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"A selection rule for flyer plates, shock sensitivity, and margin of performance"

Yasuyuki Horie[(a), (c)], Joe Olles[(b)], Christopher Molek[(c)], and Eric Welle[(c)]
a) University of Dayton Research Institute, Eglin AFB, FL 32542, USA.
b) Sandia National Laboratories, Albuquerque, NM, 87185, USA.
c) Air Force Research Laboratory, Munitions Directorate, Eglin AFB, FL 32542, USA.

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Old Chinese wisdom on a sake bottle

Study old materials to gain new understanding

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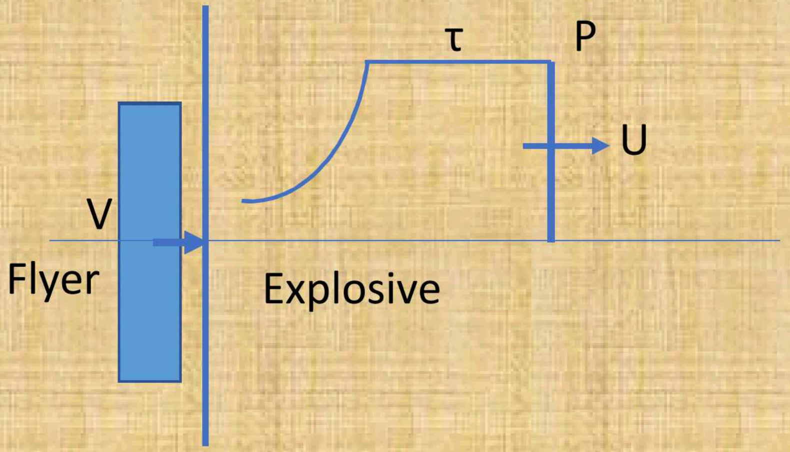
Outline

- A brief review of Hayes' idea of flyer optimization.
- Application to newer initiation threshold functions.
  - H. James.
  - E. Welle.
- Optimum flyer and performance gain.

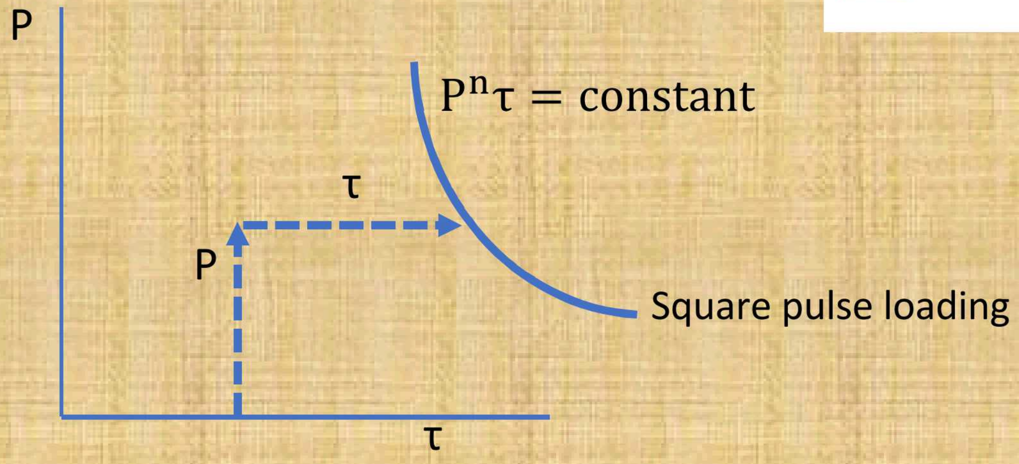
- Self-consistent non-dimensional groups.
- Concept of "distance" in the loading space.
  - A new measure of shock sensitivity.
  - Performance and safety margins
- Conclusions.

