Results from Gaseous Methane/Oxygen Mixture Testing

Reema Reveles

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2018 International Explosives Safety Symposium & Exposition

Introduction

- LOX-LNG fueled launch vehicles
  - BE-4 by Blue Origin
- Advantages of LOX/LNG
  - Denser than LH_2 requiring smaller tanks
  - Simpler turbopump design
  - Unlike RP-1 methane can be used to self-pressurize
  - Cost
- DoD Safety Standards

Blue Origin's BE-3 throttles during acceptance testing. Credit: Blue Origin

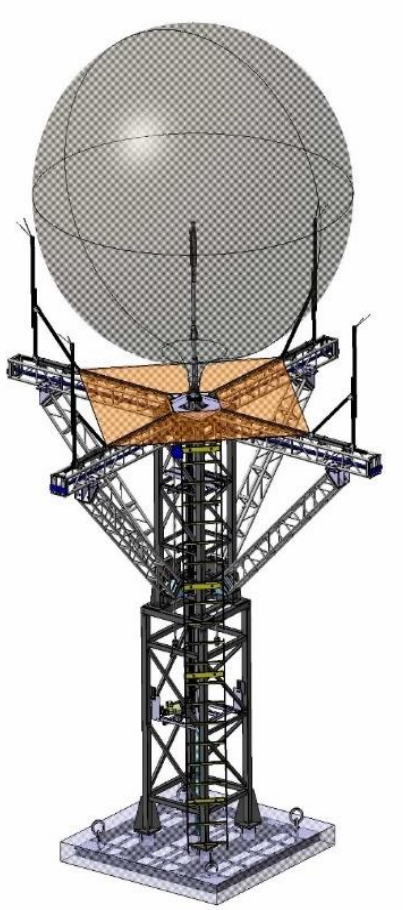
Energetic liquid	TNT Equivalence
LO_2/LH_2	Larger of 8 $W^{2/3}$, or, 14%W, where W is total weight of LO_2/LH_2
LO_2/RP-1	10%

Methane/Oxygen Unconfined Explosion/Combustion Test Series

- Establish Quantity-Distance for LOX-LNG explosions
- Expect gaseous explosion envelopes cryogenic
- Methane – oxygen gas test setup

Balloon sizes
6 ft.(7 tests)
12 ft.(18 tests)
14.5 ft.(5 tests)
16 ft. (15 tests)

Methane Mixture ratios
Stoichiometric
+-5% by volume
+-10% by volume
+-15% by volume



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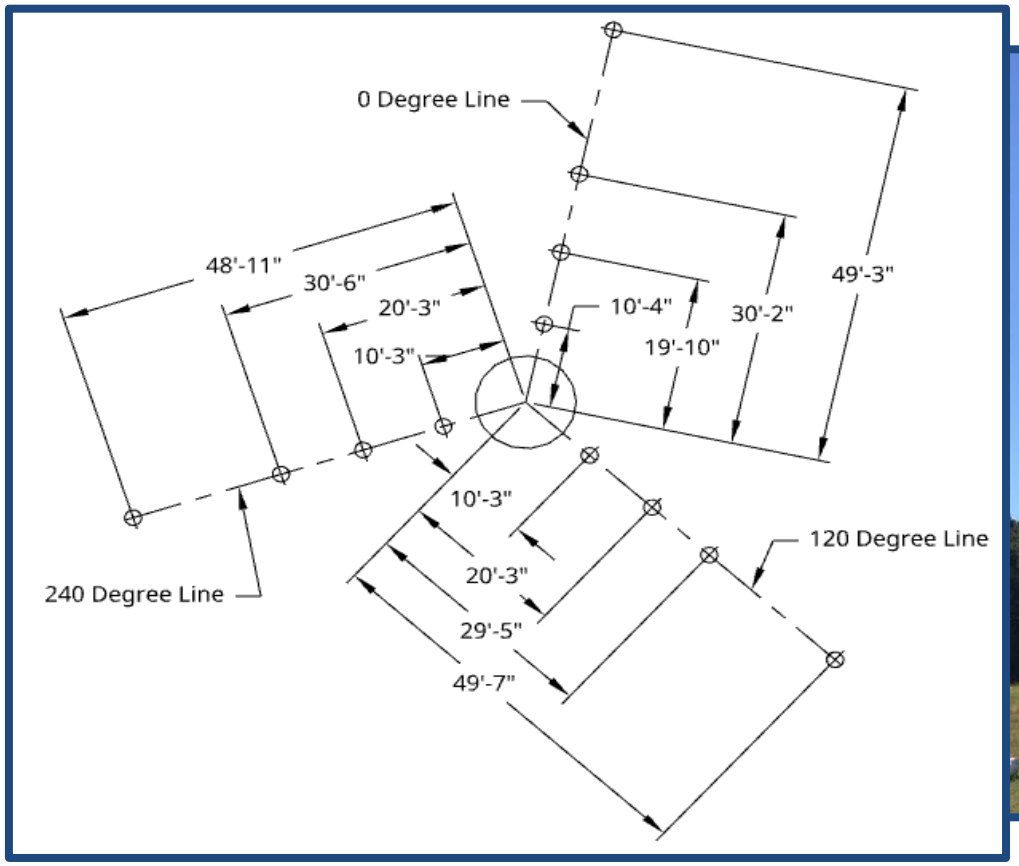
Test Site



