Void Collapse-Initiated Deflagration:
Progress Towards Predictive Modeling for Risk Evaluation Pt. 2

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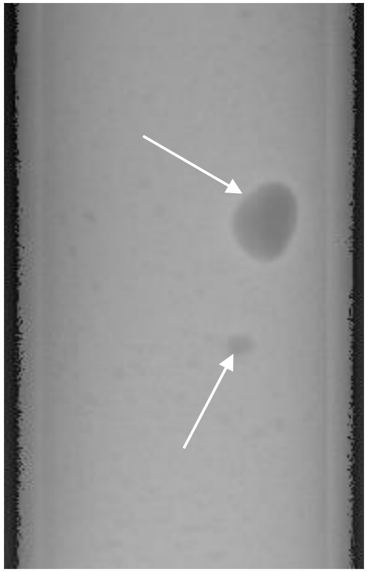
Introduction

- **ARA works with the USAAF on both high-fidelity modeling and testing of penetrating munitions.**

- **Penetrating warheads may deflagrate during deployment, leading to premature failure**
  - Non-shock induced void collapse is an initiation source of concern [2]
  - This work utilizes test data to build the foundation for predictive modeling of void collapse-initiated deflagration risk

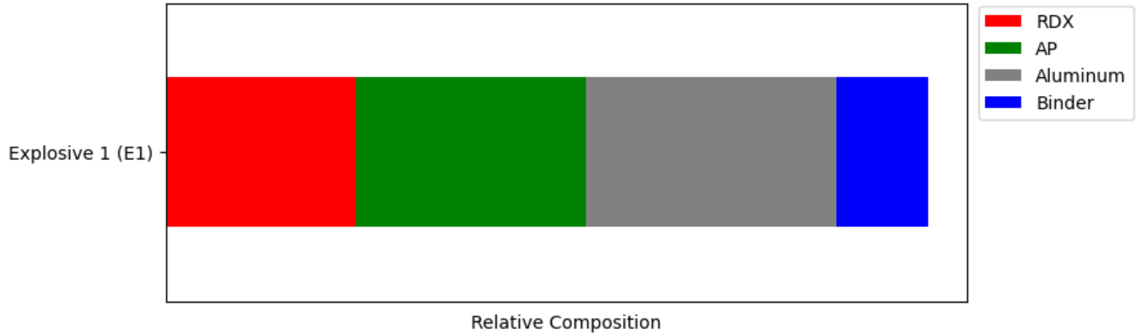
Background: *Explosive Voids*

Void Defects in High Explosive X-Ray



Not to scale

- **Cast Cured Plastic Bonded Explosives (PBXs) are susceptible to formation of gas filled pockets – “voids”**
- **Voids in penetrators are subjected to *non-shock* loads, which can result in deflagration[1]**
- **Explosive in this study:**
  - Aluminized, RDX based

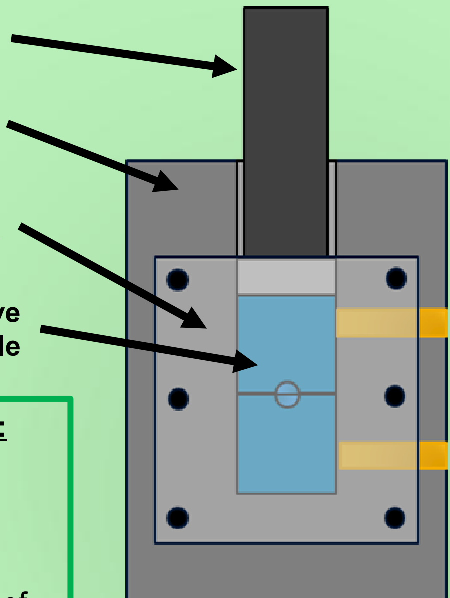


Background: *Mechanical Insult Testing*

- **ARA developed two novel tests to study void-collapse-induced deflagration events [2] :**

VIPER

Visual Insight into Penetrator Explosive Risk

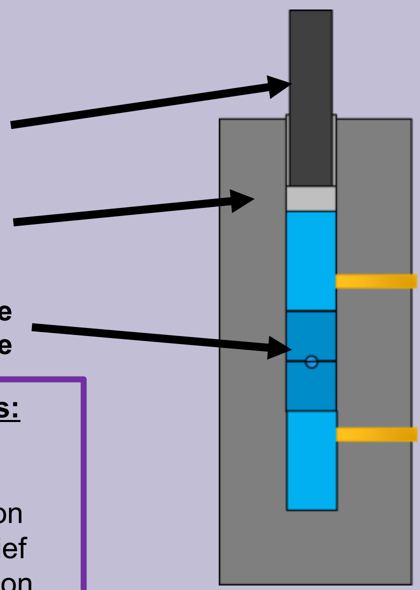


Capabilities:

- 5.5 KSI peak pressures
- ***High speed video***
- High visibility of void collapse

LIGER

Long Duration Ignition and Growth of Explosive Reaction



Capabilities:

- 50 KSI peak pressure
- 28ms duration
- Pressure relief for deflagration reactions