Thin Flyer Initiation and its Optimization

Thin Flyer Initiation



Extended Walker-Wasley Initiation boundary



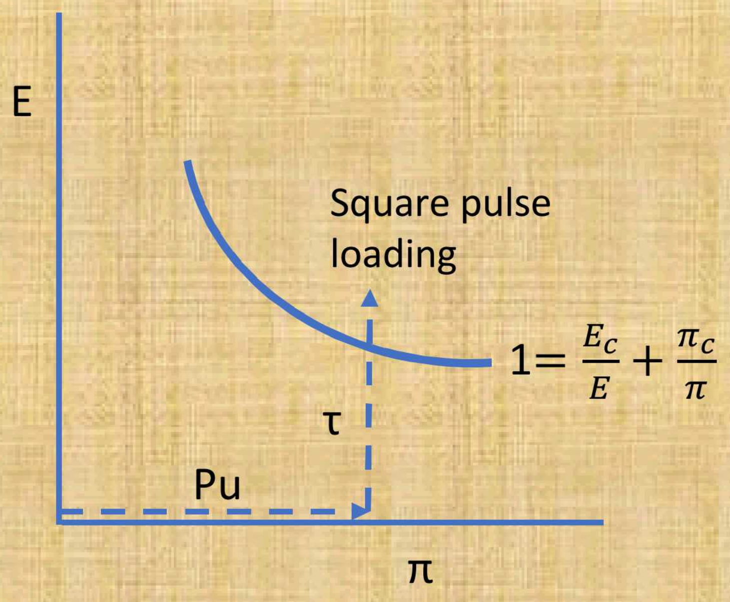
Hayes Idea of Flyer Design (SAND77-0268)

- The larger the value of $P^n\tau$, the better the design
- Adjust shock property (impedance) of the flyer
- $G = P^n\tau = 2Z_e^{n-1} m V^n \frac{\phi^{n-1}}{(1+\phi)^n}$
  - ✓ $\phi = Z_f/Z_e$ (shock impedance of the flyer/explosive shock impedance)
  - ✓ m = mass of the flyer per unit area
- Optimum ϕ that maximizes G
  - ✓ $\phi_{max} = n - 1$

Newer Initiation Functions and James Number

- **Initiation Functions** (James type)
  - ✓ $1 = \frac{E_c}{E} + \frac{\Sigma_c}{\Sigma}$ (James)
  - ✓ $1 = \frac{E_c}{E} + \frac{\pi_c}{\pi}$ (Welle)

  where $E = Pu\tau$, $\Sigma = \frac{1}{2}u^2$, and $\pi = Pu$



- **Optimization in terms of James number***
  - ✓ $\frac{1}{J} = \frac{E_c}{E} + \frac{\Sigma_c}{\Sigma}$
  - ✓ $\frac{1}{J_w} = \frac{E_c}{E} + \frac{\pi_c}{\pi}$

*Originally introduced by Greshoff and Hrousis of LLNL to describe initiation boundary in a probabilistic fashion. J=1 signifies 50% ignition probability.

Optimizing J in terms of ϕ

Consider J and J_w as G in Hayes' analysis

$$J = \left(\frac{V^2}{2\Sigma_c}\right)\frac{\phi^2}{(1+\phi)^2(1+\alpha\phi)}; \quad \alpha = \frac{E_c}{4m\Sigma_c}$$

$$J_w = \left(\frac{V^2 Z_e}{\pi_c}\right)\frac{\phi^2}{(1+\phi)^2(1+\beta\phi)}; \quad \beta = \frac{Z_e E_c}{2m\pi_c}$$

Optimum ϕ*

$$\phi_{max} = \frac{1}{2}\left[1 + \left(1 + \frac{8}{a}\right)^{1/2}\right]$$

where

$$a = \frac{E_c}{4m\Sigma_c}(= \alpha) \text{ for the James type}$$
$$= \frac{Z_e}{2m}\frac{E_c}{\pi_c}(=\beta) \text{ for the Welle type}$$

For a thin flyer (m→0), $\phi_{max} \rightarrow 1$ (max K. E.)
For a sustained load (m→∞), $\phi_{max} \rightarrow \infty$ (rigid flyer)