Probe setup top view

MUCTA test site

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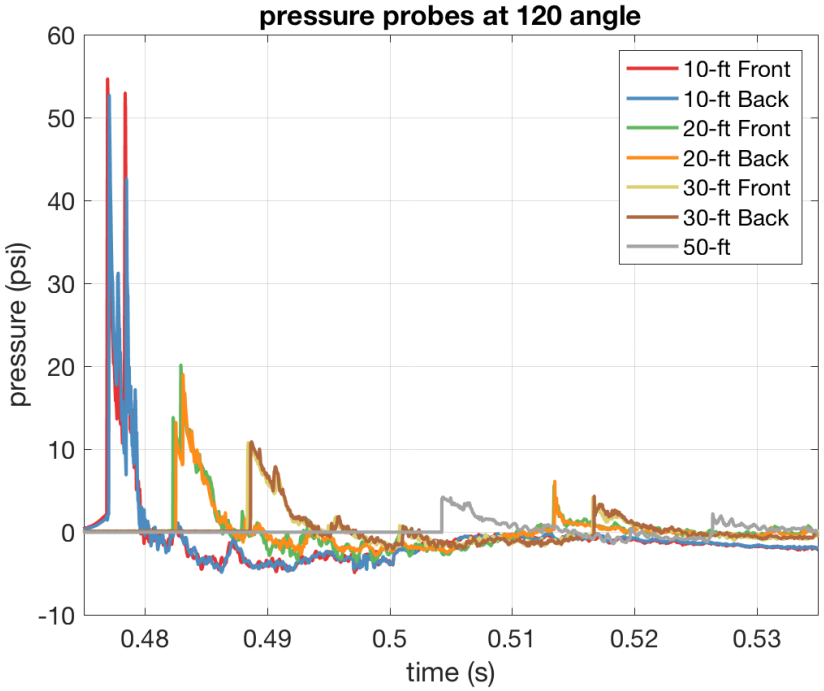
Instrumentation

- Pressure probes
  - Piezoelectronic Quartz ICP blast pressure pencil probe



12.0 ft. diameter balloon, 37% CH4, 63% GOX by volume

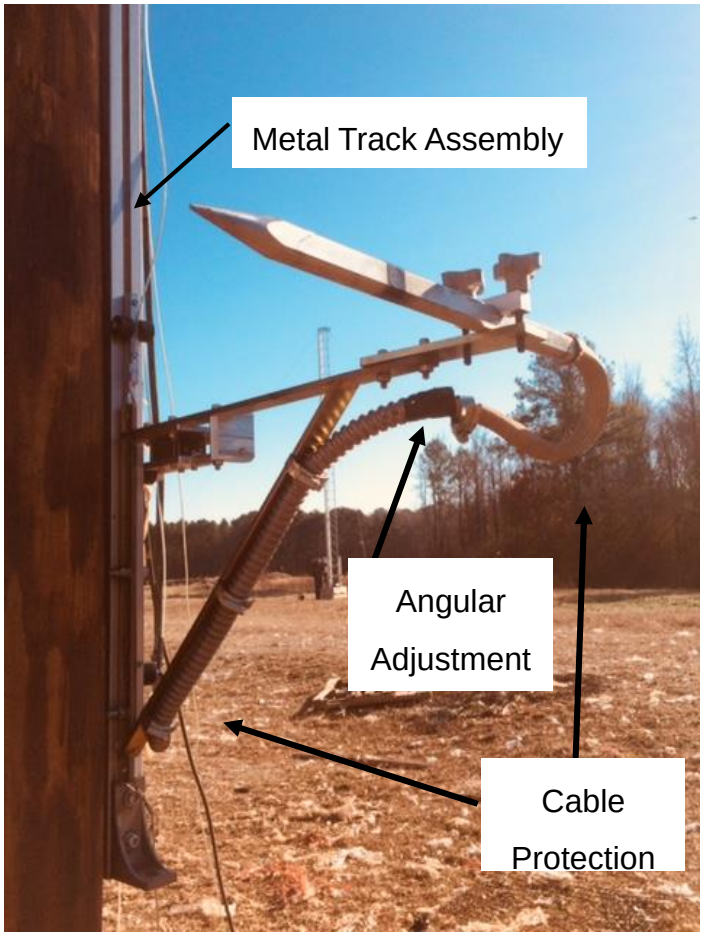


Fig: Blast pressure pencil probe mounting assembly

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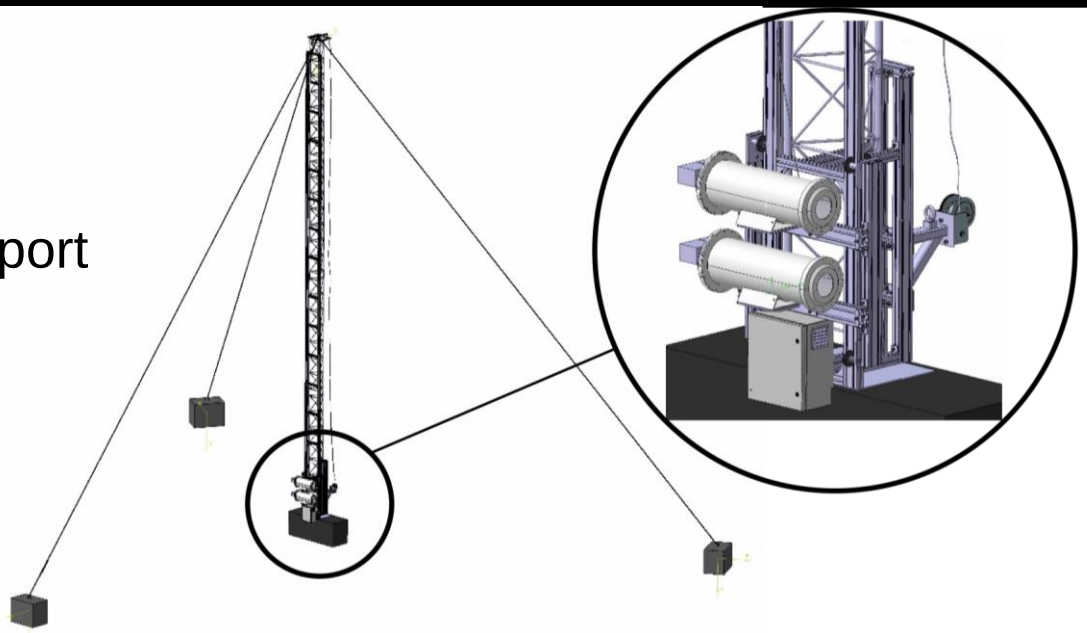
Cameras

