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Thunder Range Shock Incident Technical Advisory Team Investigation

DOE Explosives Safety Committee Meeting

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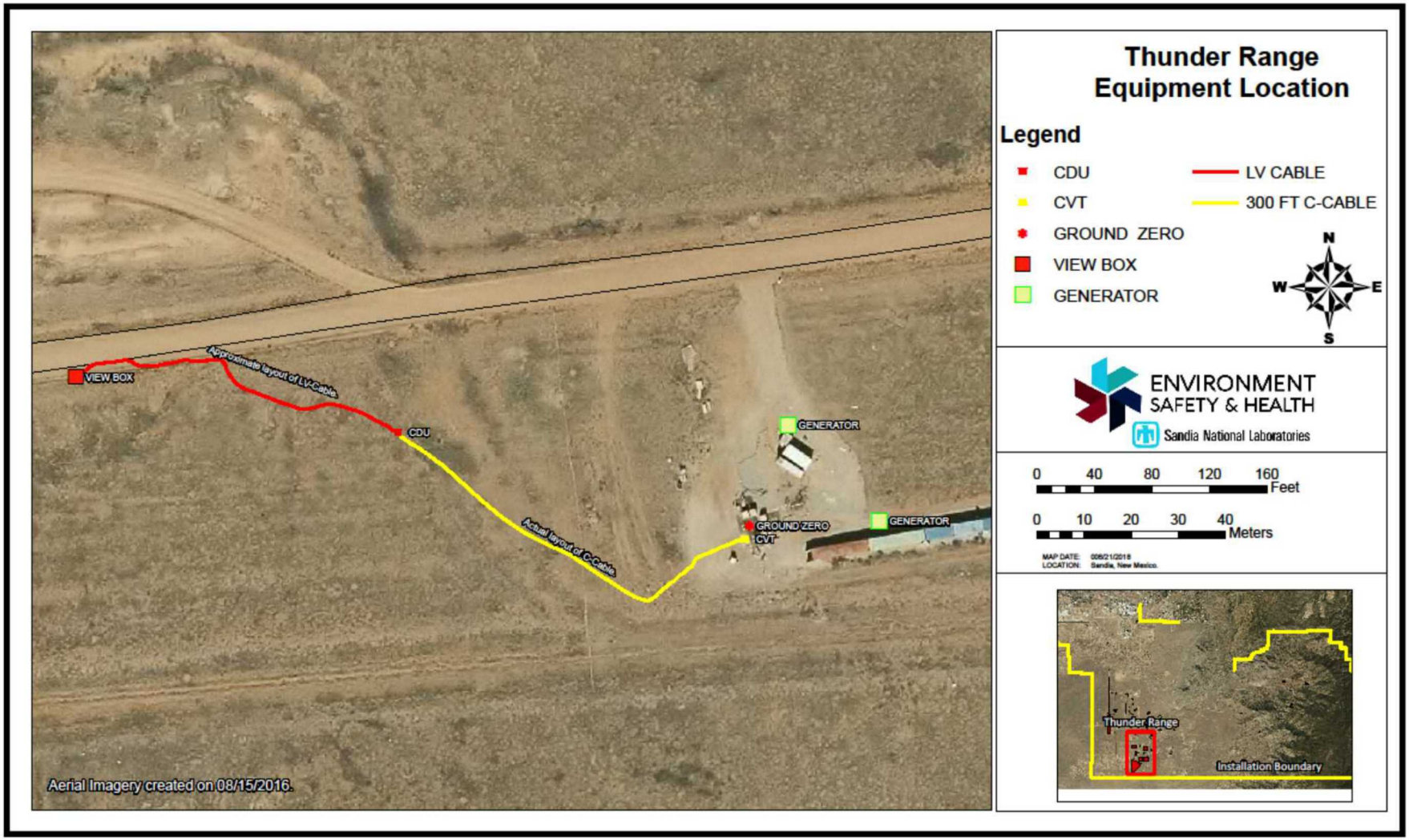
Outline

- What happened?
- Remote Command Firing System
- Hypotheses
- Tests and analyses
- Conclusions