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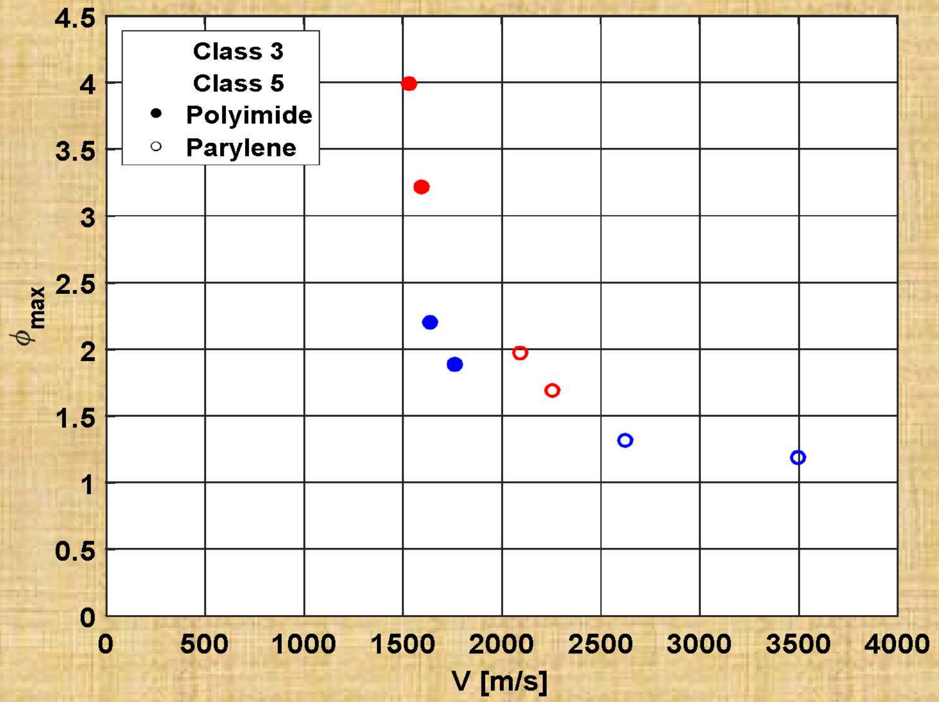
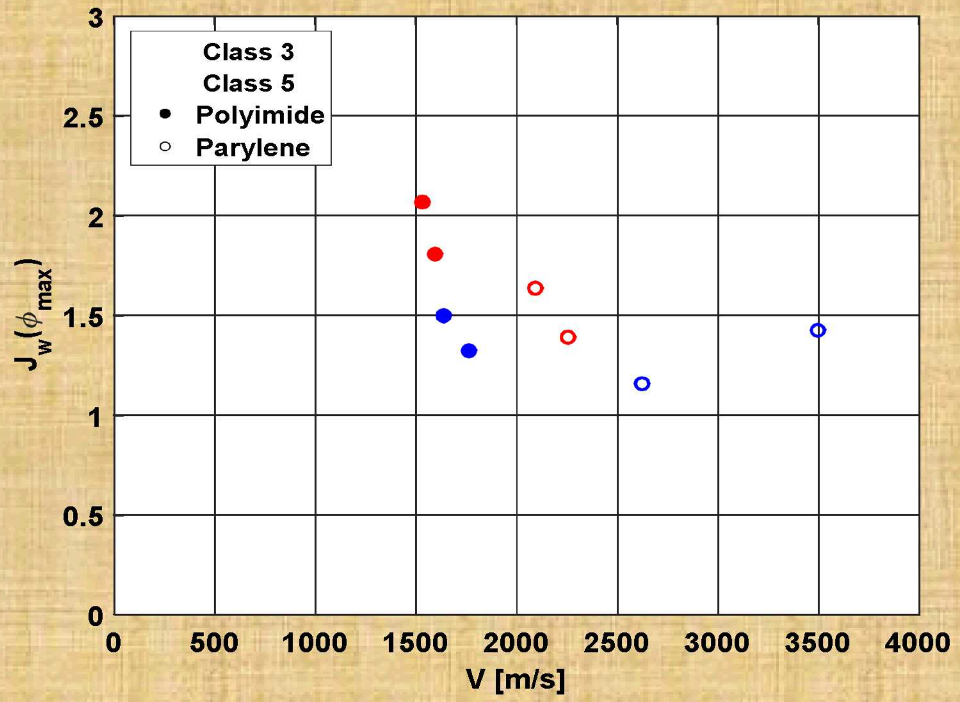
*Other parameters are assumed fixed

ϕ_{max} and J_w based on experimental data

[E. Welle et al, J. Phys., Conference ser., 500, 052049 (2014)]

Polyimide and parylene flyers impact Class 3 and Class 5 HMX powders pressed to about 95 %TMD

