# Physics-based Modeling and Simulation
## Digital Engineering in CAD/PAD at Chemring Energetic Devices

Hobin Lee
Vice President, Research & Development
Chemring Energetic Devices

July 12-14, 2022

2022 CAD/PAD Technical Exchange Workshop, Indian Head, MD

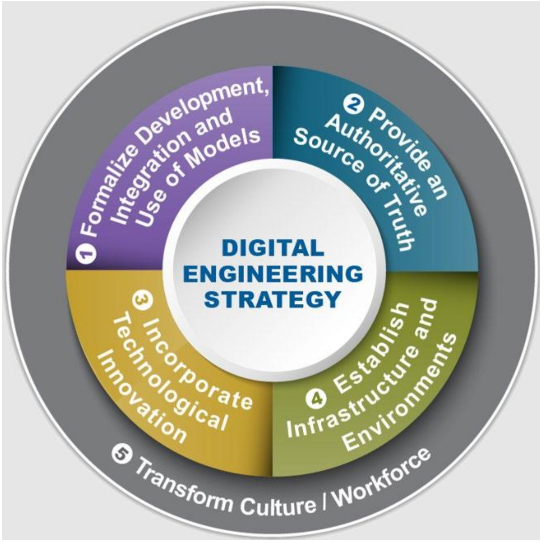
# What is Digital Engineering?

“Digital engineering is an integrated digital approach using authoritative sources of system data and models as a continuum throughout the development and life of a system.” http://ac.cto.mil/digital_engineering/

From *Department of Defense Digital Engineering Strategy*, (published June 2018 by Office of the Deputy Assistant Secretary of Defense for Systems Engineering):

- “To securely and safely connect peoples, processes, data, and capabilities across an end-to-end digital enterprises”
- “Emphasizes continuity of the use of models across the lifecycle”
- “Expected benefits of digital engineering include better informed decision making, enhanced communication, increased understanding of and confidence in the system design, and a more efficient engineering process”

**Digital Engineering is *model-based process* best address and manage complex technologies over the product/system lifecycle**




http://ac.cto.mil/digital_engineering/

# Digital Engineering for a CAD/PAD Supplier?


Photo credit: Chemring Energetic Devices

**Devices / Components**

**Subsystems**

**System**


Photo credit: U.S. Air Force


Photo credit: U.S. Air Force

## ***Digital twins* of components**

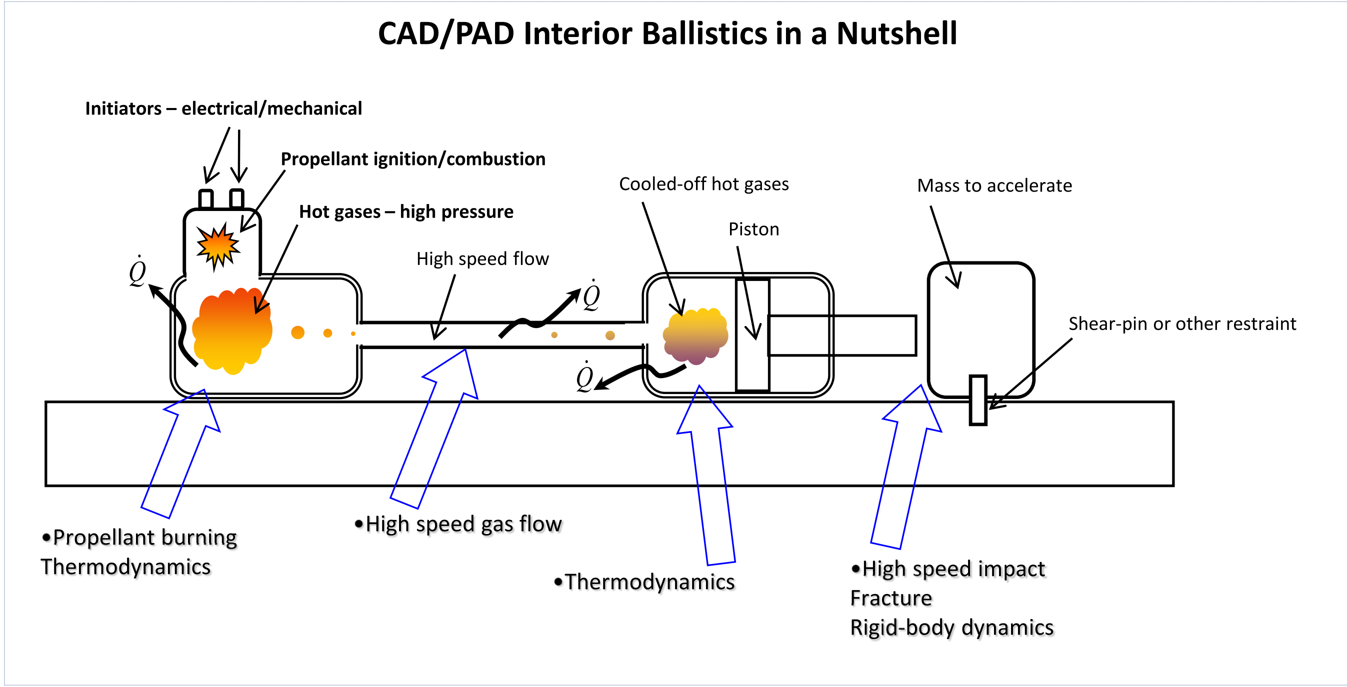
- **Physics-based performance models**
- 3D computer design models
- Digital database for critical parameters:
  - Propellant characteristics
  - Hardware characteristics
  - Manufacturing process
  - Performance characteristics
  - Other trends

