

# Test and Evaluation of Black Swans in Early System Development for Maximum Effectiveness: A Case Study of Lightning Protection of Insensitive High Explosives

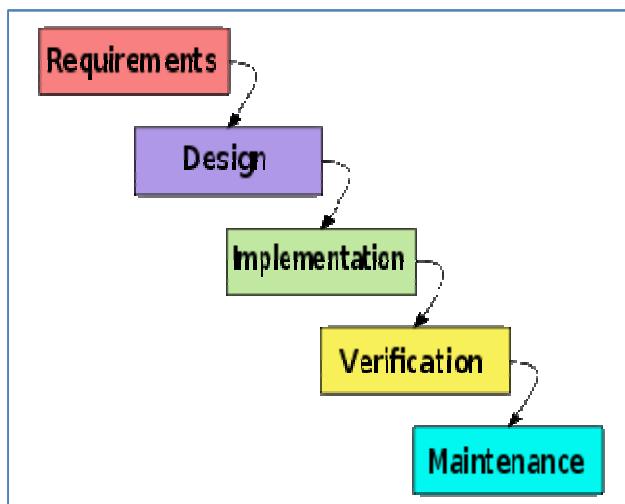
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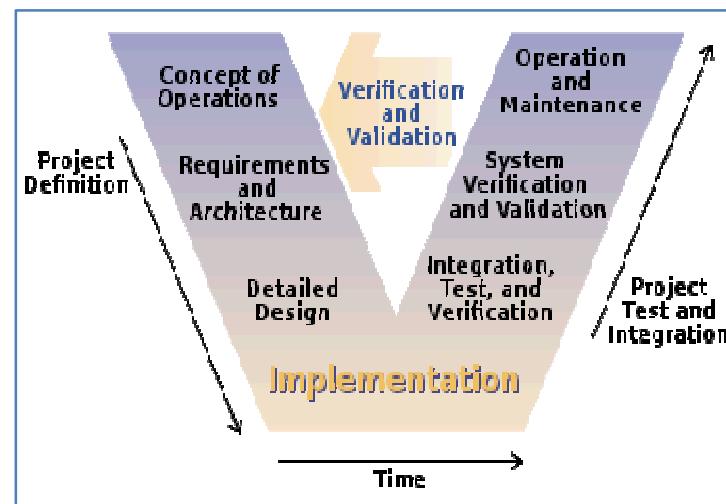
Co-authors: Dr. Shahram Sarkani, GWU  
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- Most systems engineering processes include risk assessment during the concept exploration phases
- The models and simulations may not address rare events with little data
- Testing, validation and verification mainly occur in later design development phases when hardware is available



Royce Waterfall Systems Model



U.S. Vee Systems Model

- Royce, W. (1970). Managing the Development of Large Software Systems. Proceedings of IEEE WESCON, 26:1-9.
- INCOSE. (2007). Systems Engineering Handbook Version 3.1, August 2007, pp 3.3 to 3.7.

# Black Swans

- Some safety requirements and design architectures may be dominated by low probability/high consequence vulnerabilities
- Black Swans: extremely rare, high consequence events that have little or no precedence but - after the fact – appear obvious



