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Microenergetics: Combustion and Detonation at Sub-Millimeter Scales

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Acknowledgements

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Especially Anita Renlund, Greg Long, John Nogan, Pat Ball, Stan Kravitz, and Brian Wroblewski.

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- **Enhanced Surety Campaigns**
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- **Joint DoD/DOE Munitions Program**

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Outline

- Introduction
  - Motivation
  - Microenergetics
  - Energetic material considerations
- Combustion in glass microcapillaries
- Combustion in silicon microchannels
- Detonation in microchannels
- Patterning work
- Conclusion

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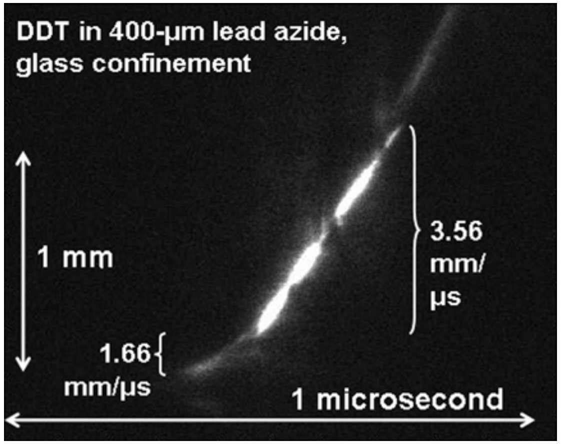
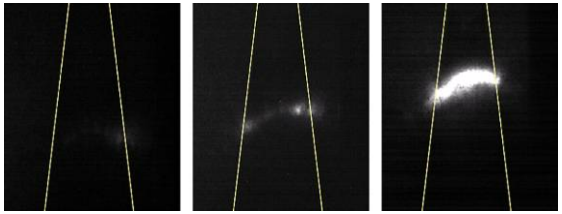
Motivation

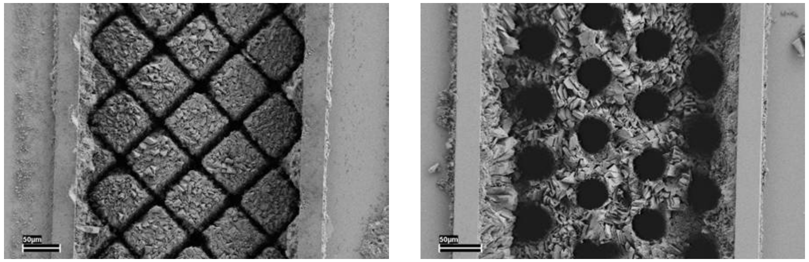
- **At some scale, all energetic materials are heterogeneous**
- **Heterogeneity is a critical parameter for initiation and growth processes:**
  - **Ignition and surface burning**
  - **Acceleratory processes**
  - **Detonation**
- **Transient phenomena can be amplified through charge miniaturization, facilitating their observation**
- **Develop microelectronics and mesoscale manufacturing techniques to produce test samples**



Deflagration-to-Detonation Transition in 400-µm diameter lead azide.



Shock-to-Detonation Transition in 500-µm PETN film.



"Engineered" heterogeneity – Patterned PETN films. 50-µm bar.

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Microenergetics

- Microenergetics definition
  - Non-bulk energetic materials that have been manufactured such that some important feature (length dimension, engineered void) is at the microscale
- Sample preparation philosophy
  - Sample preparation is performed using methodologies borrowed from the microelectronics industry
  - Controlled heterogeneity can be introduced for fundamental experimentation

Bare substrates

Photo of silicon microchannel die.

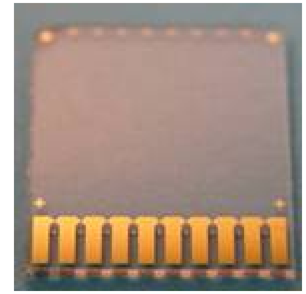


Photo of fused silica ignitor lid die.

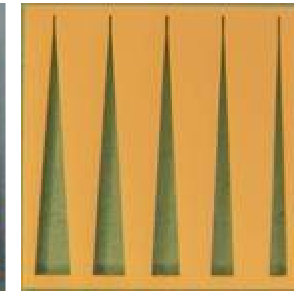
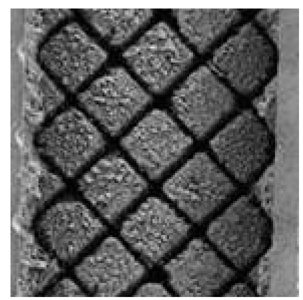


Photo of alumina wedge die.

Substrates with energetic materials



SEM of fs laser patterned PETN.

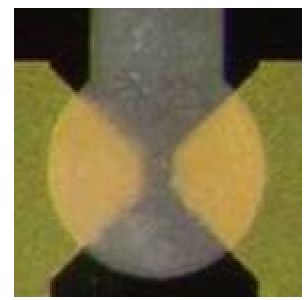
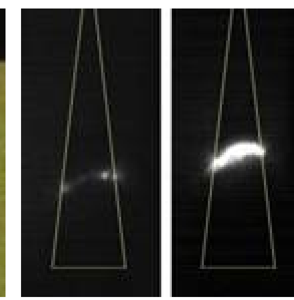


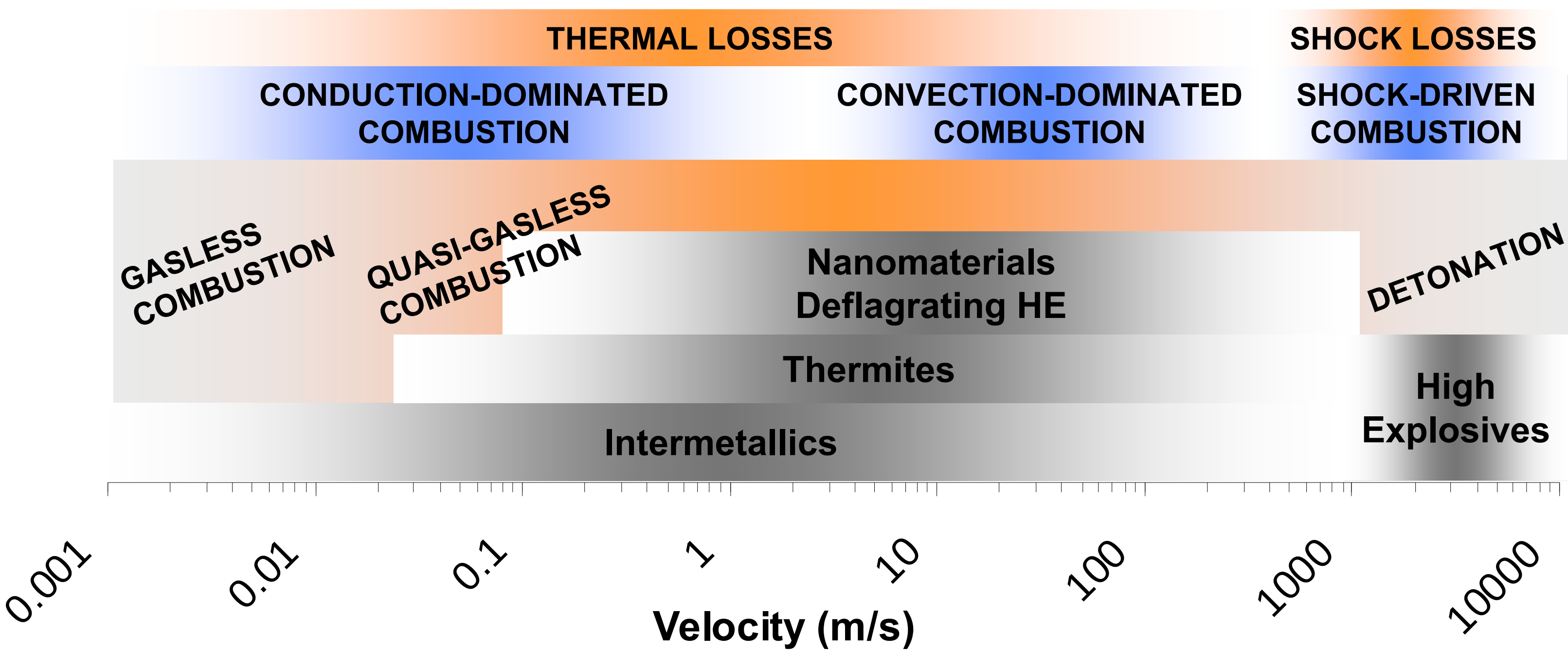
Photo ignitor lid die with deposited PETN.