Component digital twins can be important building blocks of the digital twin of the subsystem they serve, and ultimately of the digital twin of the system

# *CIBAC,* Chemring Internal Ballistics Analysis Code

## Physics-based Performance Modeling at CED

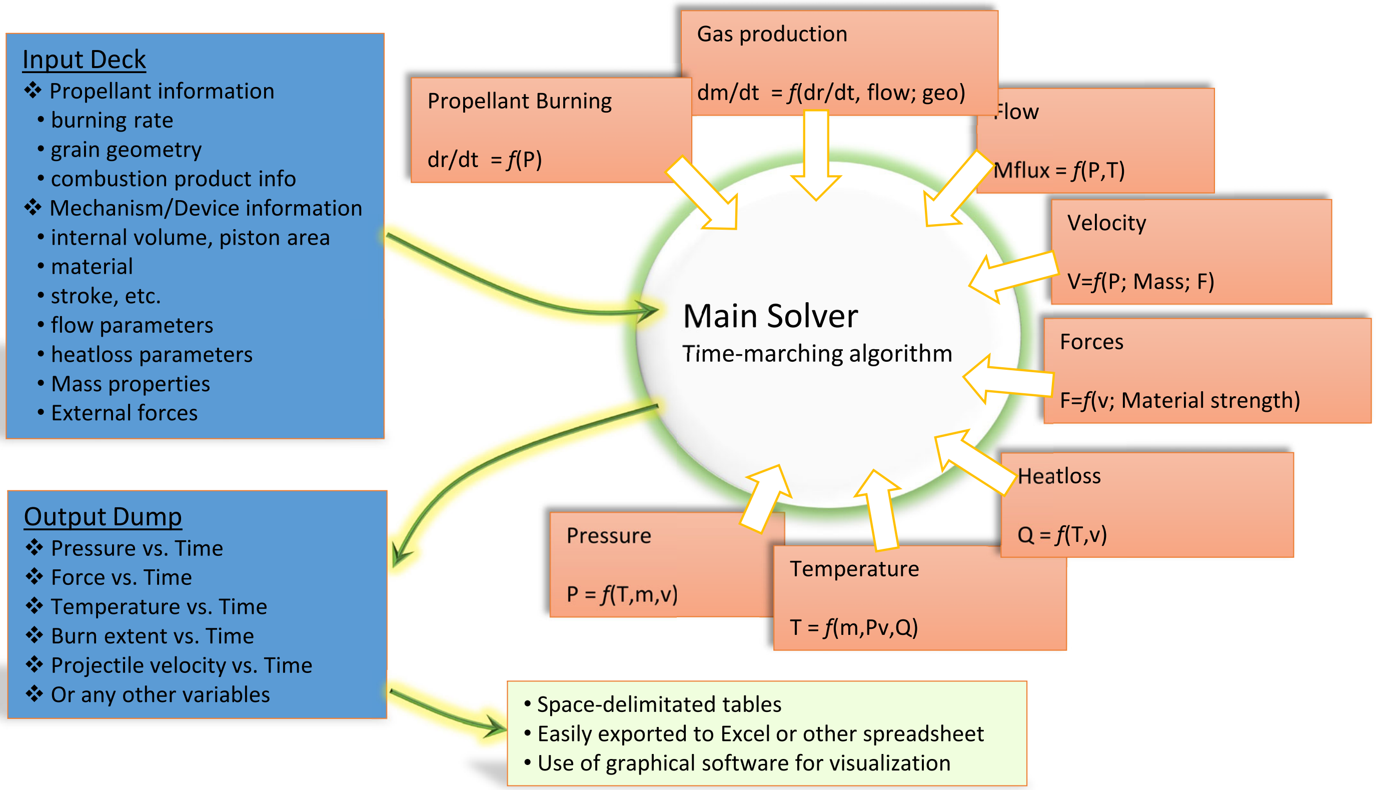
**Establish physics-based models to aid all lifecycle stages: concept, development, and production**




- Performance
  - Pressure vs. time
  - Velocity vs. time
  - Other critical performance variables
- Effects of hardware variation
  - Orifice are
  - Weight
  - Shear-pin strength
- Effects of propellant lot variation
  - Gas production
  - Rate of burning
  - Burn geometries
  - Aging effects
- Other effects
  - Manufacturing discrepancies
  - Other abnormalities

