On Ignition Delays in Pressure Cartridges with Loosely Packed Energetic Materials

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Introduction – Pressure Cartridges

- Pressure Cartridges
  - Used as the energy source for many ordnance or energetic application
  - Contains one or more energetic materials, propellants, or charge → when ignited, produce pressure (hot combustion gases) → pressurize a cavity and provide mechanical energy

Bomb-rack for B-2 Aircraft

Rocket Catapult for ACESII Seat [1]

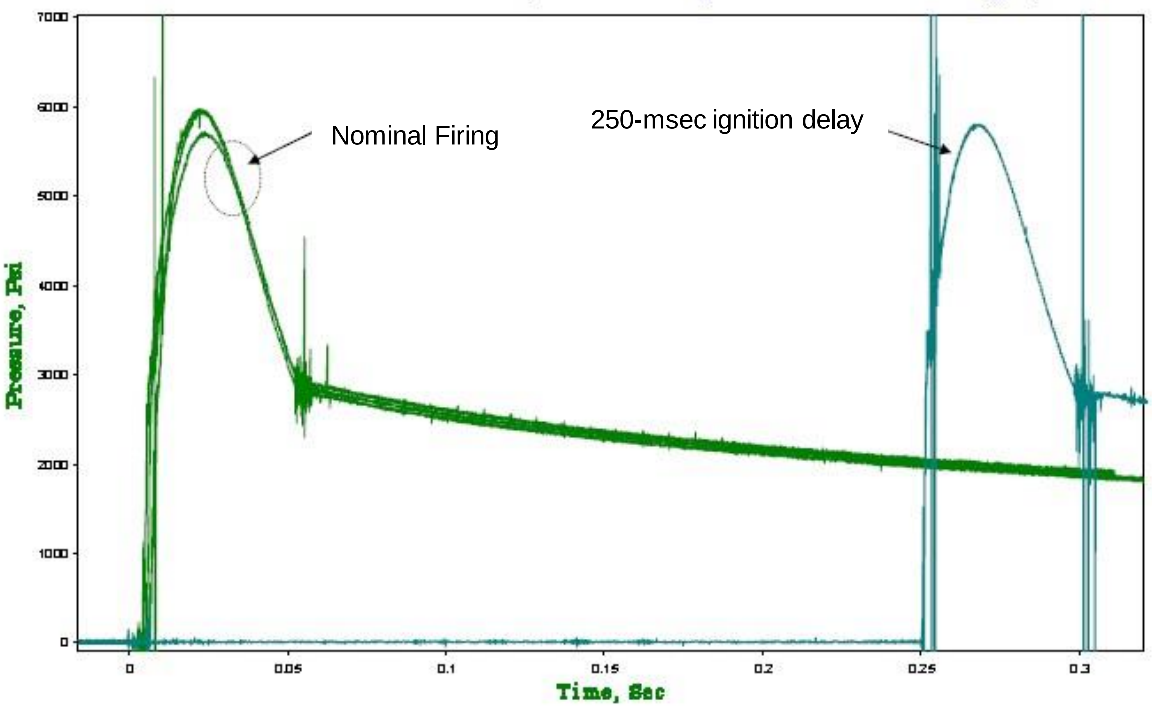
Attach/Jettison Thrusters for Atlas V

[1] Image from "CKU-5C/A Rocket Catapult ACES II Sled Test Program", C. Wheeler, M. Reese, Thomas Briscoe, the Proceedings of the 42nd SAFE Symposium, Salt Lake City, UT, September 2004

- Event/Action Time
  - The energetic event in an ordnance application using pressure cartridges usually is in the order of milliseconds (the total event time usually a critical performance criterion)