Electrical Shock Incident - June 12, 2018

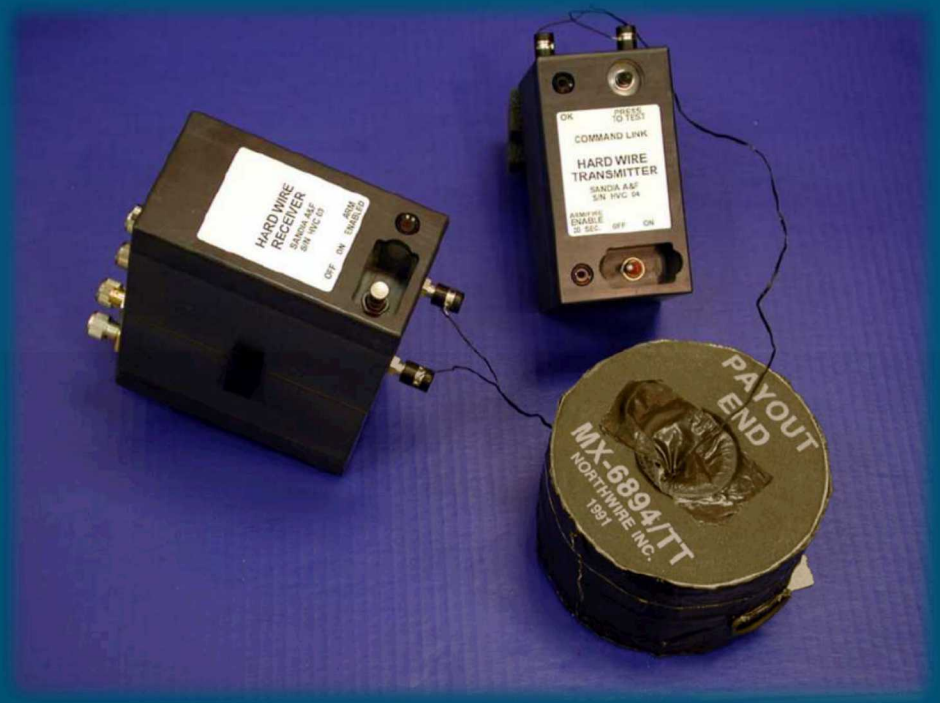
- Precursors
  - In preparation for firing a large explosive charge, the Remote Command Firing System (RCFS) was successfully tested with a bare bridge over 500 ft. of C-cable, but failed to initiate an RP-83.
  - Firing line was shortened to 300 ft.
- Shock
  - RP-83 again failed to initiate (turned out not to be connected).
  - After disconnecting the firing line from the RCFS CDU, explosive operator experienced a painful electrical shock ("like from a truck engine coil"), believed to be hand-to-hand (through chest).
- Response
  - Operator transported to hospital, released that evening.
  - Causal Analysis and Technical Advisory Team established.
  - DOE Office of Enforcement investigation resulting in Preliminary Notice of Violation and fee penalty.

Sandia's Thunder Range, Range 4



Remote Command Firing System

- Designed by Sandia's by Arming & Firing Systems group for NNSA to be portable, compact, rugged, and simple to use.
- Fielded ca 2002; design modified 2009.
- Not traditionally used at Thunder Range.



Remote Command Firing System

Low Voltage Twisted Pair

Eight Banana Plugs (LV)