# CIBAC Methodology

- “Modular” Architecture
  - Allows for quick adaptation for various design approaches and configurations
    - Separate subroutine for each physical aspect - minimal code modification for different applications
- Mathematical Models w/ Empirical Baselines
  - Theoretical equations for each physical aspect
  - Large database exists for verification and calibration
- Time-history Simulation
  - A set of time-dependent differential equations
  - Known initial condition: ambient pressure/temperature, at rest, etc.
  - Solve computationally by utilizing “marching-in-time” schemes



# Example – Drogue Mortar Pressure Cartridge

- CED supplies Mortar Cartridge for ACES-II Drogue Deployment
- 1A/1W EED initiated impulse cartridge with a “cocktail” of output energetics
- The acceptance of the cartridge is verified by testing in a fixture simulating the seat configuration

Photo credit: Chemring Energetic Devices

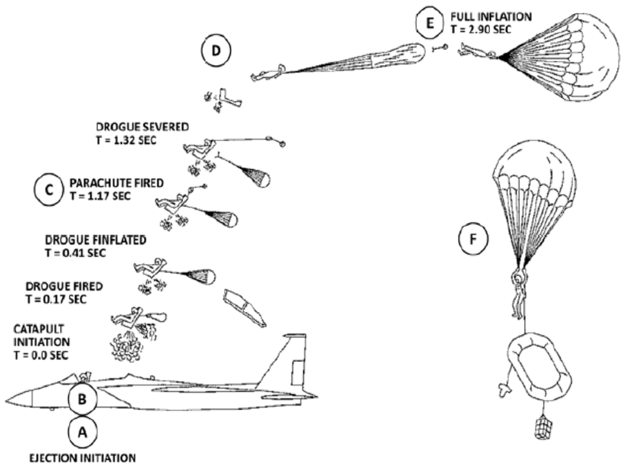



Image credit: Inspection General, U.S. Department of Defense, “Evaluation of Aircraft Ejection Seat Safety When Using Advanced Helmet Sensors

Photo credit: The Ejection Site, http://www.ejectionsite.com/f15seat.htm

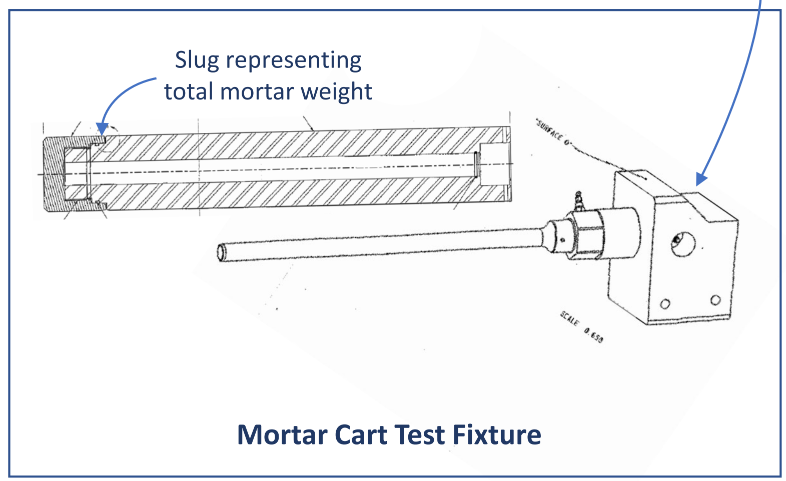
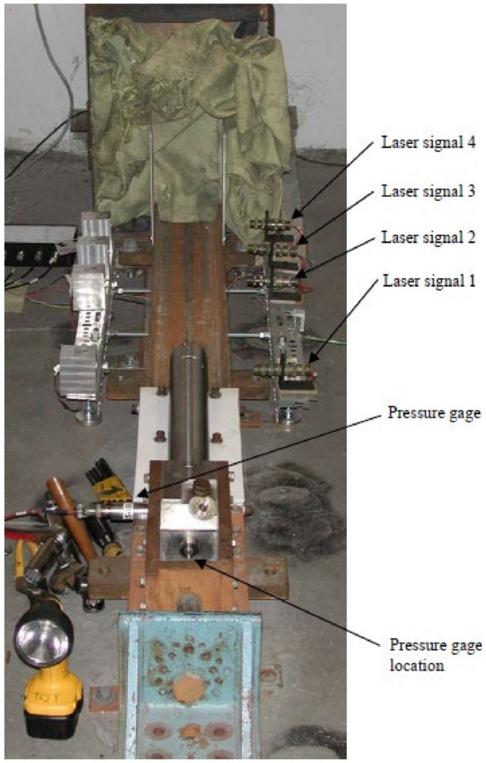