Frames of SDT ignition in PETN film.

Energetic Material Considerations

- Energetic material reaction velocities span six orders of magnitude
- Material selection related to loss mechanisms (thermal or shock)
- Intrinsic material properties define microenergetic applicability
  - Energy density, velocity, critical diameter…



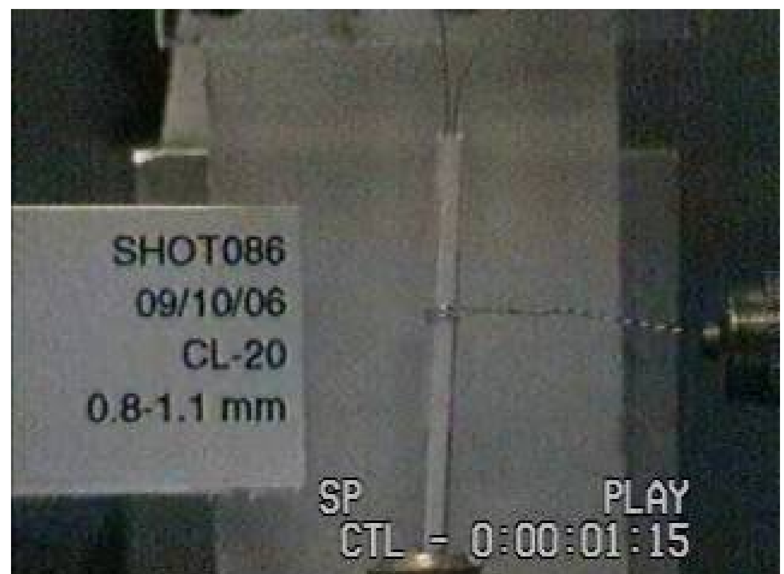
Microcapillary Combustion

DAATOx

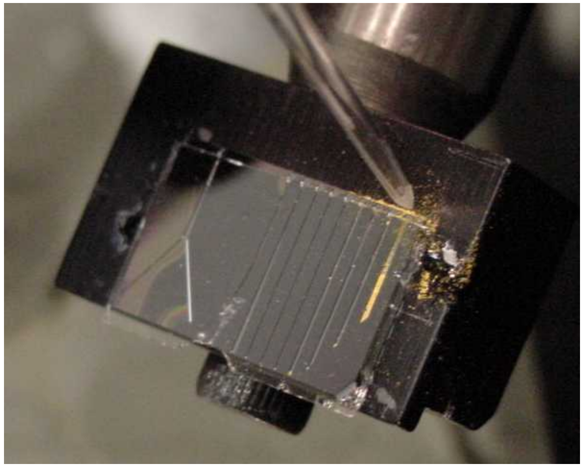
Al/CuO

BTATz

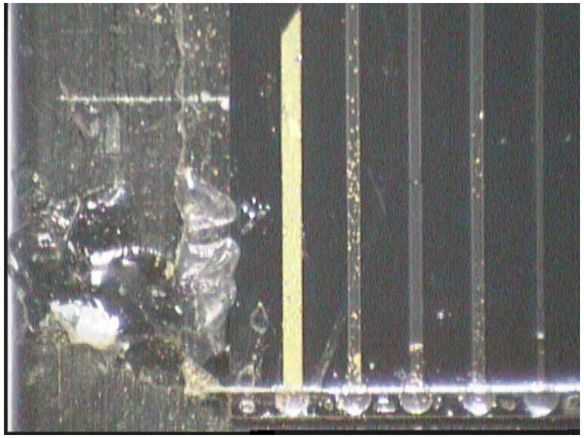
CL-20



Lead Styphnate in Silicon Microchannel

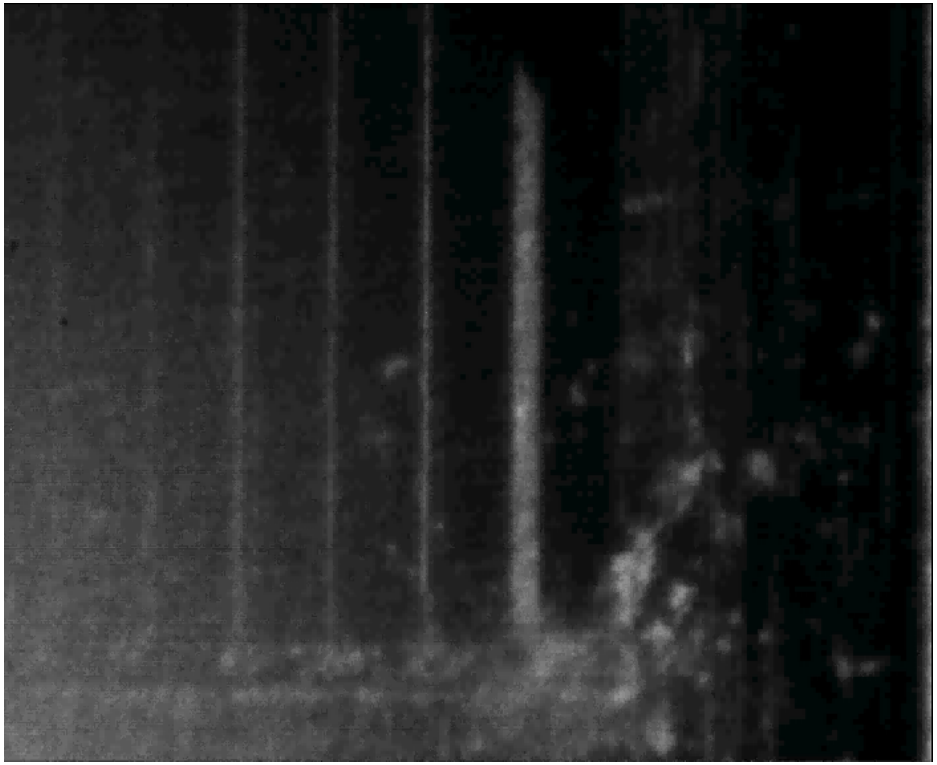


Microchannel filling process with capillary funnel.



Filled microchannel.

- Lead styphnate in 300-μm wide × 100-μm deep silicon channel
  - 16667 fps (1/60 μs)
  - Less than 100 m/s



