at Low Frequencies

Shielded Firing Cable

Cable Faults

Wireline with Faults
RF Safe Distance

Model EED System Aperture:
- Short dipole
- Half-wave dipole
- Long straight wire
- Wire longer than wavelength, not straight
- Small loop
- Mechanical aperture

Aperture of EED Alone
- Model as short dipole of length d
- Use maximum dimension of EED as d

\[ A = \frac{d^2}{16 \pi c R} \]

Safe Distance
Fundamental Expression

\[ P_r = \frac{P_i \, G_i \, A_e}{4 \pi r^2} \]

\[ r = \sqrt{\frac{P_i \, G_i}{P_r}} \frac{A_e}{4\pi} \]
Use Known No-Fire Level-

In “Safe Distance” equation, insert EED’s $P_{NF}$ value for received power $P_r$

EXAMPLE CALCULATION

- Electric detonator
- One ohm bridgewire
- 0.2 ampere no-fire current level
- Copper leadwires
- Extended leadwires and shot-line (worst case)
- Leadwires are twisted together at end
- Nearby AM radio broadcasting station
- How close can we get?

Further Assumptions

- AM radio band is 0.54 to 1.6 MHz. As a worst case, we say frequency is 1.6 MHz. Thus, wavelength is about 188 meters.
- AM radio transmitters are often very directional. As a worst case, we say $G_i = 10$.
- Transmitter power 50,000 watts – legal max
- As a worst case, we assume someone has picked up one of the EED wires, leaving the other on the ground, making a triangular loop.

PICKUP LOOP
Particulars of Pickup Loop

- Loop is much smaller than a wavelength
- Therefore, we will use our aperture formula for a small loop
- Loop area 2.3 m²
- Perimeter Length 7.3 m

Safe Distance Formula

\[ r = \sqrt{\frac{P}{P_r} \frac{G_r}{4\pi} A_r} \]

\[ r = \frac{2\pi A f}{c} \sqrt{\frac{G_r P_r (1/c)}{P_c} \left( R \right)^2 + \left( \frac{\ell}{\sigma R} \right) \left( \frac{\mu f}{\sigma} \right)} \]

Recommended Distances from Commercial AM Broadcast Transmitting Antennas 0.54 to 1.6 MHz

<table>
<thead>
<tr>
<th>Transmitter Power Watts</th>
<th>Safe Distance Meters</th>
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<tr>
<td>0</td>
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</tr>
<tr>
<td>10000</td>
<td>100</td>
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<td>600</td>
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</tbody>
</table>
References


Electroexplosives: Functioning, Reliability and Hazards

Testing for Safety

Presented by Franklin Applied Physics, Inc.
Anechoic Chamber

MILITARY STANDARD

TABLE: SAMPLING PROCEDURES AND TABLES

Note: All tables are subject to change without notice. Distribution is unlimited.
Functioning, Reliability, and Hazards:

**Non-destructive Tests**

Presented by Franklin Applied Physics, Inc.

• The firing of an electroexplosive device is irreversible, non-repeatable, and not fully predictable in advance. A number of indirect methods have been developed that can determine whether a given EED might be defective, without actually firing it.  

  
  *Joseph McLain*

**Bridgewire Resistance Test**

- Special ohmmeter to limit current
- < for hot-wire device
- < 10 microamps for carbon bridge
- Check every item
  - on production line
  - before and after test exposure
  - system check
- RF Impedance

**Thermal Transient Response Test**

**Rosenthal Equation**

\[ C \frac{dT}{dt} + aT = P(t) = I^2 R_o (1 + bT) \]

- C is heat capacity of the system
- T is temperature above ambient
- t is time
- a is heat loss coefficient of the system
- b is thermal coefficient of resistance of bridgewire material
- \( R_o \) is initial resistance of the EED
Solutions for constant current

\[ T = \frac{I^2 R}{a - I^2 R b} \left[ 1 - \exp \left( -\frac{a - I^2 R b}{C} \right) t \right] \]

If \( t \ll C/a \) i.e. very short time

\[ T = \frac{I^2 R}{C} t = \frac{\text{Energy}}{\text{Heat Capacity}} \]

- If \( t \) is very large i.e. equilibrium situation

\[ T_e = \frac{I^2 R_o}{a - I^2 R b} \propto \text{power} \]

Increasing "a" decreases equilibrium temperature

Increasing C increases time to equilibrium

Increasing R_o increases equilibrium temperature
Leak Test

- Keep out moisture
- Hermetically sealed
- Seals between different materials – metal, glass or ceramic, plastics, etc.
- Helium
- Krypton-85
- Red dye

X-rays of EEDs

Testing EEDs

- Random sample from large lot of EEDs
- Sampling by attributes
- MIL-DTL-23659D
- Don’t re-use test samples

Turn-On Time

- Bridgewire posts
- Current Heating
\[ \frac{dT}{dt} = k I^2 R \]
- Conduction Cooling
\[ \frac{dT}{dt} = \frac{T - T_0}{\tau} \]
• Current rise rate $I = \alpha \, t$
• Combine effects $\frac{dT}{dt} = k \, \alpha^2 \, t^2 \, R \, \frac{T - T_o}{\tau}$

Alternative Explanations
• Current overshoot
• Dudding

Electrical Test Stimuli for EEDs
• All-fire – Short Time
• No Fire – Long Time
• ESD
• Constant Current or Voltage
• Constant Power
• Capacitor Discharge
• RF Power

ESD Tester
Photo of ESD Tester

Simulator Set Up
-Leads should be short!

HV Lead in Conduit
-Not Recommended!

ESD Pin-to-Pin Test
Current, Instantaneous Power

\[ I(t) = \frac{V}{\beta} e^{-\frac{t}{RC}} \]

\[ P(t) = [I(t)]^2 R \]

Energy Bridge Wire Temperature

\[ E = \frac{C V^2}{2} = \frac{C V^2 \beta}{2 (\beta + R)} + \frac{C V^2 R}{2 (\beta + R)} \]

\[ T_{ESD} = \frac{C V^2 R}{2 c_v (\beta + R)} \]

Constant-Current Tester

\[ I = \frac{V}{R_1 + R_2} \quad R_1 \gg R_2 \]

\[ I = \frac{V}{R_1} \left( 1 - \frac{R_2}{R_1} + \ldots \right) \]

\[ I = \frac{V}{R_1} \]

Constant-Voltage Tester
Constant-Power Test

- Semiconductor bridge (SCB) initiators
- Conductive mix initiators
- Ratio of voltage to current (apparent resistance) depends on temperature

Power as Function of Constant Voltage or Current

- $P = \frac{V^2}{R}$
- $P = I^2 R$
Capacitor-Discharge Tester

\[ \beta \ll \gamma \]

