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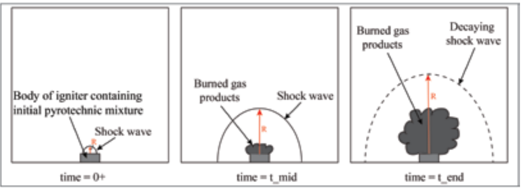

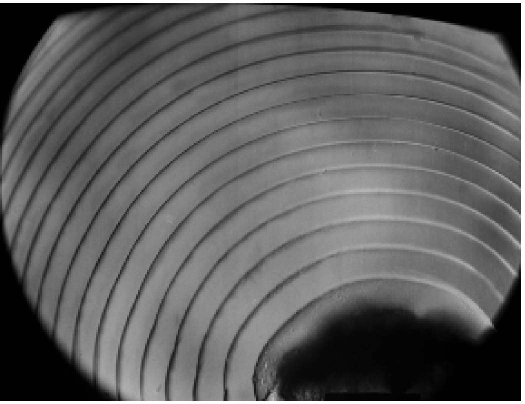

ASSESSING POST-IGNITION PYROTECHNIC BEHAVIOR

Michelle N. Skaggs, Marcia A. Cooper,
William W. Erikson

Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY

NNSA
National Nuclear Security Administration

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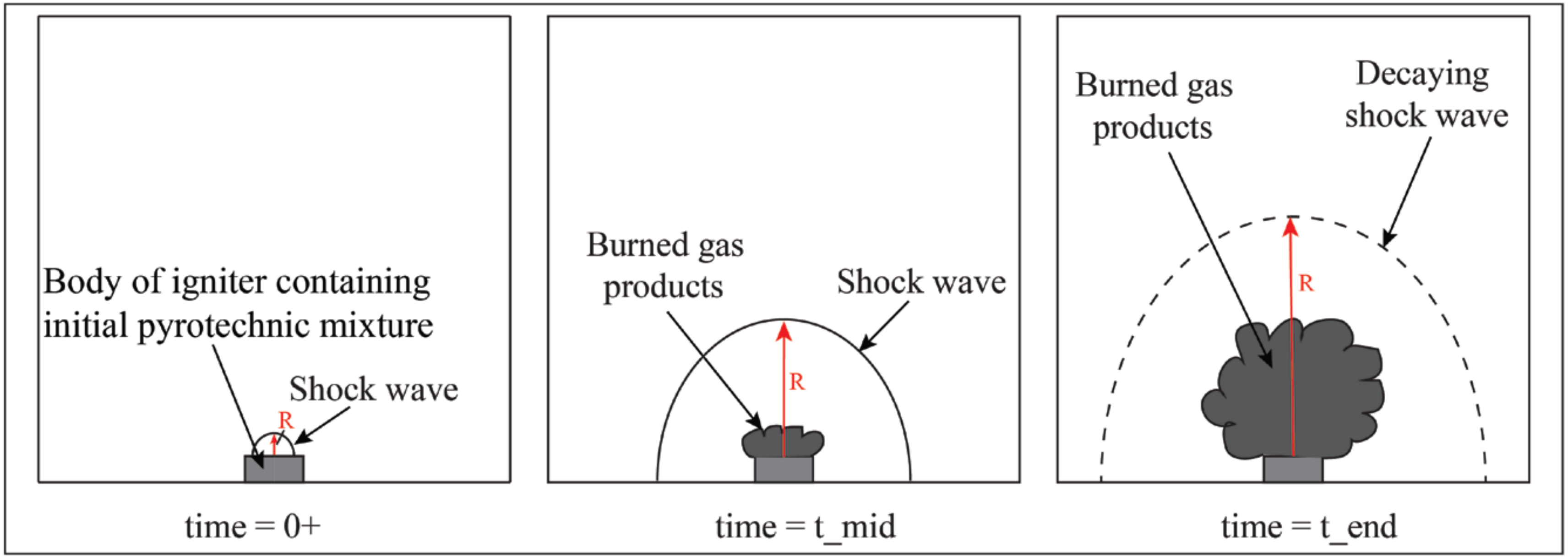
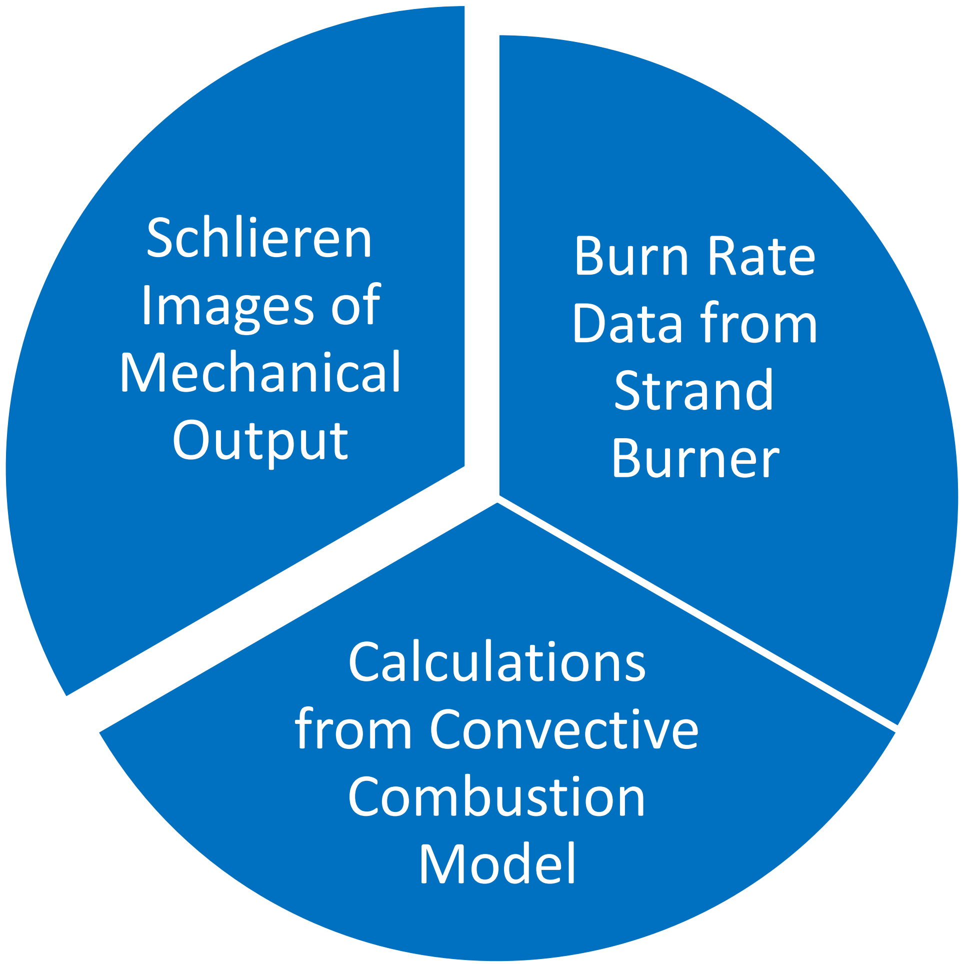
Schlieren Images