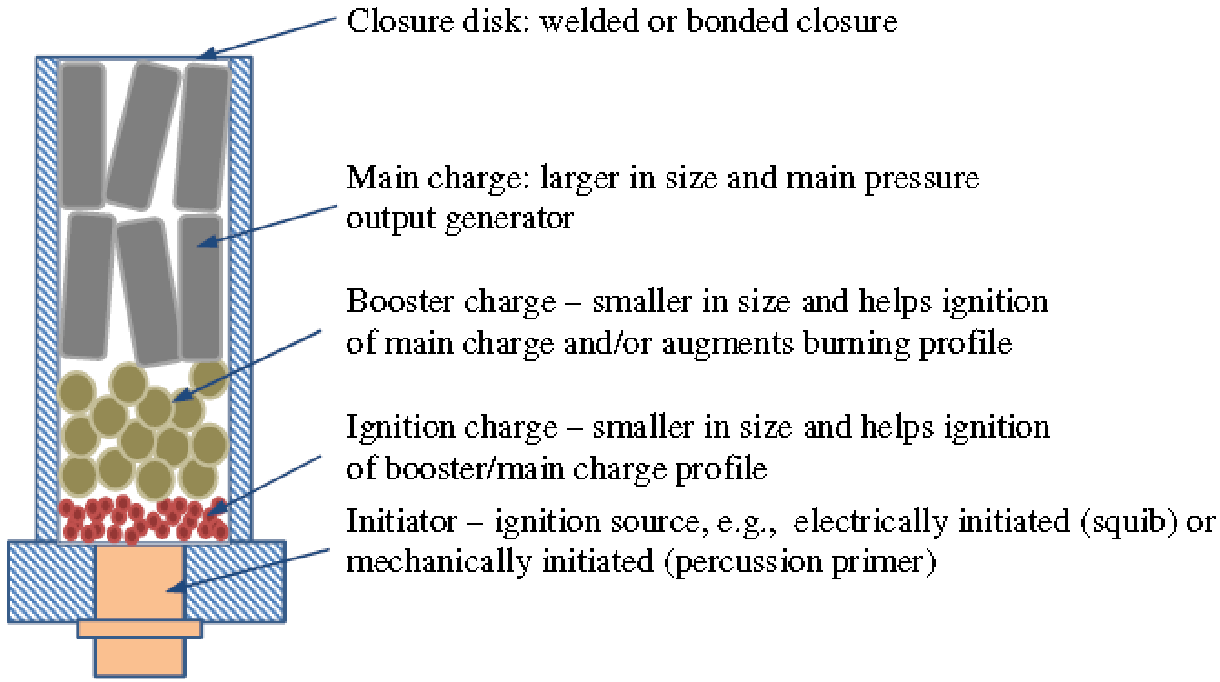
Introduction – Ignition Delay

- 1st order Approximation
  - Instantaneous ignition
  - Time from application of “firing pulse” to ignition of propellants in PC is so short compared to the event following it, it can be safely neglected
    - E.g., Ignition time ~ 2 msec vs. total even time ~ 100 msec.
- Non-trivial Ignition Delay
  - When ignition time is in the order of the total event time
  - When an anomalously long ignition delay is encountered



PCs with Loosely-packed Propellants

- Loading of Propellants or Energetic materials in Pressure Cartridges
  - Can have several different propellants
  - Packed or consolidated on top of each other, or loosely filled
- "Ignition Train"
  - From most sensitive to least (or most easily ignited to most difficult)
  - Initiator: the very first in line
  - Ignition charge: hot by-products/particles for igniting others in line
  - Booster charge: usually for fast pressure ramp-up
  - Main charge: main pressure generator



Ignition Model – "Thermal" Model (Heat Balance)

- Semenov Ignition Theory
  - Spatially invariant thermal model – spontaneous ignition occurs when heat being generated is greater than heat being lost
  - Heat sources: heat from Initiator output, heat being generated by each propellant
  - Heat sinks: surrounding medium, cartridge wall, each propellant