**Capacitor-Discharge Test**

**DISCHARGE TIME < THERMAL TIME CONSTANT**

RF Voltage and Current

RF Voltage and Power

\[ V = V_0 \cos \omega t \]

\[ P = \frac{1}{T} \int_{t=0}^{t=T} V I \, dt \]
RF Period

\[ T = \frac{2 \pi}{\omega} \]

RF Voltage and Current out of Phase

\[ V = V_0 \cos \omega t \]
\[ I = I_0 \cos (\omega t + \theta) \]

\[ P = \frac{1}{T} \int_{t=0}^{T} V I \, dt \]
\[ P = \frac{1}{T} \int_{t=0}^{T} V_0 I_0 \cos \omega t \cos (\omega t + \theta) \, dt \]
\[ P = \frac{1}{2} V_0 I_0 \cos \theta \]

Measure Voltage, Current, and Phase Angle. \( V_2 = \beta \)

Phase Difference
Phase Angle and Measured Average RF Power

\[ \theta = 2 \pi \frac{d}{D} \]

\[ P = \frac{1}{2} V_0 I_0 \cos \theta \]

\[ P = \frac{\alpha}{2} V_1 V_2 \cos \left( 2 \pi \frac{d}{D} \right) \]

Lead Length for EED RF Tests

\[ R_{LEAD} \ll R_{EED} \]

Allowable Lead Length

\[ R_{LEAD} = \frac{2 \Lambda}{2 \pi \delta} \]

\[ R_{LEAD} = \frac{2 \Lambda}{r \sigma} \sqrt{\frac{f}{c}} \]

\[ \frac{\Lambda}{r} \ll 1.2 \times 10^4 \frac{R_{EED}}{\sqrt{f}} \frac{\text{MHz}}{\text{ohm}} \]

\[ \frac{\Lambda}{r} \ll 10.7 \times 10^{18} \frac{R_{EED}}{\sqrt{f}} \frac{\text{cm}}{\text{sec}^{3/2}} \]

Output Tests on EEDs

• Squibs - hot gas – closed bomb

• Detonators – shock wave – witness
Card Gap Test

Data From Card Gap Test

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</tbody>
</table>

Timing

Light Output After Capacitor Discharge
Light from 2 EEDs Fired in Parallel

Light Sensor Module

Light Sensor System

Firing Chamber Safety Factor
Sealed Tube

Ultimate Tensile Strength

\[ S = \frac{F}{A} \]

Thin-Walled Metal Tube

Upper Half of Tube

\[ F_{down} = 2 \, S \, t \, d\ell \]
\[ F_{up} = \int_{0}^{\pi} P \, r \, \sin \theta \, d\theta \, d\ell = 2 \, P \, r \, d\ell \]
Barlow’s Formula for Burst Pressure

\[ P = \frac{S t}{r} = \frac{2 S t}{D} \]

Tube Calculation

Pressure from 3 grams HE

\[ C_3 H_6 N_6 O_6 \rightarrow 3 N_2 + 3 H_2 O + 3 C O \]

\[ 3 g \text{ RDX} = 0.0135 \text{ mol} \rightarrow 0.12 \text{ mol gas} \]

\[ P = \frac{n R T}{V} \]

Safety Factor for Tube

(Greater for Test Chamber)

\[ SF = \frac{P_{\text{bursting}}}{P_{\text{from explosive}}} = 194 \]
One-Level Test

- Uniformity
- Few Defectives
- Poisson Distribution
- Test Lots with Defectives

EEDs with Varying Resistance

\[ P = I^2 R \]

- Divide test units into two lots by resistance
- Perform all-fire test on low-resistance lot
- Perform no-fire test on high-resistance lot

Assumption: Few Defectives

- Large population with few defectives
- Fraction of defectives \( \theta \)
- Value of \( \theta \) is small
- Sample size \( n \)
- We find number of defectives \( x \)
- Sample size \( n \gg x \)
- Product \( n\theta \) is small (less than 25)

What We Need to Know

- What value of \( x \), i.e., how many defectives, can we reasonably expect to find?
- If we obtain a certain number of defectives \( x \), what can we say about the value of \( \theta \)?
- How many items \( n \) do we need in our test lot?
Poisson Distribution

\[ \mu \equiv n \theta \]

\[ p ( x \mid \theta) = \frac{\mu^x e^{-\mu}}{x!} \]

\[ \alpha = p (0 \mid \theta) = \frac{\mu^0 e^{-\mu}}{0!} = e^{-\mu} \]

\[ \alpha = p (1 \mid \theta) = \frac{\mu^1 e^{-\mu}}{1!} = \mu e^{-\mu} \]

\[ \alpha = p (1 \mid \theta) + p (0 \mid \theta) = \mu e^{-\mu} + e^{-\mu} \]

Zero Defectives, Lot Size 10

\[ p (0 \mid \theta) = \alpha = \frac{\mu^0 e^{-\mu}}{0!} = e^{-\mu} \]

<table>
<thead>
<tr>
<th>( \alpha )</th>
<th>( \theta )</th>
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<tr>
<td>0.065</td>
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<td>0.910</td>
<td>0.009</td>
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</table>

Reliability & Confidence

\[ \alpha = 0.100 \text{ for } \theta = 0.230 \]

\[ \alpha < 0.100 \text{ for } \theta > 0.230 \]

probability \( \leq 0.100 \) that \( \theta \geq 0.230 \)

probability \( > 0.900 \) that \( \theta < 0.230 \)

probability \( > 0.900 \) that \( (1 - \theta) > 0.770 \)

confidence = 90\% that reliability \( \geq 77\% \)
Probability of \( c \) or fewer defectives

\[
\mu \equiv n \, \theta \\
\alpha = \sum_{x=0}^{c} \frac{\mu^x \, e^{-\mu}}{x!}
\]

Confidence and Reliability

- If we draw a sample of size \( n \) from a population with a defective fraction \( \theta \), then the probability that we will find \( c \) or fewer defective items is \( \alpha \).
- If we test \( n \) items, from a population with a defective fraction less than or equal to \( \theta \), then the probability that we will obtain \( c \) or fewer defectives is \( (1 - \alpha) \).
- If we draw a sample of size \( n \), and we find \( c \) or fewer defective items, then the probability is \( \alpha \) that the population has defective fraction \( \geq \theta \).

Another Way of Putting It

- If we draw a sample of size \( n \), and we find \( c \) or fewer defective items, then we have \( 100(1-\alpha)\% \) confidence that the population has defective fraction \( \leq \theta \).
- If we draw a sample of size \( n \), and we find \( c \) or fewer defective items, then we have \( 100(1-\alpha)\% \) confidence that the population has reliability \( \geq 100(1-\theta)\% \).