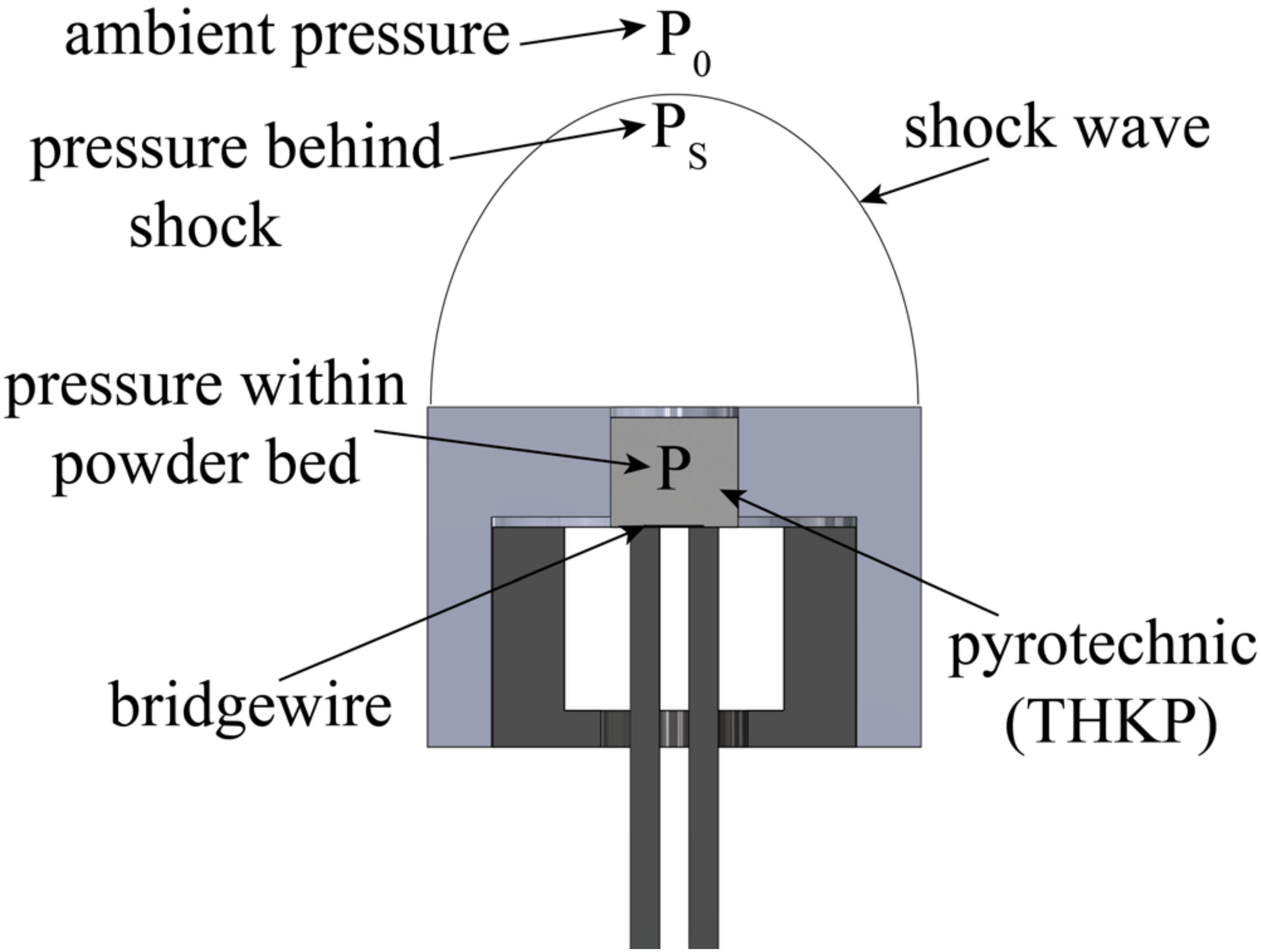


- Pyrotechnic within igniter reacts and releases high pressure into surrounding environment
- High pressure creates an expanding blast wave with radius R
- Images capture expanding blast wave and combustion products as a function of time