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

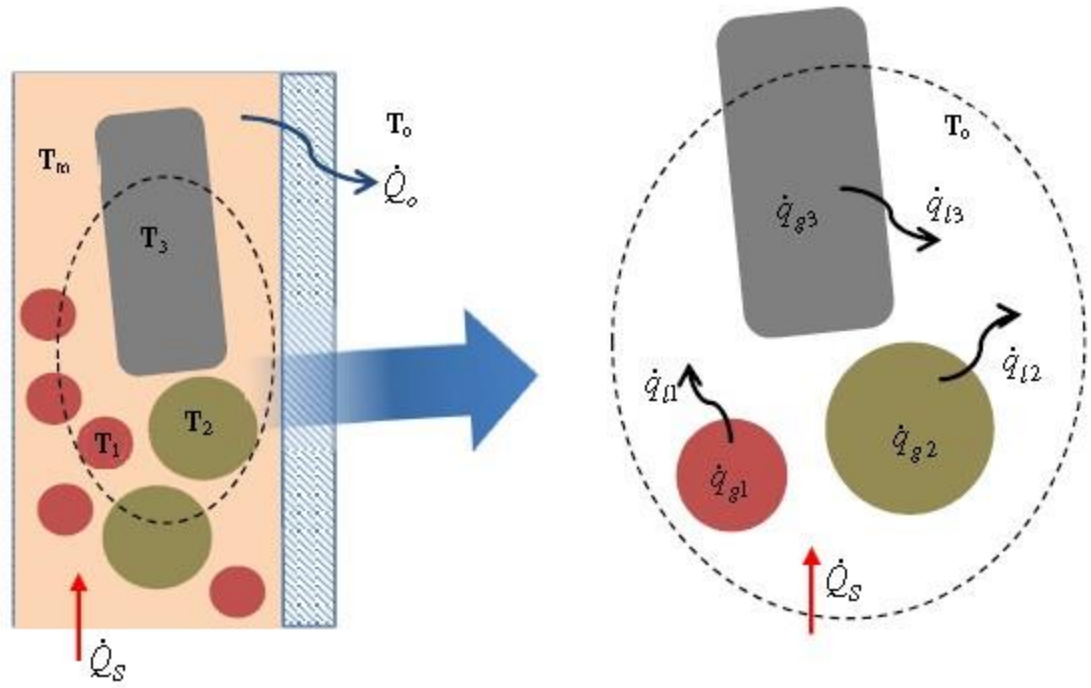
$$\dot{q}_{g\,j} = \rho_i V_j \Delta H_i k_{ni} \bar{p}_m^{\,n} e^{-E_{Ai}/RT_j}$$

$$\dot{q}_{l_j} = h A_j (T_j - T_m)$$

$$\rho_m c_m V_m \frac{dT_m}{dt} = \sum_{N} \sum_{i=1} \dot{q}_{l\,j} + \dot{Q}_S - \dot{Q}_o$$

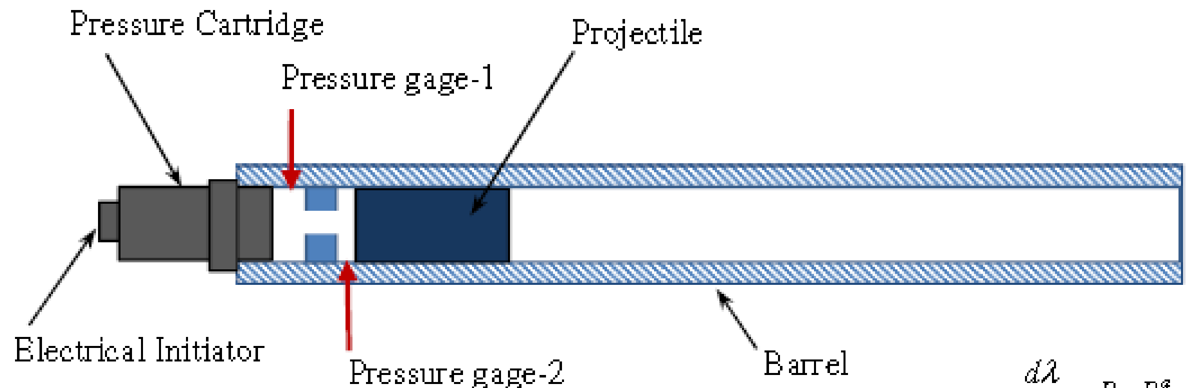
$$\dot{Q}_S(t) = \dot{m}_S c_{p_S} T_S$$

