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Shock Interactions in Multilayer Explosive Films

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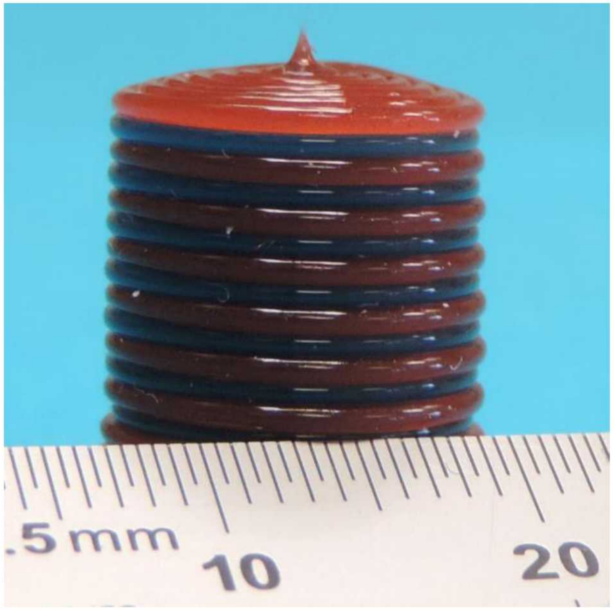
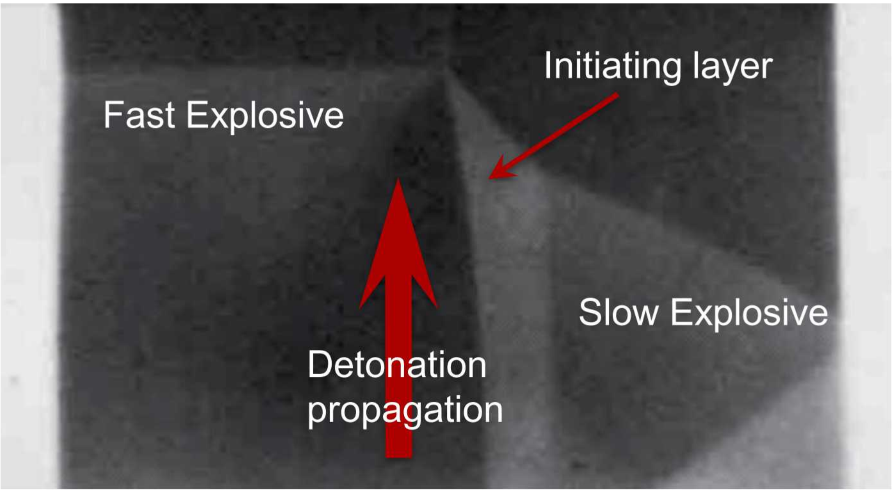
Motivation

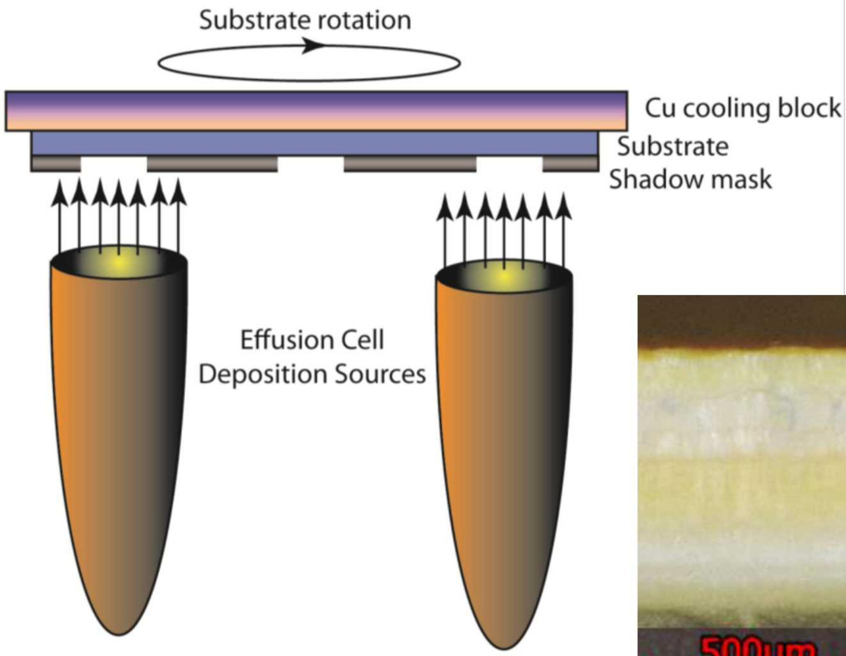
- Additive manufacturing of energetic materials can be used to create multilayer structures with different explosive materials
  - Potential to control detonation properties
- Lots of unknowns in how detonation propagates in multi-material systems
  - Not a simple rule of mixtures…
  - Effects of mixing length scale?
  - Effects of non-ideal interfaces?