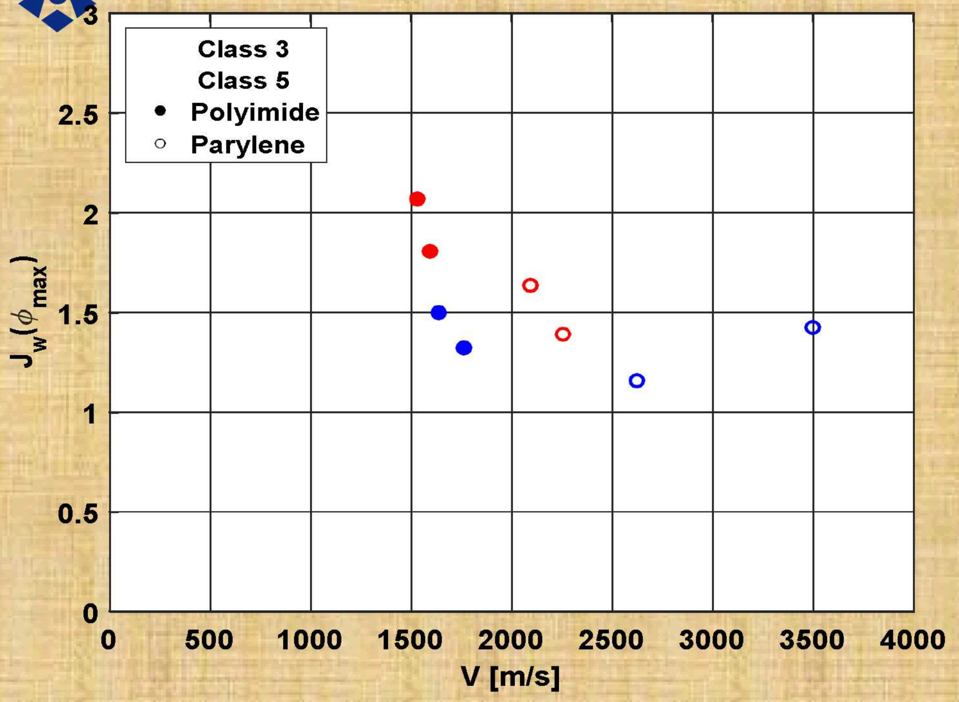


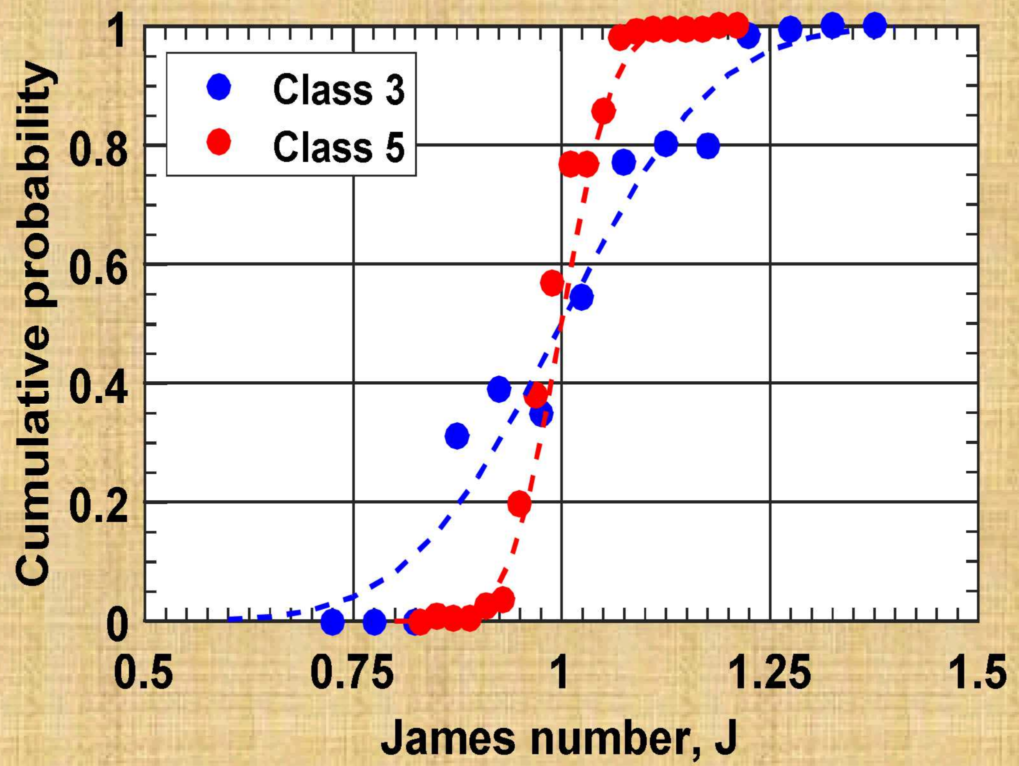


- At high velocities the best tactic is to maximize the kinetic energy transmission (ϕ=1).
- At low velocities, increase the shock impedance to the optimum value using e.g. a metallic flyer or add a metallic powders to the polymeric flyer as discussed by Hayes.
- Significance of J_w requires information on cummulative ignition probability.