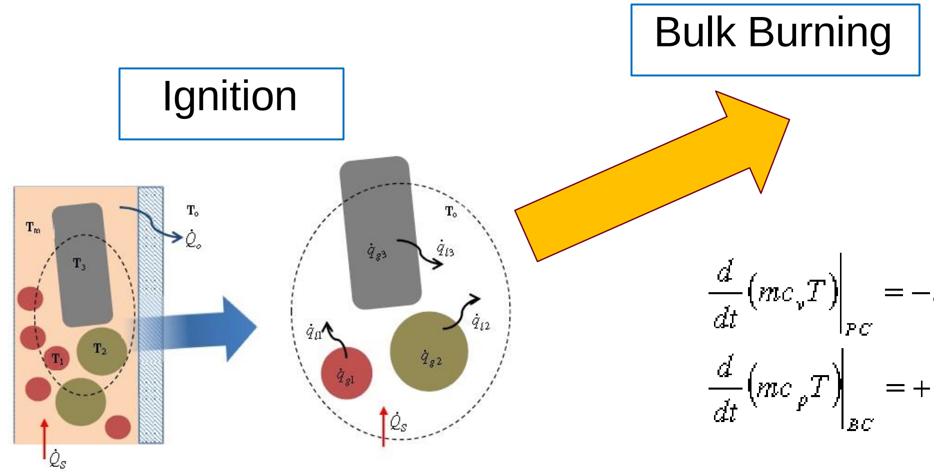
$$\hat{\Delta}_{c_i} = \frac{\Delta H_i k_{n_i} \bar{p}^{\,n} e^{-E_{Ai}/RT_{c_i}} E_{A_i} a_i^{\,2}}{\kappa R T_{c_i}}$$



Case Study: Ignition Delay in a Ballistic Gun

- Performance Criteria
  - Not to exceed maximum pressure
  - Projectile velocity
  - “Action” time
- Pressure Cartridge
  - Three loosely loaded charge
  - Initiated by electrical initiator
  - Ignition charge = $BKNO_3$
  - Booster charge = Double-base
  - Main charge = RDX-based
- Internal Ballistics Equations
  - Governing equations for pressure generation and projectile acceleration once ignition occurs
  - Until then, there is no “bulk” burning or production of gases





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

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

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

$$\left.\frac{d}{dt}(m c_v T)\right|_{PC} = -\dot{m}_{flux} c_p T + \dot{Q}$$

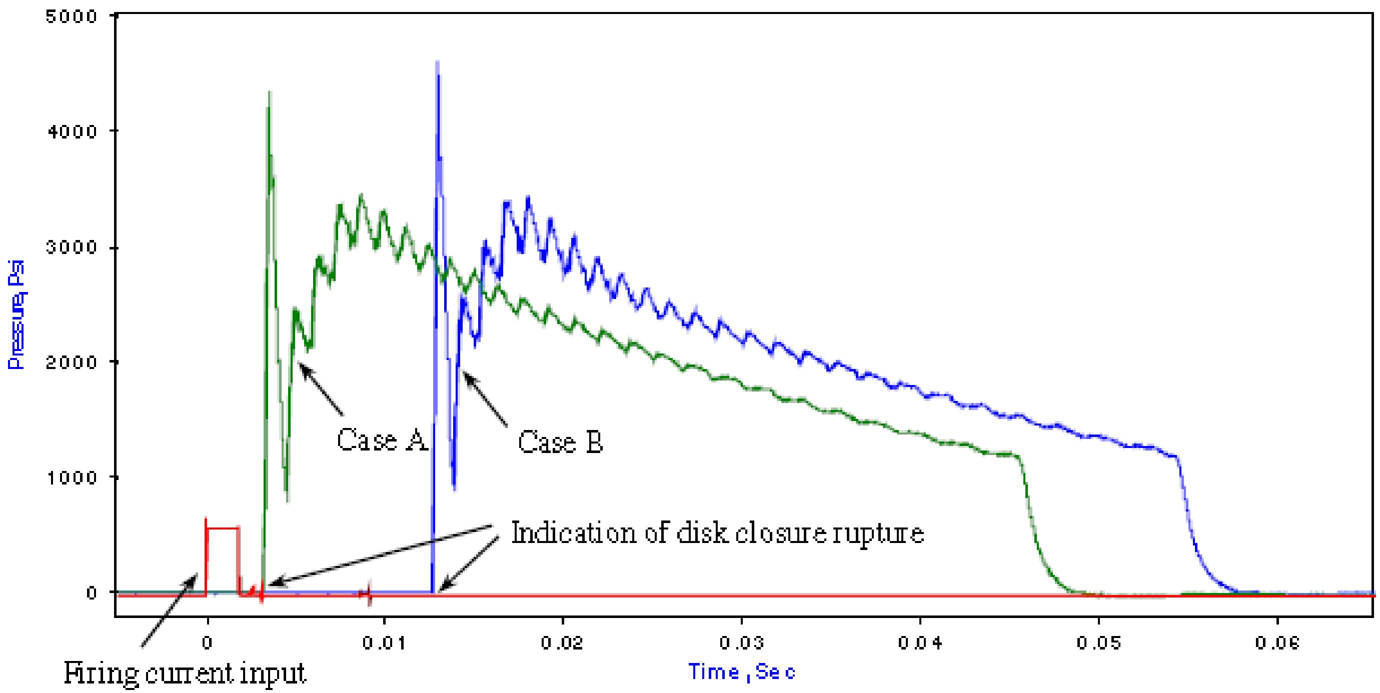
$$\left.\frac{d}{dt}(m c_p T)\right|_{BC} = +\dot{m}_{flux} c_p T - P A_B \cdot v + \dot{Q}$$