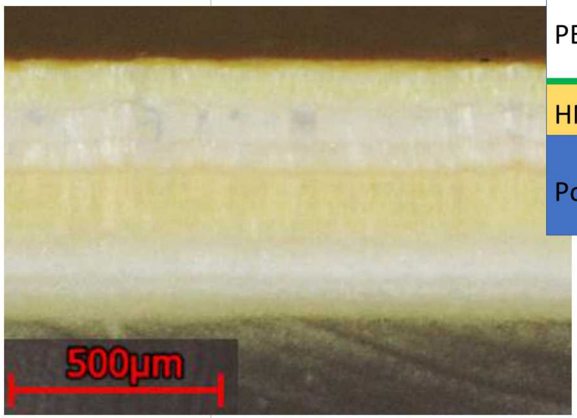


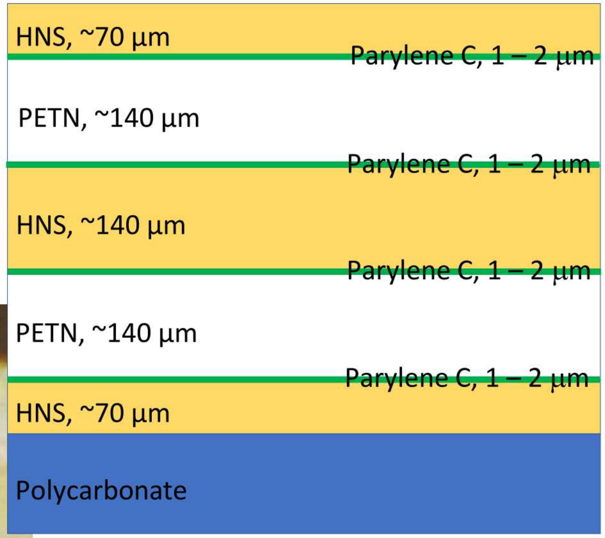


[1] Anderson *et al.*, Combustion and Flame (2014)

Physical Vapor Deposition as a Model System

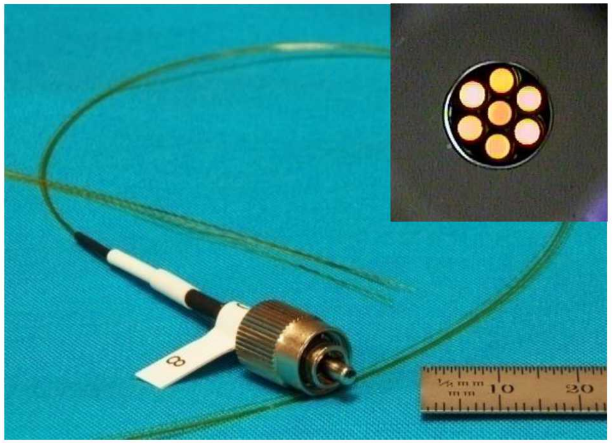




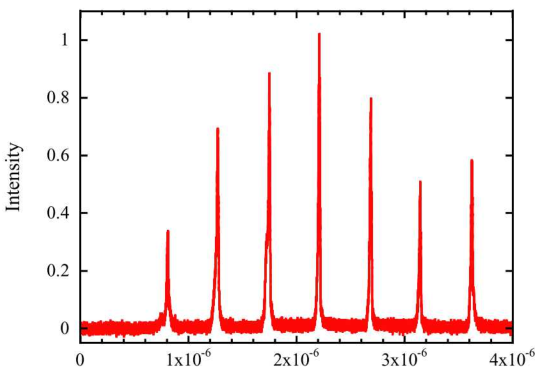


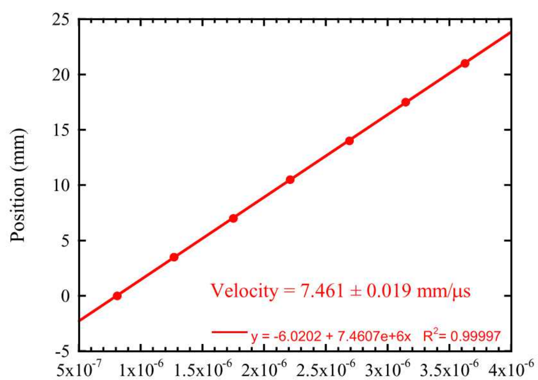
- Uses pure explosives that have existing equation of state information and near-failure performance data
- Excellent geometric control
- PETN and HNS chosen for large difference in detonation velocity
- Parylene C interlayers added to mitigate stress-induced delamination