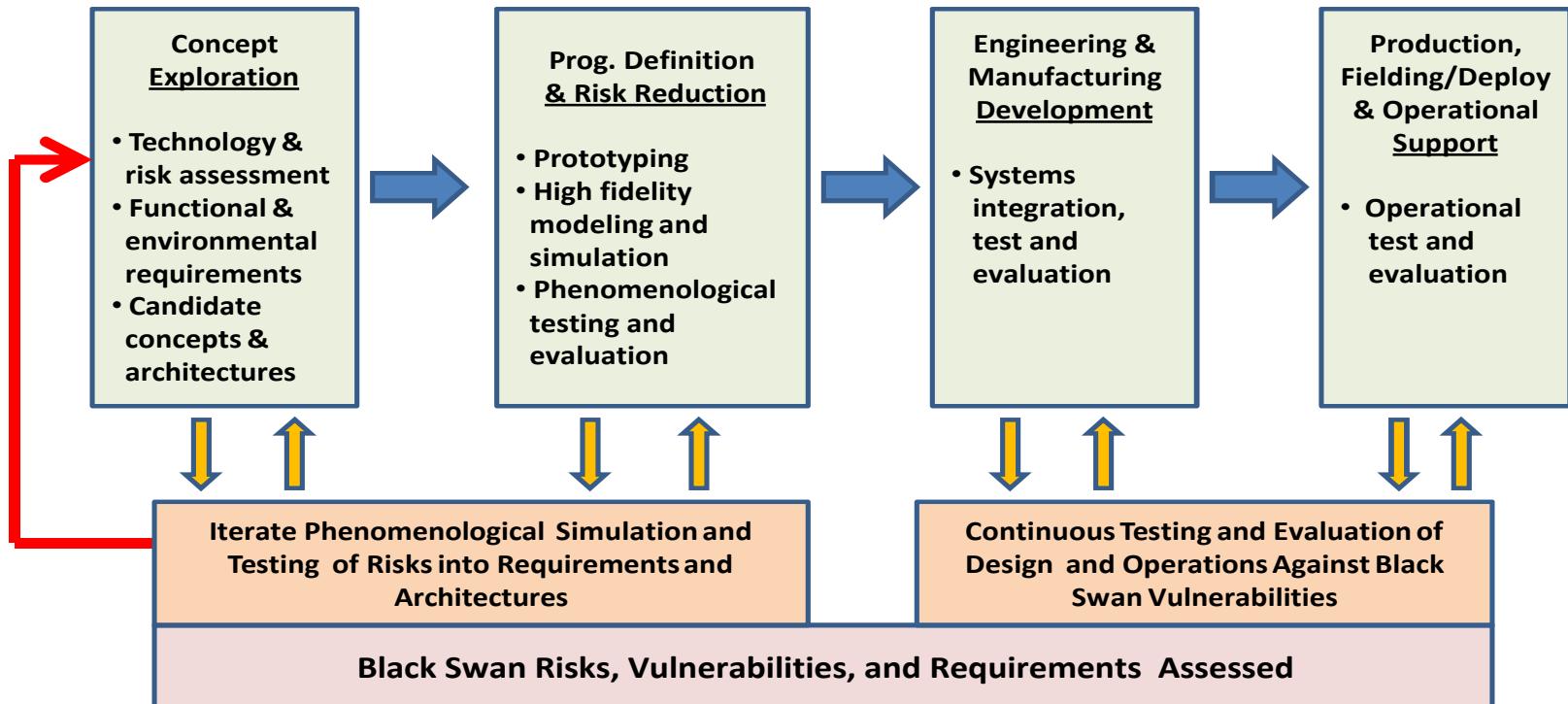
- Taleb, N. (2007). *The Black Swan: The Impact of the Highly Improbable*. 2<sup>nd</sup> edition, New York, NY: Random House

1. Identify, characterize and assess threats
2. Assess the vulnerability of critical assets to specific threats
3. Determine the expected consequences of specific types of threats
4. Identify ways to prioritize those risks
5. Prioritize the risk reduction measures

So, the first step is the identification of the full range of possible threats – regardless of the probabilities