C-Cable to Detonator

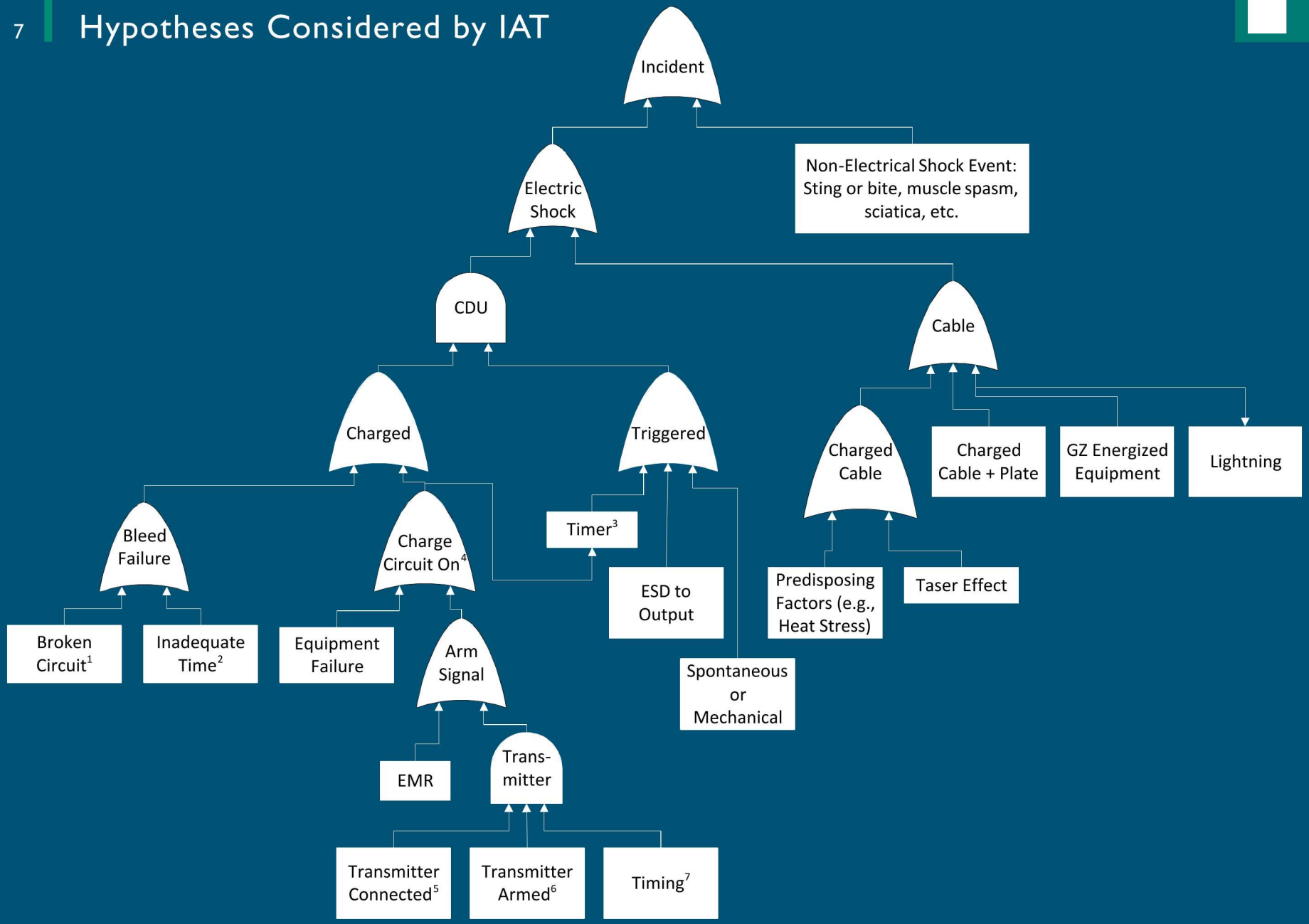
Transmitter

Receiver

Capacitive Discharge Unit (CDU)

- Transmitter and Receiver are hardwired together through a low-voltage twisted pair connection.
- Transmitter sends low voltage DC ARM signal to Receiver when operator holds switch in ON position.
- Receiver charges CDU and delivers FIRE signal after 20 sec, then turns off.
- CDU bleeds down internally, $\tau \approx 13$ sec.

Hypotheses Considered by IAT



Primary Hypotheses

1. Shocked by charged C-cable
   - Probably was charged
     - Three firing attempts
     - No bleed path (detonator not connected)
   - 3000 V, 15.36 nF (320 ft, 48 pF/ft) = 0.0691 J
2. Shocked by CDU
   - 3000 V, 1 μF = 4.5 J
   - Why was it charged?
   - Why did it trigger?
   - How did the Operator contact the high voltage?