Confidence and Reliability

Confidence \( \leftrightarrow \alpha \)
Confidence = \( 100(1 - \alpha)\% \)

Reliability \( \leftrightarrow \theta \)
Reliability = \( 100(1 - \theta)\% \)
Two or Fewer Defectives

\[ \mu = n \theta \]
\[ \alpha = e^{-\mu} + \mu e^{-\mu} + \frac{\mu^2 e^{-\mu}}{2} \]

<table>
<thead>
<tr>
<th>( \theta )</th>
<th>( \alpha )</th>
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<tbody>
<tr>
<td>( \theta )</td>
<td>( \alpha )</td>
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</table>

Expose 500 to AF, all but 2 fired:
Reliability w/ 90% confidence?

\[ 100(1-\alpha)\% = 90\% \]
\[ \alpha = 0.10 \]
\[ c = 2 \]
\[ \alpha = 2 \sum_{x=0}^{c} \frac{\mu^x e^{-\mu}}{x!} \]
\[ 0.10 = e^{-\mu} + pe^{-\mu} + \frac{\mu^2 e^{-\mu}}{2!} \]
\[ \mu = 5.322 \]
\[ \theta = \frac{\mu}{n} = \frac{5.322}{500} = 0.010644 \]
\[ 1 - \theta = 0.9896 \]

One or Fewer Defectives

\[ \mu = n \theta \]
\[ \alpha = e^{-\mu} + \mu e^{-\mu} \]

<table>
<thead>
<tr>
<th>( \theta )</th>
<th>( \alpha )</th>
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<tr>
<td>( \theta )</td>
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Zero Defectives

\[ \mu = n \theta \]
\[ \alpha = e^{-\mu} \]

<table>
<thead>
<tr>
<th>( \theta )</th>
<th>( \alpha )</th>
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</thead>
<tbody>
<tr>
<td>( \theta )</td>
<td>( \alpha )</td>
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</tbody>
</table>
Examples of Values Not in Tables

• Find lot size
• Find Confidence Level
• Find Reliability
• Increase Lot size

Find Lot Size

• AF=3.5A, 97.5% Reliability, 92% Confidence
• Equation for Zero Defectives $\mu \equiv n \theta$
  $\alpha = e^{-\mu}$

Find Confidence

• Test 30 squibs (n=30). None fires.
• No-fire level (95% reliability) is 0.400 A
• What confidence that squibs meet spec?
• Probability for zero defectives

\[
\mu \equiv n \theta \\
\alpha = e^{-\mu}
\]

Find Reliability

• What is reliability of firing unit?
• 22 caps; all of them fire
• Use formula for zero defectives

\[
\mu \equiv n \theta \\
\alpha = e^{-\mu}
\]
Increase Lot Size

- Specify DC no-fire current 0.150 ampere
- Specify 90% reliability, 90% confidence
- “Zero Defectives” table: 24 squibs
- Expose 24, the last one fires
- Expose more – how many?
- “One or Fewer Defectives” table: 39
- We must obtain & expose 15 more
- If no more fire, specification is met.

Drawbacks

- Many useful conclusions from the kind of test where we expose explosive devices to a single stimulus level.
- This kind of test does not tell us what might happen at a different level of stimulus.
- Large number of explosive items required, particularly when we test high levels of reliability, at high levels of confidence.

Testing at Many Stimulus Levels

How to determine all-fire and no-fire levels for EEDs

Cumulative Firing Probability

![Cumulative Firing Probability Graph](image-url)
Fitting Data

All-Fire & No-Fire
- Bayes Principle
- Notion of Accuracy Does Not Apply
- Percentage Points of Normal Distribution (ALL-FIRE)

<table>
<thead>
<tr>
<th>α</th>
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<tbody>
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</table>

Measurement Protocols

Bruceton Protocol
- Bruceton, Pennsylvania, U.S.A.
- Up-and-down test
- Pencil-and-paper calculations
- Determine mean and standard deviation
- Determine all-fire & no-fire levels
(n+1) evenly spaced levels
\[ y_0, y_1, \ldots, y_n \]
\[ y_i = y_0 + i \cdot d \]

STIMULUS VALUES
- Not the same thing as evenly-spaced levels
- \[ h_0, h_1, \ldots, h_n \]
- Stimulus values need not be evenly-spaced

Linear Transformation
\[ y_i = \alpha \cdot h_i \]
\[ h_i = \frac{1}{\alpha} \cdot y_i \]

Logarithmic Transformation
\[ y_i = \beta \ln h_i \]
\[ h_i = e^{\frac{y_i}{\beta}} \]
Common Logarithmic Transformation

\[ \beta = \frac{1}{\ln 10} \]

\[ y_i = \log_{10} h_i \]

\[ h_i = 10^{y_i} \]

Example of Common Logarithmic Transformation

<table>
<thead>
<tr>
<th>Stimulus Value, amperes</th>
<th>Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.37</td>
<td>0.73</td>
</tr>
<tr>
<td>4.27</td>
<td>0.63</td>
</tr>
<tr>
<td>3.39</td>
<td>0.53</td>
</tr>
<tr>
<td>2.69</td>
<td>0.43</td>
</tr>
<tr>
<td>2.14</td>
<td>0.33</td>
</tr>
<tr>
<td>1.70</td>
<td>0.23</td>
</tr>
</tbody>
</table>

Example Continued

- Protocol predicts no-fire level -0.05
- No-fire stimulus value is \( 10^{-0.05} \)
- No-fire stimulus value is 0.89 ampere

LINEAR TEST DATA

<table>
<thead>
<tr>
<th>Du</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lev el</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
</tr>
</tbody>
</table>

| 30 | X |
| 25 | O X x x x |
| 20 | X O X O O O X X |
| 15 | X O O O O O O X X |
| 10 | O O O O O O O O |

www.franklinphysics.com
ALL-FIRE STIMULUS CALCULATION FROM DATA

<table>
<thead>
<tr>
<th>Confidence Percent</th>
<th>Probability α</th>
<th>Probability β</th>
<th>k</th>
<th>t</th>
<th>All-Fire Stimulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>95</td>
<td>0.95</td>
<td>99.9</td>
<td>0.999</td>
<td>3.090</td>
<td>1.645</td>
</tr>
<tr>
<td>90</td>
<td>0.9</td>
<td>99.9</td>
<td>0.999</td>
<td>3.090</td>
<td>1.282</td>
</tr>
<tr>
<td>95</td>
<td>0.95</td>
<td>99</td>
<td>0.990</td>
<td>2.326</td>
<td>1.645</td>
</tr>
<tr>
<td>90</td>
<td>0.9</td>
<td>99</td>
<td>0.990</td>
<td>2.326</td>
<td>1.282</td>
</tr>
</tbody>
</table>