Fig: High speed camera tower with accompanying support and camera enclosures



- Photron AX200 monochrome camera
  - Max. pixel resolution: 1024 x 1024
  - Max. frame speed: 6,500 fps at 1 megapixel
  - Captures the combustion flame front
- Phantom v2512 colored camera
  - Max. pixel resolution:1280 x 800
  - Max. frame rate: 25,700 fps
  - Wide-angle view capturing the shock wave created from the blast

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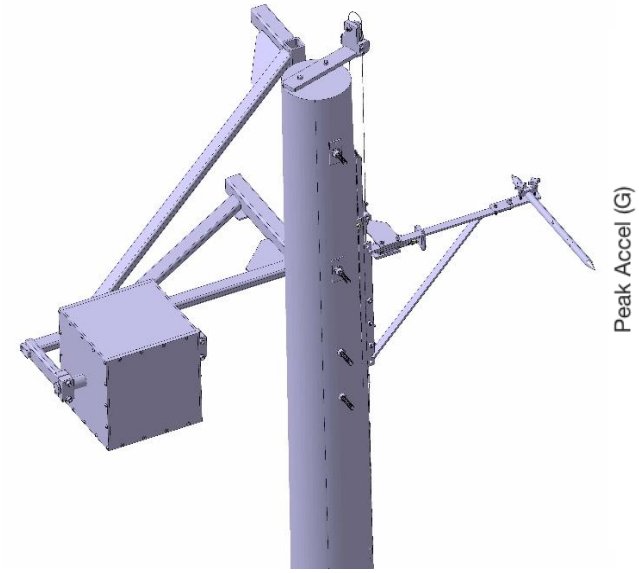
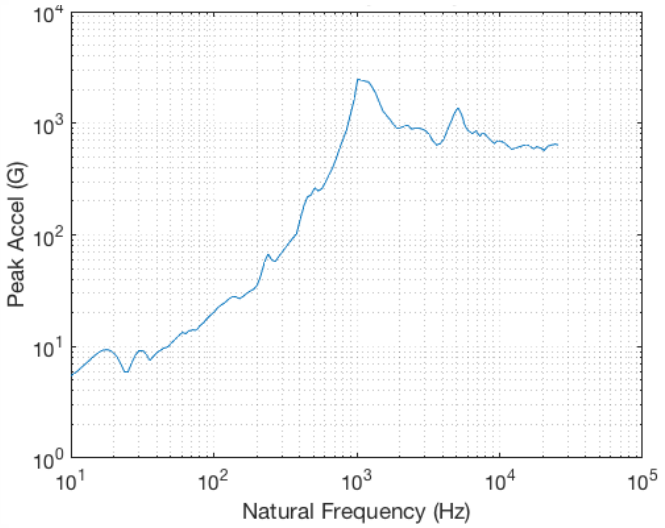
Instrumentation

- Long distance acoustic sensors
  - PCB 377C10 piezoelectric microphone
- Triaxial Accelerometers mounted inside witness object
  - +-500g pk PCB Piezoelectric 356A02

Triaxial accelerometer mounted to welded stud plate inside witness object



CAD of witness object mounted on the pole with pressure probe



SRS of 16-ft diameter balloon CH4-GO2 blast event at 50 ft. from COE

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Instrumentation

- Sensor arm with pressure probes mounted inside the balloon for the last test
  - PCB Piezoelectronics model 113B26 ICP pressure sensors

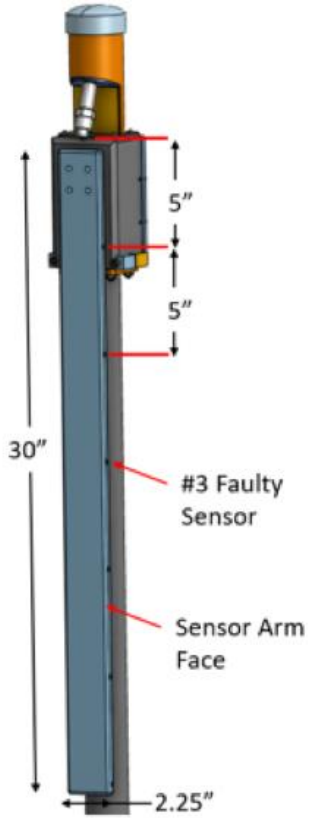
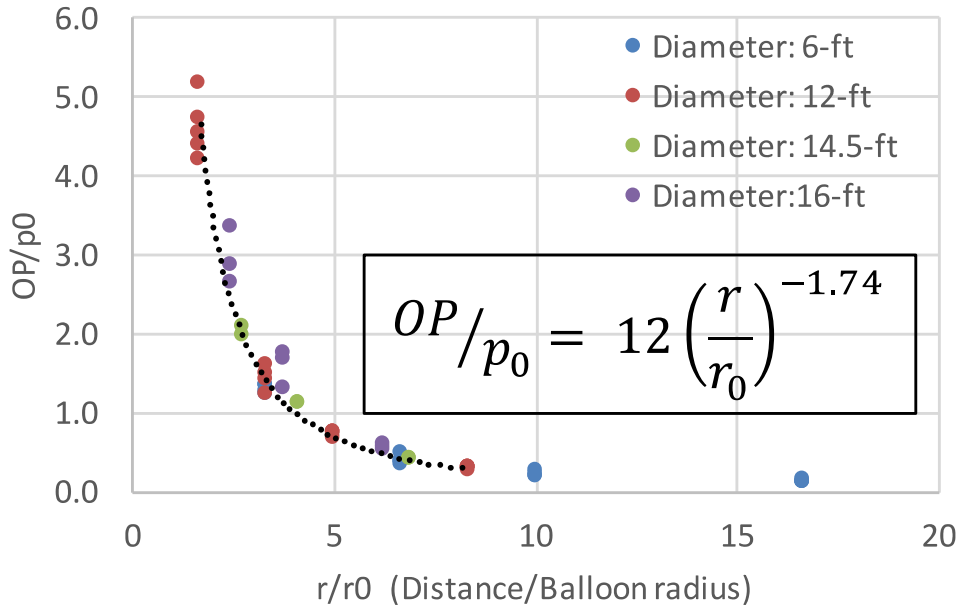