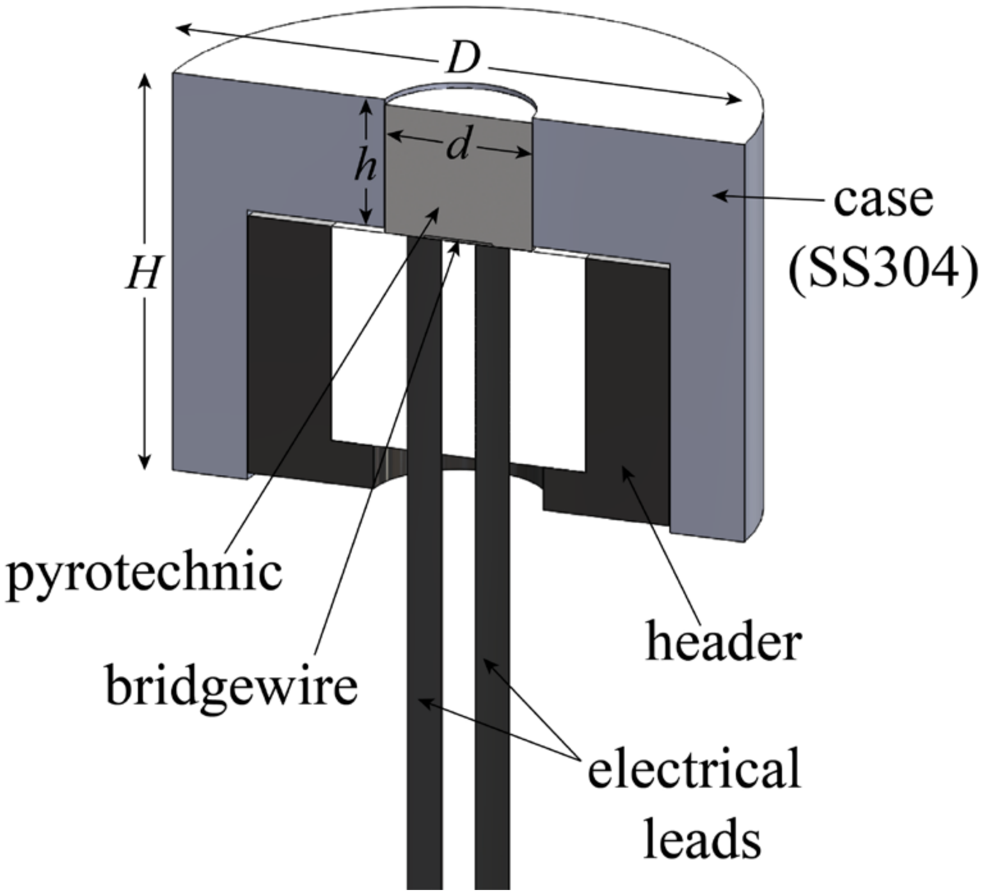
Combined Research Effort

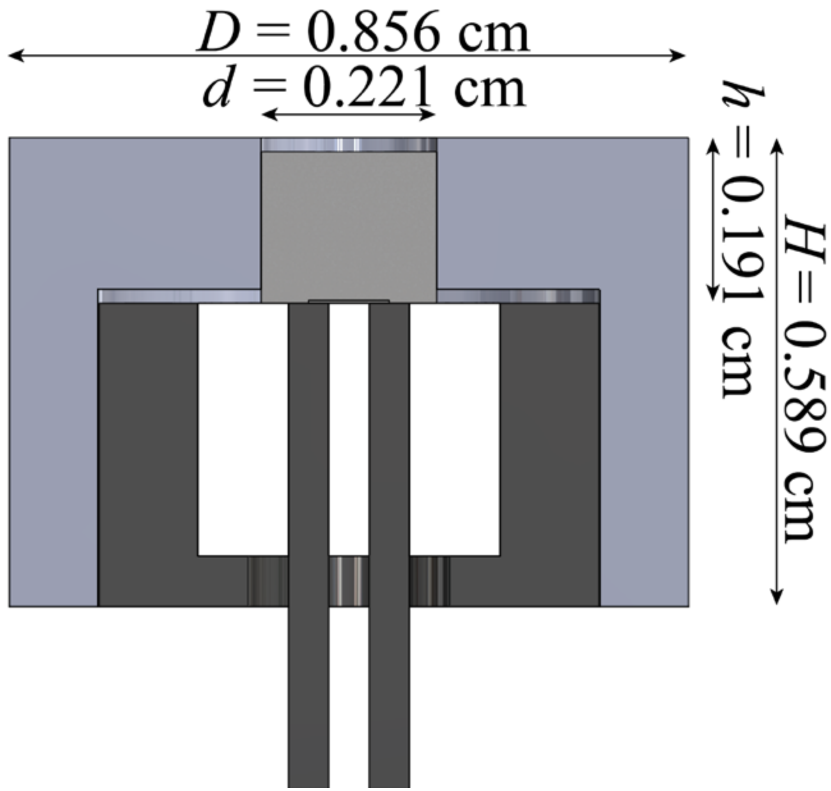


Study within *and* external to device



Research igniter



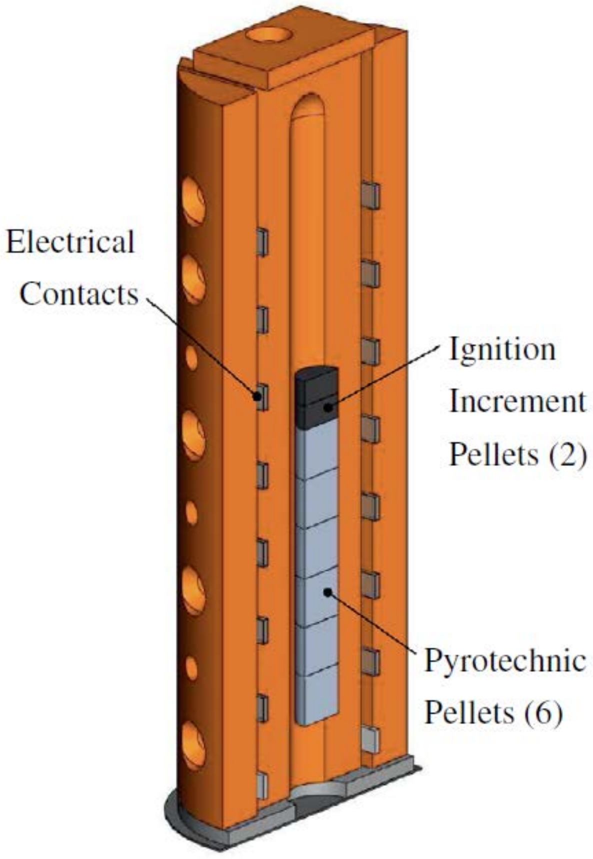


Pyrotechnic

- $TiH_{1.65}/KClO_4$ (THKP)
  - 33% $TiH_{1.65}$: 67% $KClO_4$ by weight
  - $TiH_{1.65}$ particles are nominally 13 µm
  - $KClO_4$ particles are nominally 22 µm
  - TMD = 2.845 g/cm^3
  - THKP density studied for this work is nominally 80% TMD

Relating strand burner burn rate data to device scale

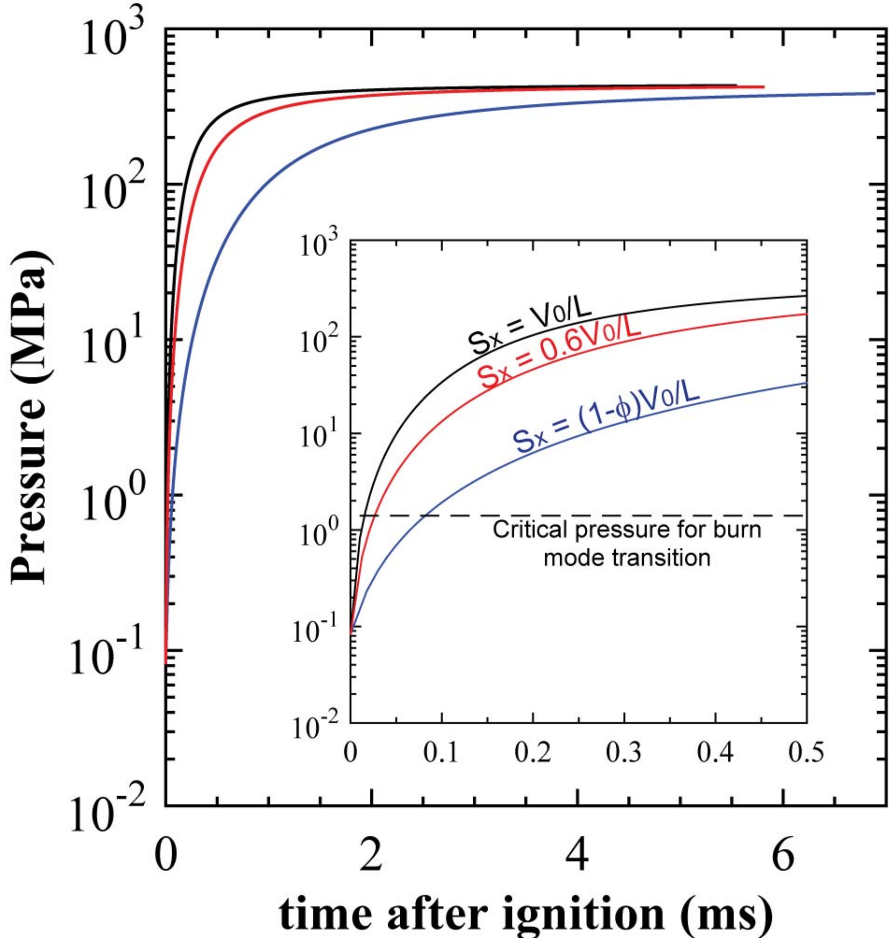
- Steady conductive burn rates previously measured in hybrid closed-bomb strand burner
- Data fitted to Vieille's equation $r=BP^n$ (B = 1.5054 cm/s and n = 0.5239)
- Relate these burn rates to much smaller device scale through derived universal relationship
- Pressure rise in free volume dependent on gas phase products generated by combustion of initial solid material with burn surface area (S_x)



Source: M.A. Cooper and M.S. Oliver (2013) *Combustion and Flame*.