Langlie Protocol

- Differently spaced levels
- Requires a computer

Langlie Parameters

\[ t_i = \frac{s_i - \mu}{\sigma} \]

\[ g(t) = \frac{1}{\sqrt{2\pi}} e^{-\frac{t^2}{2}} \]

\[ h_i = \frac{u_i}{1 - G_i} - \frac{1 - u_i}{G_i} \]

\[ G_i = \int_0^t g(t) \, dt \]

Langlie Sums

\[ \sum_{i=1}^{N} g(t_i) \, h_i = 0 \]

\[ \sum_{i=1}^{N} t_i \, g(t_i) \, h_i = 0 \]
Langlie Test Data

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>TOTALS</th>
<th>Sum of Squares</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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</tbody>
</table>

Other Protocols

- Probit
- Robbins-Monro
- Neyer
- Einbinder (OSTR)
- Equivalence
- Which is better? – the class decides

Minimum Contradictoriness

<table>
<thead>
<tr>
<th>Stimulus T</th>
<th>Functioned</th>
<th>Did not function</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>4.8</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>4.6</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>4.4</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>4.2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>4.0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>3.8</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>3.6</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

Incremental Functioning Probability

\( y(T) \)

Stimulus T
Incremental Non-Functioning Probability

\[ y(T) = \frac{1}{\sqrt{2\pi} \sigma} e^{-\frac{(T-\mu)^2}{2\sigma^2}} \]

Stimulus T

Incremental Probability for Contradictory Result

\[ y(T) = \frac{1}{\sqrt{2\pi} \sigma} e^{-\frac{(T-\mu)^2}{2\sigma^2}} \]

Stimulus T

Normal Distribution of Incremental Probability

Joint Probability Sum of Squares

\[ \prod_{i=1}^{n} y_i = \prod_{i=1}^{n} \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{(T_i-\mu)^2}{2\sigma^2}} \]

\[ \prod_{i=1}^{n} y_i = \left( \frac{1}{\sqrt{2\pi} \sigma} \right)^n e^{-\frac{\sum_{i=1}^{n} (T_i-\mu)^2}{2\sigma^2}} \]

\[ Q(\mu) = \sum_{i=1}^{n} (T_i - \mu)^2 \]
Excel Spreadsheet
D6 is =IF(A6>$B$1,C6,B6).

<table>
<thead>
<tr>
<th></th>
<th>Column A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Trial</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>µ</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Stimulus</td>
<td>Did Function</td>
<td>Did not &amp; Function</td>
<td>Contradictory</td>
<td>Contribution</td>
</tr>
<tr>
<td>4</td>
<td>5.0</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>4.8</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0.1058</td>
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<tr>
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<td>0.0289</td>
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<tr>
<td>9</td>
<td>4.0</td>
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<td>0.1369</td>
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<tr>
<td>10</td>
<td>3.8</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>11</td>
<td>3.6</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>12</td>
<td>Q(µ)</td>
<td></td>
<td></td>
<td></td>
<td>0.2734</td>
</tr>
</tbody>
</table>

Uses of No-Fire & All-Fire Levels

- For safety, ensure no extraneous signal reaching the EED exceeds the no-fire level.
- For reliability, design your firing circuit so that its output exceeds the all-fire level.

Optimal Firing Circuit

\[
E = \frac{CV^2}{2}
\]
Input (Sensitivity) Tests

- Quantal Response
- Important to know exactly how sensitive
- Tests on EEDs

Continuous Statistics

- Sample of EEDs
- On each one, turn up the power until it fires
- Record final (firing) power level
- Sample \((x_1, x_2, \ldots, x_n)\)
- Assume sample from normal distribution \(N(\mu, \sigma^2)\).

Normal Distribution

![Normal Distribution Diagram]

Estimate Population Parameters

- Values \(\mu, \sigma\) represent entire population

\[
\bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i
\]

\[
(n-1)s^2 = \sum_{j=1}^{n} (x_j - \bar{x})^2
\]
Standard Normal Distribution

\[ \mu = 0, \quad \sigma = 1 \]

Percentage Points of Normal Distribution

\[
\phi(z) = \frac{1}{\sqrt{2\pi}} e^{-z^2/2}, \quad -\infty < z < \infty
\]

\[
P(z \geq z_{\alpha}) = \int_{z_{\alpha}}^{\infty} \phi(z) \, dz = \alpha
\]

References


Sample Comparison Test

Sensitivity same?
Contamination?
Possibility: 2 Bruceton tests
Example Bruceton Test on #1

Samples of #1 and of #2

Underline Differing Results

One Bruceton Test

- If ignition, decrease stimulus
- If no ignition, increase stimulus
- Subject sample of 2nd explosive to same stimulus as sample of 1st explosive
- Use only pairs of results with different responses
- Pairs n, explosive A has fewer ignitions
- Have x cases where A ignited, B did not
Distribution of Results
Example: BBBBABB BBBB

\[ x \leq (n - x) \]

Probability

- Probability that first one will be B is \( \frac{1}{2} \)
- Probability that second one will be A is \( \frac{1}{2} \)
- Probability first two will be BA is \( \left( \frac{1}{2} \right) \cdot \left( \frac{1}{2} \right) \)
- Probability of any given sequence of n As and Bs is \( (1/2)^n \)

Number of Combinations
Probability of \( x \) A's in \( n \) Trials

\[ p(x) = \frac{n!}{x! (n-x)!} \]

\[ p(x) = \frac{1}{2^n} \frac{n!}{x! (n-x)!} \]

Probability of \( x \), given \( n=10 \)

![Graph showing probability distribution for 0 to 12 A's with n=10 trials](image)
Cumulative Probability
“x or fewer” - Example for n=10

\[ p(x \text{ or fewer}) = \sum_{i=0}^{x} \frac{1}{2^n} \frac{n!}{i!(n-i)!} \]

Confidence that Coin is not “Fair”

\[ K = 100 \left\{ 1 - \left[ \sum_{i=0}^{x} \frac{1}{2^n} \frac{n!}{i!(n-i)!} \right] \right\} \]

References


Conductive Floor Hazard
Movie: High Power Worker

Bird on Wire Not Shocked

Person Shocked

High voltage across source and load

Path for current through the dirt
Grounding Necessary

Electric Current → Bodily Harm

\[ I = \left( \frac{V}{R} \right) \]

Electric Current Hazard Guidelines

<p>| | | |</p>
<table>
<thead>
<tr>
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<tbody>
<tr>
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<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| Electric Current Hazard Guidelines

Safe Practices

- Zero energy state
- Lockout/tag out
- Check with voltmeter
- Initial contact with the back of hand
- Keep other hand in pocket
- Remove ground strap
- Special wrist-to-wrist strap
- Ground fault interrupters
Care for Electric Shock Victim