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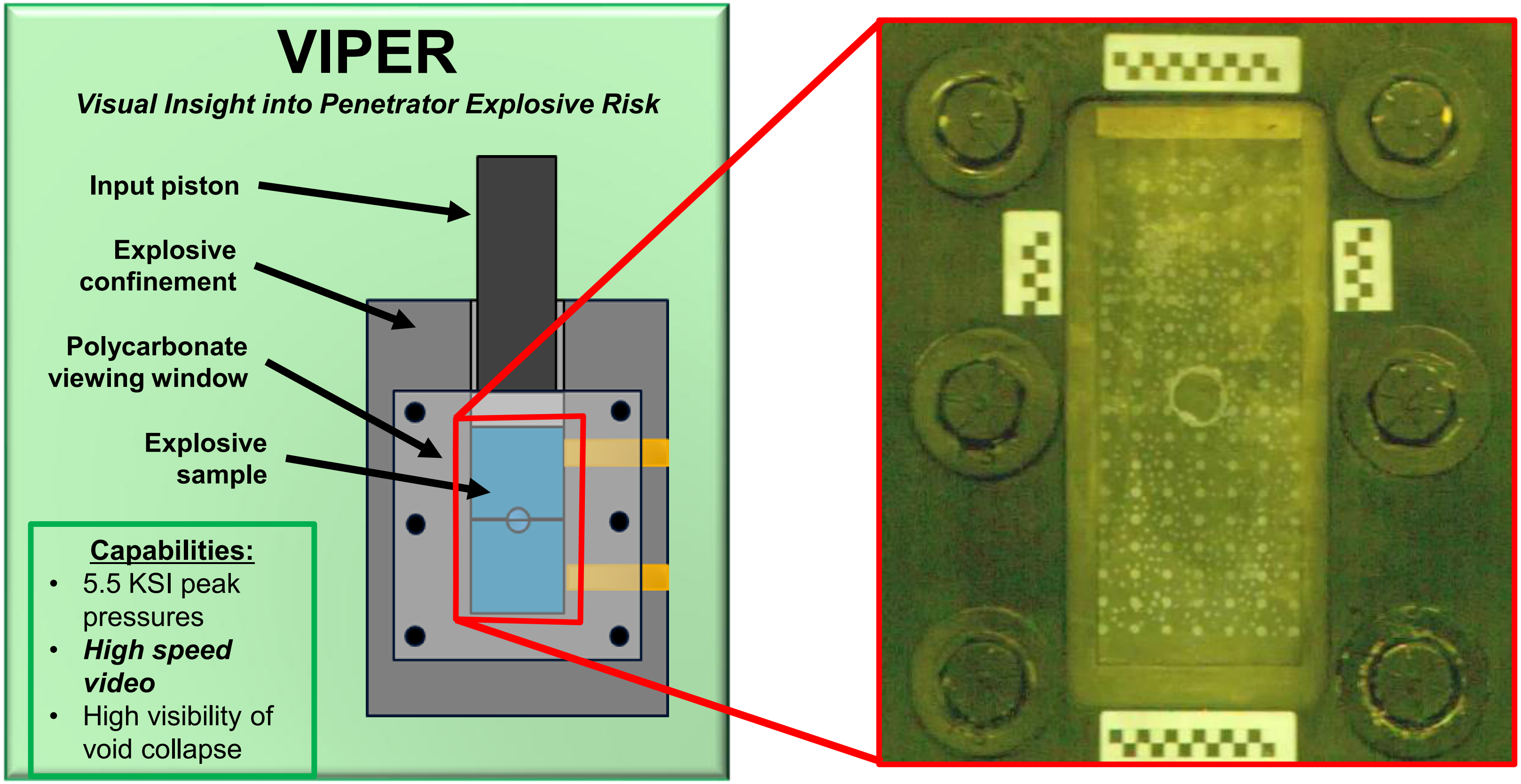
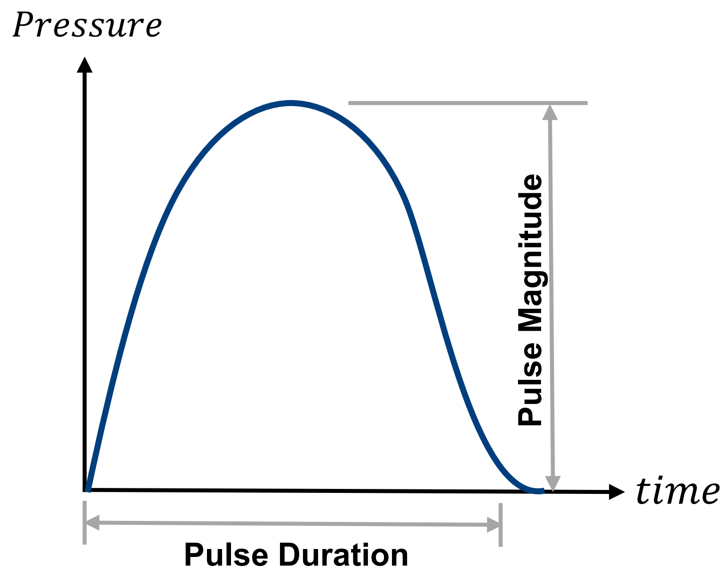
Background: *Mechanical Insult Testing*