Burn rate pressure prediction

- Predictions vary with assumption of S_x
- Previous studies have shown that red curve best represents strand burner experiments
- Predicted pressure is >100 MPa at 500 µs after ignition
- Predicted pressure is >200 MPa at 2 ms after ignition
- Evidence of transition to unsteady (deconsolidated) burning mode



Convective Combustion Model

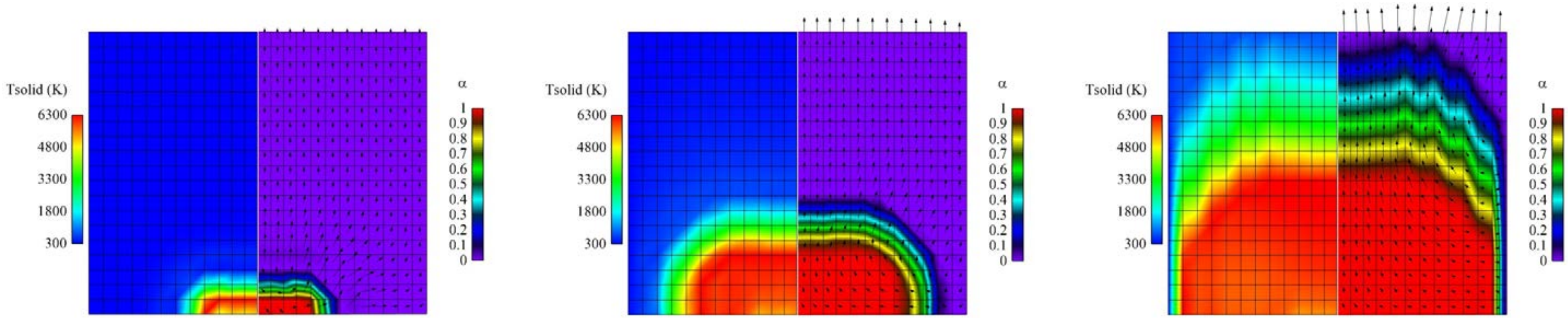
- Simple convective combustion model = solid particle combustion coupled with porous flow model for gas transport
  - Particles treated as shrinking spheres
  - Gas transport via Forchheimer-corrected Darcy's law
  - Ideal gas or Noble-Able equations of state are used
  - Neglect particle bed compaction and certain flow effects (turbulence, supersonic flow, etc.)

- THKP initial values:

  C_P = 850 J/kg-K, W = 39 g/mol, ΔH_{rxn} = -3.8e7 J/kg, F_g = 0.5

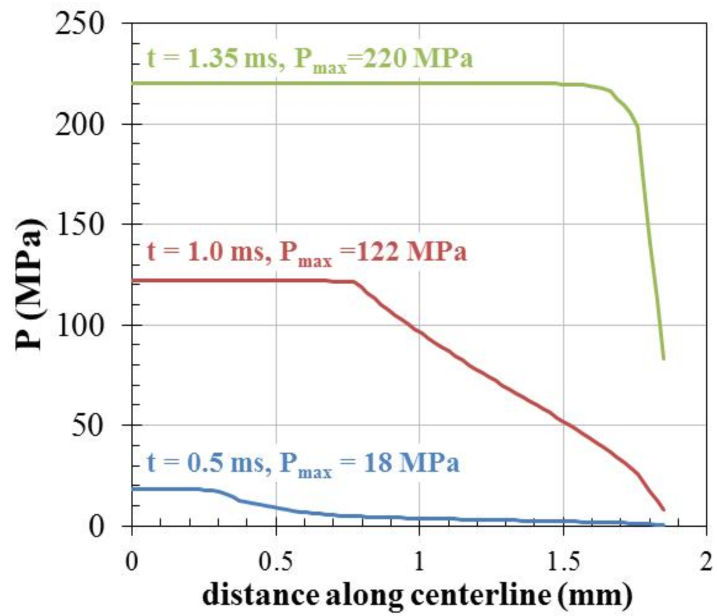
Combustion Model pressure predictions

(Left) solid temperature and (right) extent of reaction with velocity vectors

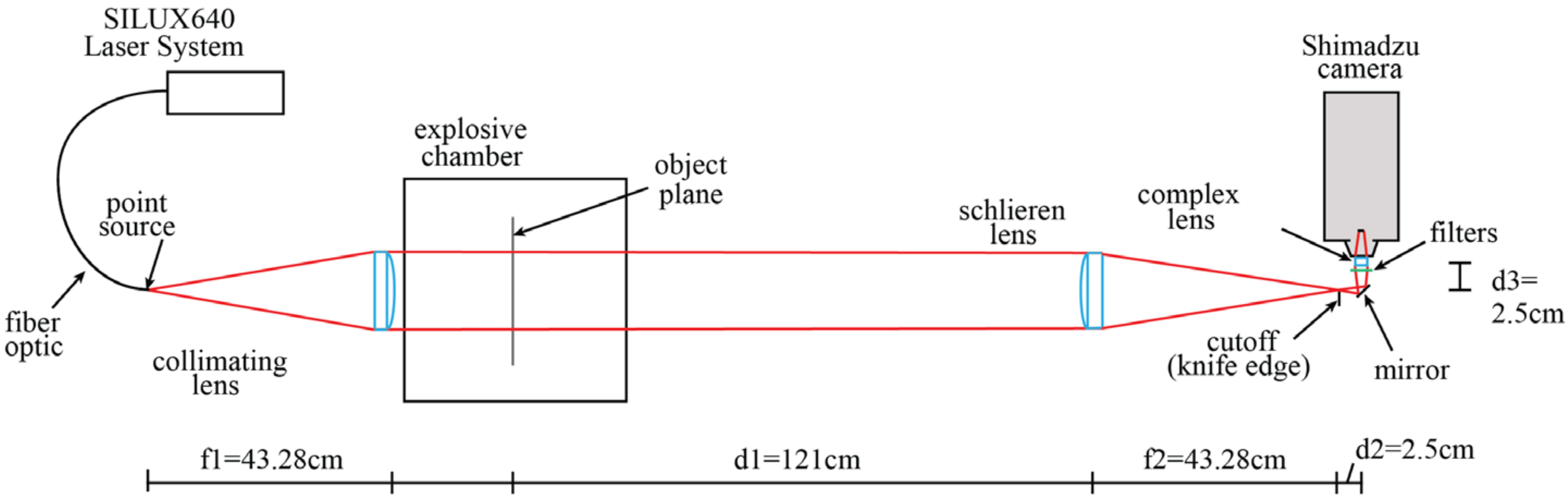


t = 0.5 ms   t = 1.0 ms   t = 1.35 ms

- Predicted pressure is 18 MPa at 500 µs after ignition