Thin Film Critical Thickness Experiments

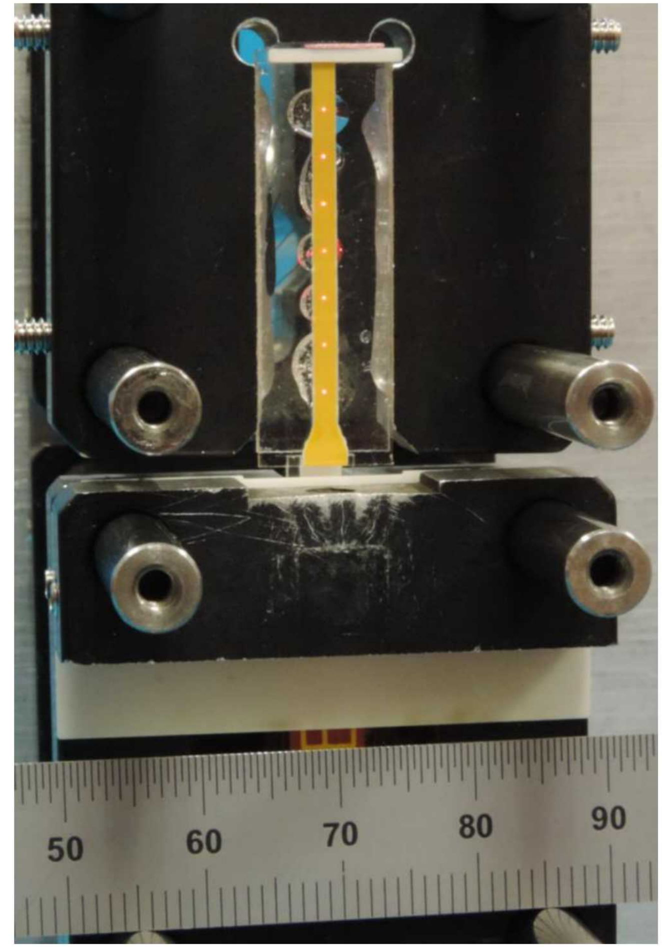


Photograph of an optical fiber probe with inset showing a six-around-one connector.





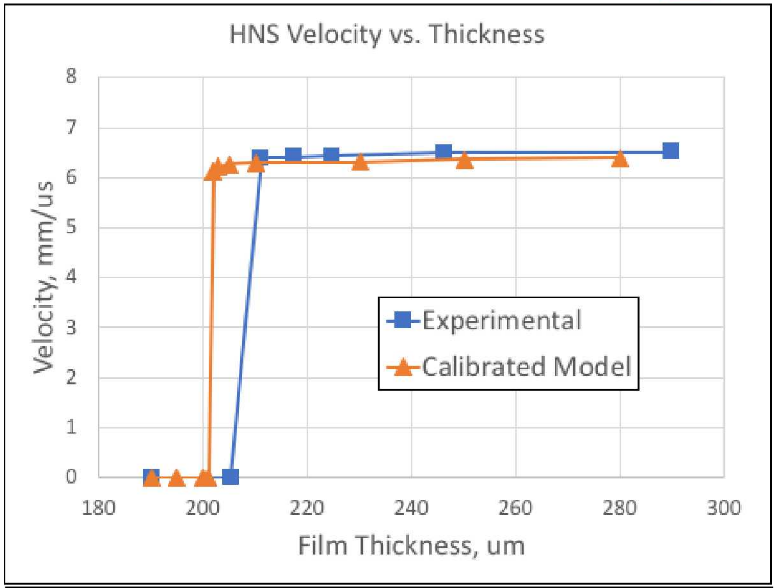
Example oscilloscope data and resultant position vs. time plot used to determine detonation velocity.

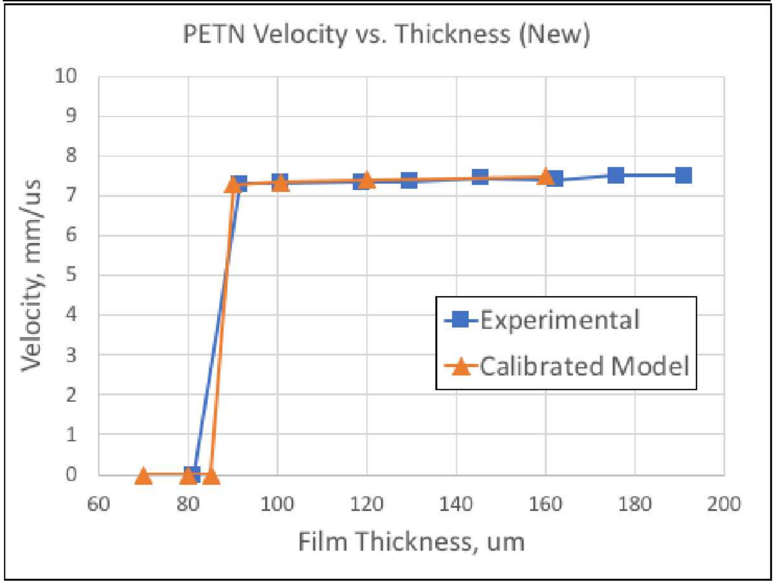


Photograph of an optical fiber probe lid on a deposited explosive film. Fibers are illuminated to show their locations.