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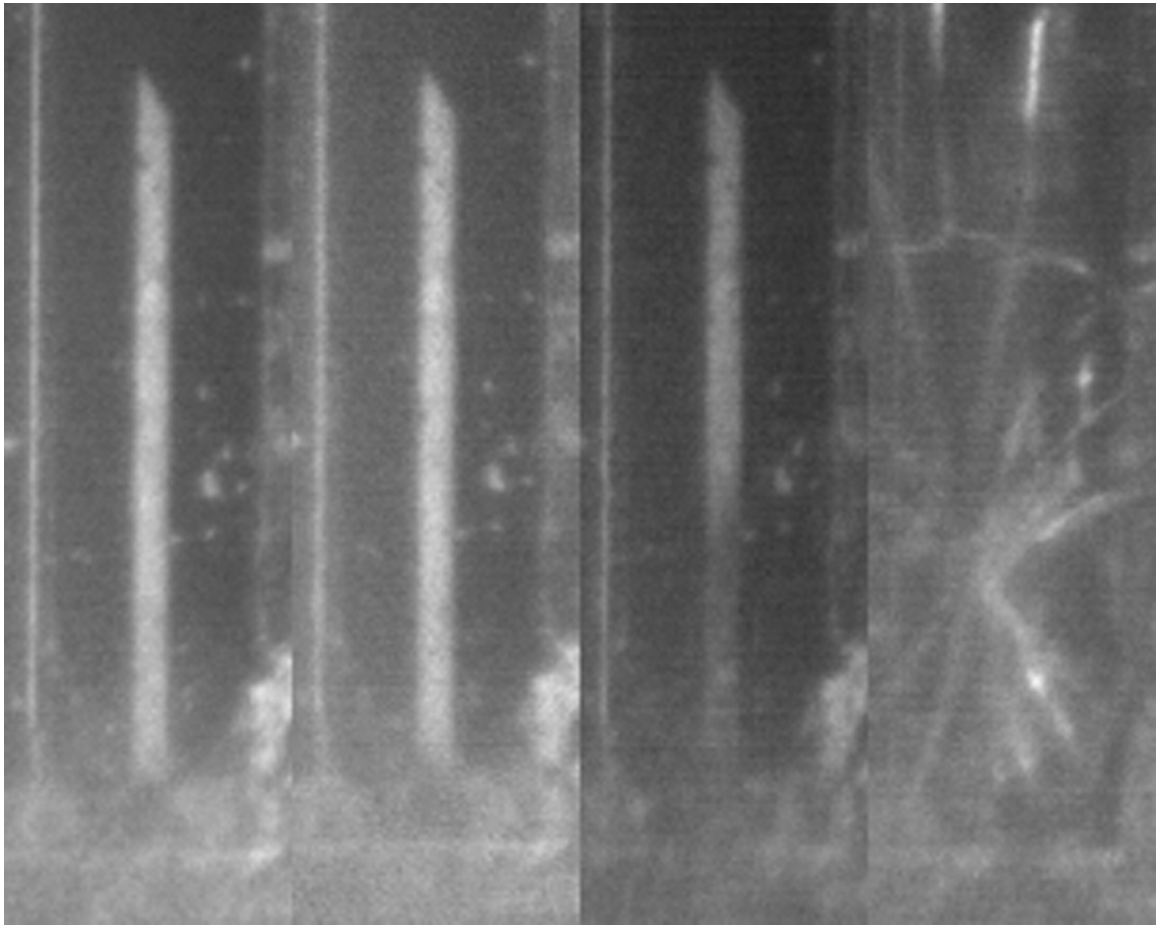
Lead Styphnate in Silicon Microchannel

- If the movie doesn't work



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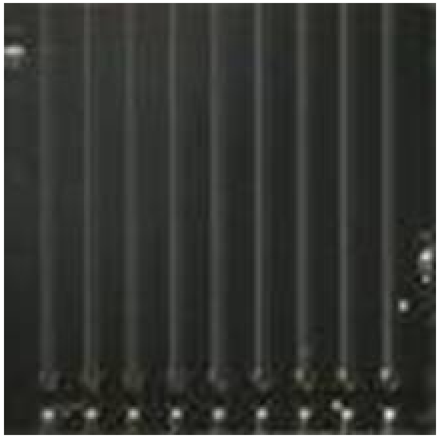
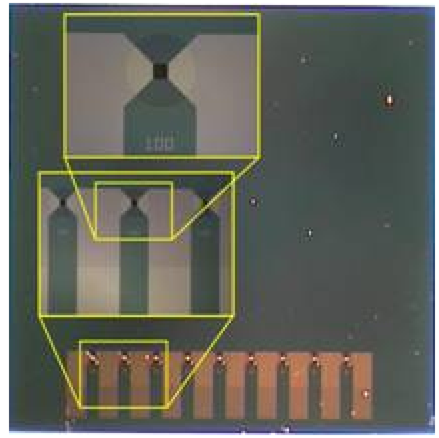
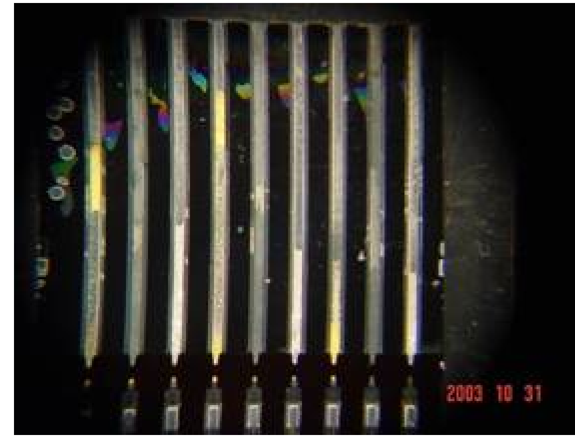
Powder-Filled Samples Preparation and Testing



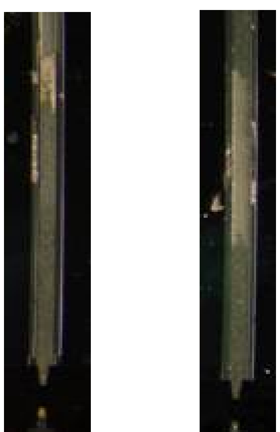
1. Bare substrate, 1.2-cm.



2. Bare closure with ignitors.

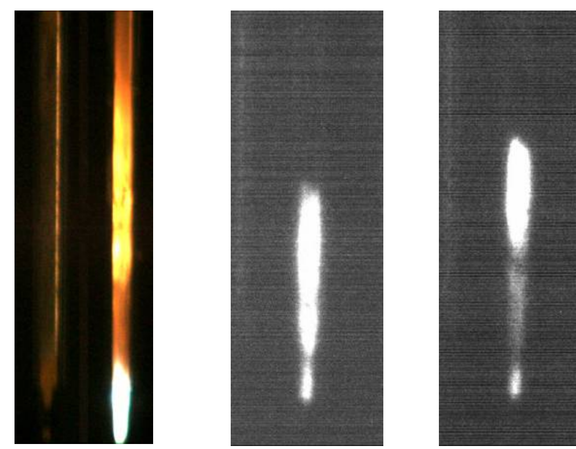


3. Closure installed with ignitors.



4. Powder poured in, piston installed if used.

5. Installed in firing chamber.



6. Fired.

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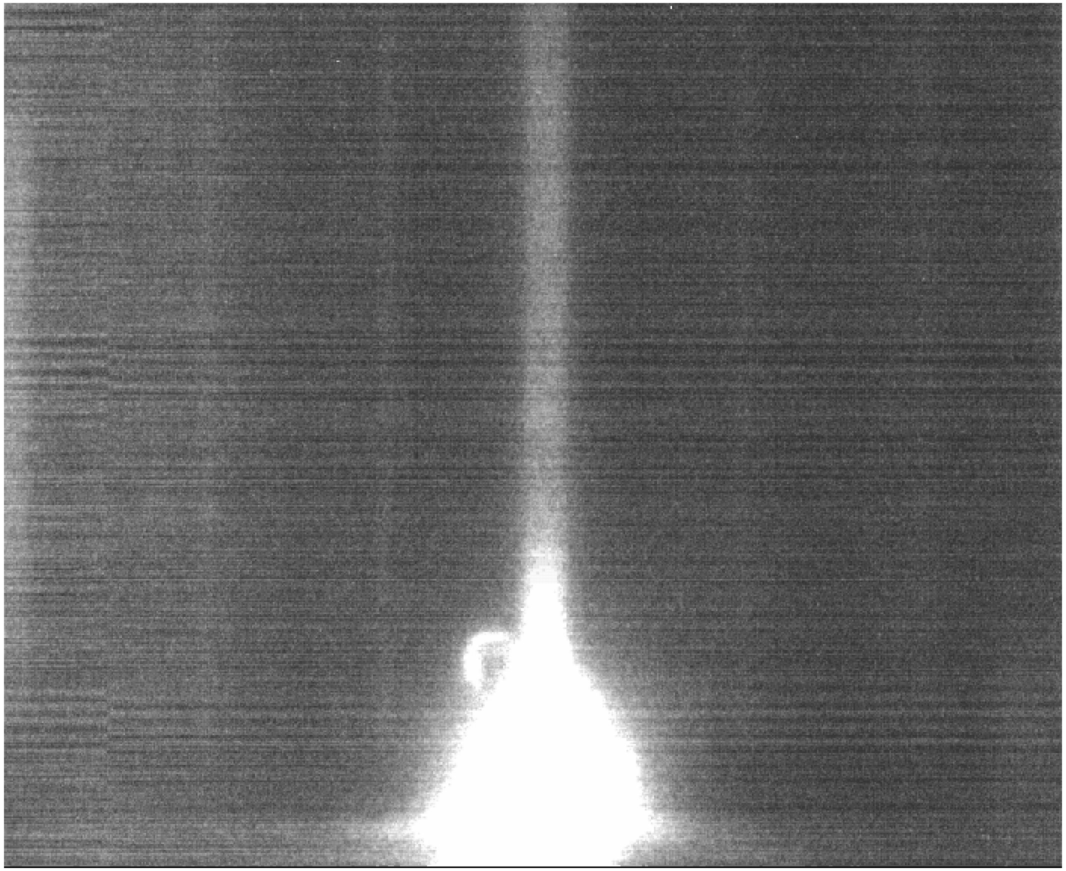
Nanocomposite Thermite and CL-20 in Silicon Microchannel