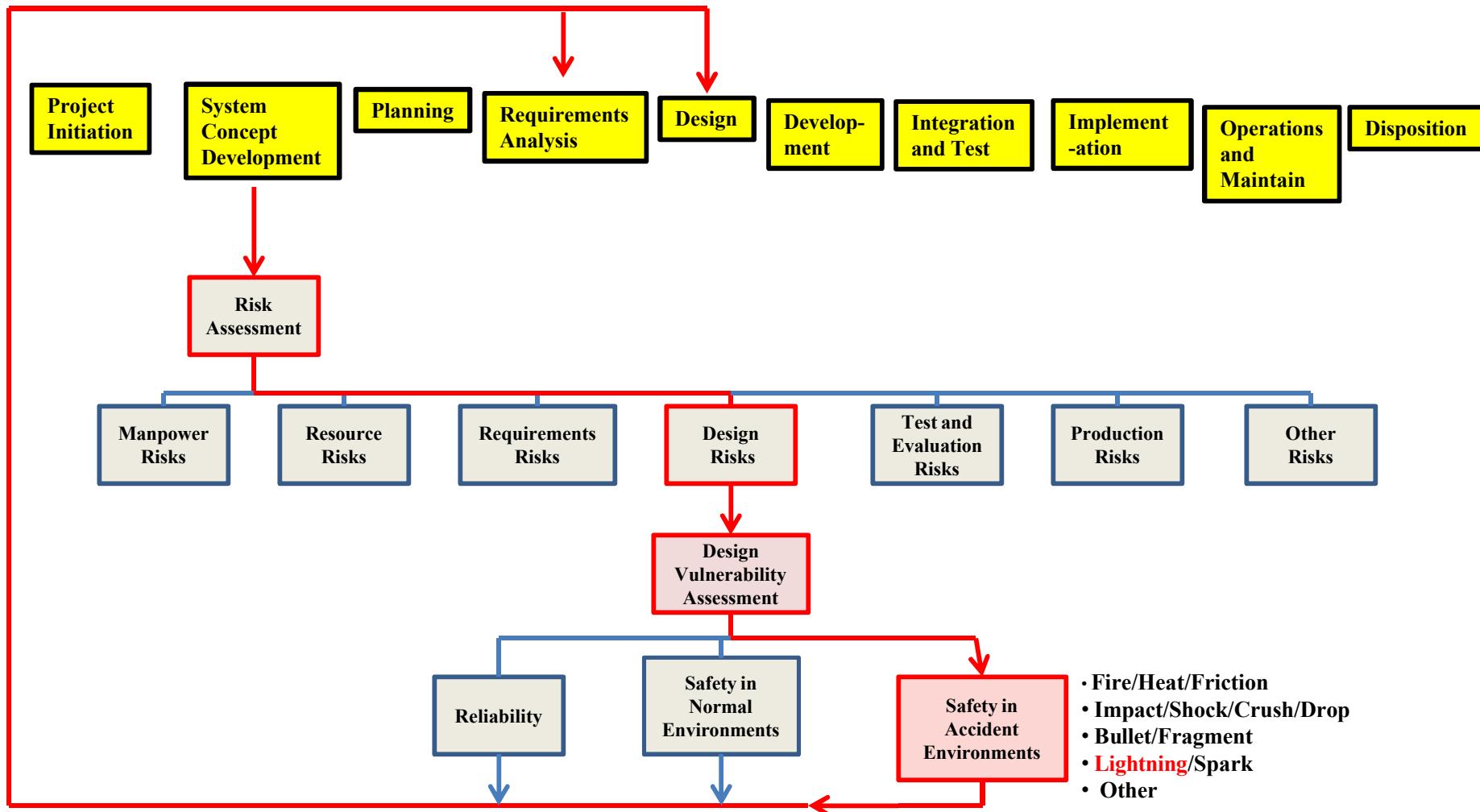
- Institute of Risk Management/AIRMIC/ALARM (2002). A Risk Management Standard. London: Institute of Risk Management.

# Proposed Risk Management Framework with Emphasis on Black Swan Assessment



- **Insensitive High Explosives** – a form of explosive recognized for its uniqueness according to the following definition: “Explosive substances which, although mass detonating, are so insensitive that there is a negligible probability of accidental initiation or transition from burning to detonation.”
- **Question:** Are there rare event accidents which could pose a vulnerability to designs which utilize IHE and which require continued use of mitigation design features or operational restrictions?
- (McGuire, R. R. and Guarienti, R. P. (1984), DOE Hazard Classification for Insensitive High Explosives, UCRL-91429, Lawrence Livermore National Laboratory, Livermore, CA.)

# Example Risk Assessment for Insensitive High Explosive (IHE) Projects



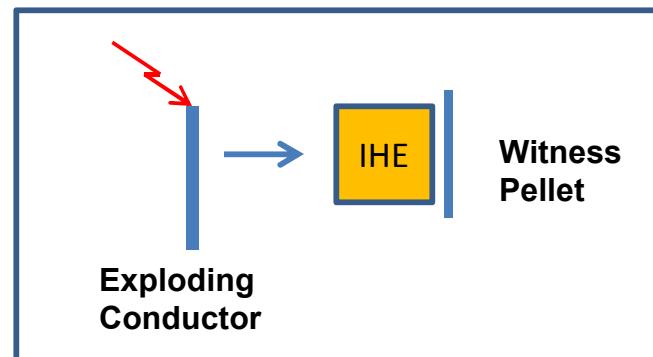
<b>1. Drop-weight impact test</b>	<b>Comparable to or less sensitive than Explosive D (ammonium picrate). Minimum of 20 drops per test series.</b>
<b>2. Friction test</b>	<b>No reaction on Pantex friction machine (10 trials).</b>
<b>3. Spark test</b>	<b>No reaction at minimum of 0.25 joules (10 trials).</b>
<b>4. Ignition and unconfined burning test (small-scale burn)</b>	<b>Any shape, minimum thermal path of .9842 in (25 mm), no explosion.</b>
<b>5. Card gap test</b>	<b>No reaction at Explosive D 50 percent gap thickness (or less) using a Pantex modified NOL card gap test (6 trials). The test diameter must be greater than the unconfined failure (critical) diameter of the candidate IHE.</b>
<b>6. Detonation (cap) test</b>	<b>Test procedures - no detonation (5 trials).</b>
<b>7. Cookoff</b>	<b>No reaction of more than a pressure release using the large-scale ODTX test conducted such that a reaction must occur in not less than 4 hours (6 trials).</b>
<b>8. Spigot test</b>	<b>No reaction for 120 ft (36.6 m) drop in LANL test (3 trials).</b>
<b>9. Skid test</b>	<b>No reaction up to 20 ft (6.1 m) (or sample failure) drop at 14-15 degrees test angle using standard size billets (3 trials at worst-case condition).</b>
<b>10. Susan test</b>	<b>Less than or equal to 10% TNT output at a minimum of 1092 ft/sec (333 m/sec)</b>
<b>11. Bullet impact</b>	<b>No violent reaction with 5.56 mm and .50 cal. projectile impact</b>