- Predicted pressure is >220 MPa at 2 ms after ignition (only half of research igniter column height)



Schlieren Imaging System



- SILUX640 Laser system = non-coherent illumination at 640nm
- Shimadzu HPV-2 high-speed camera records 102-frame image sequences at 500 kHz with 312 × 260 pixels
- FOV is 8 cm × 8 cm

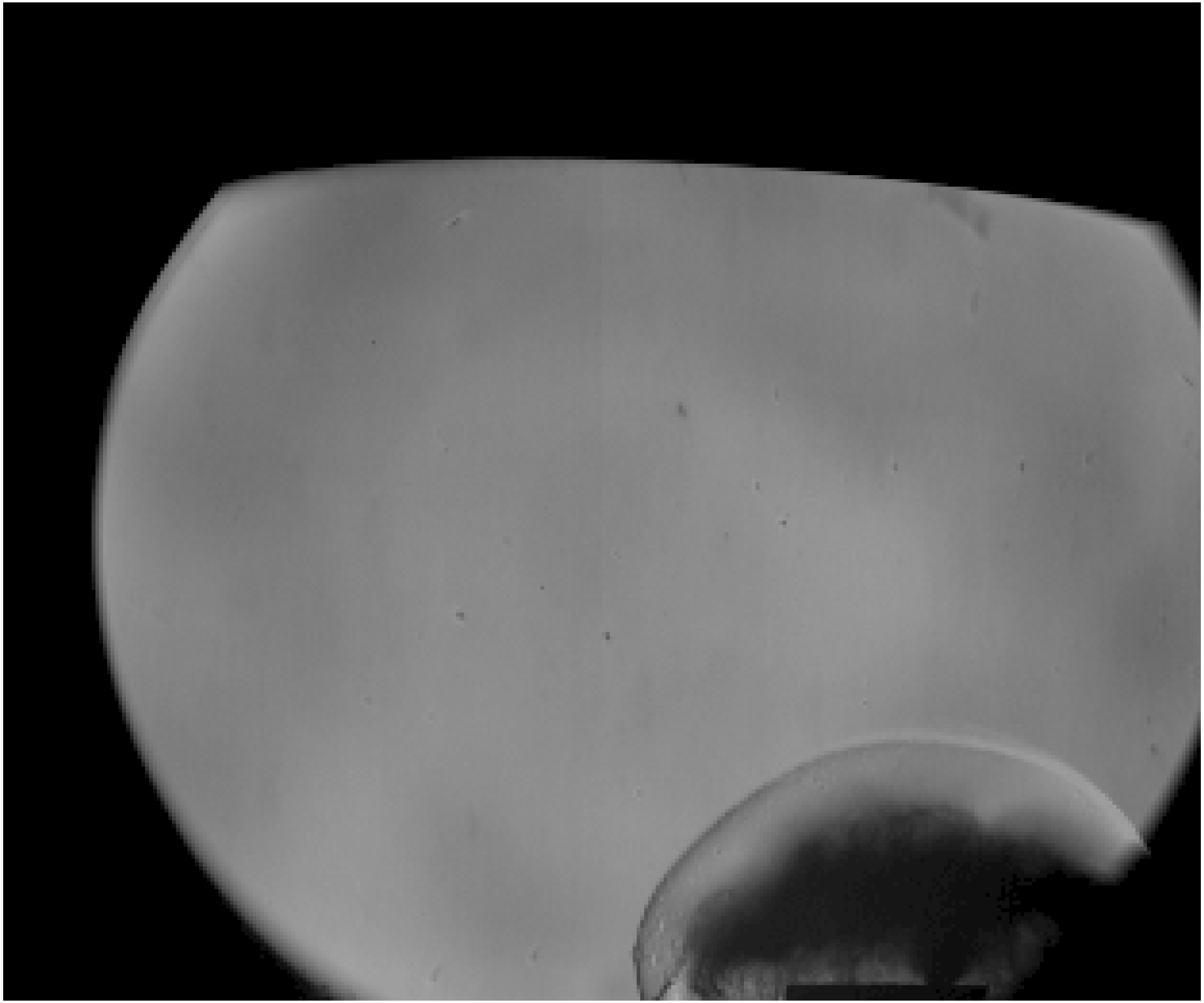
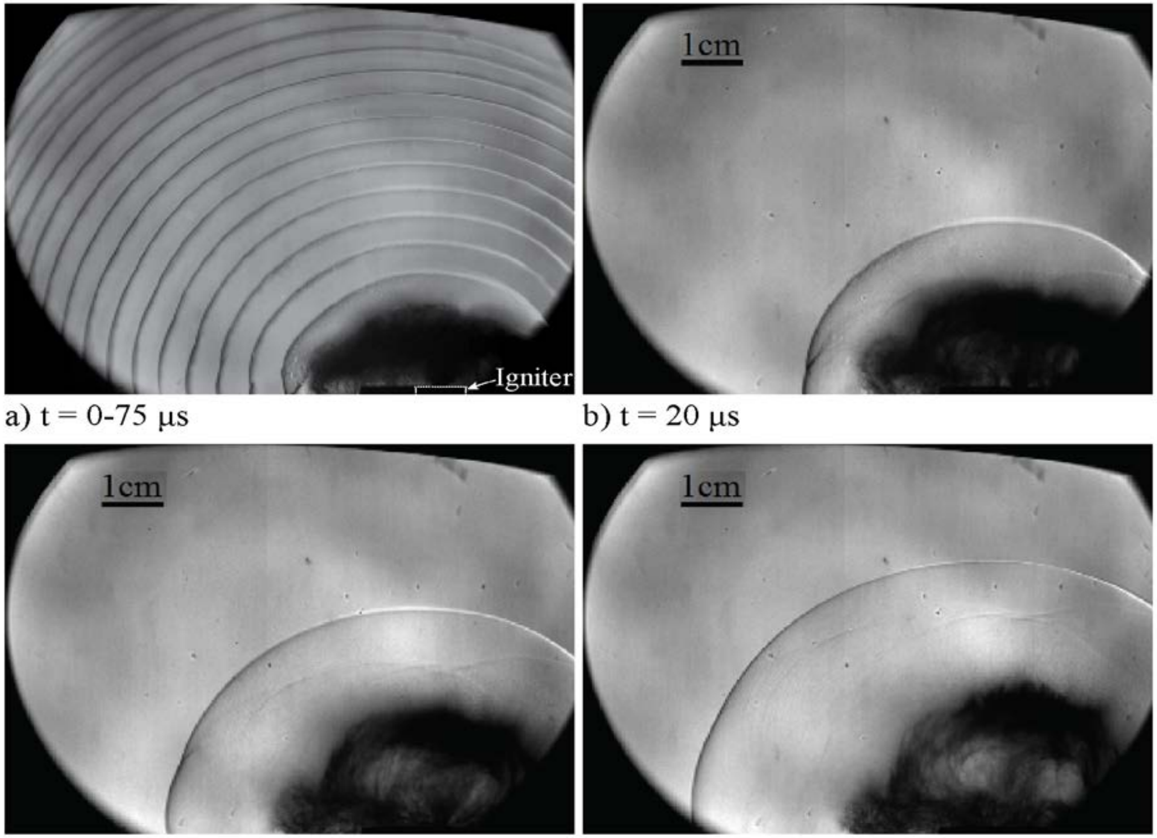