- **300-μm wide × 200-μm deep rectangular channel**
  - **Channel 5 filled with CL-20, bridge buttered with nanocomposite thermite, Steve Son (LANL) ignition increment**
- **Fired at 700 V**
- **500,000 fps (1/2 μs)**
- **Rapid deflagration**
- **through powder**
- **120-160 m/s**



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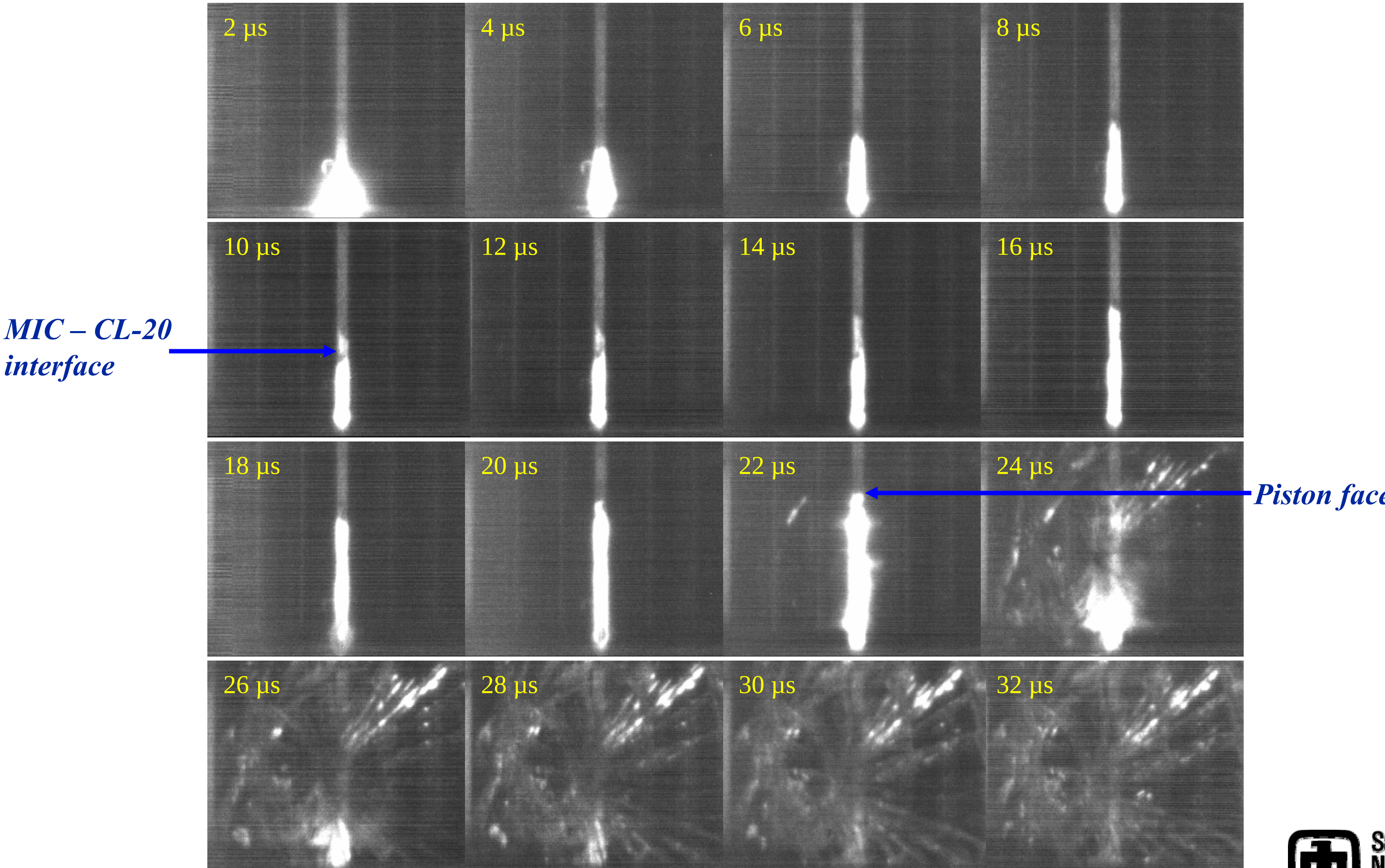
Nanocomposite Thermite and CL-20 in Silicon Microchannel



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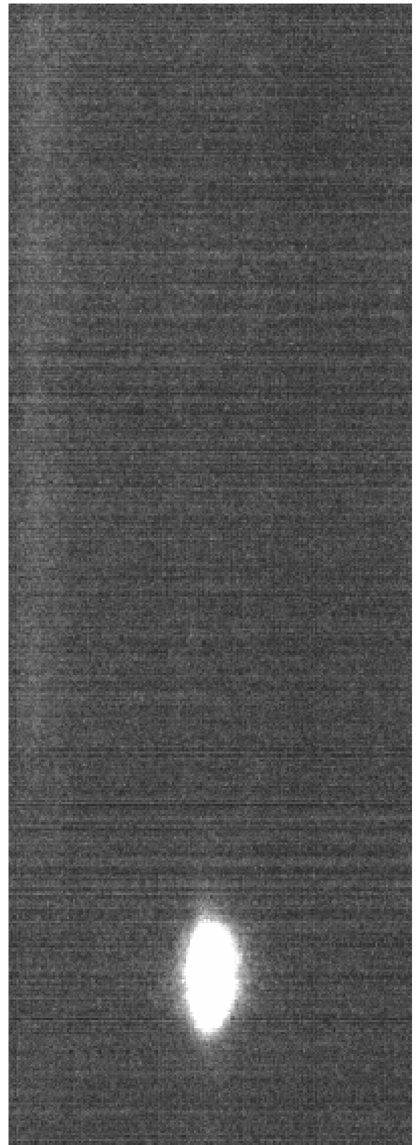
Nanocomposite Thermite Microchannel with Piston

- **300-μm wide × 100-μm deep rectangular channel**
- **Device was powder-filled with nanocomposite thermite, 40:60 Al:MoO_3, Steve Son at LANL**
- **Piston was 300×100 μm × 2 mm and weighed 313 μg**
- **500,000 fps (1/2 μs)**
- **2 μs exposure time**