Image credit: NSWC IHD Dept. E

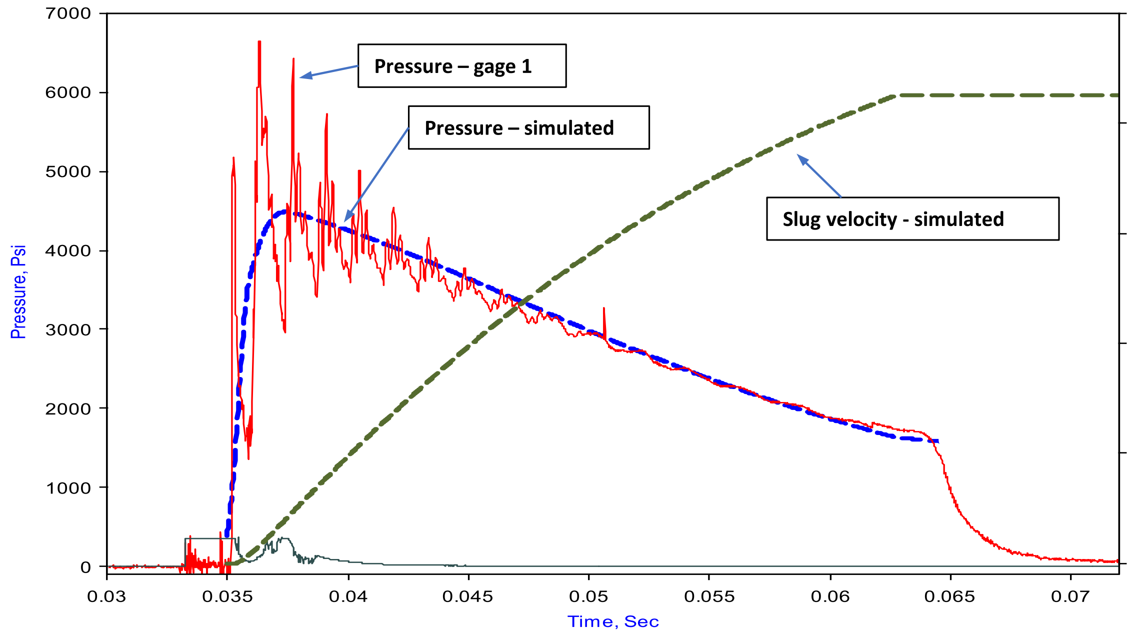
# CIBAC Model of Drogue Mortar Pressure Cartridge




**Mortar Cartridge Slug Test Fixture**

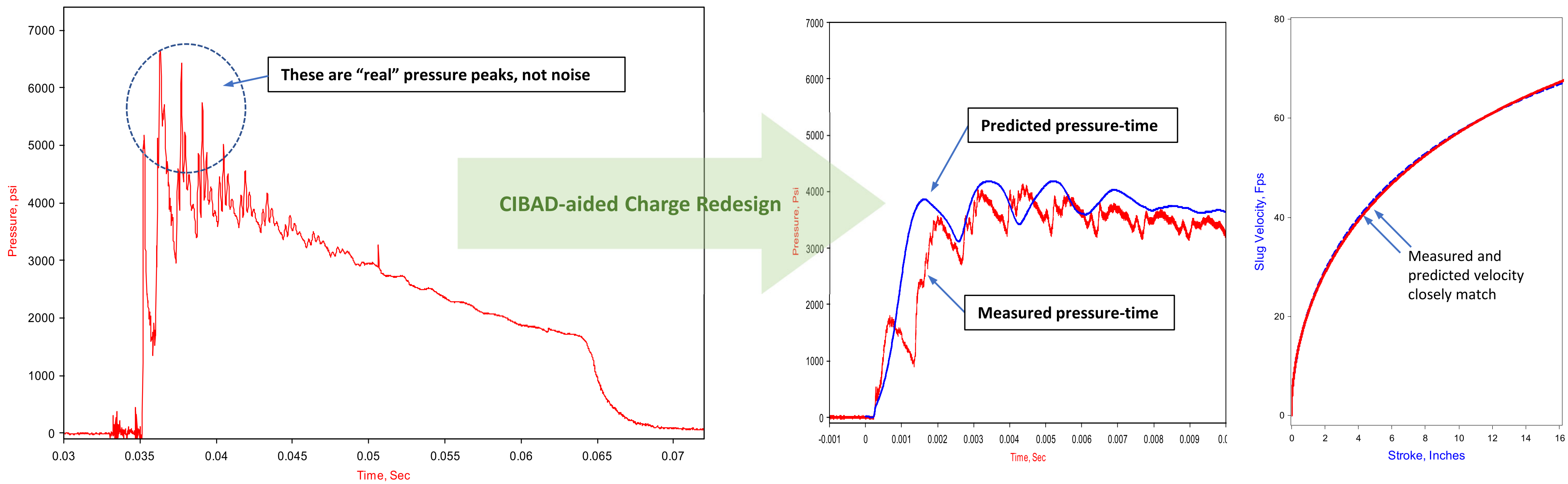
Photo credit: Chemring Energetic Devices