Simulations

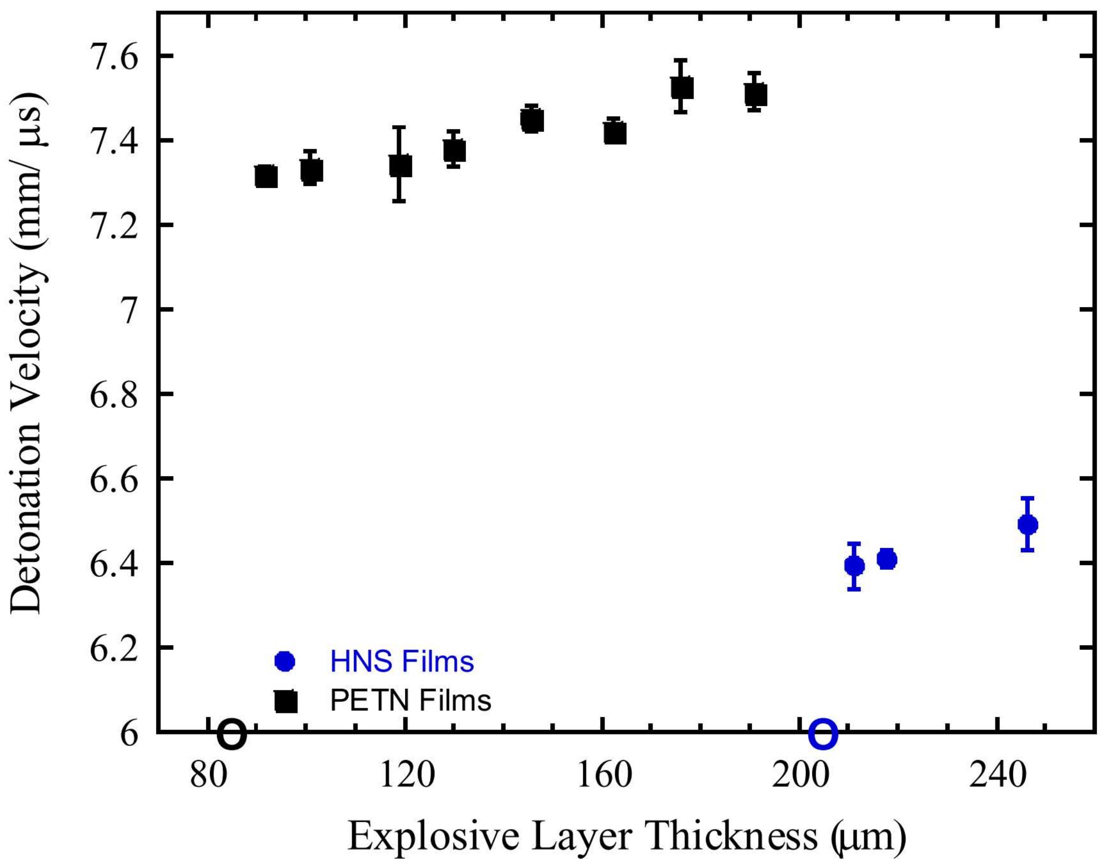
- Preliminary continuum 2D simulations of multilayer samples performed in CTH
- Arrhenius reactive burn (ARB) model used
  - ARB has been shown to work reasonably well for small-grained, pure explosives [2]
  - ARB parameters for PETN and HNS manually fit to detonation velocity and failure thickness data for vapor-deposited films
- 1 micron mesh resolution





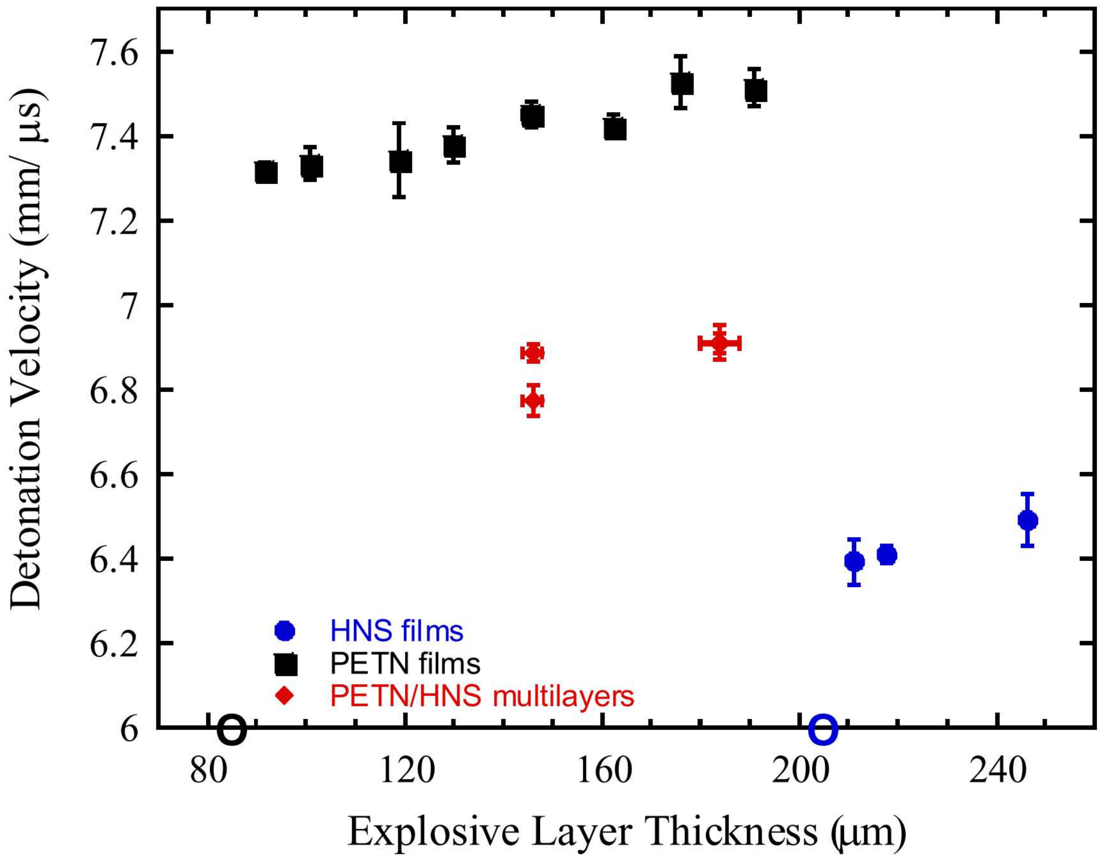
[2] Kipp and Setchell, 9th Symposium (International) on Detonation (1989)