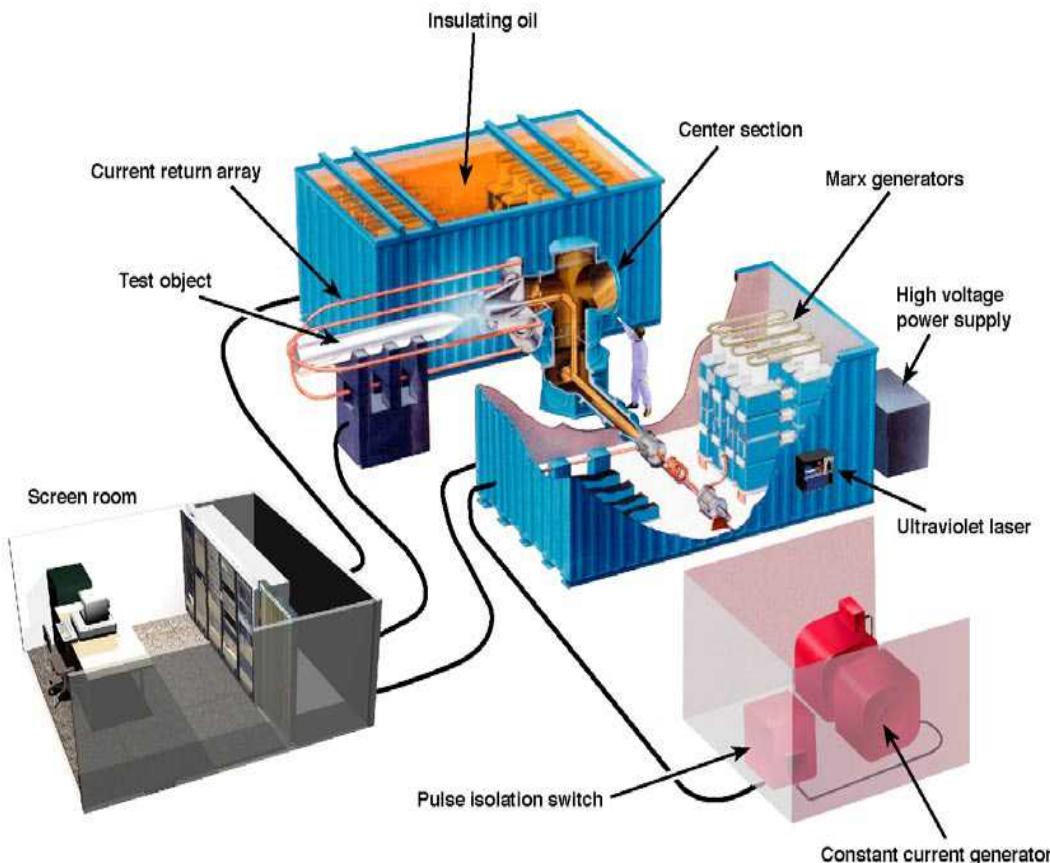
# Black Swan Hypothesis

- Many system safety requirements also specify lightning as a credible abnormal environment
- Three lightning threat mechanisms: a) direct arcing to surface; b) arcing across the surface; c) exploding adjacent conductors
- **Hypothesis** – Simulated lightning pulses can create kinetic energy effects sufficient to directly initiate insensitive high explosives to full scale detonation.
- **Study Approach** – Conduct a test series of experiments to study the effect of lightning generated slappers on insensitive high explosives (specifically triaminotrinitrobenzene - TATB) to explore one of the key unintended ways that lightning might cause initiation and the continued need for system electrical safety architectures