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

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

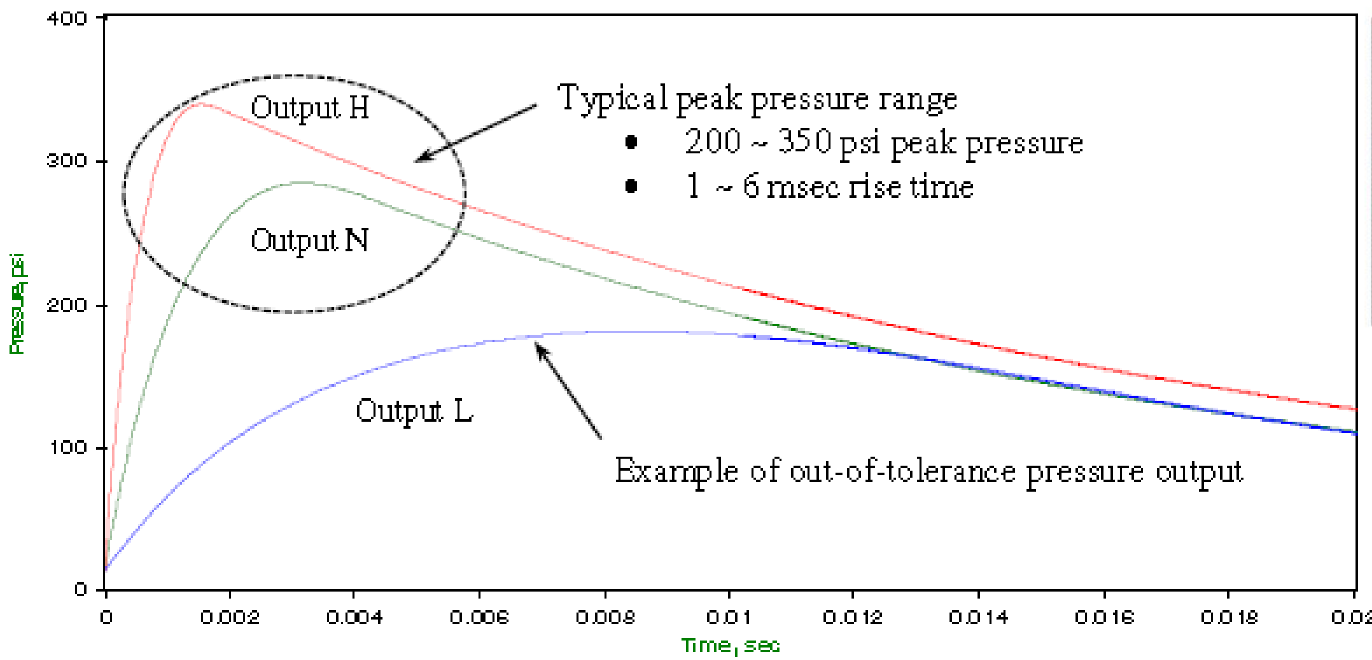
Case Study: Ignition Delay in a Ballistic Gun *continued*