Multilayer Detonation Velocities



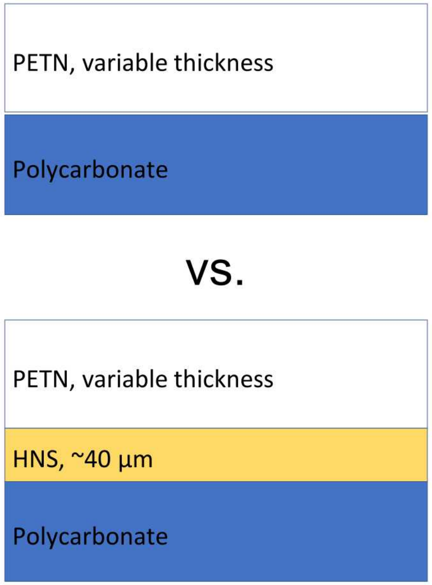
- PETN films detonate at 7.3 – 7.6 mm/μs and fail to detonate below ~ 90 μm
- HNS films detonate at 6.4 – 6.6 mm/μs and fail to detonate below ~ 205 μm

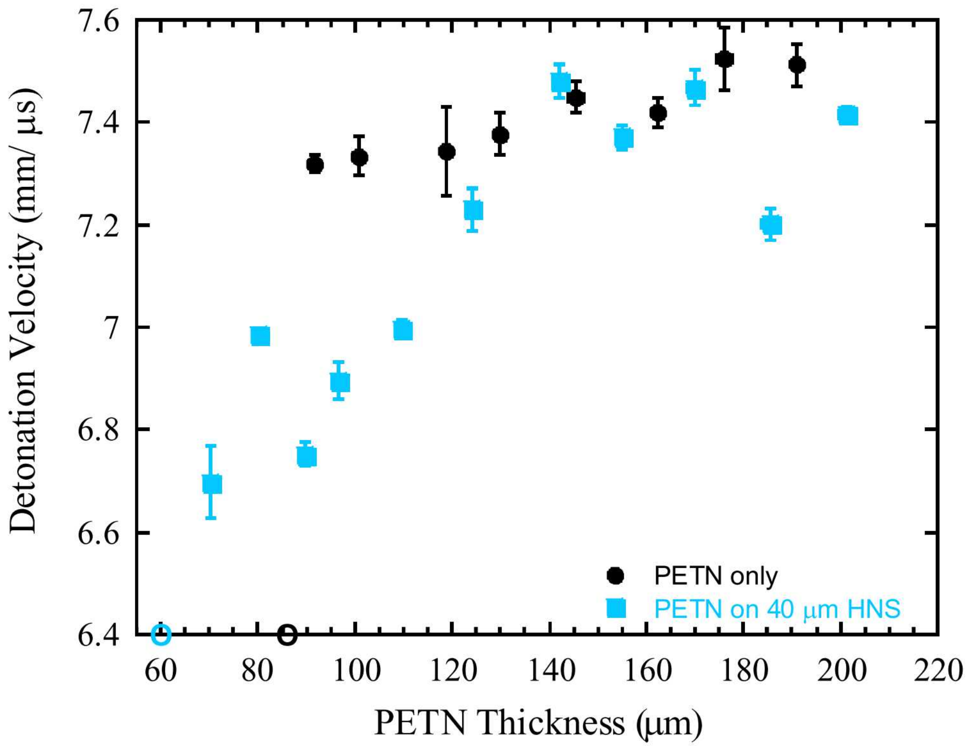
Multilayer Detonation Velocities



- Detonation velocities in multilayer explosive films are much lower than expected for fairly large layer spacings (~ 6.8 – 6.9 mm/µs)
- Why doesn't PETN dominate detonation velocity? Due to interfacial effects?