Fig: CAD diagram of Sensor arm dimensions and specifications

Fig: Sensor arm after the test

Overpressure curve fit



- As $r \rightarrow r_0$, i.e. at the edge of the gas cloud $OP \rightarrow 180psi$
- $\mathbf{OP_{max} \sim 220psi}$ to account for increase with eq. ratio and 10% margin

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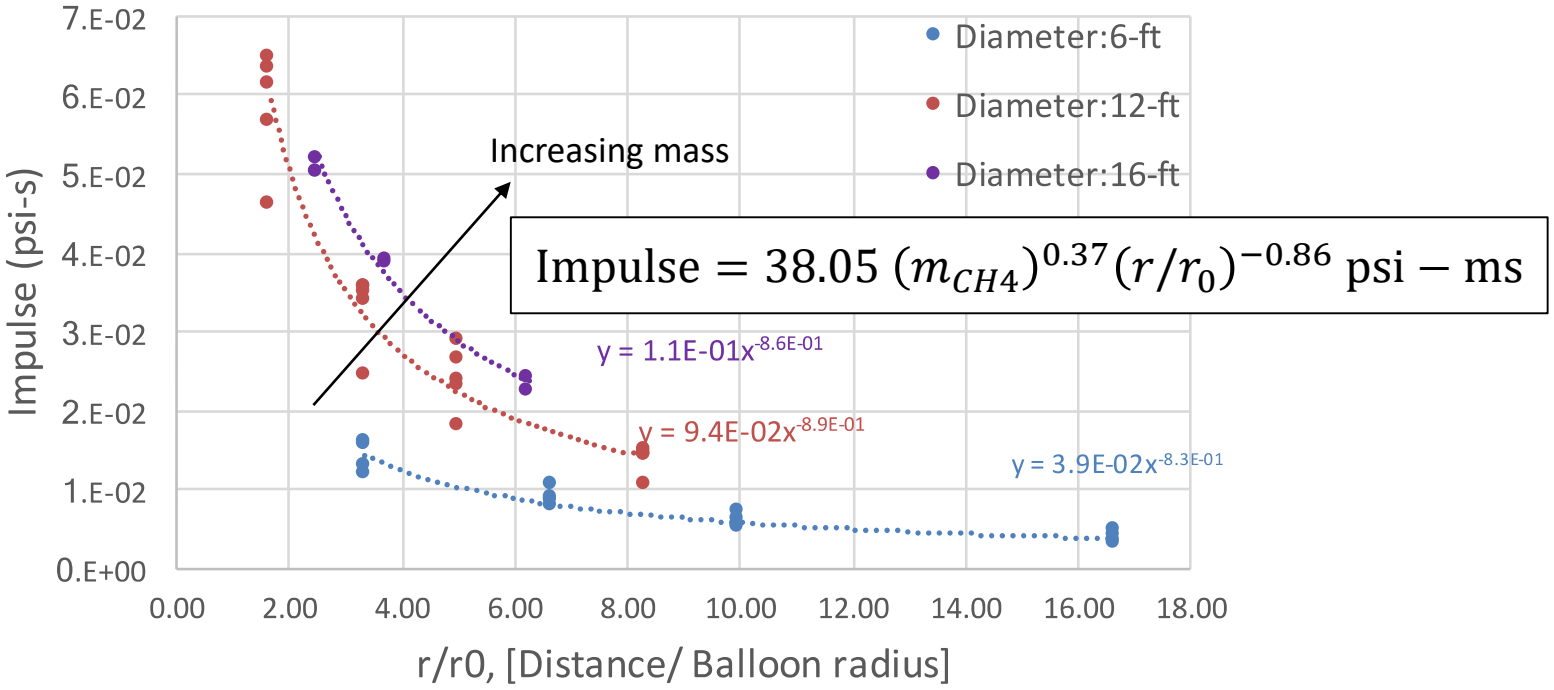
Impulse



- As Impulse decays with scaled distance, it increases with increasing mass.
- The autoignition limit on impulse needs to be verified in the cryogenic test