# Phenomenological Case Study Methodology

- Select formulation and various densities of insensitive high explosive
- Use computer models to characterize shock and slapper velocities to design multiple credible exploding conductors
- Design test apparatus for explosive confinement and velocity measurement
- Ensure recording of electrical pulse waveforms
- Develop witness pellets to prove detonation
- Develop and obtain facility approval for safety plan for tests
- Test full experimental configuration
- Conduct test series
- Have experts confirm test results
- Record all results and document





### Pulse

<b>Peak Current</b>	$\leq 200\text{kA}$
<b>Current rise time</b>	$1 \text{ to } 5\mu\text{sec}$
<b>Pulse width @ 50% level</b>	$50 \text{ to } 500 \mu\text{sec}$
<b>Number of pulses</b>	$\leq 24$
<b>Interval between pulses</b>	variable

### Continuing current

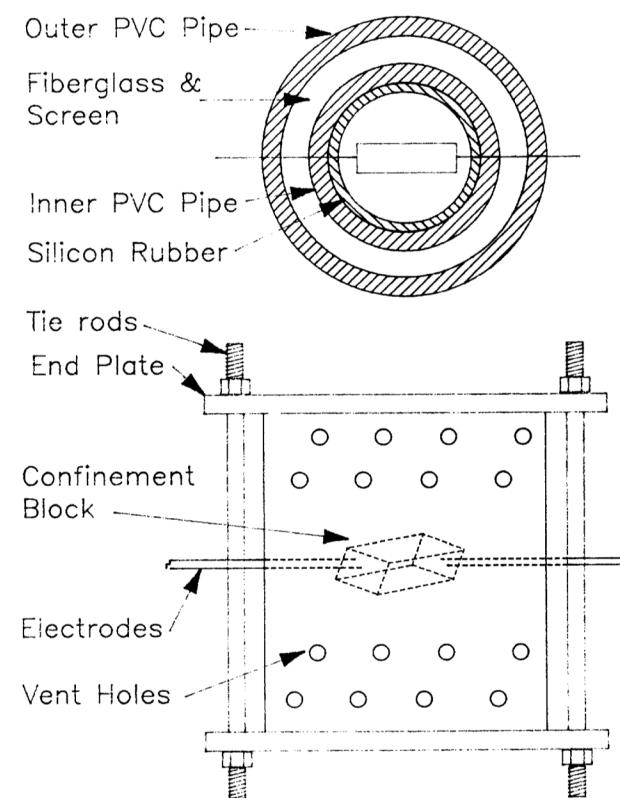
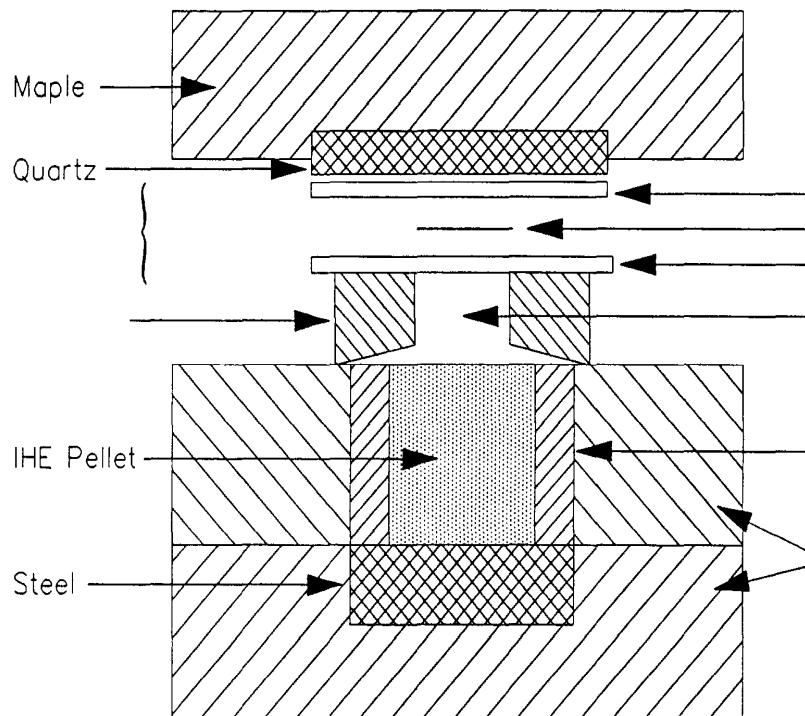
<b>Avg current</b>	100 A
<b>Duration</b>	$\leq 1 \text{ sec}$