Safe Circuit Design

Grounding An Electrical Circuit

Example Appliance
Function Classification

- High explosives detonate to:
  - Create shock waves
  - Burst
  - Shatter
  - Penetrate
  - Lift and heave
  - Create air blast
  - Create underwater bubble pulses

Function Classification

- Propellants burn to:
  - Propel projectiles and rockets
  - Start I.C. engines and pressurize other piston devices
  - Rotate turbines and gyroscopes
Function Classification

- Pyrotechnics burn to:
  - Ignite propellants
  - Produce delays
  - Produce heat, smoke, light and/or noise

Sensitivity Classification

- A primary high explosive can detonate easily.
- A secondary high explosive can detonate, but less easily.
- We do not require a propellant explosive to detonate at all.
- It is probably true that all primary explosives are capable of detonation. We do not require this. We require only deflagration.
IOC 5.0 MT 21 Dec 2005

Exploding Whale

Electroexplosives: Functioning, Reliability, and Hazards

Chemistry

Presented by Franklin Applied Physics, Inc.
Molecular Energy Levels

Burning (oxidation)

- $2H_2 + O_2 \rightarrow 2H_2O$
- $C_3H_8 + 5O_2 \rightarrow 4H_2O + 3CO_2$
- (propane)
- Exothermic reactions

Explosive and pyrotechnic mixtures

- Black powder
- ANFO
- Emulsions
- Thermite
- Safety matches
Some explosive molecules

- RDX $\text{C}_3\text{H}_6\text{N}_6\text{O}_6$
- PETN $\text{C}_5\text{H}_8\text{N}_4\text{O}_{12}$
- Lead styphnate $\text{C}_6\text{H}_3\text{N}_3\text{O}_9\text{Pb}$
- Mercury fulminate $\text{C}_2\text{N}_2\text{O}_2\text{Hg}$

“Green” explosives

- Many primaries have heavy metals
- DBX-1
- Substitute for lead azide
- Similar properties
- Less reactive with other substances (copper, some secondary explosives)

TNT - Trinitrotoluene

$2\text{C}_7\text{H}_5\text{N}_3\text{O}_6 \rightarrow 3\text{N}_2 + 5\text{H}_2\text{O} + 7\text{CO} + 7\text{C}$

Other products include:
- $\text{H}_2$
- $\text{NH}_2$
- $\text{NH}_3$
- $\text{HCN}$
- $\text{NO}$
- $\text{NO}_2$
- $\text{CO}_2$
- $\text{CH}_4$
- $\text{CH}_3\text{OH}$
- $\text{C}_2\text{H}_2$
- $\text{C}_2\text{H}_3$
- $\text{C}_2\text{H}_4$
- $\text{CH}_2\text{O}$
- $\text{CH}_2\text{O}_2$
- $\text{C}_2\text{H}_5\text{OH}$

Oxygen Balance

$\Omega (%) = 100 \frac{\text{AW}_\text{Ox} \left[ \text{N}_0 - 2\text{N}_c - \frac{1}{2}\text{N}_H \right]}{\text{MW}_{\text{expl}}}$

$\text{AW}_\text{Ox} = 16.000$

$\text{MW}_{\text{expl}} = 12.01\text{N}_c + 1.008\text{N}_t + 14.008\text{N}_o + 16.000\text{N}_0$
• $\Omega = 0$ maximum energy output

• $\Omega < 0$ underoxidized, fuel rich

• $\Omega > 0$ overoxidized, fuel lean

Nitroglycol $\text{C}_2\text{H}_4\text{O}_6\text{N}_2$, $\Omega = 0$

TNT $\Omega < 0$

Nitroglycerin $\text{C}_3\text{H}_5\text{O}_9\text{N}_3$, $\Omega > 0$

TNT - Trinitrotoluene

$2\text{C}_7\text{H}_5\text{N}_3\text{O}_6 \rightarrow 3\text{N}_2 + 5\text{H}_2\text{O} + 7\text{CO} + 7\text{C}$

Afterburn:

$2\text{CO} + \text{O}_2 \rightarrow 2\text{CO}_2$

$\text{C} + \text{O}_2 \rightarrow \text{CO}_2$

First Law of Thermodynamics

• Energy cannot be created or destroyed, it can only be transformed from one form of energy into another

• The total energy of a closed system remains constant

• (conservation of energy)
• Heat of formation = internal energy of final state minus sum of internal energies of initial components
• (a negative quantity)

• Heat of reaction = $[\Sigma \text{heat of formation of products}] - [\Sigma \text{heat of formation of reactants}]$
• Negative for exothermic reaction
• Often labeled $Q$ or $\Delta H$
• Heat of explosion
• Heat of detonation
• not constant, depend on conditions during explosion

Temperature of explosion

\[ T_{\text{expl}} - T_{\text{ambient}} = \frac{Q}{\Sigma c_{\text{mean}}} \]

• Molar heat capacities (\( c \)) are smaller for smaller molecules
• 2500 – 5000 °C

Volume of gas from explosion

• 1 mole of gas at STP has volume 22,400 cm³
• RDX \( \text{C}_3\text{H}_6\text{N}_6\text{O}_6 \rightarrow 3\text{N}_2 + 3\text{H}_2\text{O} + 3\text{CO} \)
• 9 moles from 1 mole (222 gm)
• \( 9 \times 22,400 \text{ cm}^3 \approx 1000 \text{ cm}^3 / \text{gm} \) at STP
• 222 gm

Pressure of explosion

\[ P \approx \frac{1}{4} \rho D^2 \]

• RDX: \( \rho = 1.767 \text{gm/cm}^3 \) \( D = 8.79 \text{km/s} \)
• \( P = 34.1 \text{ GPa} \approx 300,000 \text{ atm} \)
Chemical Reactions in Just a Few Molecules

- Decomposition
- Thermal runaway

Electroexplosives: Functioning, Reliability, and Hazards

Physical Effects

Presented by Franklin Applied Physics, Inc.

Comparison of Energy Storing Devices

<table>
<thead>
<tr>
<th></th>
<th>CAR BATTERY</th>
<th>HAND GRENADE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>40 lbs</td>
<td>2 lbs (0.9 kg explosive)</td>
</tr>
<tr>
<td>Time</td>
<td>10 sec</td>
<td>1/2</td>
</tr>
<tr>
<td>Energy</td>
<td>10 expiry</td>
<td>10 expiry</td>
</tr>
</tbody>
</table>
Why use explosives?