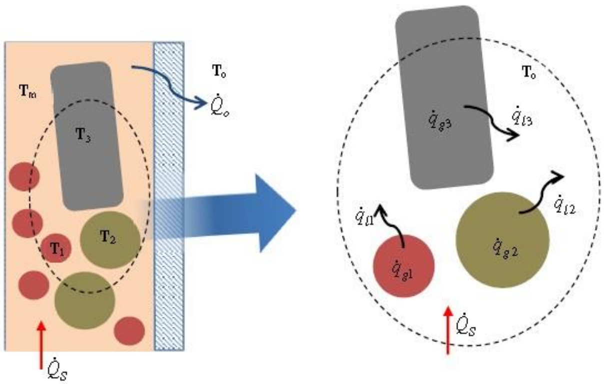
- Case A: Nominal Ignition Delay ~ 3.5 milliseconds
- Case B: Anomalously long Ignition Delay ~ 12.5 milliseconds
  - Pressure profile is almost identical to that of Case B
    - Additional delay not caused by anomalous burning of booster/main propellants
  - 1st indication of pressure at pressure gage 1 location is 9 milliseconds later than Case A
  - Exceeds the required not-to-exceed event time (firing signal to projectile exit from barrel)



Effects of Initiator Output on Ignition Delay

- Initiator's output usually characterized in its generated pressure in a closed vessel
  - 10cc or other "closed bombs" of internal volume
  - Peak pressure and time-to-peak pressure
  - Initiator energetics: ZPP (zirconium potassium perchlorate), flame temperature > 4000^o C
- How does the Initiator's output variation in 10cc closed-bomb affect the ignition process in the ballistic gun application?