Image Results – blast wave

- Igniter located in bottom right corner
- a) Composite frame showing blast wave shape evolution every 10 µs
- b-d) Shows gas volume expansion and particle motion every 20 µs

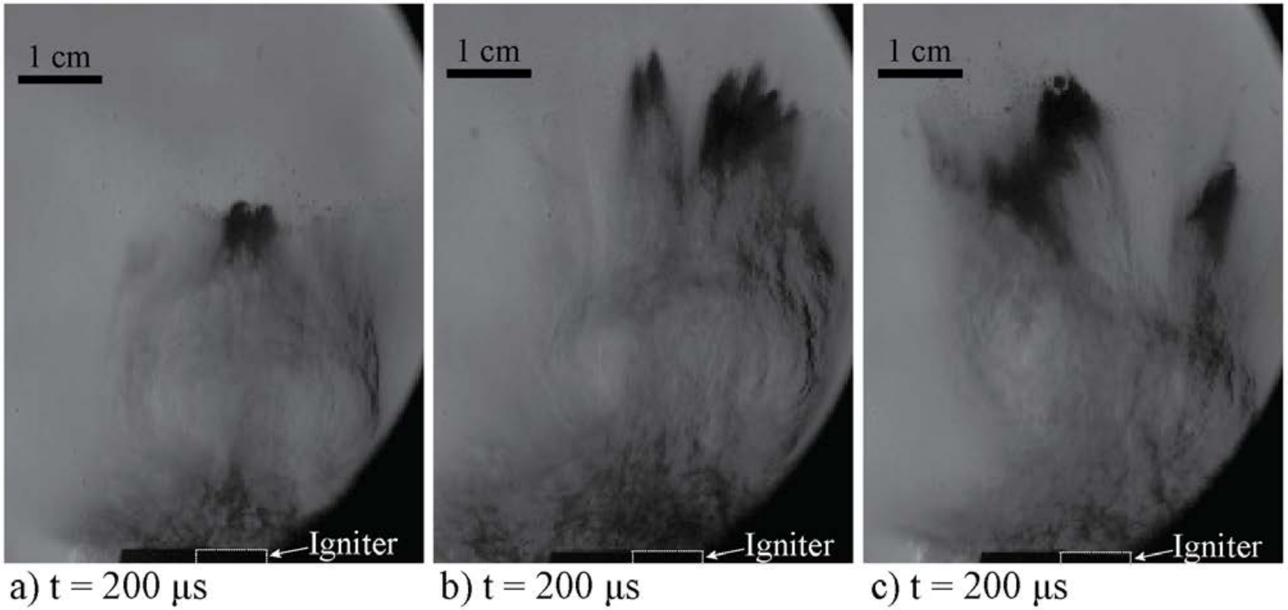


a) t = 0-75 µs b) t = 20 µs c) t = 40 µs d) t = 60 µs

- t=0 µs corresponds to trigger time required to synchronize laser pulses, camera frames, and firing signal (t=0 µs ≈ t = 2 ms after ignition)