Interfacial Effects: Bilayer Experiments

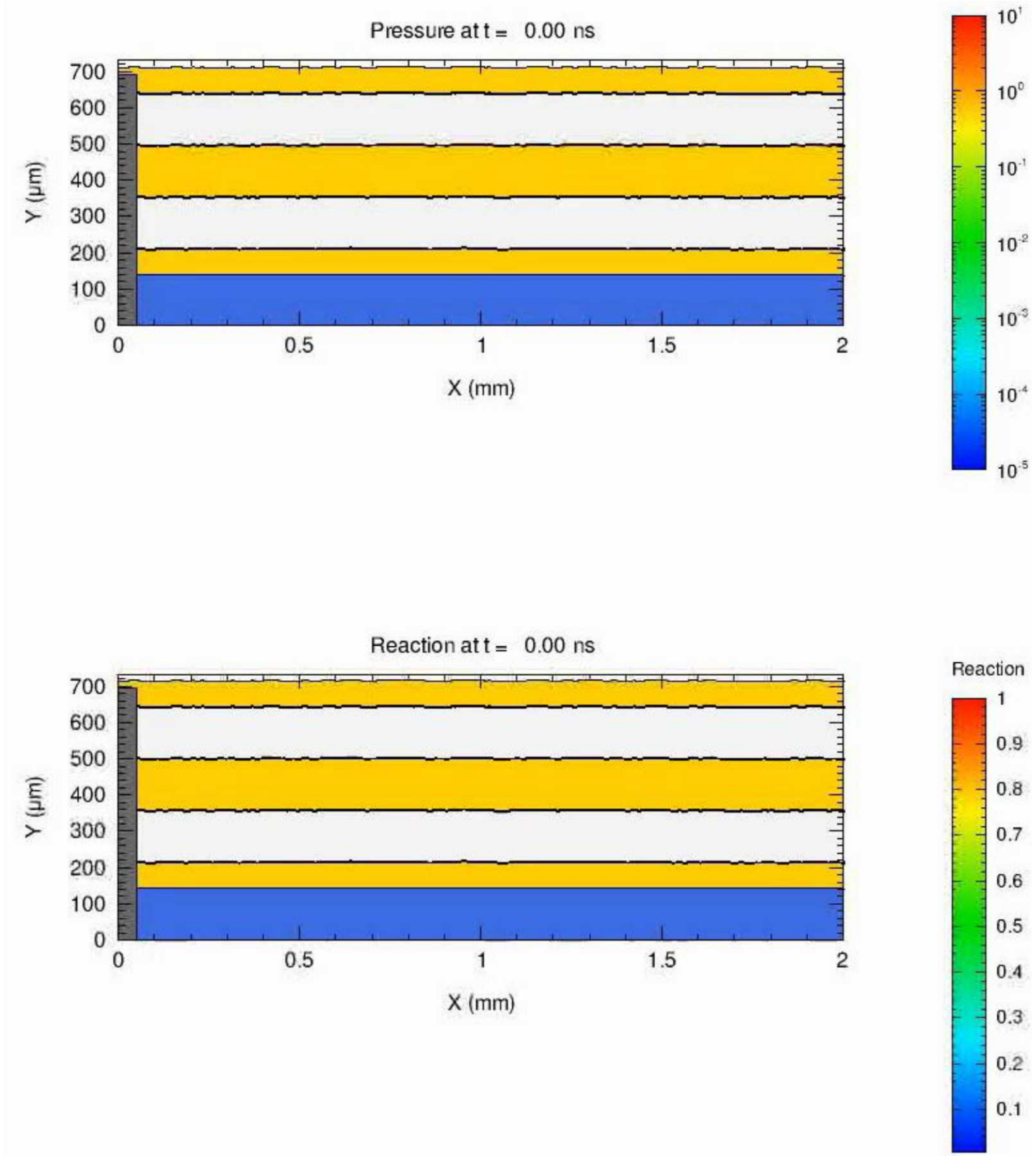




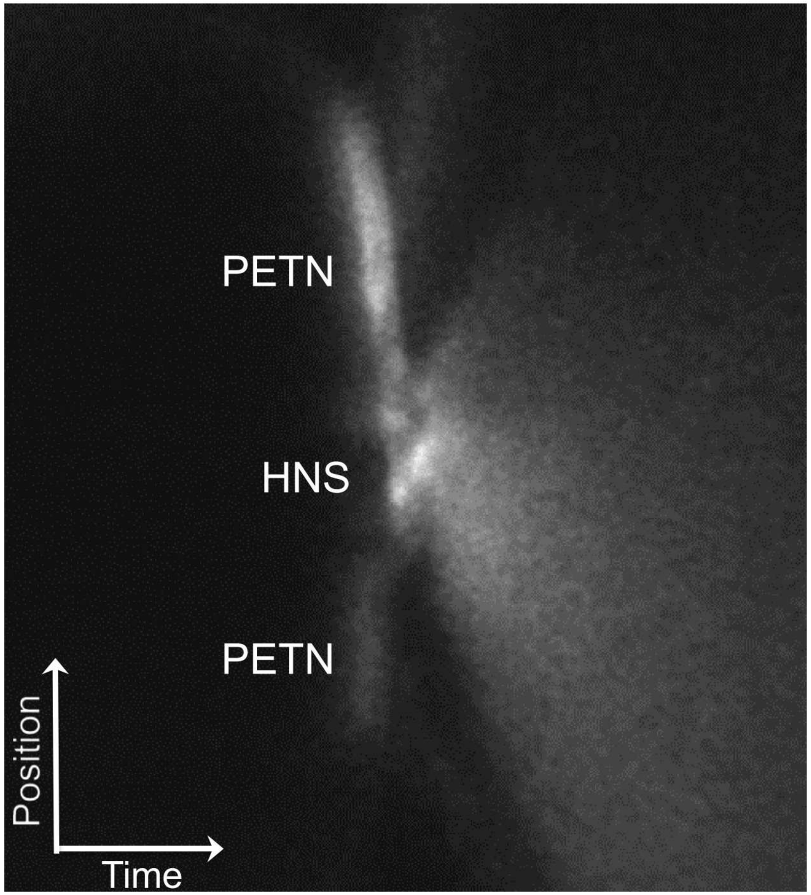
- HNS underlayer appears to have little effect at large PETN thicknesses
- Substantial deviation in detonation velocity at smaller PETN thicknesses
  - Likely controlled by microstructure/roughness around the interface
- HNS underlayer allows detonation to be sustained at smaller PETN thicknesses