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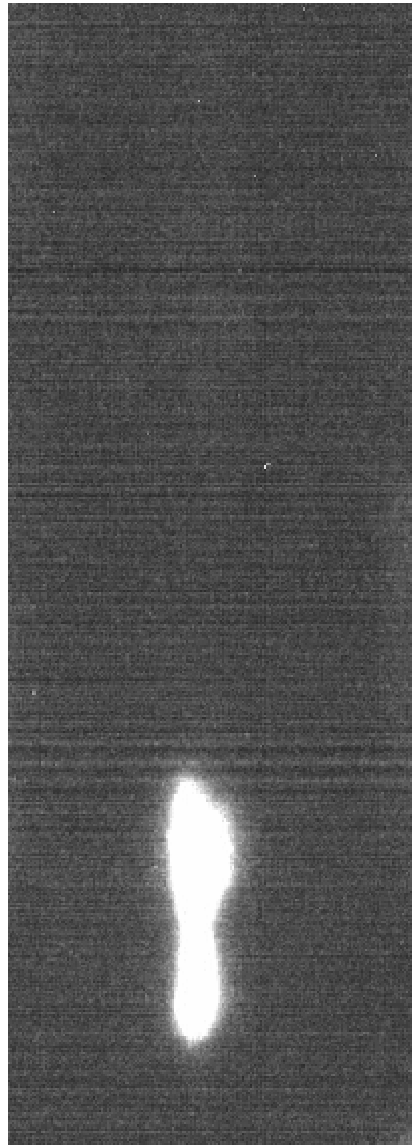
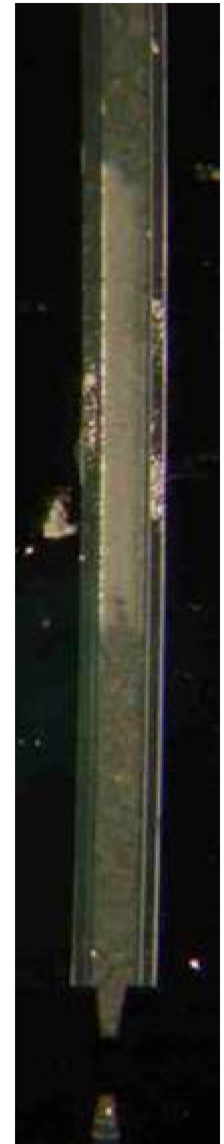
Nanocomposite Thermite Microchannel without Piston

- 300-μm wide × 100-μm deep rectangular channel
- Device was powder-filled with nanocomposite thermite, 40:60 Al:MoO_3, Steve Son at LANL
- No piston and visible air gap
- 500,000 fps (1/2 μs)
- 2 μs exposure time





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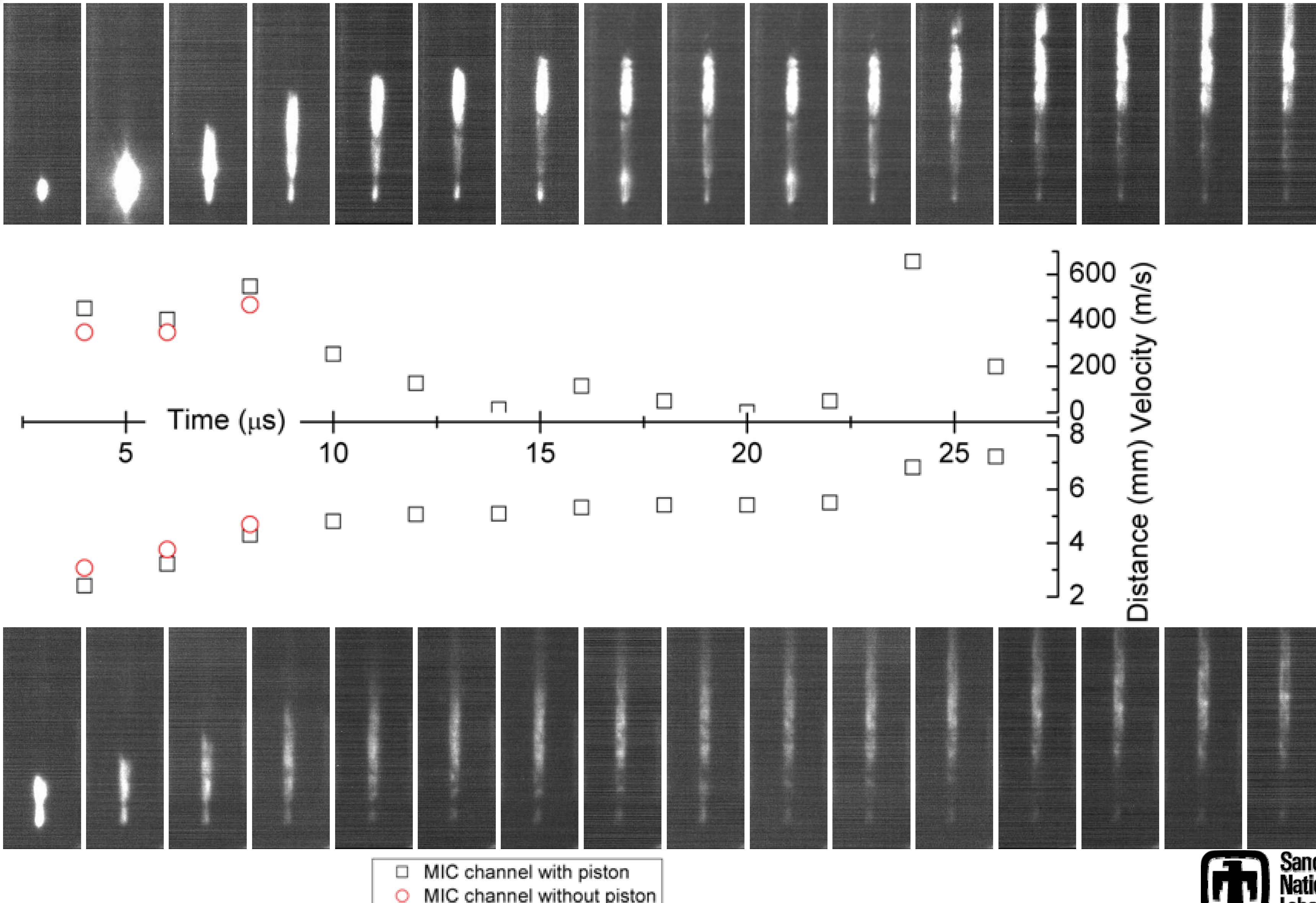
Comparison of Nanocomposite Thermite Microchannels



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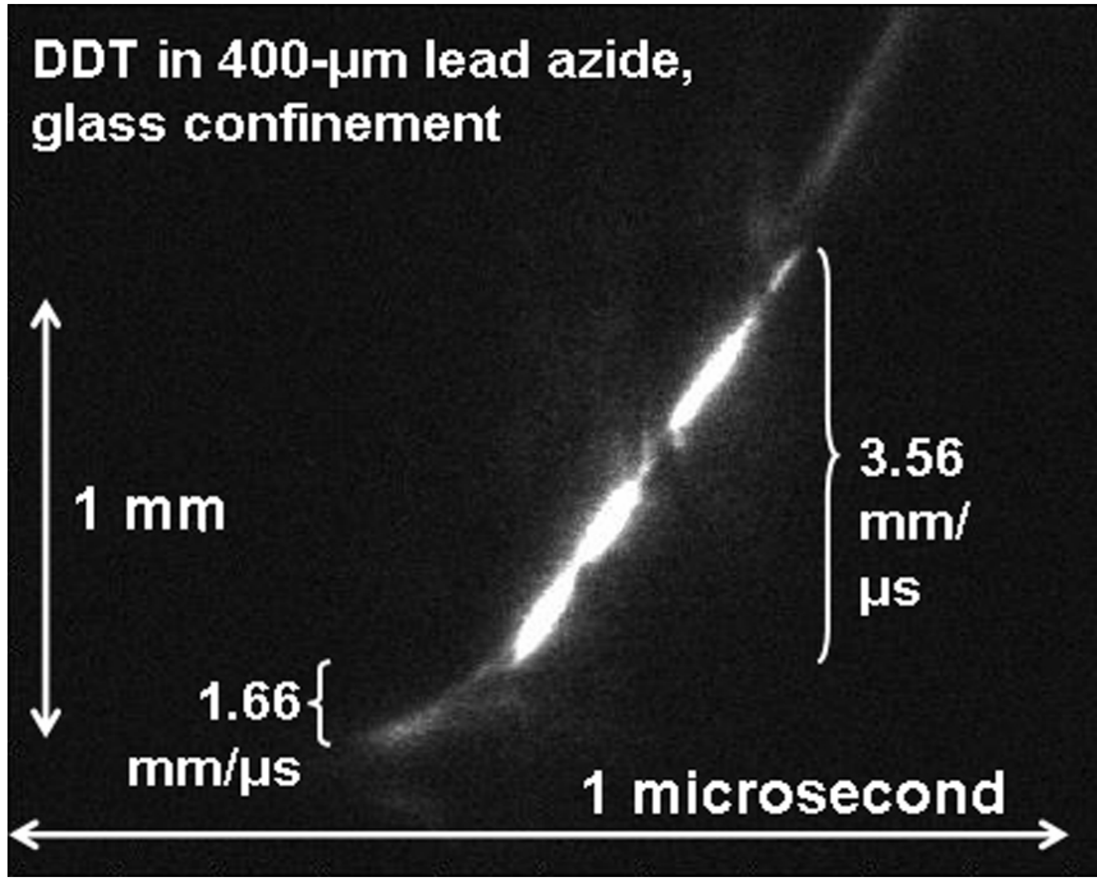
Lead Azide DDT in Glass Capillary