Payoff of adjusting flyer impedance

[S. Kim et al., J. App. Phys. 120, 115902 (2016)]

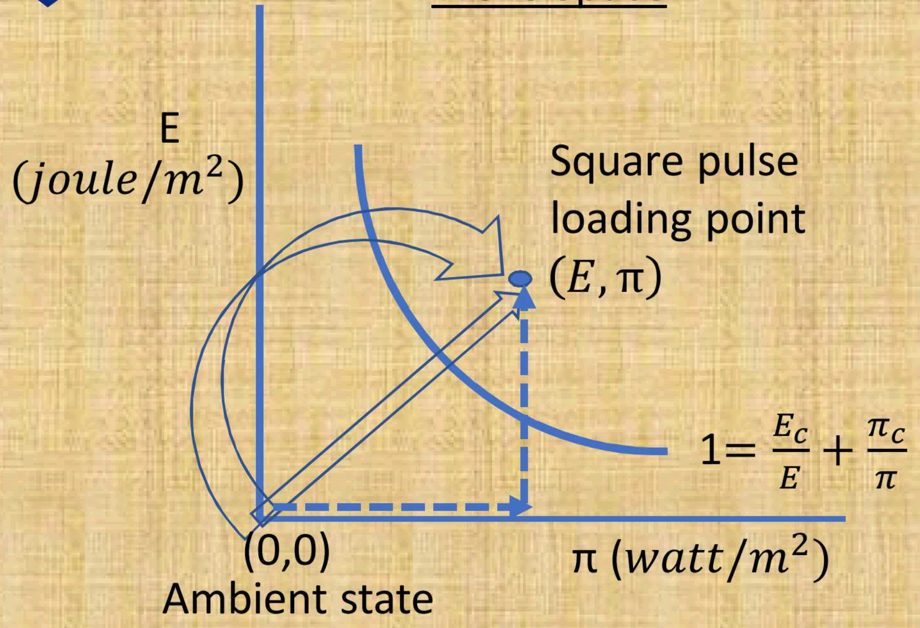




- By properly choosing ϕ, cumulative ignition probability can be increased to 100%.
- Adjusting flyer impedance is an attractive alternative to increasing flyer velocity in order to raise the cumulative ignition probability.