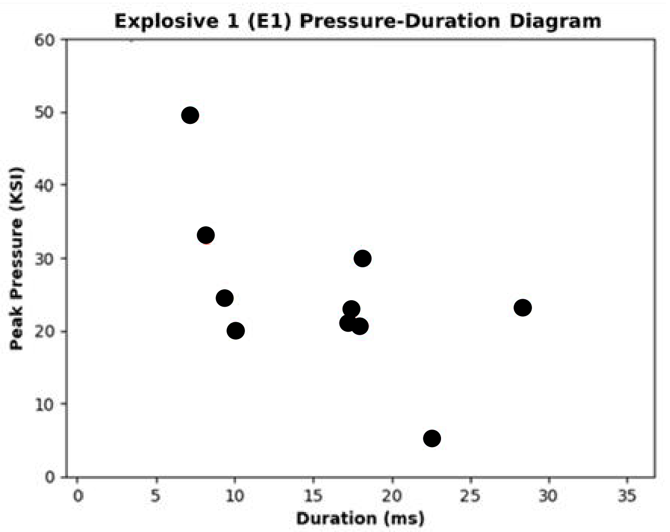
- **This work focuses on data from VIPER testing:**



Background: *Pressure-Duration Domain*

- Pressure pulses in the charge of penetrating munitions typically have a *half-sine* or *haversine* shape

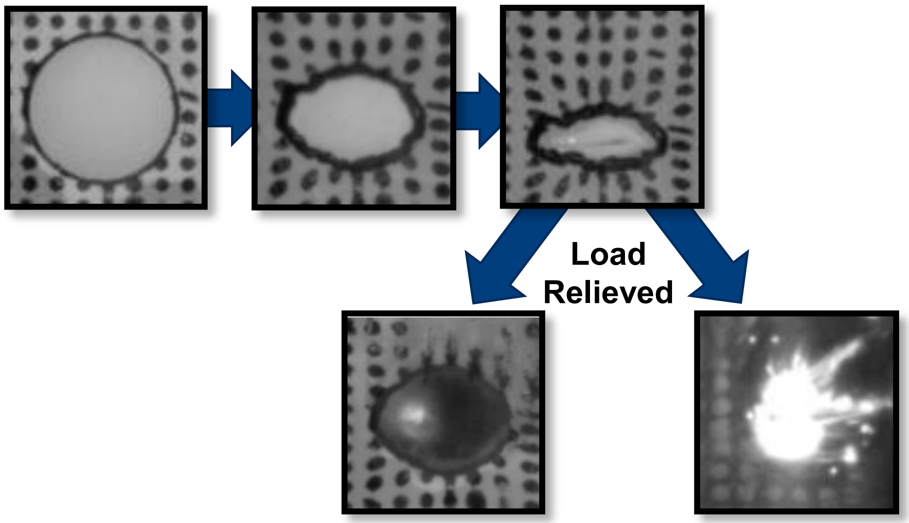




Pulses are characterized on pressure-duration diagrams.

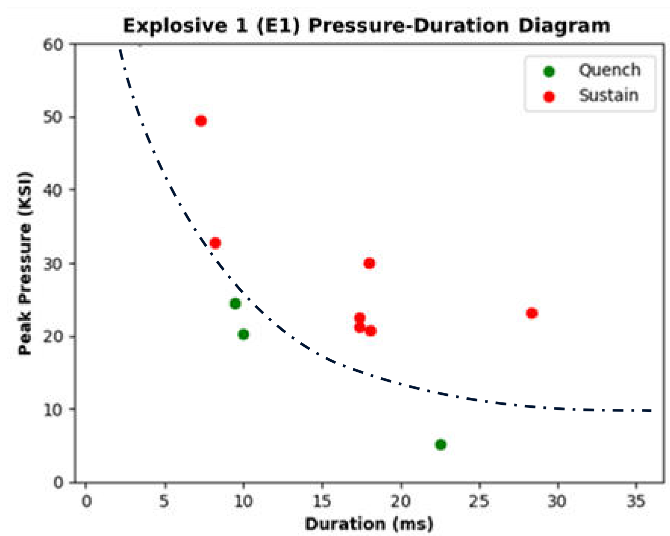
Background: *Quench and Sustain*

- **Visible thermal ignition is not enough to cause deflagration.**
  - **Quench – Reactions that extinguish over time**
  - **Self Sustaining – Violent reactions that lead to deflagration**



Quench
No weapon risk

Sustain
Considerable weapon risk



A quench-sustain threshold may exist in the pressure-duration domain.

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Background: *Previous Work*

- Image processing used to determine void compression ratios
- Compression ratio used for *ideal gas* temperature estimates under adiabatic compression[3]