- Simulate Pressure in the barrel and the slug velocity
  - Propellants (weight, burning rates, physical dimensions, chemical properties)
  - Barrel volume, slug weight, pressure area, flow orifices, etc



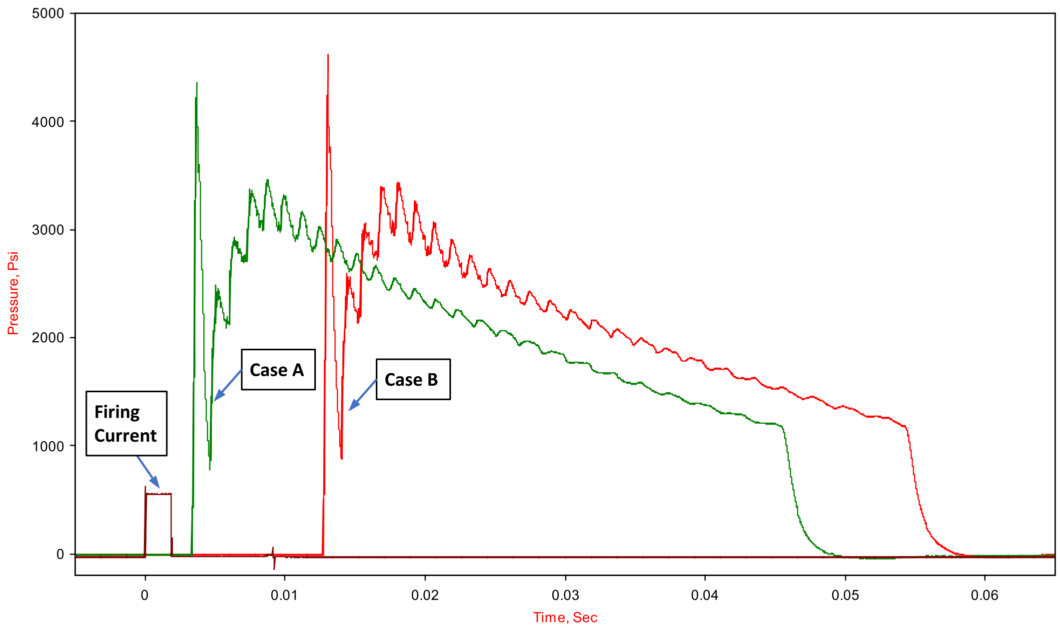
# CIBAC for Mortar Cart Charge Redesign

- High amplitude pressure fluctuations resulting in structural issues
- Redesign propellant charge: reduce high pressure fluctuations without compromising on the energy
- Spatial-dependent CIBAC version used to aid to meet the goal quickly



# CIBAC for Mortar Cart Ignition Delay

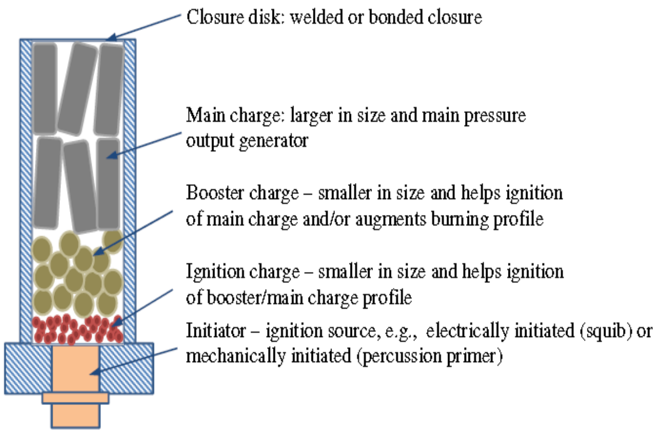
- Prolonged ignition time can negatively affect total time to fully deploy
- Understand the cause of the ignition delay and implement corrective actions

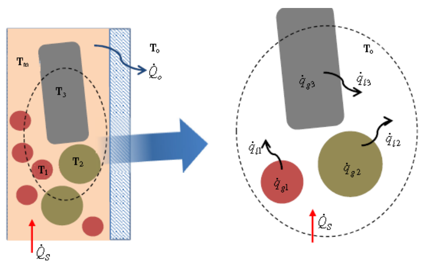



- Case A
  - Nominal Ignition Delay ~ 3.5 milliseconds
  - Nominal pressure-time profile
  - Nominal slug velocity
- Case B
  - Long Ignition Delay ~ 12.5 milliseconds
  - Exceeds the max. allowed action time (firing signal to projectile exit from barrel)
  - Nominal pressure-time profile. Almost identical to Case A
  - Nominal slug velocity
  - Nothing anomalous about overall burning of the charge
  - Long delay occurred before pressure cartridge's closure disk was ruptured