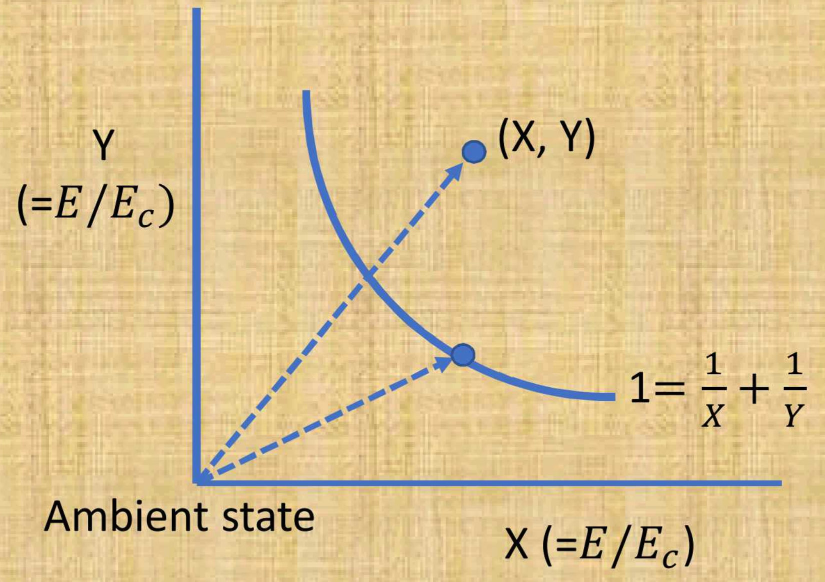
Distance in the Loading Space

Welle Space



Non-dimensionalization

Non-dimensional Welle Space

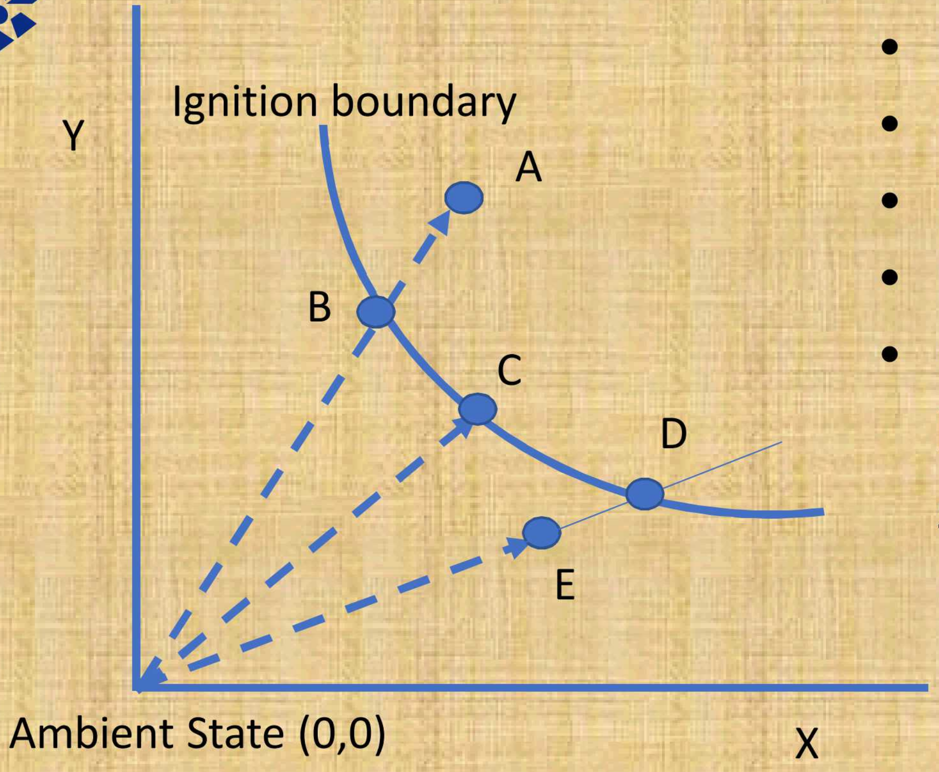


Initial Inspiration:

$$J_w = \left(\frac{V^2 Z_e}{\pi_c}\right)\frac{\phi^2}{(1+\phi)^2(1+\beta\phi)};\quad \beta = \frac{Z_e E_c}{2m\pi_c}$$

Usefulness of non-dimensional loading space

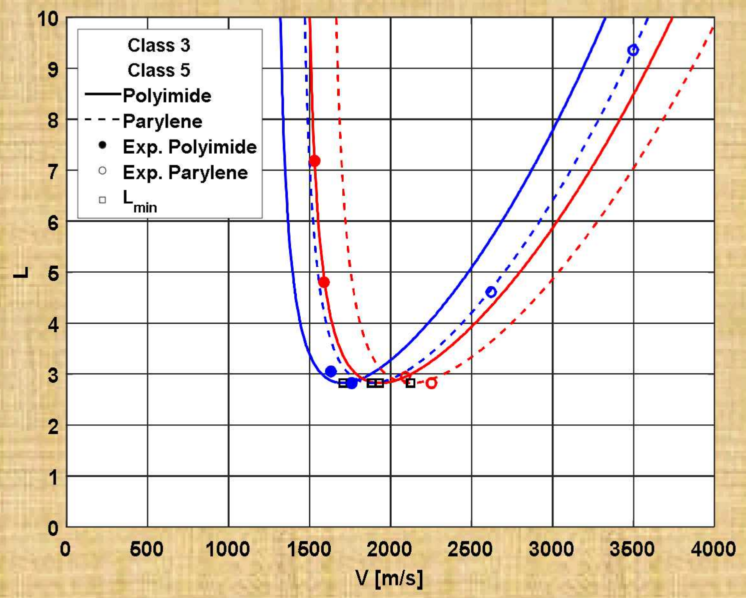
Geometric Interpretation of Performance Measures