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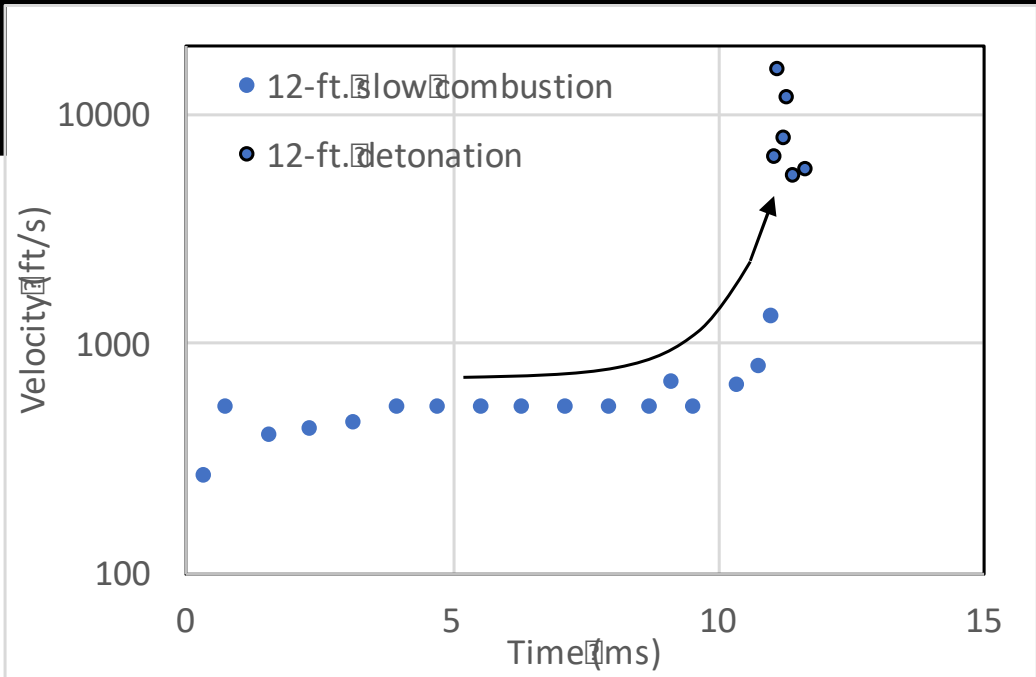
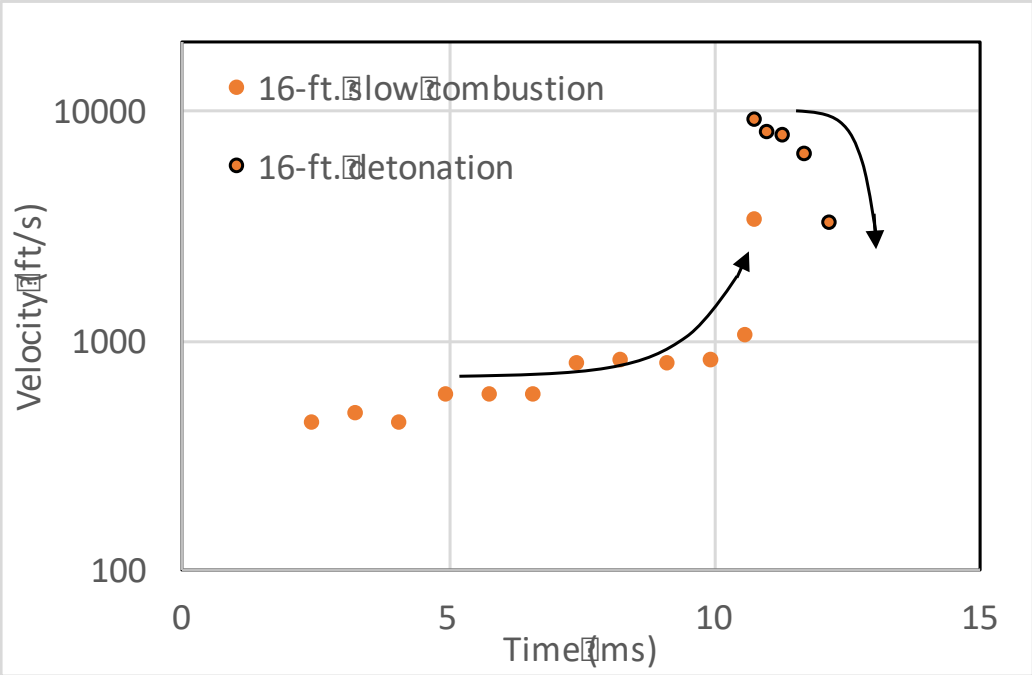
16 ft Methane/Oxygen Video

Flame speeds

- Flame speed is based on speed of burning gas outwards from the ignitor till it reaches the balloon ~560-600ft/s
- Subsequent detonation around 5000-15000 ft/s





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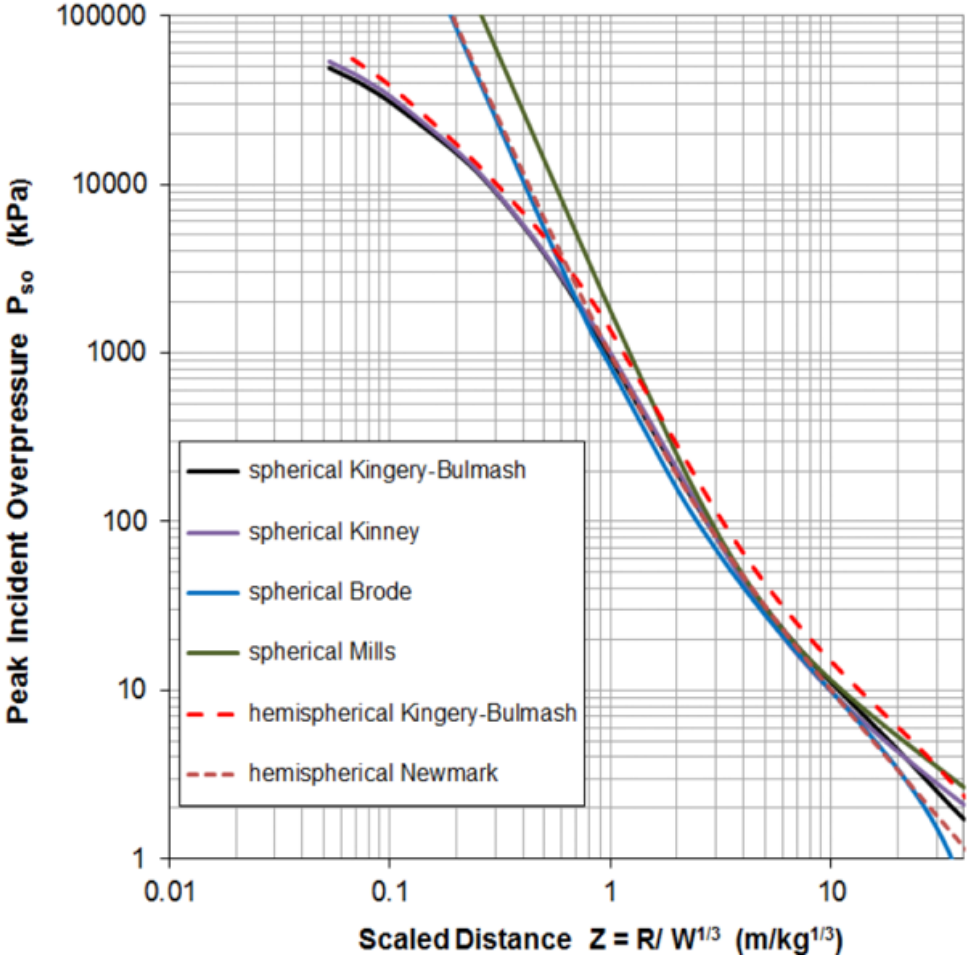
TNT Equivalency