# CIBAC for Mortar Cart Ignition Delay – Ignition Model

- Ignition of propellants is balancing act between chemical decomposition and heat transfer



**Decomposition, Heat Generation and Heat Transfer inside Cartridge**

$$\rho_i c_{v_i} V_j \frac{dT_j}{dt} = \dot{q}_{g\,j} - \dot{q}_{l\,j}$$

$$\dot{q}_{g\,j} = \rho_i V_j \Delta H_i k_{ni} \overline{p}_m^n e^{-E_{ki}/RT_j}$$

$$\dot{q}_{l_i} = hA_i (T_i - T_m)$$

$$\rho_m c_m V_m \frac{dT_m}{dt} = \sum_N \sum_{j=L} \dot{q}_{l\,j} + \dot{Q}_S - \dot{Q}_o$$

$$\dot{Q}_S(t) = \dot{m}_S c_{p_s} T_S$$

$$\hat{\Delta}_{c_i} = \frac{\Delta H_i k_{n_i} \overline{p}^n e^{-E_{ki}/RT_{C_i}} E_{A_i} a_i^2}{\kappa R T_{c_i}}$$

**Post Ignition Burning and Internal Ballistics**

$$\frac{d\lambda}{dt} = B \cdot P^a$$

$$\dot{m}_p = \frac{d}{dt}\left( m_{p_o} \sum_j l_j \lambda^j \right)$$

$$P(V - \overline{\eta}) = m_p \overline{R} T$$

$$\frac{d}{dt}(mc_v T)\Big|_{PC} = -\dot{m}_{flux} c_p T + \dot{Q}$$

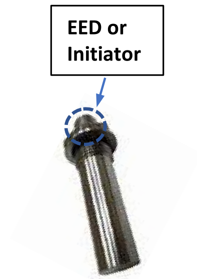
$$\frac{d}{dt}(mc_p T)\Big|_{BC} = +\dot{m}_{flux} c_p T - PA_B \cdot v + \dot{Q}$$

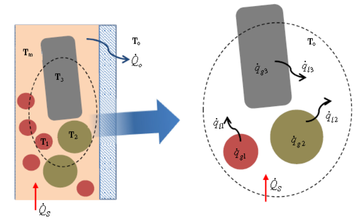
$$\dot{m}_{flux} = f(T, P)$$

$$\frac{dv}{dt} = \frac{d^2 x}{dt^2} = (PA_B - F_{opp}) / M_B$$

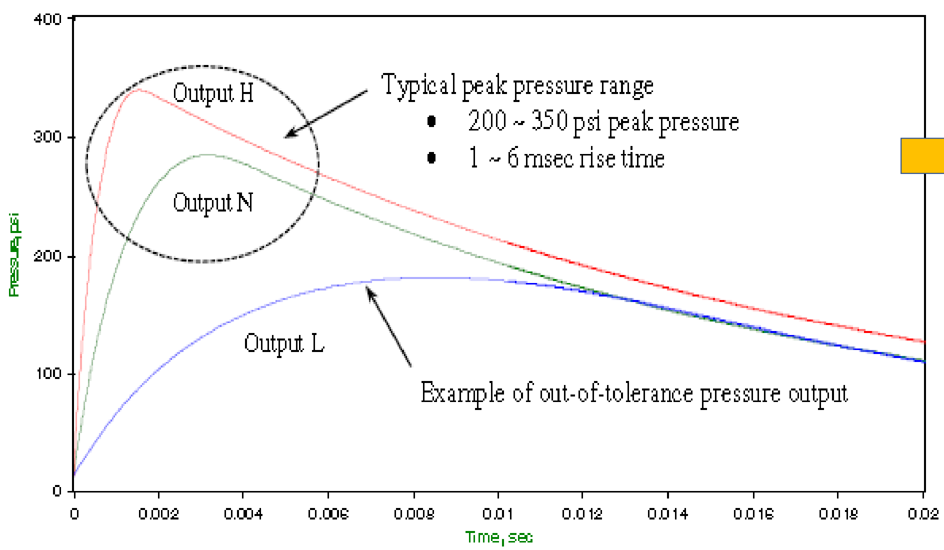
# CIBAC for Mortar Cart Ignition Delay – Effects of EED output