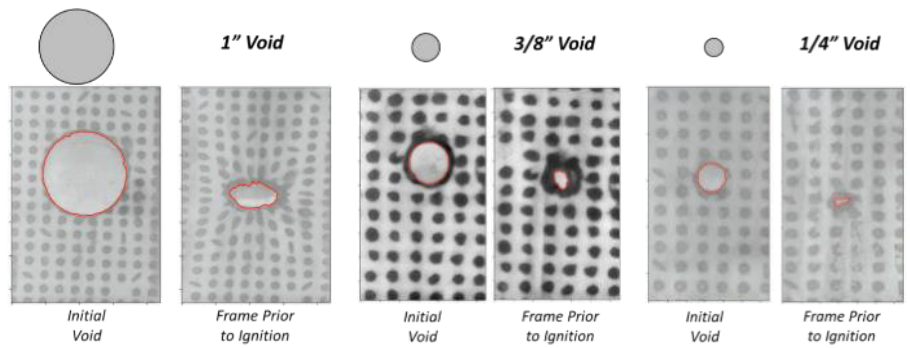
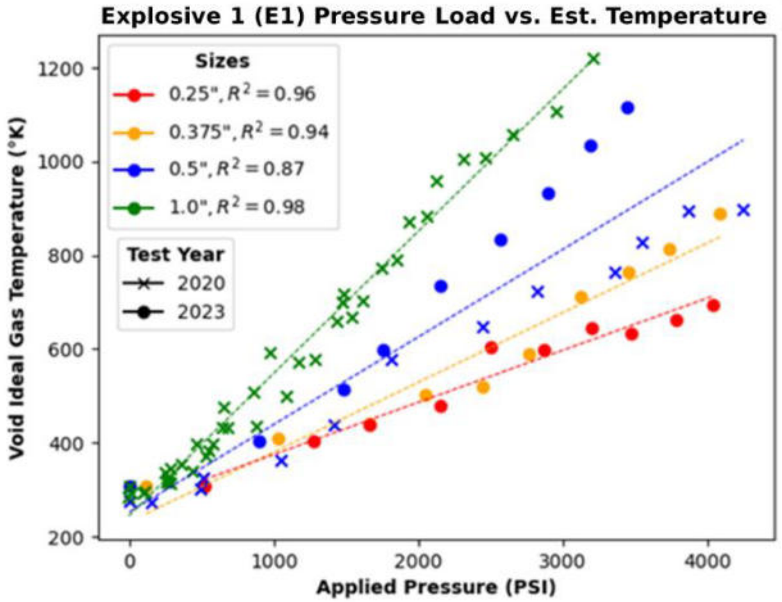
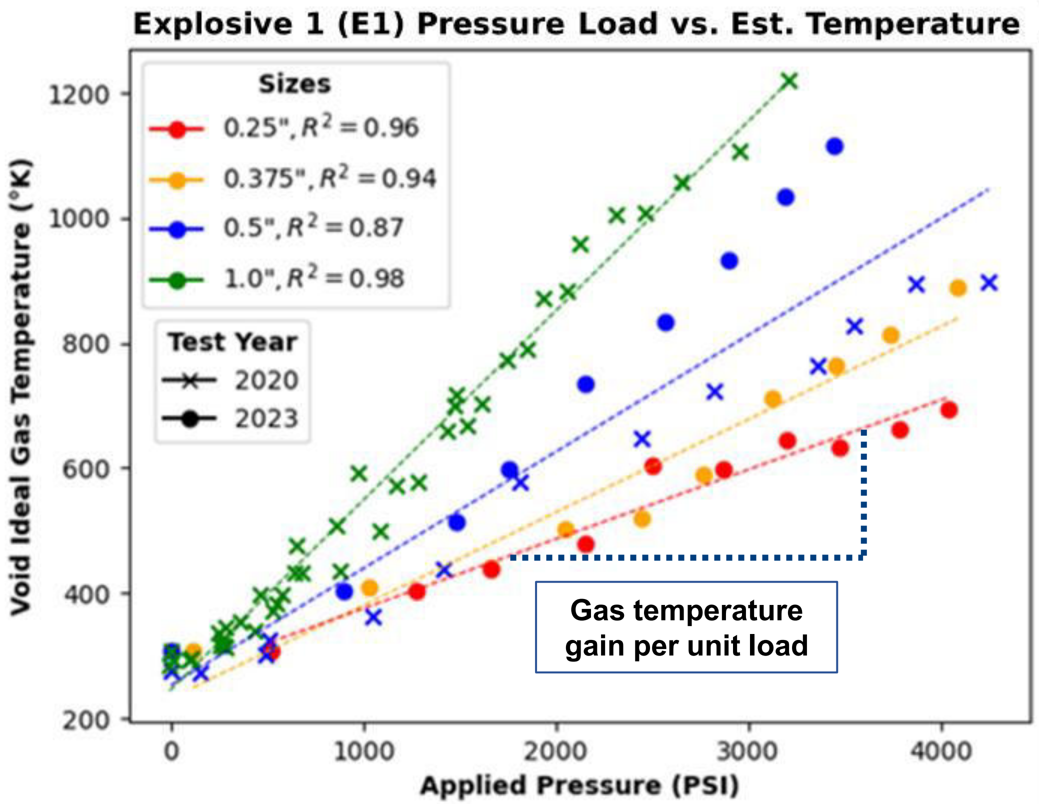