- 400-μm inner diameter capillary
- Filled with fine-particle lead azide
- By approaching critical diameters, transient effects (DDT) are amplified and easier to study



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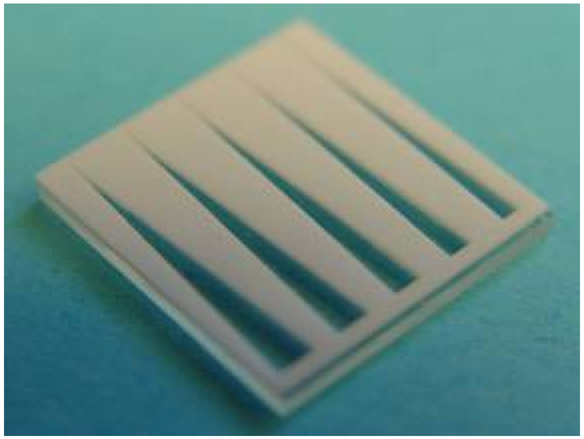
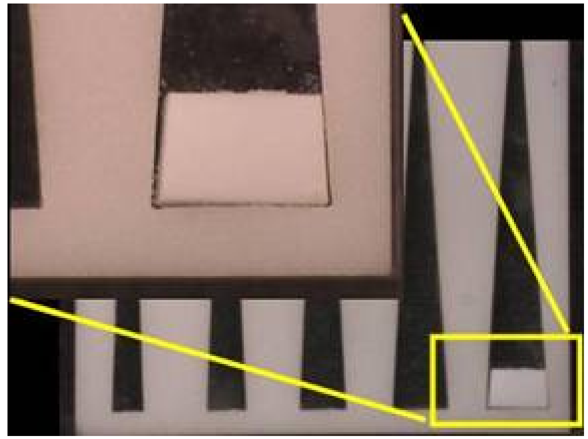
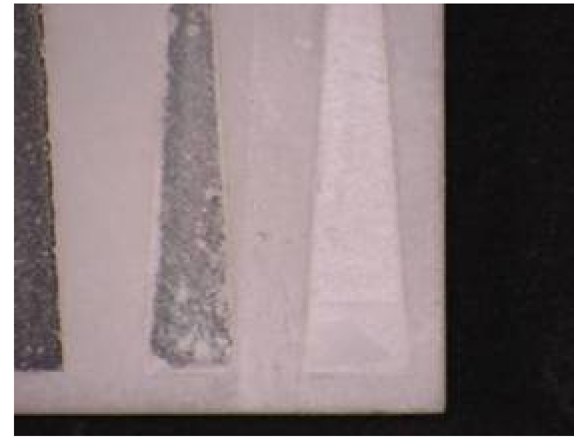
Sample preparation and testing arrangement



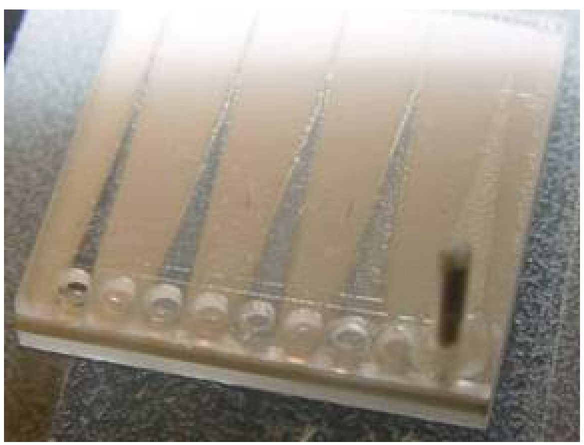
1. Bare substrate, 1.2 cm.



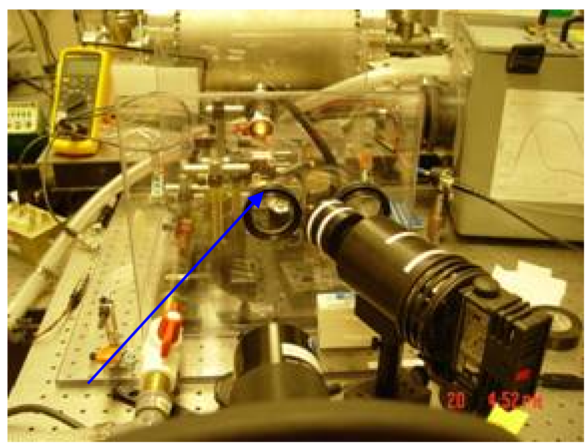
2. Femtosecond laser micro-machined CL-20 pellet inserted.



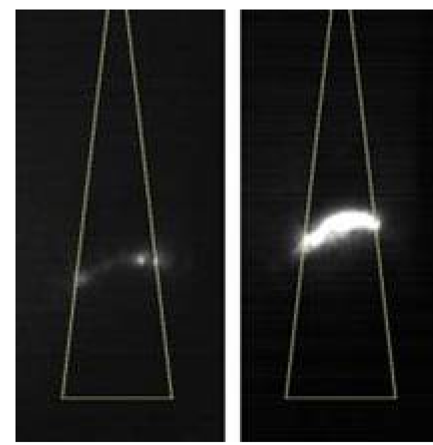
3. PETN film deposited.



4. Closure installed with ignition pellets.



5. Installed in firing chamber.



6. Fired.

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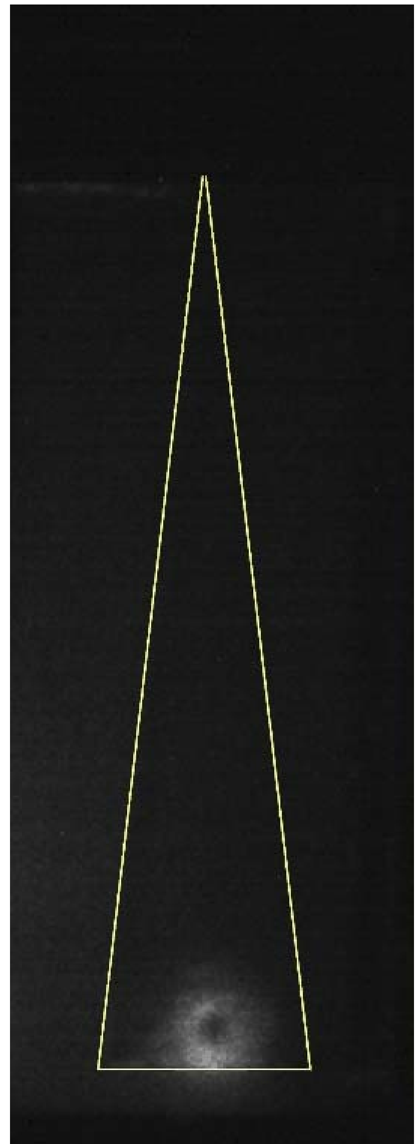
Non-Luminous Shock and SDT In Deposited PETN Film

- 508-μm thick wedge
- 2.8-mm wide at base
- 11.6-mm long
- 14º wedge full angle
- Vapor-deposited PETN film
- CL-20 pellet in plane with film
  - 88 % TMD
  - 34 GPa
- Hadland Imacon 200 framing camera
  - 3,333,333 fps (1/300 ns)
  - 50 ns exposure time