- Powerful
- Fast
- Compact
- Self-contained
- Cost effective
- Adequately accurate
- Simple
- Sturdy
- Reliable
- Versatile
- Usable once

Comparison of energy releasing processes

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>PRESSURE (atmospheres)</th>
<th>RATE (g/sec)</th>
<th>POWER DENSITY (watt/cc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetylene Flame</td>
<td>1</td>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>Propellant in Gun</td>
<td>2,000</td>
<td>1,000</td>
<td>1,000,000</td>
</tr>
<tr>
<td>Detonating High Explosive</td>
<td>400,000</td>
<td>1,000,000</td>
<td>10,000,000,000</td>
</tr>
</tbody>
</table>

From W.C. Davis

Comparison of Power and Energy for Various Fuels and Storage Means

<table>
<thead>
<tr>
<th>REACTION TYPE</th>
<th>REACTION RATE (m/sec)</th>
<th>ENERGY OUTPUT (g)</th>
<th>POWER OUTPUT (watt/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burning Fuel OI</td>
<td>000001</td>
<td>10,000</td>
<td>10</td>
</tr>
<tr>
<td>Detonating Explosive</td>
<td>001</td>
<td>1,000</td>
<td>10,000</td>
</tr>
<tr>
<td>Detonation</td>
<td>7,000</td>
<td>1,000,000,000</td>
<td>10,000,000,000</td>
</tr>
</tbody>
</table>
Detonating Explosive

- Initiating Detonation
- Burning to Detonation (Milliseconds to Minutes)
- Shock to Detonation (Microseconds)

Partition of Energy
- Propellants
- Detonation in Air
- Confined Detonations
- Measuring the Partition of Energy

Detonation Velocity & Pressure

\[ D_1 = D_2 + \left(3.5 \times 10^5 \ \text{g}^{-1} \ \text{cm}^4 \ \text{s}^{-1}\right)(\Delta_1 - \Delta_2) \]

- Effect of Density of Loading (\(\Delta\))
- Effect of Confinement (charge diameter)
- Effect of Detonator Strength
### Detonation Velocity of Commercial Explosives

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### Detonation Parameters of Military Explosives

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</table>

### Chapman-Jouguet Condition

\[ D = C + w \]

### D'Autriche Apparatus

![D'Autriche Apparatus Diagram]
VOD Measurement – Resistance Method

Voltage vs. Time

at bottom, $VOD = \frac{d}{t_2 - t_1}$
at top, $VOD = \frac{d}{t_4 - t_3}$

Four and More Resistors

Detonation Pressure

$\rho = 2.5 \times 10^{-7} \Delta D^2 \text{ bar cm}^2 \text{ g}^{-1}$
**SHAPED CHARGE**

**SHOCK WAVE SHAPING**

**Damage Capacity - 2 Effects**

**Shock Wave in Cylindrical Charge**

- Cooling prevents plane wave
- Constant convex

**Internal Shaping: Plane Interface**
Internal Shaping at Curved Interface – Explosive Lens

High-to-Low or Low-to-High Transition To Produce Planar Wave

Implosion Device Nuclear Fission Bomb

Explosive-Metal Wave Shaper Air Lens
CORED CHARGE APPROXIMATELY PLANAR

Surface Wave Shaping

Detonation Wave from Cylindrical Charge

Shock Wave from Plane-Ended Charge
Shock Wave from Hemispherical End, Wedge

SHAPED CHARGE

Hollow Charge

Liner Acceleration
Uses for Shaped Charge

Penetration

\[ \text{Penetration} \propto \frac{Mv^2}{2A} \]

- Proportional to \( \frac{Mv^2}{2A} \)
- \( M \) is mass of jet
- \( v \) is speed of jet, very great
- \( A \) is cross-sectional area of jet, very small

Variables Affecting Shaped Charge Use

- Detonation parameters of the explosive
- Ratio of charge length to cone diameter \( CD \)
- Ratio of stand-off to \( CD \)
- Ratio of liner thickness to \( CD \)
- Liner geometry
- Symmetry
- Liner material
- Fuzing mechanism (for a missile)
- Effect of spin (for a gun projectile)
- Cost effectiveness
Depleted Uranium Liner

- Non radioactive
- Byproduct of enrichment
- Heavy, 1.7 times density of lead, more like gold & tungsten; heaviness enhances kinetic energy
- Low melting point, 1132 deg C, half that of tungsten; facilitates jet control
- Pyrophoric – burns in air – hot!

Shaped Charge

Perforating Gun

Underwater Shaped Charge
Linear Cutting Charge

Shaped Charge and Explosively Formed Projectile

Fragmentation Munitions
- Antipersonnel: small
- Anti-vehicle: 5-10 grams
- Ratio charge weight/case weight
- Increase velocity, thin cloud of fragments
- Need more than 1000 m/s to penetrate 10 mm steel

Scabbing (Spalling)
EMP Warhead

Explosive-driven, magnetic-flux compression generator

Flux Compression

Energy Storage

Flux Generation
Coil with Copper Tube

Explosive Compression

Details of Tube

Peak B-Field
Rock Blasting

Avalanche Control
- Explode charge in snow (cannon) – water
- Explode on surface (flying saucer) – crater
- Explode above surface – shock wave spreads out over large area
- Gondola story

Steel Cable (Wire Rope) and Closed Spelter Socket

Swaging Process
Swaging with Det Cord

Explosively Swaged Cross Sections

High Energy Rate Forming (HERF) has advantages over...

Spelter Method

- Unlay cable strands and wires
- Insert into spelter socket
- Pour in molten metal
- Fills & bonds
- Zinc, 850 degrees Fahrenheit
- No heavy equipment. Quick.
- Heat hazardous, awkward
- Zinc is a hazard
Propellants
Burning
Guns
Gun Propellants
Rocket Propellants

BURNING

- All explosives burn
- Burning can occur when confined
- Burning at or just above the surface
- Surface itself recedes layer by layer (Piobert’s Law, 1839)
- Traité d’artillerie Théorique et Pratique by Guillaume Piobert (1845)

BURNING

- Heat radiated from reaction zone
- Heat conducted from reaction zone
- Heat from decomposition

Rate of Regression

\[ r = \beta P^\alpha \]

- Burning Rate Index \( \alpha \)
- Mass Rate of Burning
- A Surface Phenomenon
GUNS


French 75

Long Recoil System

Spring-Loaded Magazine Positions
Cartridge in Front of Bolt
Typical Gun Propellant Grain Geometry

Properties Required in a Propellant

- An acceptable high energy/bulk ratio.
- A predictable burning rate over a wide range of pressures.
- An acceptably low flame temperature.
- A capability of being easily and rapidly ignited.
- An acceptably low sensitiveness to all other possible causes of initiation.
- A capability of cheap, easy and rapid manufacture and blending.
- A long shelf life under all environmental conditions.
- A minimum tendency to produce flash or smoke.
- A minimum tendency to produce toxic fumes.