Image Processing Workflow



Background: *Mechanical-Thermal Relationship*

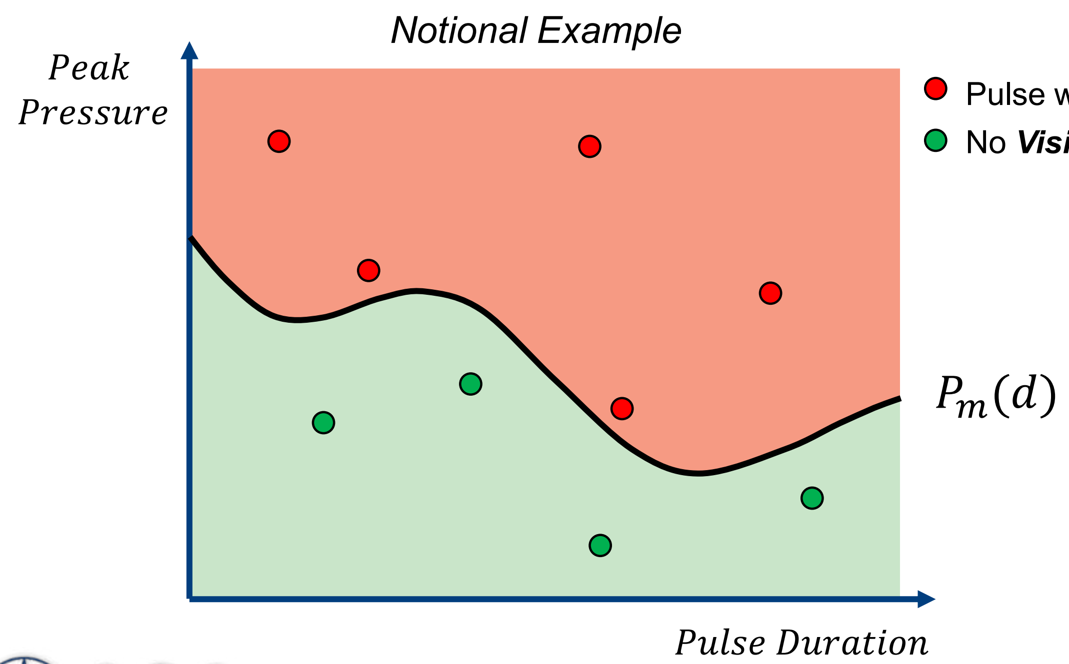


- **Relationship appears to be <u>linear</u> in pressure range**
- **Void size effect:**
  - **Small voids:** low temperature gain
  - **Large voids:** large temperature gain
- **Some dispersion in the data.**

A void size effect seems to be apparent in the data.

Development of an Ignition Risk Model

- Testing with the VIPER apparatus has shown that void defects show visible signs of ignition at low pressures; around 4.5 KSI
- Can a model be developed to explain thermal ignition of voids in the pressure-duration domain?



Can an ignition risk threshold be developed using the Arrhenius Kinetic model?

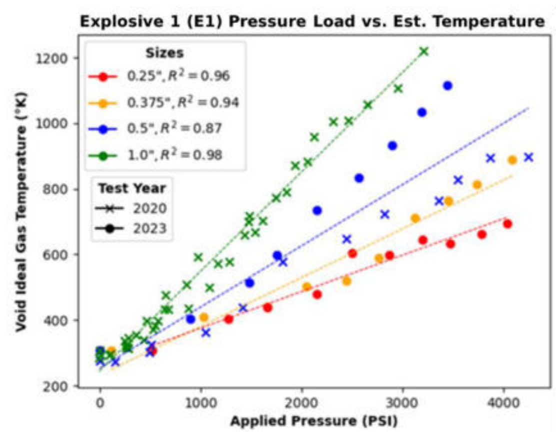
Model Development: *Relationships*

$$\tau(T) = e^{\left[\frac{E_n}{T} - Z'\right]}$$

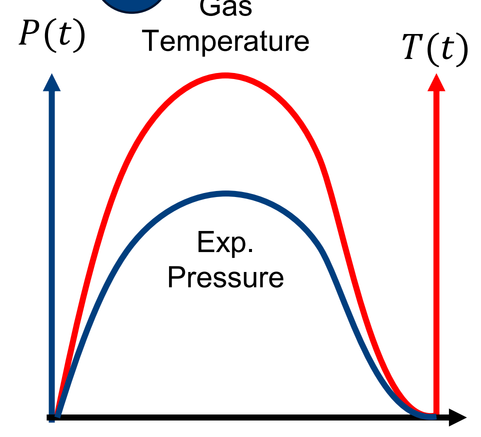
1 $$T(P) = \alpha + \beta P$$

2 $$P(t) = P_m \sin(\omega t)$$

1



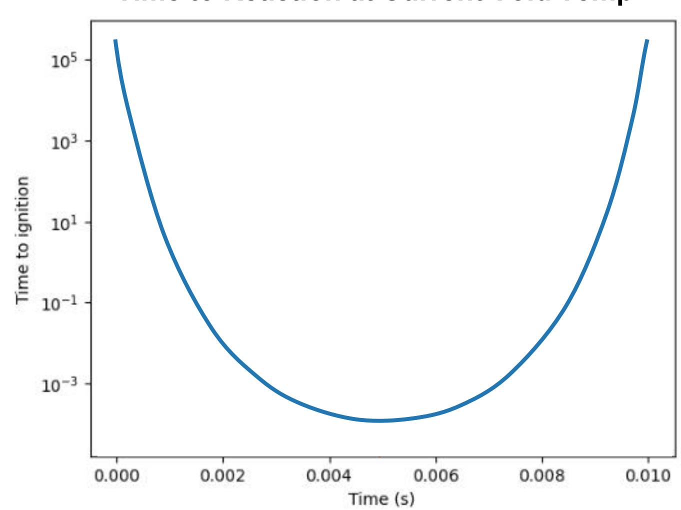
2



By substitution:

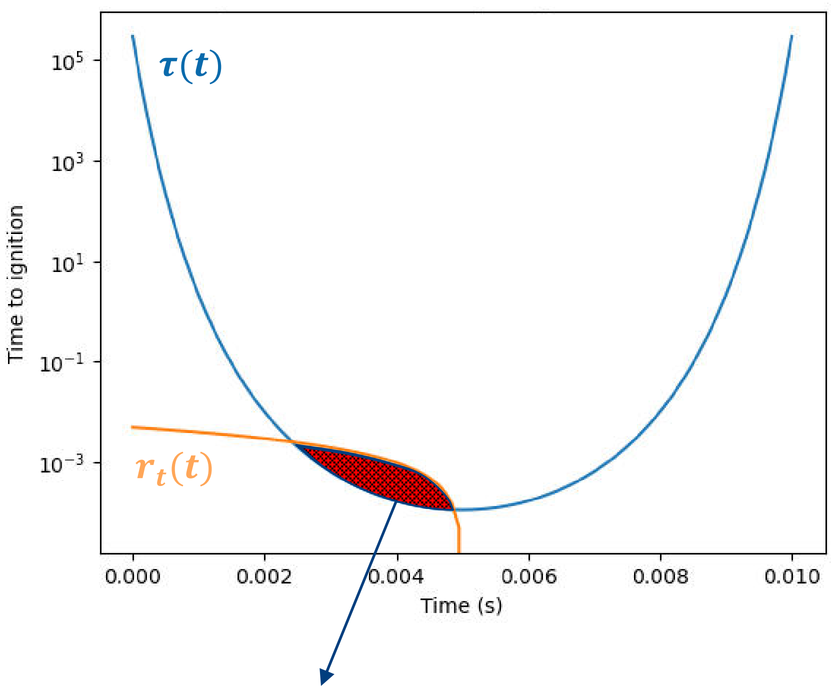
$$\tau(t) = e^{\frac{E_n}{\alpha + \beta P_m sin(\omega t)} - Z'}$$

Time to Reaction at Current Void Temp.

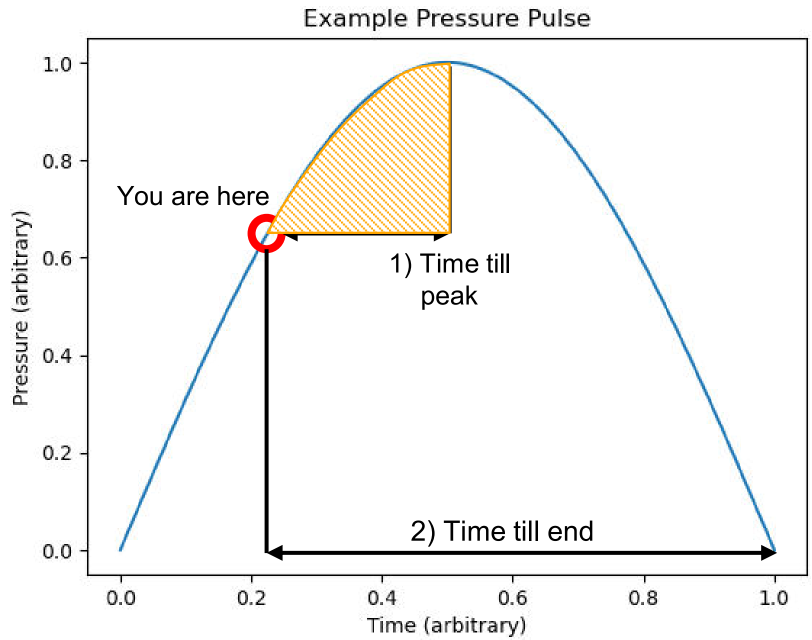


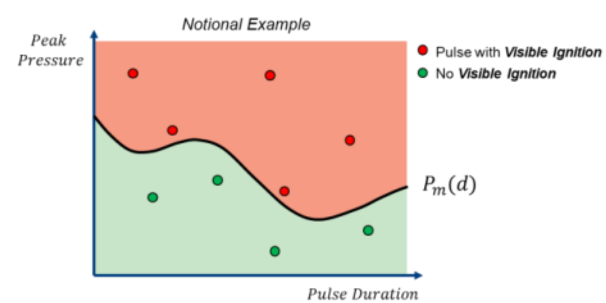
Model Development: *Relationships*

Time to Reaction at Current Void Temp.



Overlapping area represents some probability of ignition risk



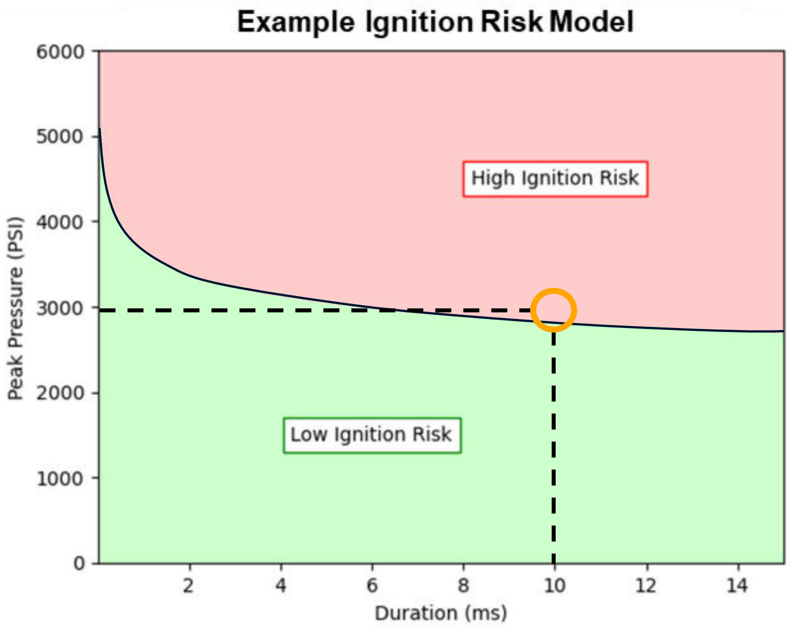


Goal is to find $P_m(d)$ that minimizes the overlap area.

Ignition Risk Model

- **Risk model solution was developed computationally:**

$$P_m(\omega) = \frac{1}{\beta sin\left(\frac{\pi^2}{8}\right)}\left[\frac{E_n}{ln\left(\frac{\pi}{\omega}\right) + ln\left(\frac{4-\pi}{8}\right) + Z'} - \alpha\right]$$



Model describes pressure pulse shapes that are *risky* from a void compression POV.