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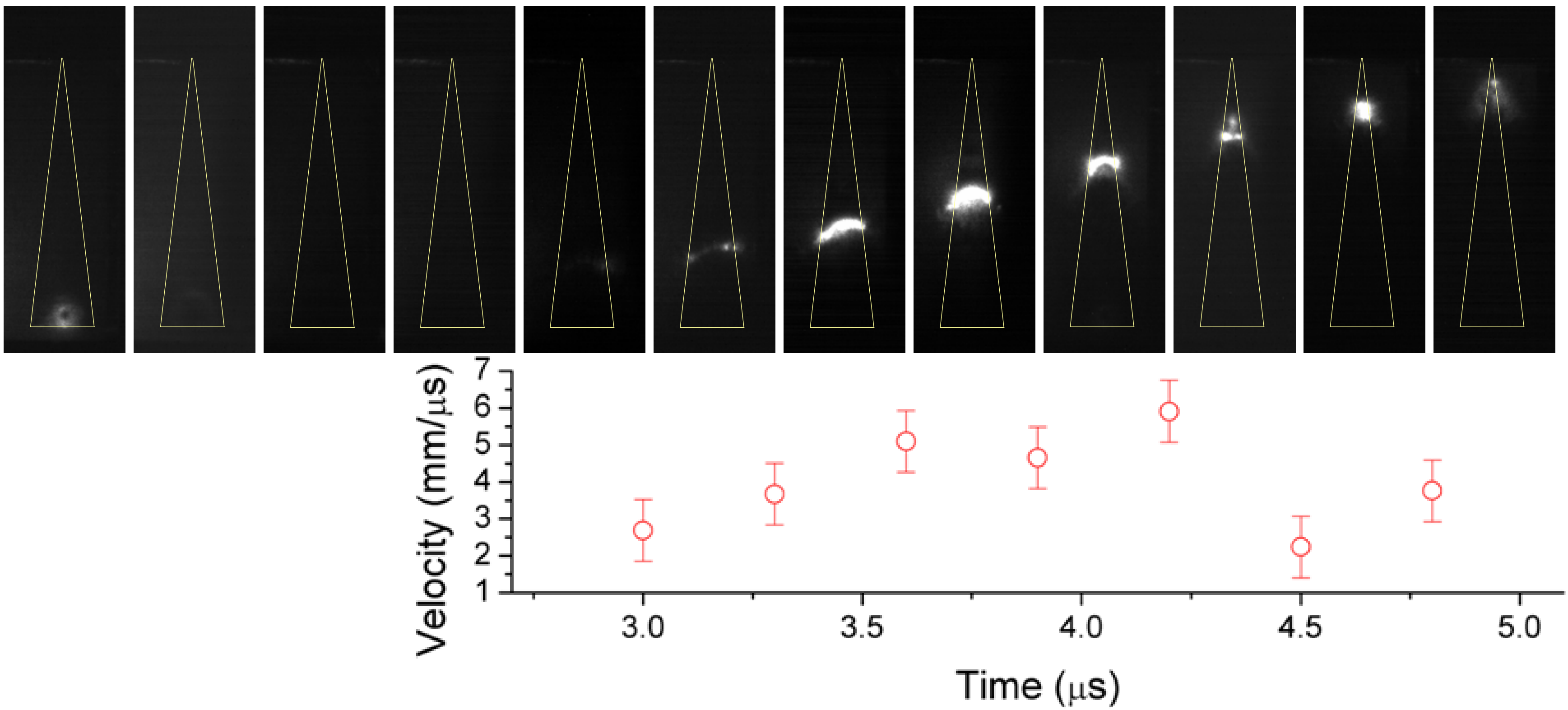
Non-Luminous Shock and SDT In Deposited PETN Film



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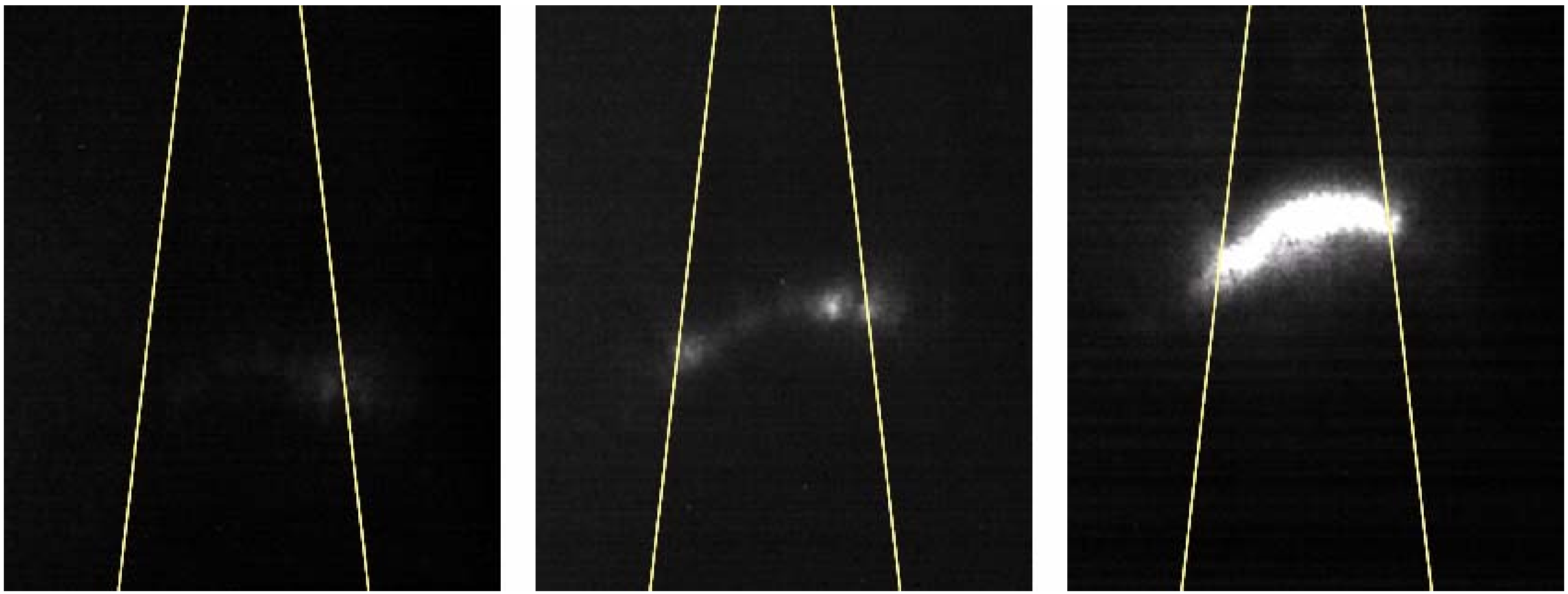
Non-Luminous Shock and SDT In Deposited PETN Film