- Equivalent weight of TNT



- Inaccurate representation of vapor cloud explosions

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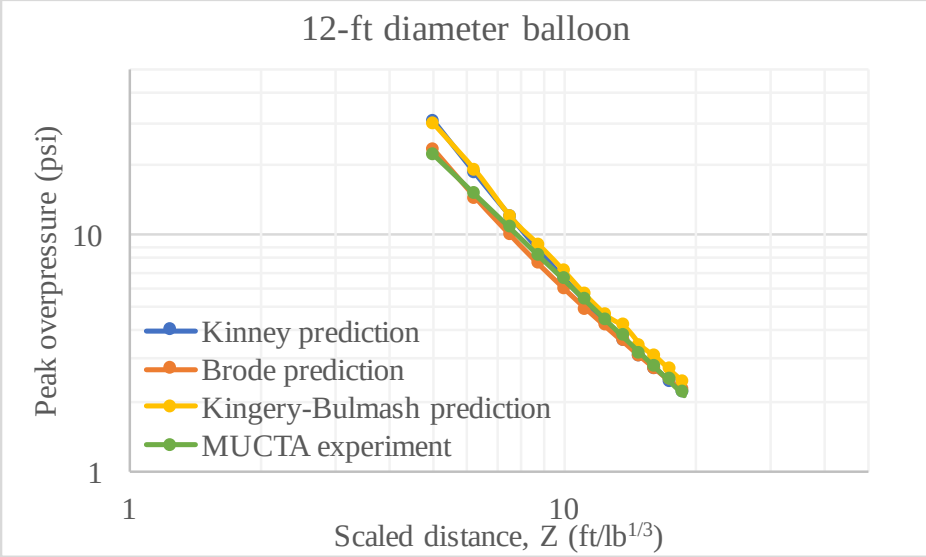
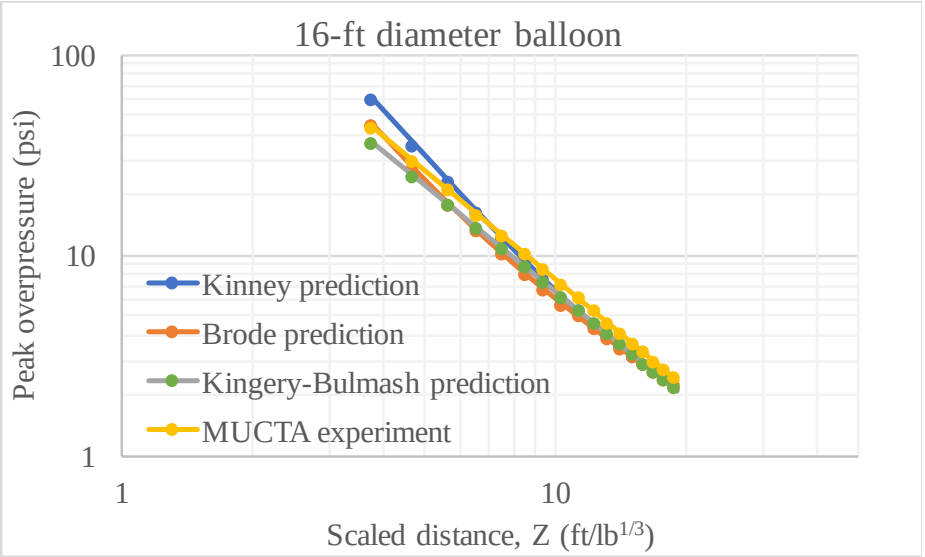
Overpressure comparison





- In general, TNT based predictions are higher than MUCTA in the near field, and matches the far field data.
- The discrepancy increases with increasing fuel mass
- The comparison with cryogenic explosions might reveal a larger discrepancy

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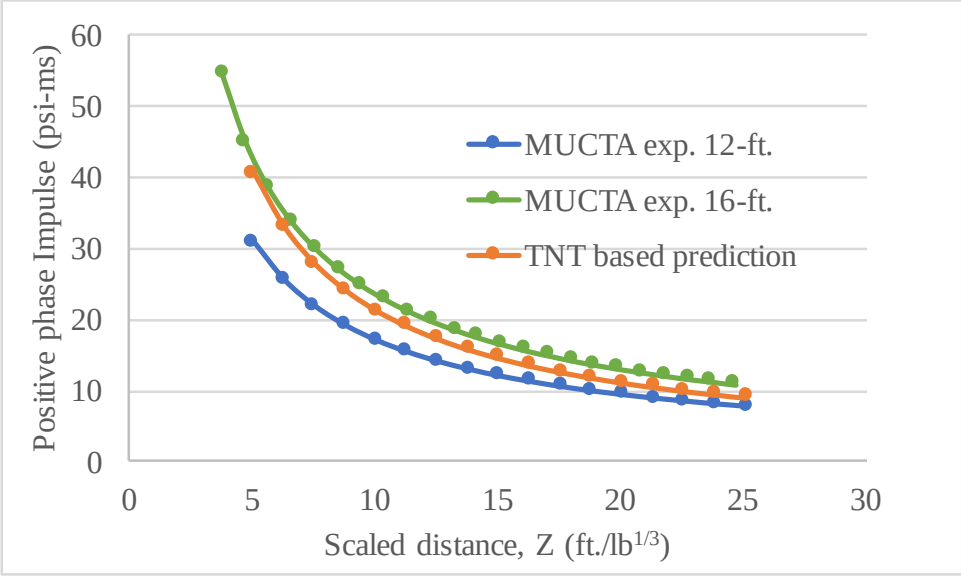
Impulse comparison



- TNT predicted impulse is only dependent on the scaled distance
- MUCTA models impulse decay with scaled distance and a simultaneous rise with increasing mass of fuel involved in the explosion
- Limiting of impulse with autoignition needs to be modeled.