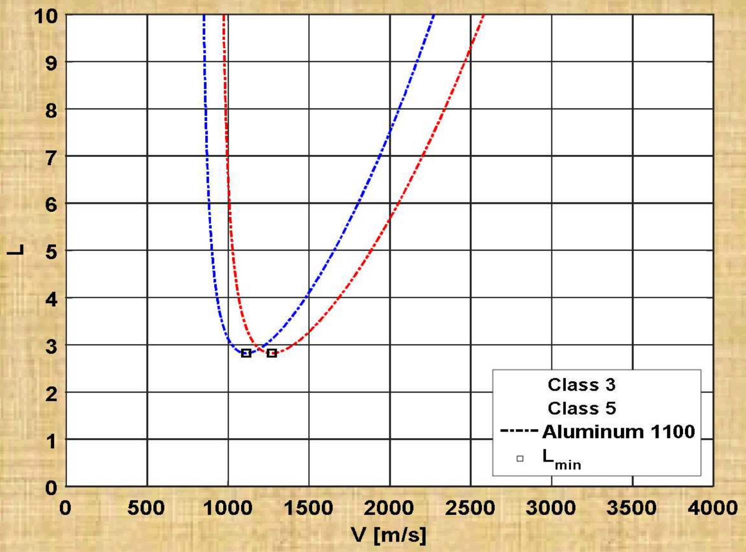


- Performance margin: A-B.
- Factor of performance: A/B.
- Margin of safety: D-E (for no-go).
- Factor of safety: D/E (for no-go).
- C is the minimum distance to the ignition boundary and may be used as a measure of shock sensitivity of energetic materials

Symbols (A,B,C,D,E) represent Cartesian distances from the ambient state to respective loading points

Minimum distance to the ignition boundary





Minimum speed required to reach the ignition boundary

$$V_{min} \begin{cases} =1.707 \text{ km/s (Class 3/polyimide)} \\ =1.885 \text{ km/s (Class 3/parylene)} \\ =1.935 \text{ km/s (Class 5/polyimide)} \\ =2.127 \text{ km/s (Class 5/parylene)} \end{cases}$$

According to this measure, Class 3 (av. particle size = 358 μm) is more sensitive than Class 5 (av. particle size = 6.7 μm).

V_{min} can be obtained by solving

$\pi = \rho_e U_e u \cdot u = \rho_e (C_e + s_e u) u^2 = 2\pi_c$ (minimum condition)

$\rho_e (C_e + s_e u) u = \rho_f \left(C_f + s_f (V - u) \right) (V - u)$ (pressure equality)

Since u is determined by the minimum condition only, the effect of the flyer can be understood by rearranging the 2nd equation.

$$V^2 + \left(\frac{C_f}{s_f} - 2u \right) V + \left(1 - \frac{\rho_e s_e}{\rho_f s_f} \right) u^2 - \left(\frac{C_f}{s_f} + \frac{\rho_e C_e}{\rho_f s_f} \right) u = 0$$

An example is shown for an aluminum flyer (Al 1100).

$$V_{min} \begin{cases} = 1{,}113 \text{ m/s (Class 3)} \\ = 1{,}270 \text{ m/s (Class 5)} \end{cases}$$

Conclusions

1. Hayes' idea of optimizing detonation initiation by thin flyer pate is extended to more recent threshold functions (James and Welle functions).

2. Results show an attractive way of increasing the cummulative ignition probability to 100%.

3. One of the by-products is the idea of non-dimensionalizing the loading space and the threshold functions.

4. Non-dimensional space allows intuitive geometric interpretation of various performance measures such as margin of safety, and performance margin, etc.

5. A new measure of shock sensitivity.