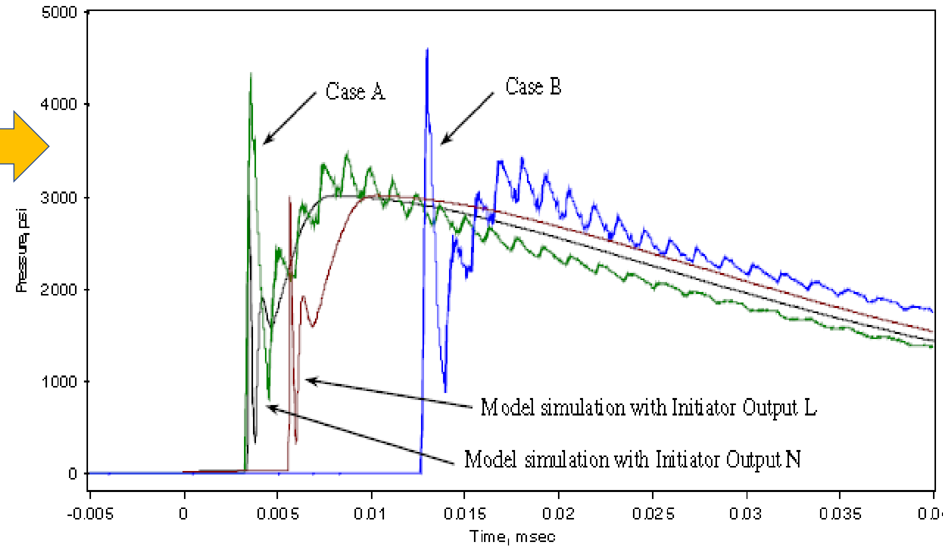
- EED's output usually characterized in a closed bomb, i.e. peak pressure and time-to-peak pressure
- How does the EED's output variation in a closed-bomb translate to the overall Mortar Cart performance in the drogue test fixture?



$$\dot{Q}_S(t) = \dot{m}_S c_{p_S} T_S$$



# CIBAC for Rapid Concept to Design

- Quickly assess concept design feasibility of pyro-mechanical actuator system for upper cover jettison application

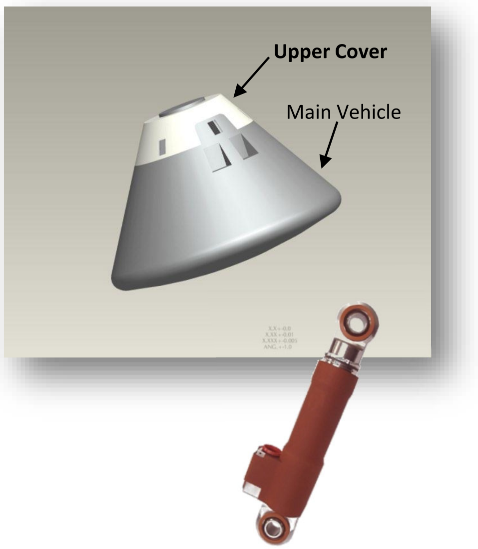
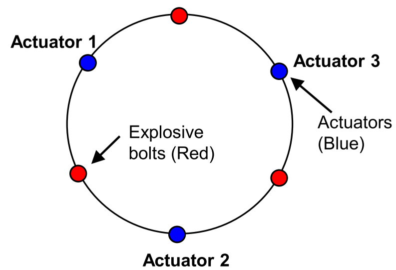
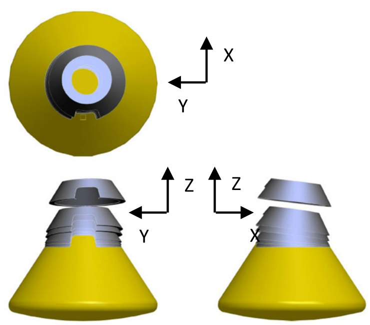



Image credit: Chemring Energetic Devices



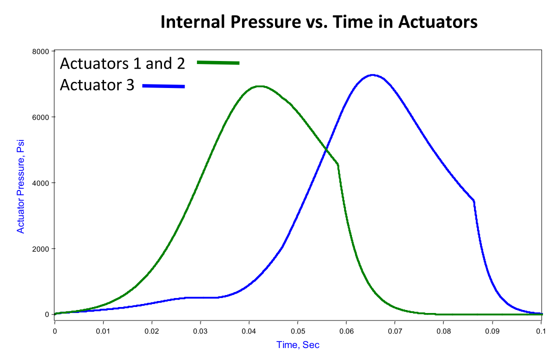




<u>Essential Design Parameters</u>

- How heavy: Internal operating pressure & external forces
- Impact to surrounding structure: Setback or reaction force
- How fast: Acceleration/velocity
- Effect of non-synchronistic actuation
  - Effect of non-simultaneity on trajectory
  - Trajectory's influence (feed-back) on actuation

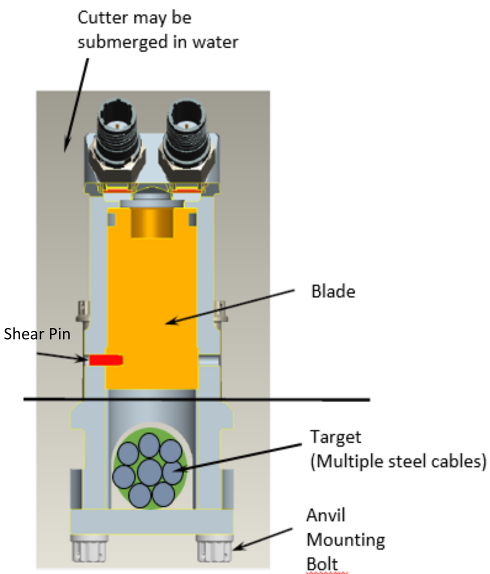
<u>Worst "Tilt" Case Analysis</u>

- Three actuators spaced evenly around Main Vehicle
- Two actuators perform "statistic high" while the third perform "statistic low"