Rate of Burning
Guillaume Piobert (1839)

Vieille’s Burning Rate Law (1893)

\[ r = \beta P^\alpha \]

- Rate of burning (mm s\(^{-1}\)) is \( r \).
- Burning rate coefficient is \( \beta \).
- Pressure is \( P \).
- Pressure index is \( \alpha \).
Paul Vieille (1854-1934)

Solid Form – Spheres, Plates, Cylinders
- Decrease in surface area during burning
- Degressive burning
- Decrease in $\frac{dm}{dt}$ with time (at a theoretical constant pressure)

Single-Perforated Form
- Inner surface area increases
- Outer surface area decreases
- Burning area approximately constant
- Neutral burning characteristic
- Constant $\frac{dm}{dt}$ (at theoretical constant P)

Effect of Grain Geometry on Pressure/Time Curve
Performance in Gun

Chemical Nature of Propellants

- All contain nitrocellulose
- Single-base - nitrocellulose
- Double-base – nitrocellulose, nitroglycerine (NG) – higher energy
- Triple-base – nitrocellulose, nitroguanadine (picrite) – intermediate energy – suppress flash
- Energized Propellants – RDX, NG

Other Ingredients

- Stabilizer
- Plasticizer
- Coolant
- Surface moderant (deterrent)
- Surface lubricant
- Decoppering agent
- Anti-wear additive

Recent Developments in Gun Propellants

- Caseless Ammunition – small arms
- Liquid Propellant - guns
  Regenerative
  Traveling Charge
Heckler and Koch
Caseless Ammunition

Regenerative Injection

Traveling Charge Injection

Rocket Propellants

- Liquid monopropellant
e.g. hydrazine $\text{N}_2\text{H}_4$
- Liquid bipropellant
Fuel and oxidizer
- Solid
Case bonded
Inhibited
Rocket Propellant Grains

Javelin

All Burnt On Launch - ABOL

“Materials capable of combustion when correctly initiated to produce a special effect”

- Burn, not detonate
- Importance of initiation
- Special effects distinguish pyrotechnics from other explosive types
### Pyrotechnic Special Effects

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### Basic Components

- Solid Oxidizer
- AP Additives
- Effect

### Pyrotechnic Fuels & Oxidizers

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### Binders for Pyrotechnics

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Binders
- Increase cohesion between particles
- Aid consolidation
- Coat (protect) reactive components
- Modify burning rate
- Reduce sensitivity of friction
- Enhance performance

Material Properties
- Degradation
- Salts
- Impurities
- Chemical Reactions
- Sensitivity

Devices

Requirements for First Fire
- Ignite readily from initiator
- Generate large amount of heat
- Not too rapid or violent
- Advantageous to leave a hot slag
- Chemically compatible
- Not too sensitive
- Output matches initiation requirements of base charge
Pyrotechnic Delays

Pyrotechnic Delay Rings in M54 Fuze

DELAYS

Henry Shrapnel
Time-Delay Grenades

Pyrotechnics

Heat Produced

FRH and MRE
Example of Thermite Reaction

\[ 2 \text{Al} + \text{Fe}_2 \text{O}_3 \rightarrow \text{Al}_2 \text{O}_3 + 2 \text{Fe} \]

Pipe Recovery

Thermite Initiator

Thermite Cutting Tool
AN-M14 TH3
Incendiary Grenade

Hans Goldschmidt

Disadvantages of Thermite Reactions

- Difficult to Start (magnesium, glycerin/potassium permanganate)
- Must Be White Hot
- Extremely High Temperatures
- Keep Flammables Away!
- Boiling Metals

Thermal Battery
Pyrotechnic Whistle

Entschede – May 2000

Testing Explosives

Output Tests
Input (Sensitivity) Tests

Ballistic Pendulum
Input (Sensitivity) Tests

- Quantal Response
- Important to know exactly how sensitive
- Powder tests (mfg and filling)
- Charge Tests

Ball Drop Apparatus

Bureau of Mines
Ball-Drop Apparatus

Die Cup
Drop Tester for Powder

Friction Test Apparatus

Sliding Block Friction Apparatus

Diagram of Friction Pendulum Apparatus
BAM Friction Tester

High Voltage Spark Tester

Large Scale ESD Tester
STANAG 4490, Mil-Std-1751A

SMALL SCALE ESD TESTER
STANAG 4490, MIL-STD-1751A
Nylon Washer Dimensions

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Sample Preparation

- Sample OD
- Sample ID
- Sample Thickness
- Sample Material
- Sample Notes

Bullet Impact Test

Electroexplosives: Functioning, Reliability and Hazards

Accident Prevention

Presented by Franklin Applied Physics, Inc.
• All commercial explosive materials are designed to detonate when supplied with a sufficient amount of initiating energy. Unfortunately, the explosive material cannot differentiate between initiating energy purposely supplied and that accidentally supplied. It is the responsibility of all persons who handle explosive materials to know and to follow all approved safety procedures.
  • —from IME Do’s and Don’ts

Some causes of unintended initiation

• Fire
• High temperature
• Thunderstorms
• Electromagnetic fields
• Sparks
• Static electricity
• Current and voltage sources
• Impact
• HUMAN ERROR

Fire prevention

• Good housekeeping
• Avoid storing combustibles (paper, rags)
• Avoid storing fuels
• No smoking or open flames (heaters, burners, lighters)
• Maintain electrical equipment and cords
• Care with sources of heat
• Fire extinguishers readily available (only to prevent spread to area near explosives)

Thunderstorms

• Monitor weather conditions
• Storm monitoring equipment or AM radio
• 5 miles approach
• Shut down operations and evacuate
• Use single ground point for EED systems
Electromagnetic fields

- Twist and coil leadwires (small aperture)
- Stay away from transmitters (even small ones like cell phones)
- Use RF protected devices (with ferrites, coils, capacitors) – not all frequencies
- Perform worst-case analysis and field tests before use

Spark Prevention

- Use non-sparking tools (wood, bronze, lead, "K" Monel)
- Avoid metal work surfaces, floors, etc.
- Well-maintained equipment
- Some electric motors produce sparks
- No flash bulbs or electronic flash
- Prevent static electric sparks

Static electricity prevention

- Ground everything (and check frequently)
- Avoid plastics
- Avoid contact and separation processes
- High humidity – above 55%
- Non-static equipment & environment
- Proper clothing
- Use verified static-insensitive EEDs
Current sources

- Use only approved meters to measure resistance (less than 1 mA, or 10μA for carbon bridge)
- Consider all modes of initiation
- AC sources
- Batteries
- Ground currents
- Galvanic current

Human Error

- Educate all workers
- Always follow standard operating procedures exactly
- Do not take shortcuts
- Do not improvise
- Know characteristics of what you are working with
- Don’t assume one type of device can be handled the same as another type
- Know what to do in an emergency

Reckless Way to Open a Powder Keg

Miner with Torch on Hat Pouring Black Powder
Hazard Avoidance

- Mechanical shock
- Heat

Electric Welding Hazards to EEDs

- Fire
- Electromagnetic Radiation
- Magnetic Field Coupling
- Ground Currents

Circuit with Grounds

Electric Welding Near Well
Recommendation

• Maintain 50-foot (15 meter) standoff distance.