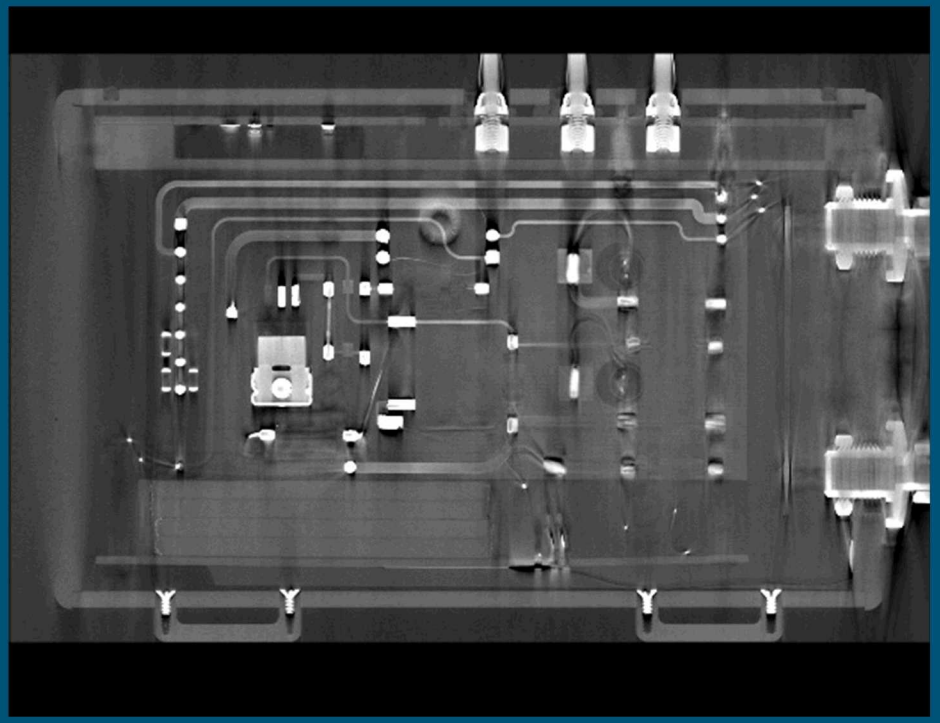
Physiological Effects of Capacitive Shocks

Energy (J)	Effect*
70	Ventricular fibrillation from external shock
10	Taser; Injury from reflex muscle contraction
1	"Undesirable"
0.25	Nuisance reflex action
0.12	Standard Man ESD

*Gordon, L.; Cartelli, L. and Graham, N., "A complete electrical shock hazard classification system and its application," IEEE Transactions on Industry Applications, 2018, 1-13.

Why was the CDU charged?

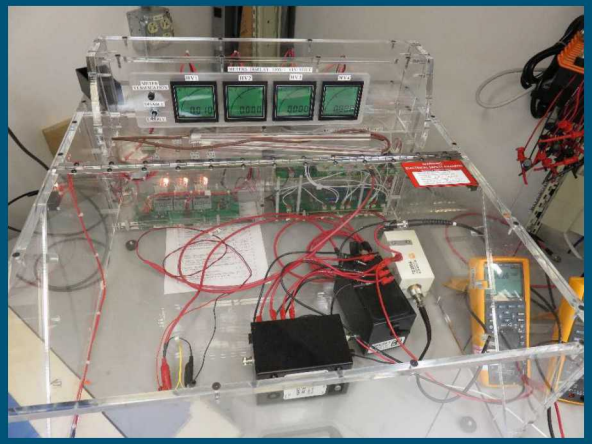
- Receiver fires after 20 sec of ARM signal and then stays off.
- Bleed time constant is 13 s.
- Walking time from View Box to CDU is ≥ 1 min.
- CT scan found no internal damage or anomalies
- Lab testing of the RCFS found the system behaved as designed when given normal signals:
  - Fired after 20 s, then stayed off.
  - Bleed resistors intact, bleed time as predicted.
  - Internal signals (HV Monitor, Power Supplies, Trigger) behaved as expected.



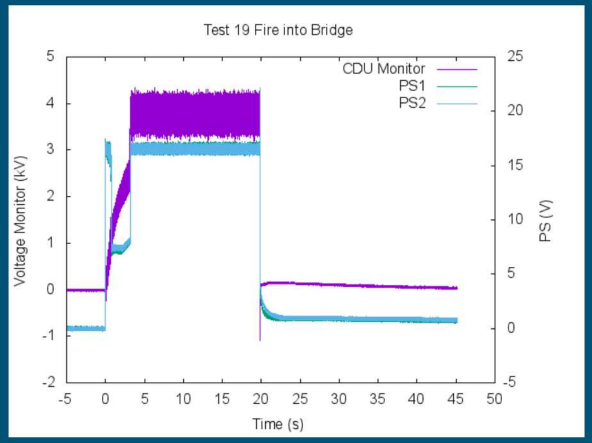
CT Cross-Section of CDU

Why was the CDU charged?