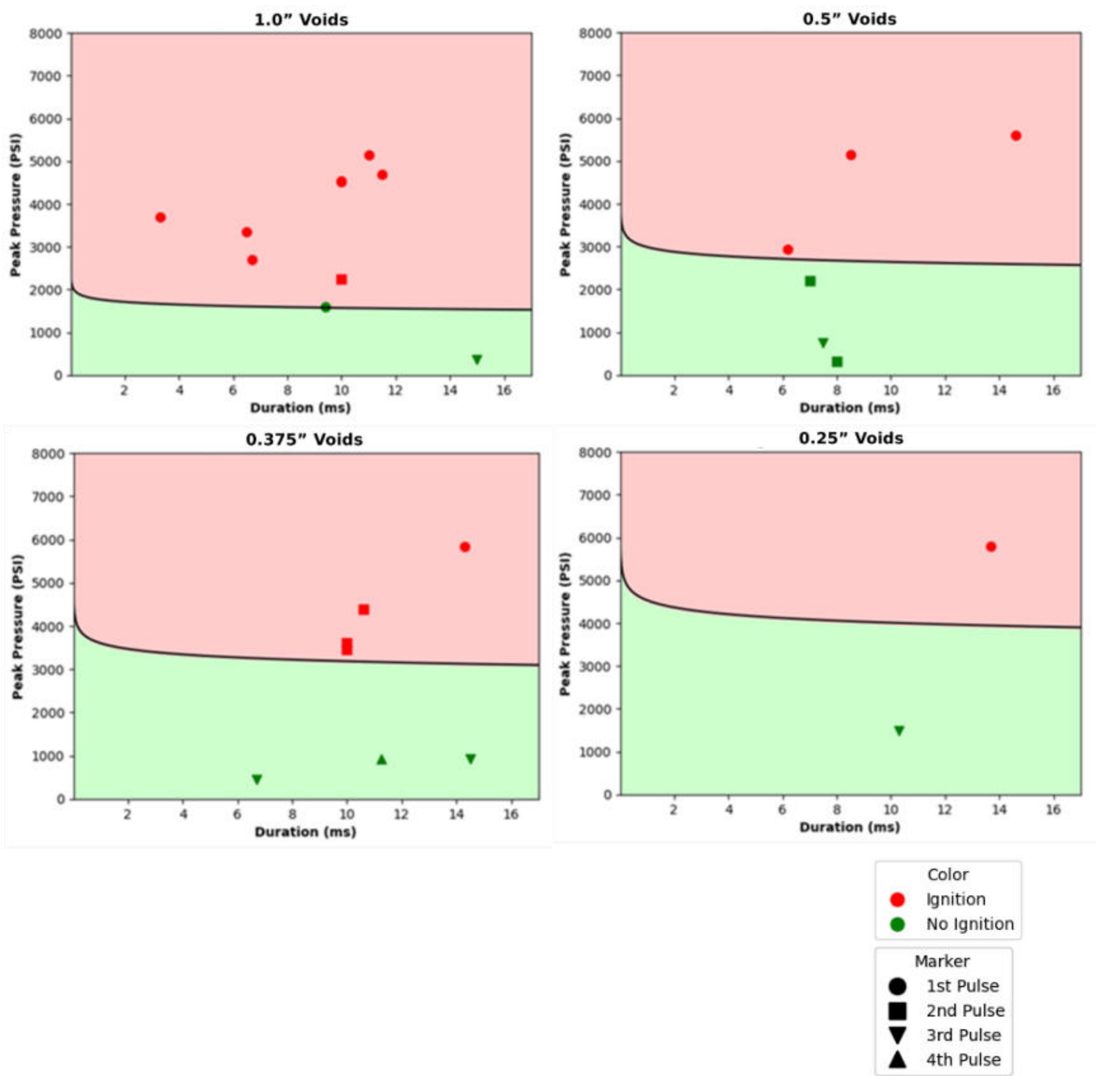
Example:
Ignition risk at 10ms, 3000 PSI.

Ignition is predicted for this pulse. But the model does not specify the **time** or **pressure** *at* ignition. Only that ignition is likely.

Model Validation Data: *Void Side Effect*

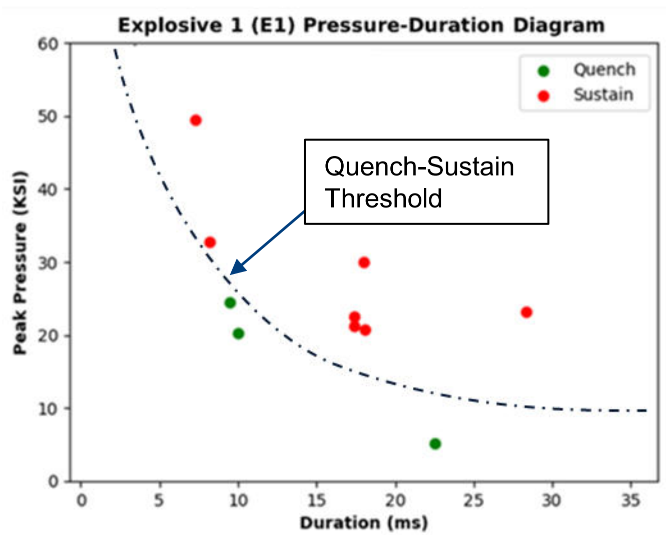
- **A body of VIPER test data can be used to test the efficacy of the ignition risk model:**
  - This explosive exhibited a void size dependent temperature effect.
- **This data was not explicitly used in model development.**

Model does a decent job of predicting pulses that will ignite voids.