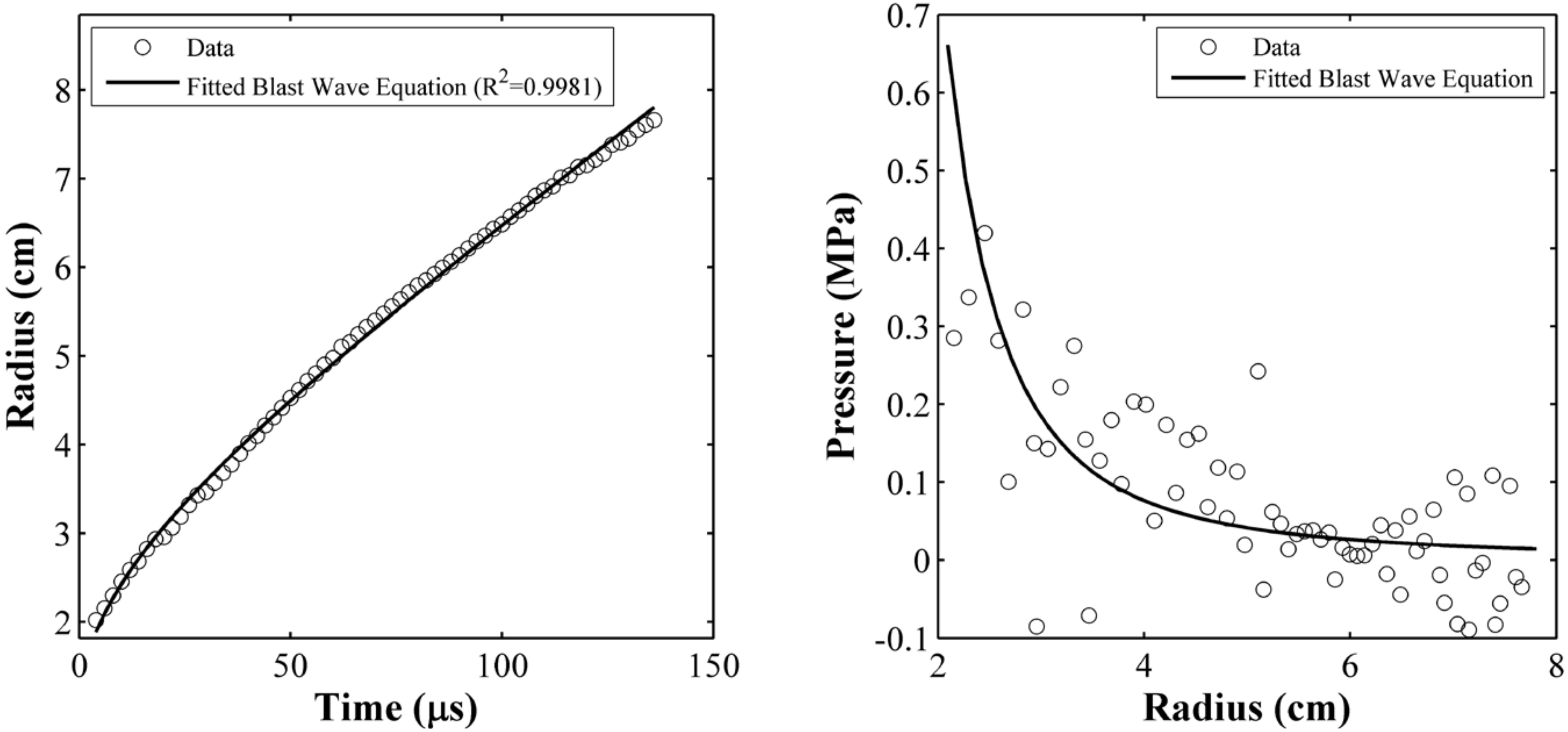
Image Results – particle motion

- Evidence of presumably unburned solid particles for several THKP tests repeating same conditions
- Lead to qualitative assessment of extent of reaction



Pressure results

Dewey Blast Wave Eq.: $R = A + Ba_0t + C\ln(1 + a_0t) + D\sqrt{\ln(1 + a_0t)}$



- Blast pressure is approximately 0.4 MPa at 2-3 cm radius

t=0 µs corresponds to trigger time (t=0 µs ≈ t = 2 ms after ignition)

Discussion

- Pressures within device agree well
  - Burn rate data predicts P>200 MPa at 2 ms
  - Combustion model predicts P>220 MPa at 2 ms
- Pressure measured within device and external to device (P=0.4 MPa) do not agree well
  - Lack of near-field, early-time data hinders direct comparison
  - Future work will pursue different triggering algorithm
- Strong correlation across all research efforts that pyrotechnic material is not completely consumed by combustion reaction
  - Unburned particles in images
  - Evidence of transition to unsteady burning mode in both other studies

Conclusions

- Presented data from three efforts aimed at improving understanding of pyrotechnic device behavior from within the device to the resulting multiphase flow output
- Consistent phenomena are suggested:
  - Generation of large pressures suitable for production of strong shock waves
  - Likelihood of steady-to-unsteady combustion mode transition within charge cavity of device leading to ejection of solid particles

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