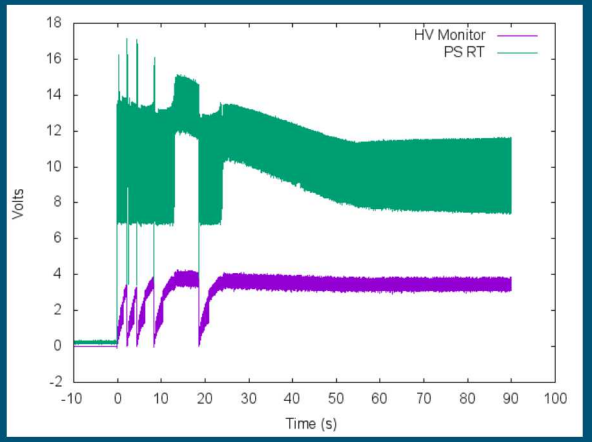
- Lab testing also found the following:
  - Anomalous behavior with AC input (60 Hz and 540 kHz) in differential and common mode. Observed:
    - Cyclic charge/discharge
    - Remain armed for >80 s
    - Charge to lower voltage than usual
  - Receiver rectifies, filters, and regulates input. Effects of varying input signal are difficult to predict.



RCFS in HV Box



Normal Cycle



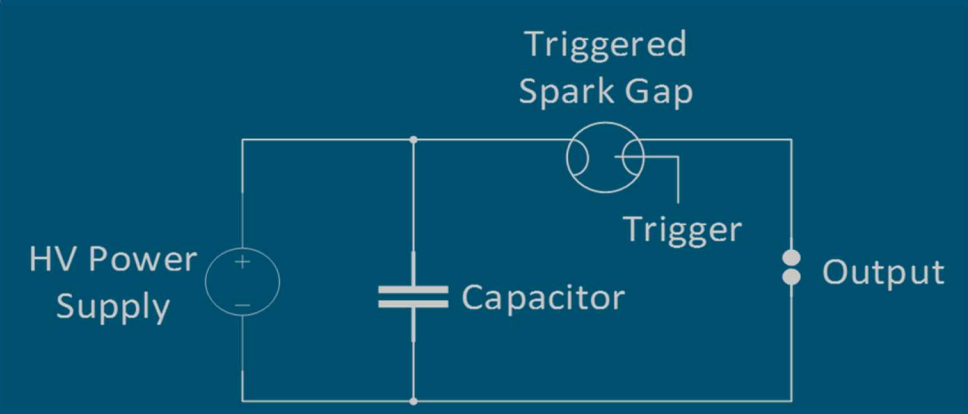
Anomalous Behavior with 7.1 V_{rms} @ 60 Hz Arm Signal

Why was the CDU charged?

- Field testing found the following:
  - Up to 496 mVp-p from cables to ground into 50 Ohm load at 20 Hz from EMR
  - Equivalent to 17.5 Vrms into 5000 Ohm load, enough to arm Receiver
  - System did not arm when connected as in incident.
    - Simplified analysis predicts system should have armed, but many factors not included.
    - Did not fire the system into open circuit like before the incident.

Why did the CDU trigger?

- Unknown, but possibilities include
  - human-borne ESD to CDU output
  - rapid change in voltage at CDU output when firing cable was disconnected
  - cable inversion (or L-C inversion)
  - receiver triggered CDU with timer circuit as designed
- Testing realistic scenarios is difficult. Tests involving energized electrical work were not performed.
- In general, if a CDU is charged (i.e., Armed), it should be assumed liable to trigger at any time.



Basic CDU Circuit

Triggered Spark Gaps

How did the operator contact HV?

Bench demonstration of contact on center conductor before shield.

- Unknown; however,
  - Reynolds 31, 310, 311 HV connectors are not finger safe.
  - Reynolds 31, 310, 311 HV connections can make contact between center conductors before shield, causing the operator to close a circuit.
    - Uniform-field arcing distance in air at 3 kV and 5000 ft elevation is 0.6 mm
  - C-cable could have provided path to ground at Ground Zero.

Conclusions

- Firing set involved in the incident was not damaged or malfunctioning.
- No "smoking gun" cause identified. Accident scenario was not reproduced.
- Most likely cause of shock was arming of the Receiver by EMR followed by one of several possible triggering mechanisms and inadvertent contact with Operator.

Recommendations

- For RCFS, turn off the Receiver power switch and wait one minute before handling the CDU.
- Verify zero energy before handling high-voltage equipment.
- Use firing sets with built-in voltage monitoring or externally accessible capacitor voltage divider contacts.
- Know your equipment.