Quench-Sustain

- **Recall, thermal ignition does not imply deflagration:**
  - **Quench** – Reactions that extinguish over time
  - **Self Sustaining** – Violent reactions that lead to deflagration



$$\tau(T) = e^{\left[\frac{E_n}{T} - z'\right]}$$

1. $T(P) = \alpha + \beta P$
2. $P(t) = P_m \sin(\omega t)$

Can we also find a quench-sustain threshold?

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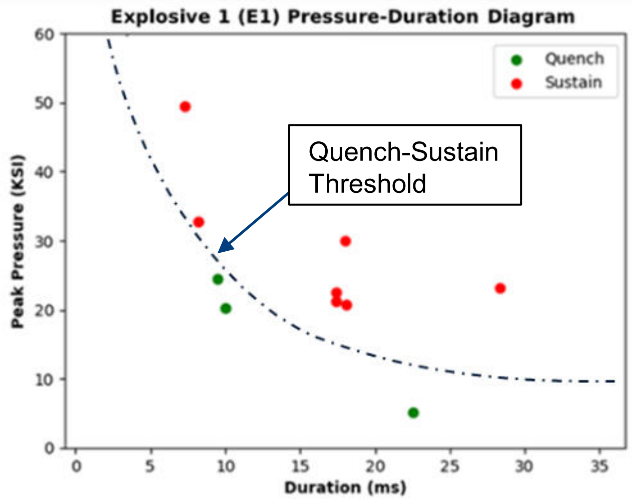
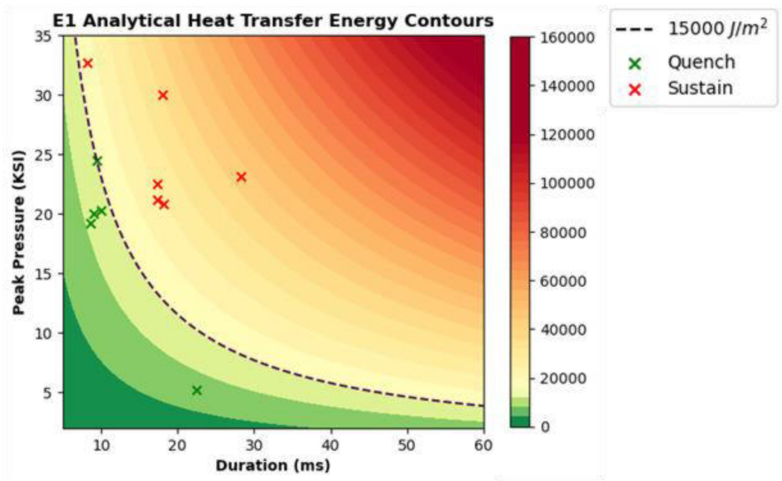
Notional Quench-Sustain: *Heat Transfer*





Iso-energy contours

- **We have noticed that is classifiable along iso-impulse contours.**
- **If we analytically model void-explosive heat transfer:**

Estimable

$$Q/A = h\int T_v(t) - T_e(t)\,dt$$

Total heat transferred may explain the difference between quenching & sustaining reactions.

**this is a notional result, and not an actual prediction of the QS threshold.*

Conclusions

- **We are testing PBXs for void-collapse-induced deflagration using novel test hardware.**
- **Test data is being used to understand the factors that lead to deflagration:**
  - Thermal (visible) ignition data used to develop a void ignition risk model.
  - Analytical/FEM models are being developed to understand what causes a self-sustaining vs. quenching reactions.

Questions?

Acknowledgements

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- **Thank you to the following**
  - **MCAAP building 142 team**
  - **ARA Moriarty Range**
  - **ARA CDG Team:** Frank Marso, Ericka Amborn, Casey Strong, Matt Hanley

References

[1] M. M. Chaudrhi, "The role of rapidly compressed gas pockets in the initiation of condensed explosives," *Proceedings of the Royal Society of London,* vol. 304, no. A, pp. 113-128, 1974.

[2] A. M. Goddard, E. K. Amborn, F. L. Marso, J. A. Conley and C. Moore, "Experimental Evaluation of Non-Shock Induced Void Collapse: Part 1: Single Load-Cycle Results," in *Ordnance and Ballistics Technology Working Group Meeting*, Monterey, CA, 2021.

[3] B. L. Johnson, F. L. Marso, E. K. Amborn, C. P. Strong, P. M. Delery and J. A. Conley, "Void Collapse-Initiated Deflagration: Progress Towards Predictive Modeling for Risk Evaluation Pt. 1," in *JANNAF 34th Energetic Systems Hazards Subcommittee Session*, Salt Lake City, 2023.

[4] M. McClelland, "Cookoff Response: Material Characterization and ALE3D Model," in *JANNAF CS/APS/PSHS Joint Meeting*, Monterey, 2000.

[5] A. Strachan, E. M. Kober, A. C. van Duin, J. Oxgaard and W. A. Goddard, "Thermal decomposition of RDX from reactive molecular dynamics," *The Journal of Chemical Physics,* vol. 122, 2005.

[6] R. L. McKenney and B. L. Allmon, "Air Force Explosives Database," Air Force Research Laboratory, Eglin, 2009.