Preliminary Simulations

- Roughness at interfaces included
- "Initiating layer" clearly visible in central HNS layer
- Simulated detonation velocity: 7.44 mm/μs
  - ⇒ Much faster than experiments
- May need better mesh resolution and/or 3D to capture effects of interface roughness



Detonation Front Shape



Streak camera image of detonation breakout from a multilayer film. (Cropped to ~ 800 μm x 400 ns)

- Preliminary experiments using a streak camera to image detonation breakout in multilayer films (detonation self-light)
- Some evidence of "initiating layer" between PETN and HNS
- Future work: Use flash material to provide brighter, more uniform illumination to allow for better temporal resolution

Conclusions

- Detonation velocities in PETN/HNS multilayers are significantly lower than expected
- Experiments with bilayer samples suggest this is due to interfacial effects
- Preliminary 2D continuum simulations qualitatively capture “initiating layer” but overpredict detonation velocity
- Future work
  - Additional bilayer experiments – vary interface roughness, effect of Parylene C interlayer
  - Simulations – mesh studies, mesoscale, 3D

Acknowledgements

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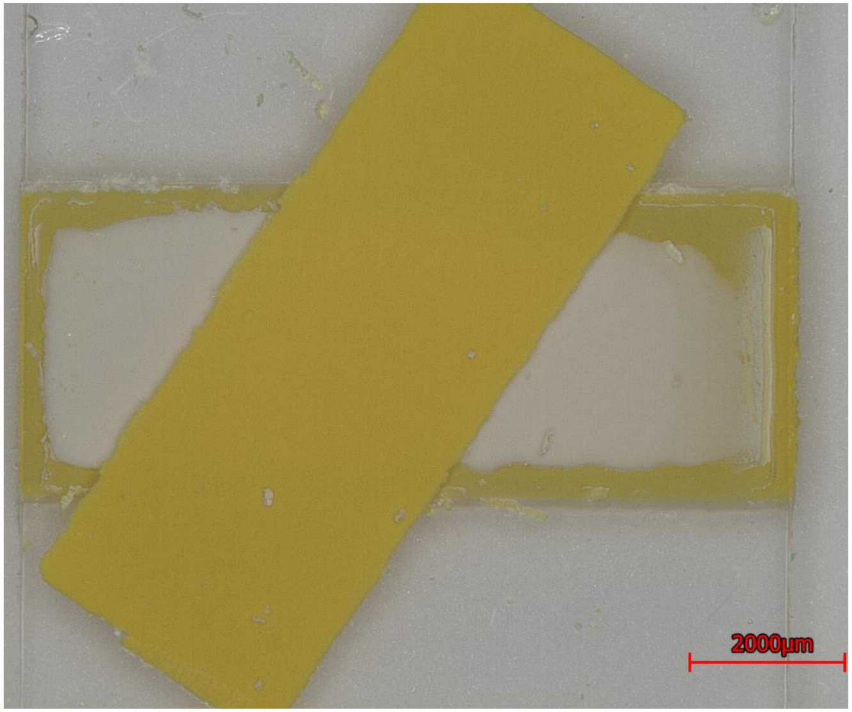
Detonation testing:

Stephen Rupper

Jon Vasiliauskas

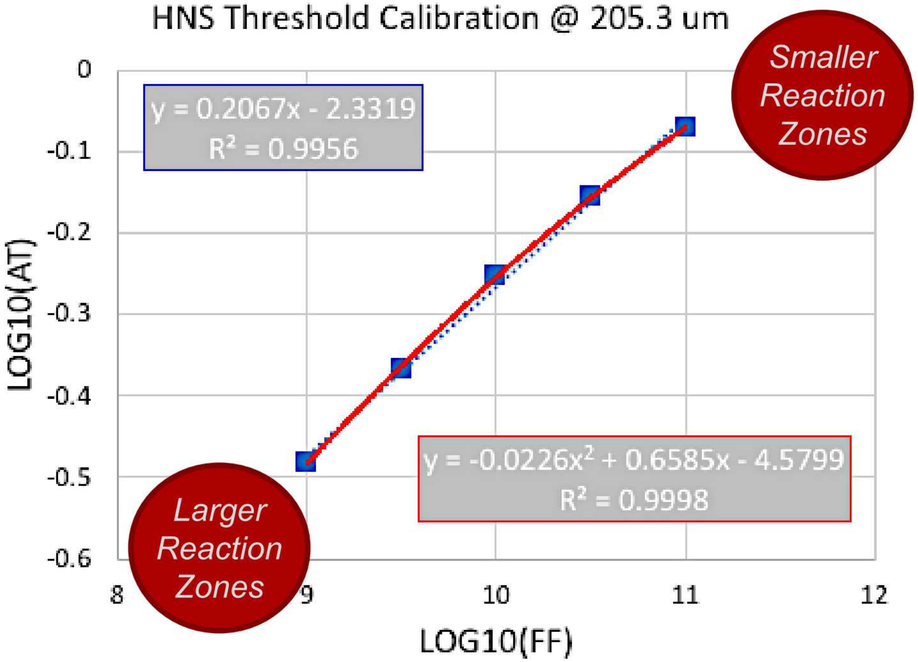
Back-up Slides

Multilayer Delamination



- Delamination occurs when HNS is deposited onto PETN layers
- Fracture generally occurs within the PETN layer, not at the PETN/HNS interface
- Appears to be related to residual stresses from the deposition process

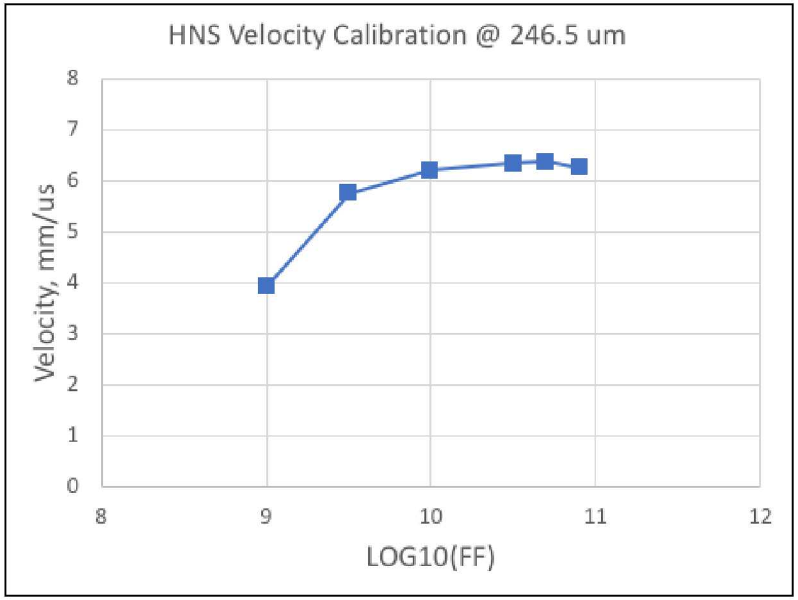
ARB Calibration Process

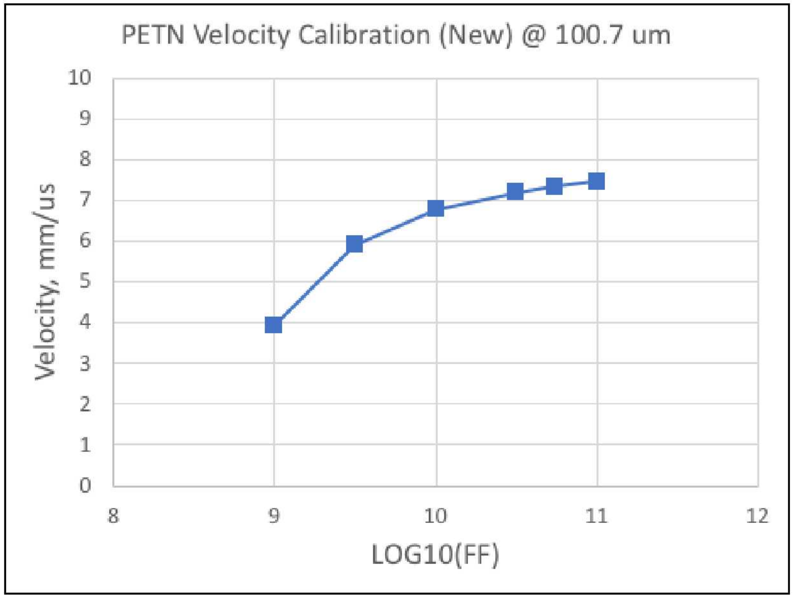


- Fitting parameters: activation energy (AT) and exponential pre-factor (frequency factor, FF)
- Generate FF and AT values that capture observed critical detonation thickness (± 0.01 eV, 116 K) and perform a quadratic fit (as shown)
- Judgement call to decide if simulation is long enough to observe detonation failure
- Eliminates 1 degree of freedom in parameterization

Must stay on this curve to get the failure thickness correct, then we can vary FF to match the detonation velocity at a propagating thickness

ARB Calibration Process





- Plot predicted detonation velocity for various FF values (while also varying AT per the previous slide to correctly capture the critical thickness)
- We choose a FF of about 5e10 s^{-1} to match experimental detonation velocities for both PETN and HNS