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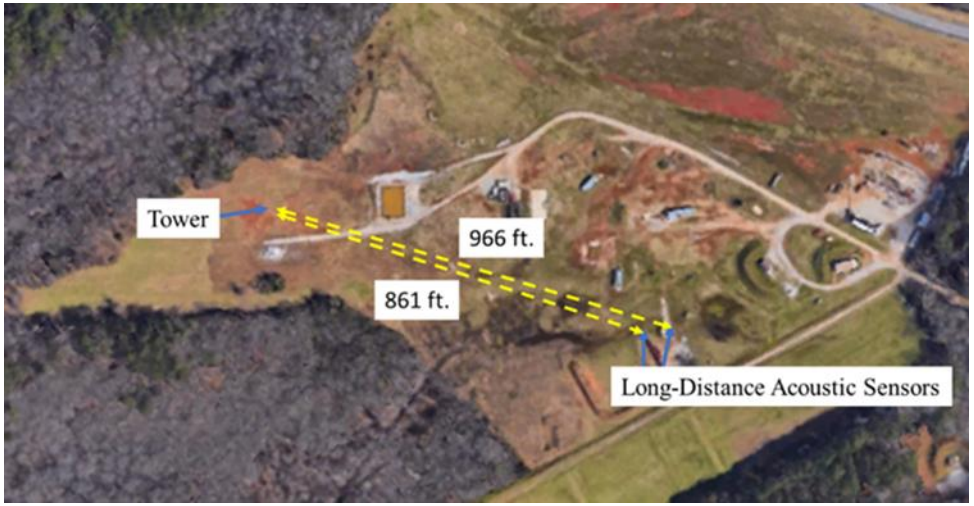
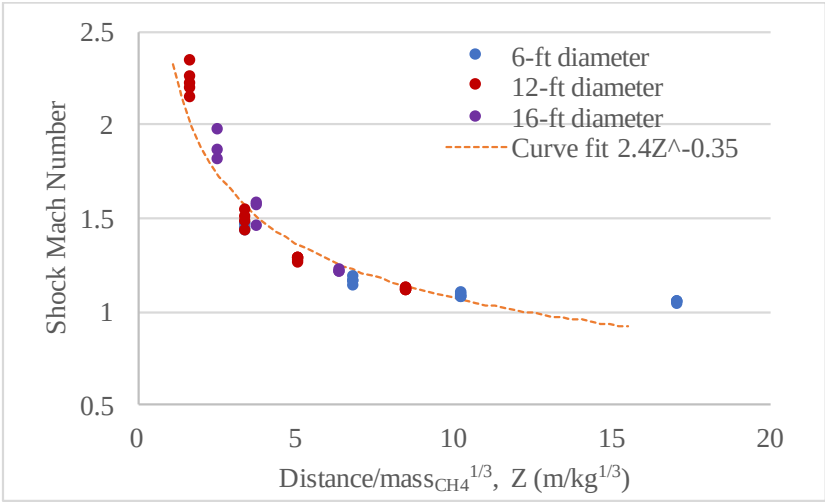
Long Distance Acoustics





- Blast shock waves decay to acoustic pressure waves at far field distances from the COE
- Overpressure and impulse models are not applicable
- Community noise and safety around test ranges are affected by blast testing.

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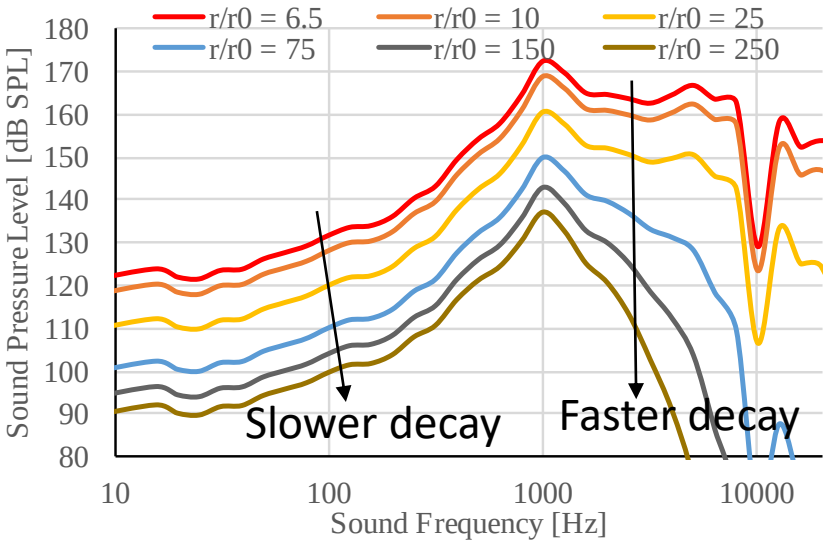
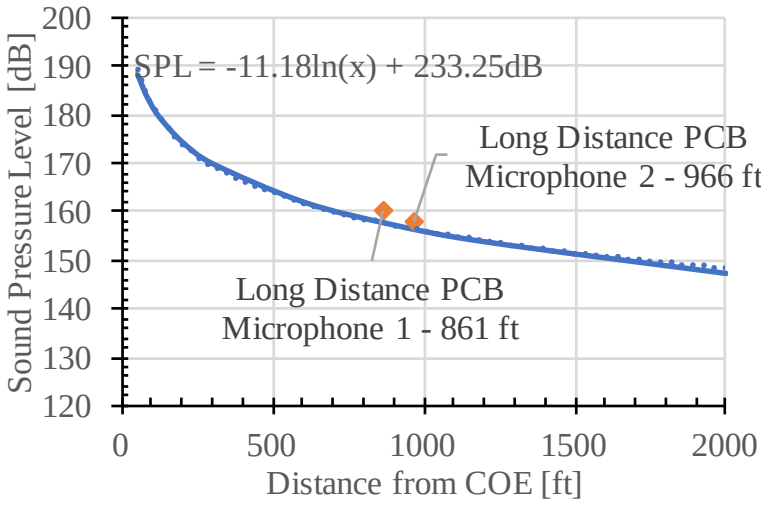
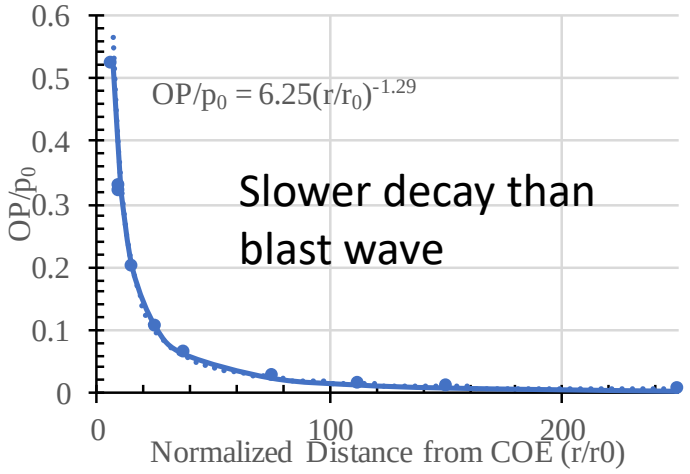
Low frequency propagation