AC Overhead Power Line

• Hazard to power line
• Hazard to blaster from electric shock

Non-Hazards

• Electromagnetic effects from AC power line
• EMP
• Radioactivity

Non-Hazards

• Modern digital camera with automatic focus and built-in flash (but be careful of batteries)
Storage and Shipment
• Receiving
• Storage
• Use
• Shipment
• Disposal

US Naval Ammunition Depot
East Camden, Arkansas

PEOPLE WHO CAN RECEIVE
AND SHIP EXPLOSIVES
• “Responsible Person” –
on license application
• “Employee Possessor” –
separate application

Receiving Paperwork
• Log book
• Unpack, saving
  materials (photo)
• Count
• Box tag
• Transaction log
• Receiving report

• Waybill
• EX letter
• MSDS
• Box card
**Storage Paperwork**

- Daily transaction summary
- Update box card
- Check locks weekly

**Use Paperwork**

- Magazine transaction log

**Shipping Paperwork**

- Log book
- Shipping report
- EX letter
- Waybill
- Labeling

**Magazine Requirements**

- Separate magazines
- Bullet-proofing
- Security
- Quantity-Distance
- Recordkeeping
- Housekeeping
- License Display
- Warning Sign – “Explosives: Keep Away”
Shipment

- CFR 49
- Proper Shipping Name, UN Number
- Hazard Classification, Orange Label
- 24-hour telephone number
- Competent Authority, EX number
- Certification – be careful what you sign!
- Training every 3 years
- Packaging
- Vehicle Requirements – placard, inspection
- Cost

Shipping Classification

IME SLP Titles
Shipping Papers
• Proper Shipping Name, Hazard Class, UNxxxx, Packing Group
  (Cartridges, power device, 1.3C, UN0276, Pkg Gp II)
• n.o.s (not otherwise specified)
  (Substances, explosive, n.o.s., 1.1D, UN0475, Pkg Gp II,
   6573.3 propellant, 5808.17 propellant, mix)
• “EX” number for explosives
• 24 hr phone (3E Company 1-800-451-8346)
• Quantity
• Package type
• Certification and signature

DOT-SP 8451 Shipping Container

Related Reading
• Institute of Makers of Explosives (IME). 1120 Nineteenth Street N.W., Suite 310, Washington, DC 20036-3605.
Disposal of life expired stocks

UK policy to return to UK everything except not safe to move

Novobogdanovka, Ukraine,
2004

Chubs for Use in Disposal

Munition with Chubs
Containment

Greek Fire

HISTORY

Congreve Rocket
History and Development of Military Pyrotechnics

- "The first preparation for the work of the future is a knowledge of what has already been accomplished in the past. Pyrotechny is the art of fire, and its history began long ago."

East London, 1917

Halifax, 1917

Picatinny Arsenal Explosion

Saturday, July 10, 1926

Cause: lightning

1500 tons of explosive
Bombay 1944

RAF Faulds, 1944, 3500 t

Blausee-Mithols, 1947, 3000 t

Texas City, 1947
Nagoya, August 21, 2000

AZF Factory, Toulouse, 2001

Enschede, Netherlands
Fireworks Explosion, May 2001
22 dead, 947 injured

(movie)

Saint Barbara –
Sigfrido Martín Begué, 2003
Martyrdom of St. Barbara

RESOURCES
Sources of Information
Inspiration
Encouragement

Technical Reports
Tests & Analyses

- Franklin Applied Physics, Inc. (1960 to present), www.franklinphysics.com
- National Technical Information Service (NTIS), www.ntis.gov

Newsletters, Journals
### I.S.E.E.

**Explosives Engineering**

### SYMPOSIA

<table>
<thead>
<tr>
<th>Event</th>
<th>Sponsor</th>
<th>When</th>
<th>Location</th>
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<tbody>
<tr>
<td>CAD/PAD</td>
<td>NSWC Indian Head</td>
<td>May Even years</td>
<td>Maryland</td>
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<tr>
<td>TEW</td>
<td>Swedish Combustion Institute</td>
<td>November Odd years</td>
<td>In a castle</td>
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<tr>
<td>Conference</td>
<td>U.S. Government</td>
<td>Every August</td>
<td>In a hot place Karlsruhe, Germany</td>
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<tr>
<td>Disposal</td>
<td>Fraunhofer ICT</td>
<td>Every June</td>
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<tr>
<td>Conference</td>
<td>I.S.E.E.</td>
<td>Every February</td>
<td>USA</td>
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<tr>
<td>DoDESB</td>
<td>India</td>
<td>November Odd years</td>
<td>India</td>
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<tr>
<td>Explosives, Blasting</td>
<td>Int’l Pyrotechnic Society</td>
<td>Every June</td>
<td>Location alternates</td>
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<td>Materials</td>
<td>HEMCE</td>
<td>December</td>
<td>Czech Rep.</td>
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<tr>
<td>Int’l Pyro Seminar</td>
<td>NTREM</td>
<td>Every April</td>
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### Proceedings, Printed, CD-ROM

**Proceedings of the 17th Symposium on Explosives and Related Items**

**Franklin Applied Physics**

**Univ. Pardubice**

### ENCYCLOPEDIA

**Encyclopedia of Explosives and Related Items**

**Franklin Applied Physics**

**Univ. Pardubice**
AMC HANDBOOKS

DOD 4145.26 - M

DOE M 440.1 - 1
G. S. Biasutti, *History of Accidents in the Explosives Industry*

**CATALOGS, WEB SITES**
Reference:

- “Forensic Investigation of Explosions,” edited by Alexander Beveridge
Chapters by Many Experts

- Military research establishments
- National police forces
- EOD (explosive ordnance disposal) units
- Government aviation experts
- Medical departments
- Legal systems
- Explosives manufacturers
- Et cetera

Outline

- Basics of energetic materials – propellants and explosives
- Explosion process in detail – blast waves and their effects
- Detection of hidden explosives
- How to gather evidence at the scene of an explosion – aircraft – gas in buildings
- Detailed laboratory methods to analyze chemical & mechanical evidence

Outline -- Continued

- Medical pathology of human victims of an explosion - photographs, x-rays
- How to give evidence in a court of law