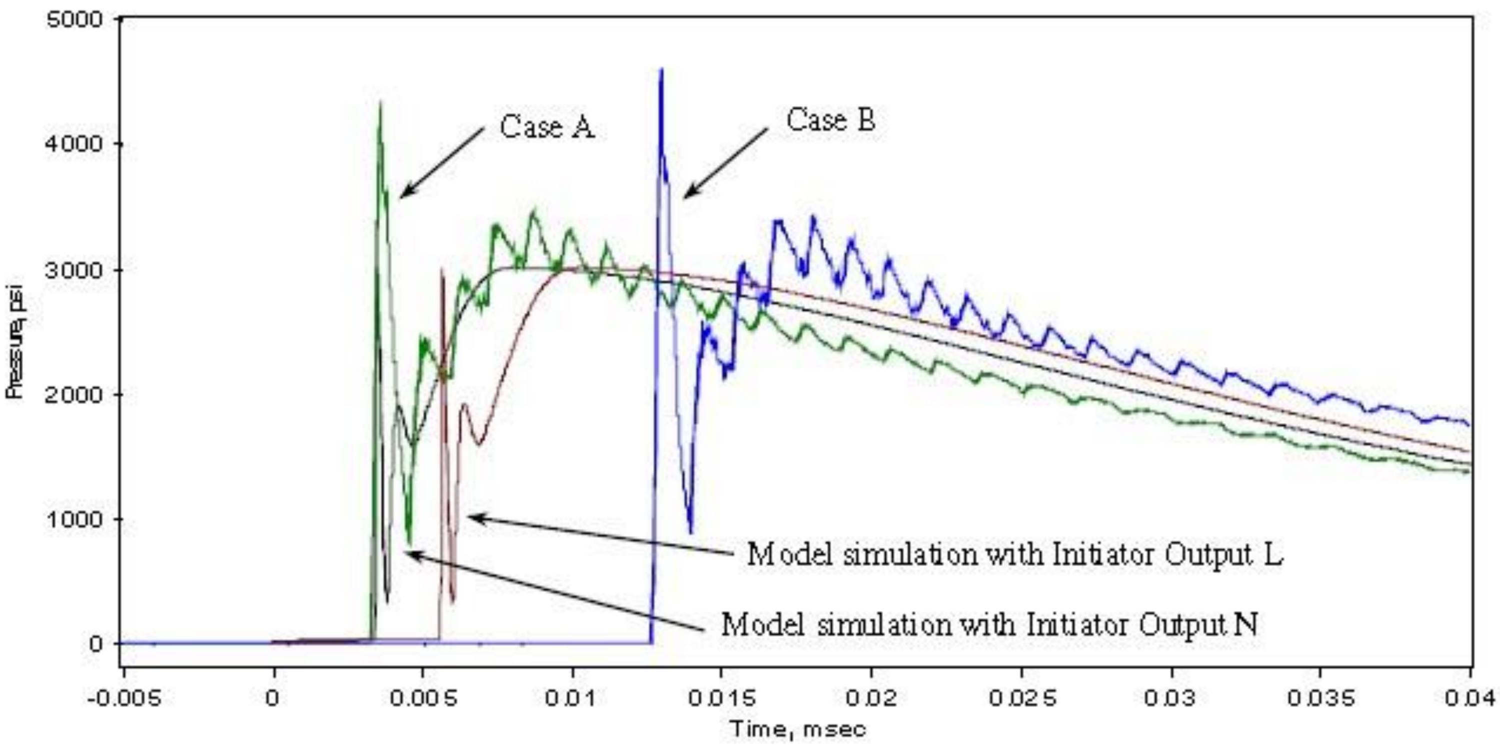




$$\dot{Q}_S(t) = \dot{m}_S c_{p_S} T_S$$

Effects of Initiator Output on Ignition Delay *continued*

- All other parameters such as Arrhenius constants kept identical
- Initiator Output N simulates the results of Case A
- Initiator Output L lengthens Ignition Delay for another 3 milliseconds



Effects of "Aged" Ignitor Charge

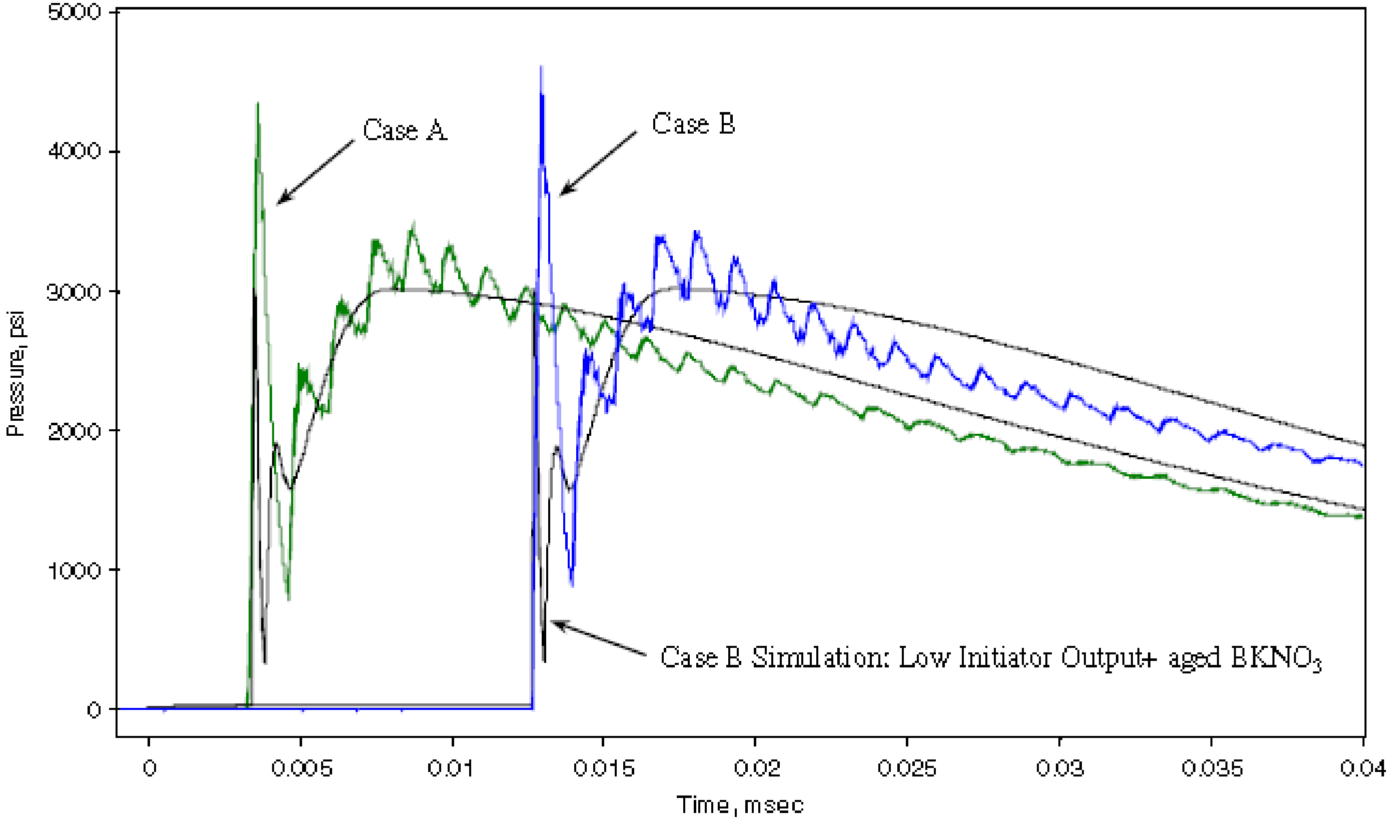
- Aging of $BKNO_3$ leads to oxidation of Boron particles
  - Arrhenius constants modified to reflect aging characteristics in decomposition of $BKNO_3$