- ISO 9613-1:1993 standard is used to model the acoustic decay
- High frequency content is rapidly absorbed by air, low frequency content is transmitted through longer distances and through any structures in the way.
- The waves inside the room can get amplified and cause room modes to occur- result in building damage through a resonance phenomenon similar to the amplification of sound in a drum



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Conclusions

- The images from the combustion zone shows that the methane-oxygen mixture transitions from a deflagration to detonation (DDT) in most of the tests.
- This bounds the pressure to an upper limit at the edge of the gas cloud irrespective of the volume
- Overpressures decay as a power law of r/r0
- Impulse decays with r/r0 and increases with mass.
- Acoustic decay is modeled to represent community noise and safety issues.

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Future Work

- Phase 1 – gas explosion tests to set probable envelope -completed
- Phase 2 – cryogenic explosion tests to establish final QD and compare with TNT based equivalent weights -ongoing
- Phase 3 – ground impact to establish public safety risks -TBD

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Acknowledgements

- ULA Contract FA8811-16-9-0004
- Douglas Gogel, ULA
- Redstone Test Center (RTC) Huntsville, AL

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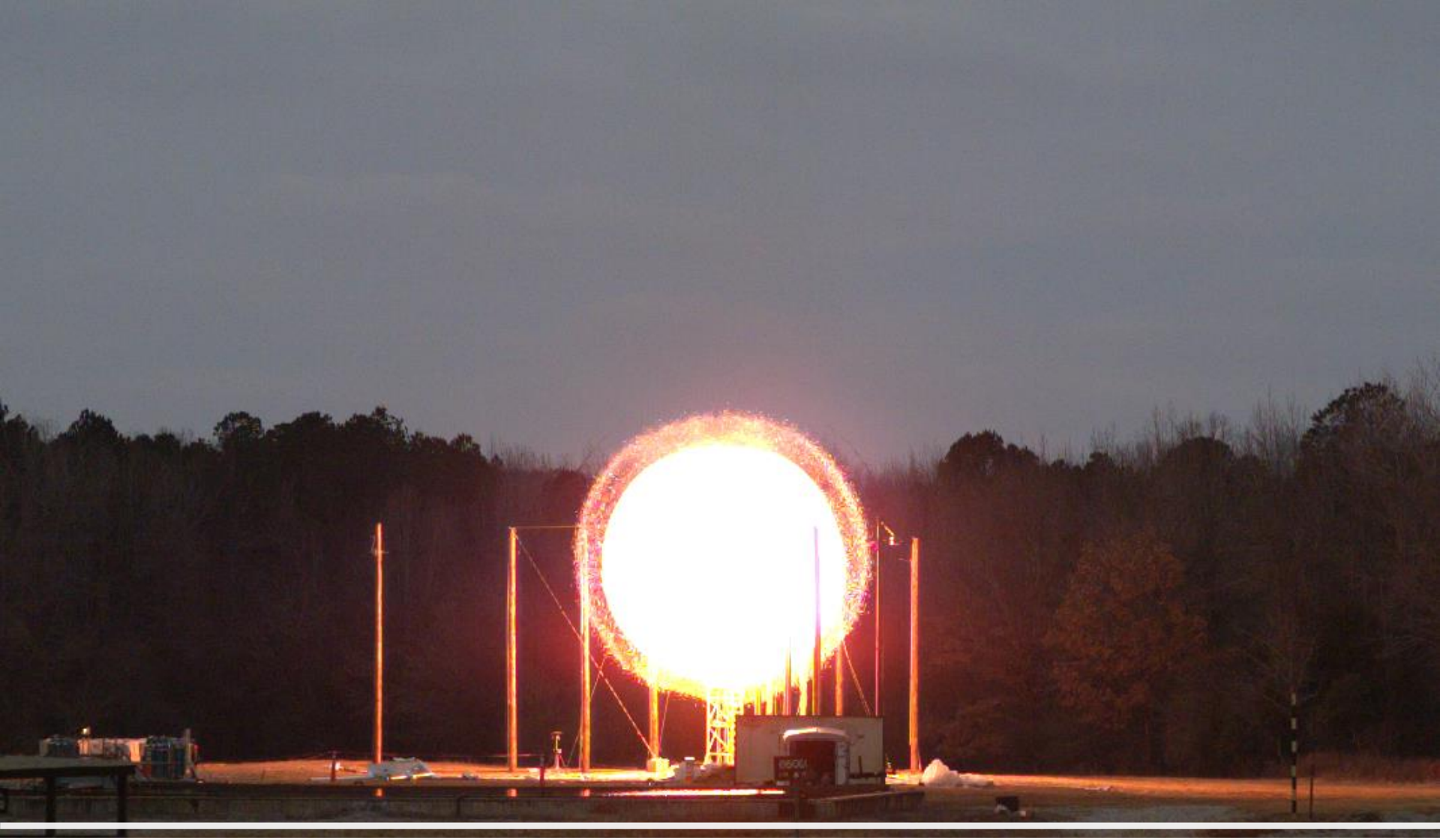

THANK YOU