# Experimental Specifics

- **Conductors –**
  - All seven tests used typical flat, flexible laminates made of copper foil and Kapton (polyimide) plastic insulation bonded with FEP (DuPont Teflon 100) adhesive.
  - A single foil of standard two-ounce copper dimensioned to provide an active area 7.6mm wide by 25 mm long (0.30 in-by-1.0 in).
  - The copper conductor thickness for these tests was 0.071 mm (2.8 mils).
  - 5 mil thickness of Kapton was used in two tests and 10 mil thickness was used in four tests. A doubled-over cable was used in the seventh test.
- **IHE –**
  - Various densities of pure triaminotrinitrobenzene (TATB) were pressed into samples of 1.2, 1.4, and 1.87gm/cm<sup>3</sup> without binder
  - Samples were confined in ceramic crucibles



# Experimental Configuration



# Steel Witness Pellet Results



Before and After Witness Pellet Response to Simulated Lightning Pulse  
Into Conductors Adjacent to Insensitive High Explosives

# Experiment Results

Conductor thickness (mm)	Flyer thickness (mm)	Approximate flyer velocity <sup>1</sup> (mm/ $\mu$ sec)	Impact area <sup>2</sup> (cm <sup>2</sup> )	TATB Type <sup>3</sup>	Spacer Aperture Configuration	TATB density (g/cm <sup>3</sup> )	Detonation <sup>4</sup>
0.071	0.13	5.2	0.90	UF	rectangular	1.20	yes
0.071	0.13	5.2	0.90	UF	rectangular	1.40	yes
0.071	0.25	3.3	0.90	UF	rectangular	1.40	yes
0.071	0.25	3.3	0.90	UF	rectangular	1.87	yes
0.071	0.25	3.3	0.90	CG	rectangular	1.87	yes
0.071	0.25	3.3	0.46	UF	circular	1.87	yes
0.033	0.076	–	0.90	UF	rectangular	1.20	no

Notes:

1. Flyer velocity estimated from VISAR measurements in shots without explosive samples.
2. Impact area determined by barrel configuration.
3. TATB type was ultrafine (UF) or conventional-grade (CG).
4. Detonation was determined by the condition of the witness disk.

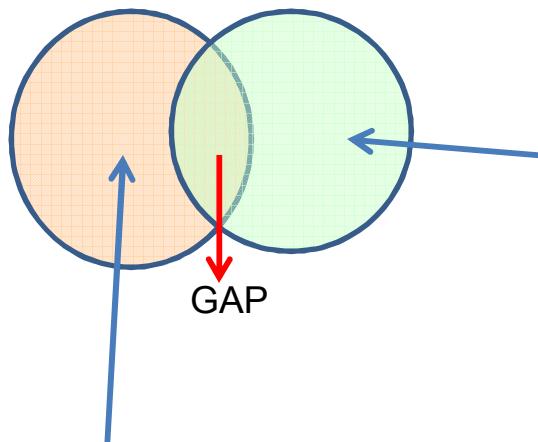
# Conclusions

- **Black Swans have caused some of the most devastating events in history**
- **The absence of data does not prove the probability or vulnerability is zero**
- **System engineers are responsible for preventing safety vulnerabilities, and computer modeling of system response to rare events is difficult**
- **Discovering vulnerabilities later in design development can be very costly or lead to project cancellation**
- **It is possible to characterize many of the phenomenological responses before prototype designs begin**
- **These phenomenological tests can clarify the safety requirements, risk assessments, and architecture definition**