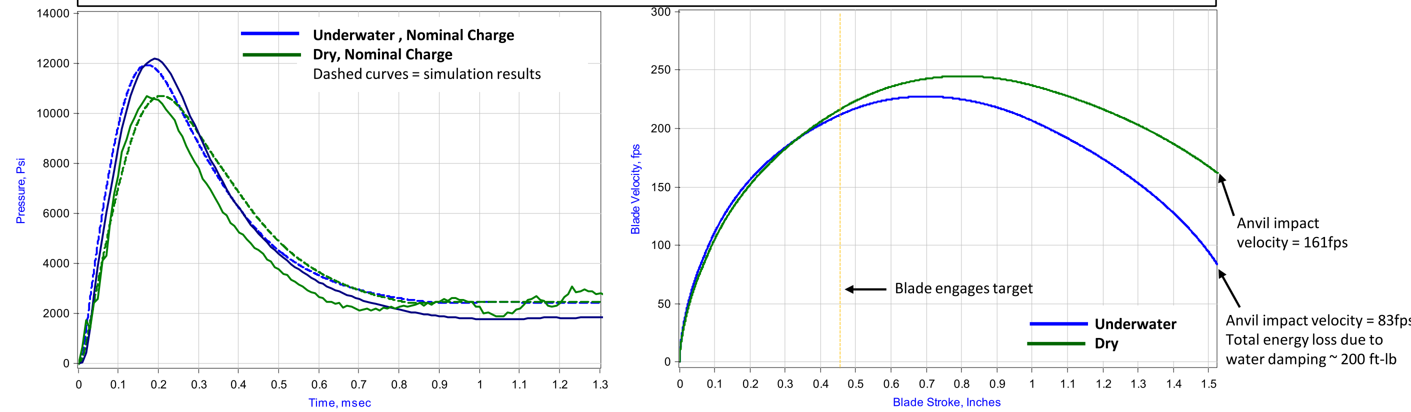


# CIBAC for Root Cause Analysis

- A pyrotechnic cutter's performance is significantly degraded when functioned submerged in shallow water. Why?
- Analysis shows when functioned underwater, hydraulics effect significantly reduces the blade velocity




**Ballistic simulation with Incompressible/Inviscid damping model ($C_D$ = 0.85, $A_H$ = 0.5 in$^2$)**




**Blade in Anvil**
post firing

Photo credit: Chemring Energetic Devices

| Test | Charge (Single PC) | Penetration depth (inch) | Ratio of Penetration depth (%) | Predicted Blade Anvil Impact Velocity (fps) | Ratio of Square of Blade vel. to Dry Firing |
|---|---|---|---|---|---|
| Dry | Nominal | 0.091 – 0.114 | - | 83 | - |
| Underwater | Nominal | 0.020 – 0.034 | 22 - 30 | 161 | 27 |

*If the ratio of penetration values is proportional to the blade energy, then it is proportional to the ratio of squares of velocities*

$$\frac{E_{Underwater}}{E_{Dry}} = \frac{Penetration_{Underwater}}{Penetration_{Dry}} = \frac{V^2{}_{B_{Underwater}}}{V^2{}_{B_{Dry}}} = 27\%$$

# Summary

- Digital Engineering requires model-based representations of devices/systems and processes
- CED has physics-based models of CAD/PAD devices it manufactures - CIBAC
  - Foundational piece for overall System Digital Engineering

*CIBAC* – Chemring Internal Ballistics Analysis Code

- Performance simulation with respect to all important design/manufacturing parameters:
  - Propellant characteristics, e.g., lot-to-lot variations
  - Hardware characteristics, e.g., dimensional variations
  - Manufacturing process, e.g, consolidation pressure
  - Vendor quality, e.g, EED lot variations
  - Others

- References

  - Lee, H. S., "Unsteady Gasdynamics Effects in Pyrotechnic Actuators", *Journal of Spacecraft and Rockets*, Vol. 41, No. 5, 2004, pp.877-886
  - Lee, H. S., "Rate-Dependent Plasticity Effects in Pyrotechnically-Driven Tensile Failure", AIAA 2008-4904, July 2008
  - Lee, H. S., "Underwater Performance Characterization of a Ballistic Guillotine Cutter at Operating Temperature Extremes", AIAA 2014-3808, July 2014
  - Lee, H. S., "A Heuristic Model for Estimating Ignition Delays for Pressure Cartridges with Loosely Packed Energetic Materials", AIAA 2015-3705, July 2015