- **Hot spot ignition in perimeter areas of wedge**

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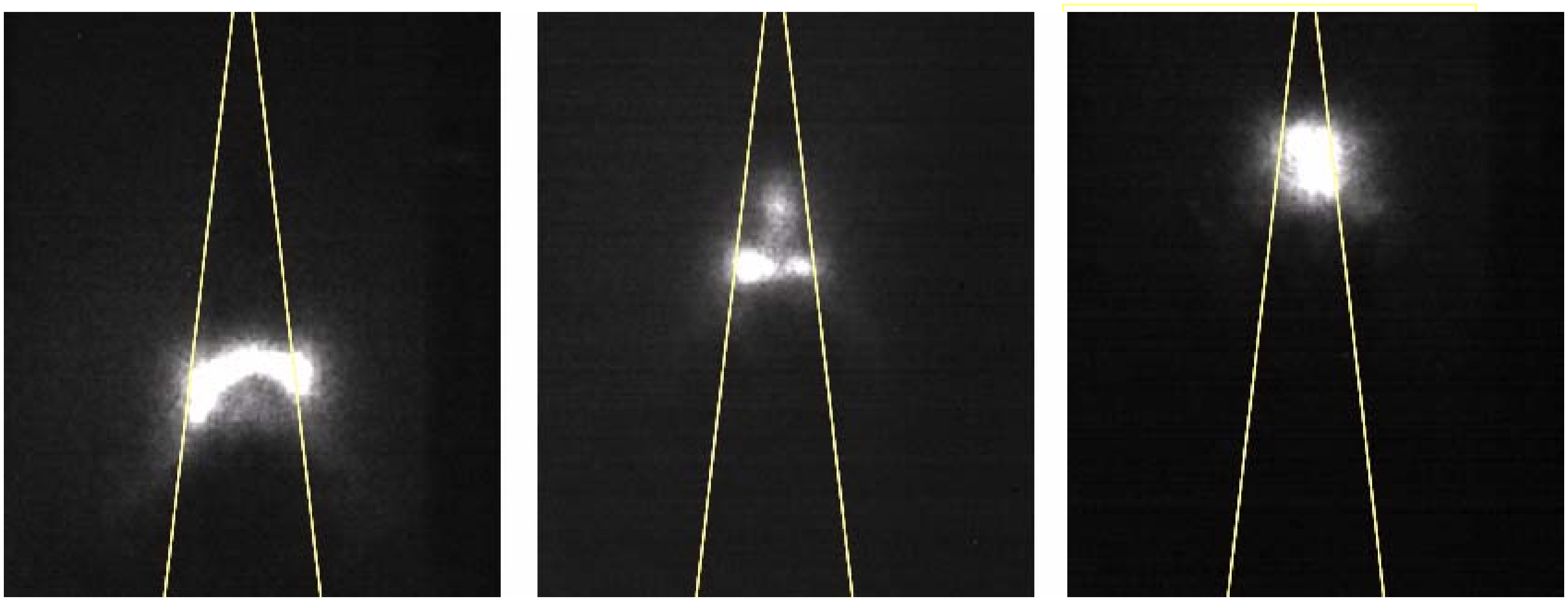
Non-Luminous Shock and SDT In Deposited PETN Film



- **Transient behavior as wedge cross-section decreases**

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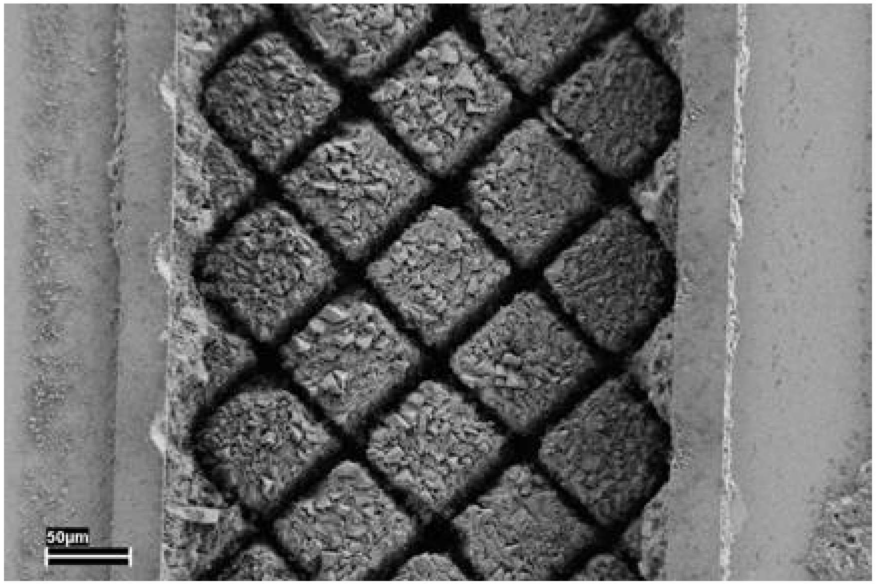
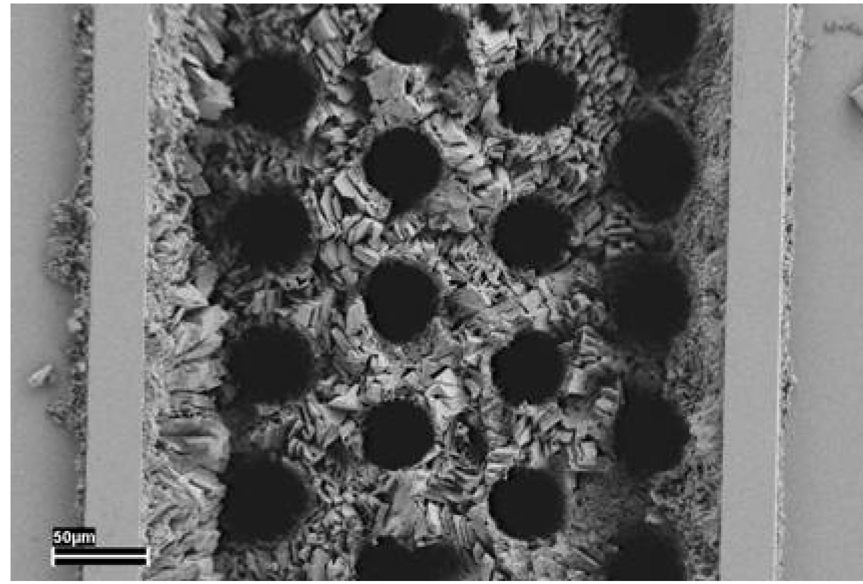
Patterning Efforts and Future Directions



Femtosecond laser micromachined PETN film. Connected porosity for combustion experiments. 50-µm bar.



Oxygen plasma etched PETN film. Isolated porosity for detonation experiments. 50-µm bar.

- **Future work will involve experiments on patterned films to investigate the effects of regular, patterned porosity in energetic material films**

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Conclusions

- Microenergetics involves the use of small samples to study microscale phenomena
- Numerous materials can function at small scales
- The most successful materials have been sensitive ones
- Work has progressed from crude powder filling to more advanced manufacturing
- Nanomaterials can be used to enhance combustion at small scales – confinement effects observed
- In deposited film samples, transient effects have been observed
  - Ignition and facile reaction during transient behavior occurs in the perimeter, low-density regions of our samples
  - Heterogeneities in the grain structure of energetic materials lead to transient effects in detonation wave structure, such as disperse reactive waves
  - The shock initiation and eventual growth to detonation in heterogeneous explosives may be the result of energy release and coalescence of multiple hot spots
  - The failure of detonation due to energy loss to the surroundings is characterized by transient behavior such as unsteady detonation velocity
- Future work involves continued patterning efforts and experiments with patterned films.

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Abstract

At Sandia National Laboratories, we have coined the term "microenergetics" to describe sub-millimeter energetic material studies aimed at gaining knowledge of combustion and detonation behavior at the mesoscale.1 Our approach is to apply technologies developed by the microelectronics industry to fabricate test samples with well-defined geometries. Substrates have been fabricated from materials such as silicon and ceramics, with channels to contain the energetic material. Energetic materials have been loaded into the channels, either as powders, femtosecond laser-micromachined pellets, or as vapor-deposited films. Ignition of the samples has been achieved by simple hotwires, integrated semiconductor bridges, and also by lasers. Additionally, grain-scale patterning has been performed on explosive films using both oxygen plasma etching and femtosecond laser micromachining.2 We have demonstrated simple work functions in microenergetic devices, such as piston motion,1 which is also a relevant diagnostic to examine combustion properties. Detonation has been achieved in deposited explosive films, recorded by high-speed photography.3 A review of progress on manufacturing and testing will be presented, as well as historical perspectives and future directions.

1 A. S. Tappan, A. M. Renlund, G. T. Long, S. H. Kravitz, K. L. Erickson, W. M. Trott, and M. R. Baer, in *12th International Detonation Symposium* (San Diego, CA, 2002).

2 A. S. Tappan, G. T. Long, B. Wroblewski, J. Nogan, J. A. Palmer, S. H. Kravitz, and A. M. Renlund, in *36th International Annual Conference of ICT, combined with 32nd International Pyrotechnics Seminar* (Karlsruhe Federal Republic of Germany, 2005).

3 A. S. Tappan, A. L. Brundage, G. T. Long, A. M. Renlund, S. H. Kravitz, J. J. Nogan, B. Wroblewski, J. A. Palmer, and M. R. Baer, in *13th International Detonation Symposium* (Norfolk, VA, 2006).

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