# QUESTIONS?

# Backups

# Literature



## Insensitive High Explosives Response

- Aydemir, E., Ulas, A. (2011) A Numerical Study on the [Thermal Initiation](#) of a Confined Explosive in 2-D Geometry, *Journal of Hazardous Materials*, 186(1), 396-400.
- De Fisher, S., Pfau, D. (2010) [Insensitive Munitions](#) Modeling Improvement Efforts, 2010 [Insensitive Munitions & Energetic Materials Tech Sym.](#), Munich, Germany.
- Sharma, J. et al. (1989). Physical and Chemical Nature of [Hot Spots](#) in TATB and HMX. 9<sup>th</sup> Sym on Detonation, Portland, OR.
- Honodel, C. et al. (1981). [Shock Initiation](#) of TATB Formulations. *Proceedings – 7<sup>th</sup> International Sym on Detonation*.
- Sandia. (2007) [Insensitive High Explosives](#). MN471011 Explosives Safety Manual, Chapter IX. Sandia National Labs.
- much more

## Lightning Characterization and Protection

- Lightning Physics and Lightning Protection. Institute of Physics Publishing, Philadelphia, 2000.
- Collier, R., Perala, R., and Eriksen, F. (1992). Evaluation of Lightning Protection Systems for Explosives. 25<sup>th</sup> DoD Explosives Safety Seminar.
- Higgins, M., and Christdoulou, C. (2008). Models for Electromagnetic Coupling of Lightning Onto MultiConductor Cables in [Underground Cavities](#), Univ of New Mexico.
- Geldenhuys, H. (1995). The Effects of Lightning in [Shallow Coal Mines](#): An Engineering Study. University of Witwatersrand, Johannesburg, South Africa.
- Collier, R. and Struck, J. (1992). Mathematical Modeling of Triggered Lightning Experiments. International Conference on Lightning and Static Electricity, Atlantic City, NJ.



## Insensitive High Explosive Testing in Literature:

- Drop-weight impact tests
- Friction and skid tests
- Electrical spark tests
- Ignition, unconfined burning and cookoff tests
- Detonation tests
- Spigot, Susan and Stevens impact tests
- Bullet impacts

**•No Lightning Testing of IHE**

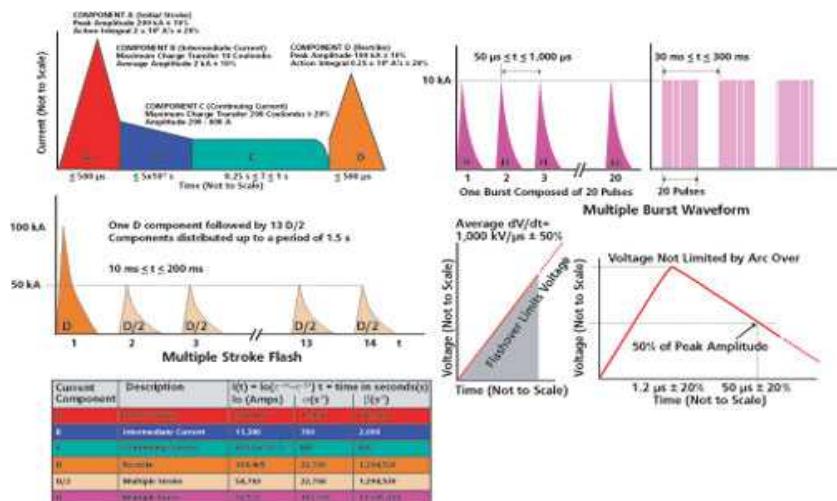
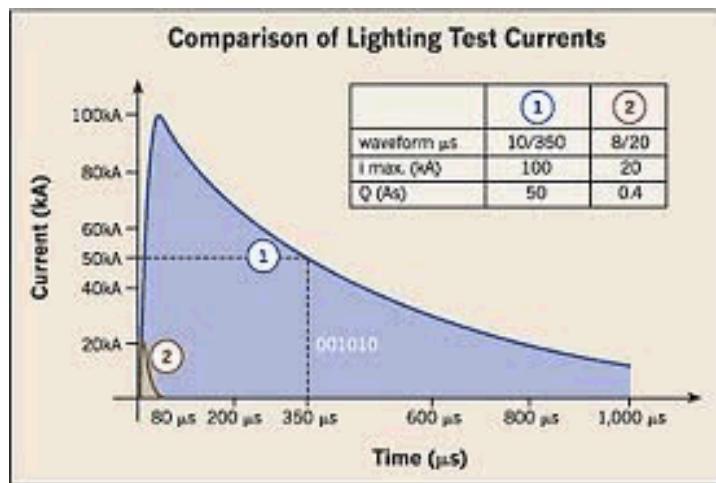
# Lightning Parameters

## Pulse

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# Experiment Results