Case	Vol (in^3)	SA (in^2)	Cp (J/kg-K)	ΔH (J/kg)	Z	E_A (J/mol)	α	T_{ig} (K)
A	5.1E-6	1.4E-3	2876	6.4E6	9.8E19	117.5E3	0.6	420
B	5.1E-6	1.4E-3	2876	6.4E6	9.8E19	121.2E3	0.6	420

  - Volume and surface area of each $BKNO_3$ particle represent an average particle size for those in between 20 and 50 US standard mesh
  - Arrhenius constants: Private communication (Dr. Bill Sanborn)
  - Case B has 3-percent higher activation energy → simulation of "agedness"

Effects of "Aged" Ignitor Charge *continued*

- Anomalously long ignition delay (Case B) simulated with
  - Low initiator output (Output L)
  - Age effects of $BKNO_3$ (increase in activation energy)



Effects of More Ignitor Charge

- When a longer than desired ignition delay is encountered, an intuitive approach may be to increase the ignition charge
  - More "hot stuff"
- Model indicates increased amount of $BKNO_3$ results in increased ignition delay

Case	E_A (J/mol)	BKNO3 wt. (gm)	Igntion Delay (msec)
A	117.5E3	0.50	3.5
A1		0.75	3.7
A2		1.50	4.5
B	121.2E3	0.50	12.5
B1		0.75	14.8
B3		1.50	17.3

- More $BKNO_3$ → increased surface area for initiator output to heat
- With already "aged" $BKNO_3$, more of it will significantly add to delay

Summary

- An analytical model based on Semenov theory of spontaneous ignition is a good tool for understanding the thermal mechanism that drives the ignition phase of the energetic materials in pressure cartridges
- The effects of the initiator's output on the pressure cartridge's ignition delay is clearly demonstrated by the model
- With some necessary calibration, the model may be used to quantify the accept/reject criteria of initiators to be used in a given pressure cartridge of which the ignition delay is an important performance criteria
- The model is also capable of simulating the effects of Arrhenius kinetics of the propellants on the ignition delay.
  - Aging, contamination, or other anomalies can directly affect the decomposition phase of the propellants by effectively modifying the Arrhenius constants such as the activation energy.
  - Thermal analysis such as DSC/TGA allows calculation of Arrhenius kinetics constants Therefore, the model in conjunction with such analysis may be used to quantify the effects of the propellant's chemical variation on the ignition delay
  - The heat exchange between the particles or the grains of the propellants is another key mechanism that should be considered when speeding up the ignition is desired.