Oak Ridge National Laboratory

Shatter Spray Analysis of the JET, KSTAR, and DIII-D Shatter Tube Designs

IAEA Technical Meeting on Plasma Disruptions and their Mitigation (Virtual)

July 20-23rd, 2020

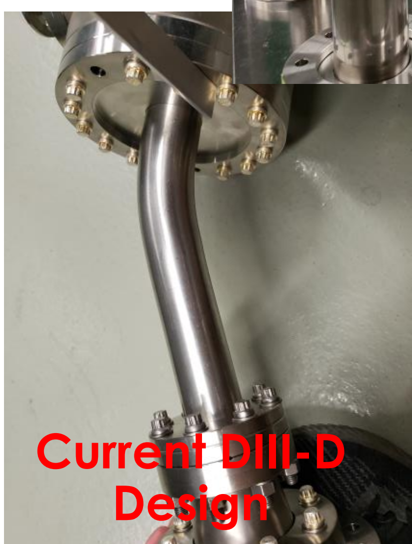
T. E. Gebhart, L. R. Baylor, S. J. Meitner, and D. A. Rasmussen

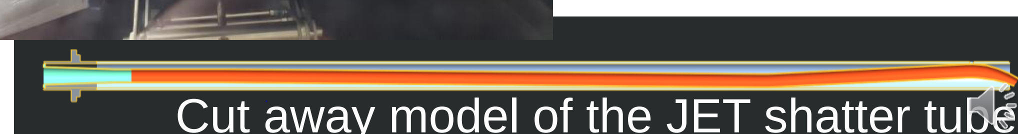
ORNL is managed by UT-Battelle, LLC
for the US Department of Energy

US iter
U.S. DEPARTMENT OF ENERGY

Shatter Tube Designs

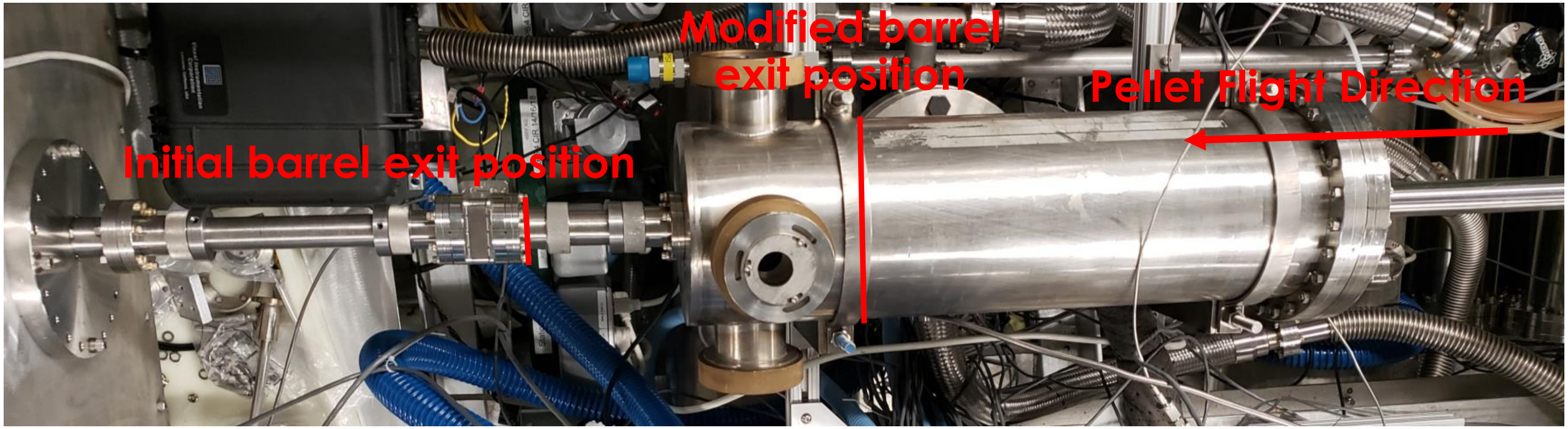
- Various shatter tube designs have been lab tested and implemented on tokamaks over the last ~12 years
- All designs are capable of shattering pellets and the fragment size distributions for single impact designs are mostly understood (angle and pellet speed dependent).





Propellant gas issues

- The SPI test setup in the ORNL pellet lab did not have any effective pumping gaps to remove propellant gas
- This was thought to have a major impact on the dynamics of the shatter plume
- Pellets were fired without any major changes then modifications were made to remove an estimated 80% of the propellant gas, then a second round of shots was conducted



Shot parameters

- Parameters:
  - ~58 bar, helium propellant
  - 2 ms pulse on valve
  - Pellets frozen at ~8K, fired at 12.5K
  - 12.5 mm pellets (largest on JET)
  - L/D's were all ~1.5-1.6
  - Shell thickness is 0.5 mm

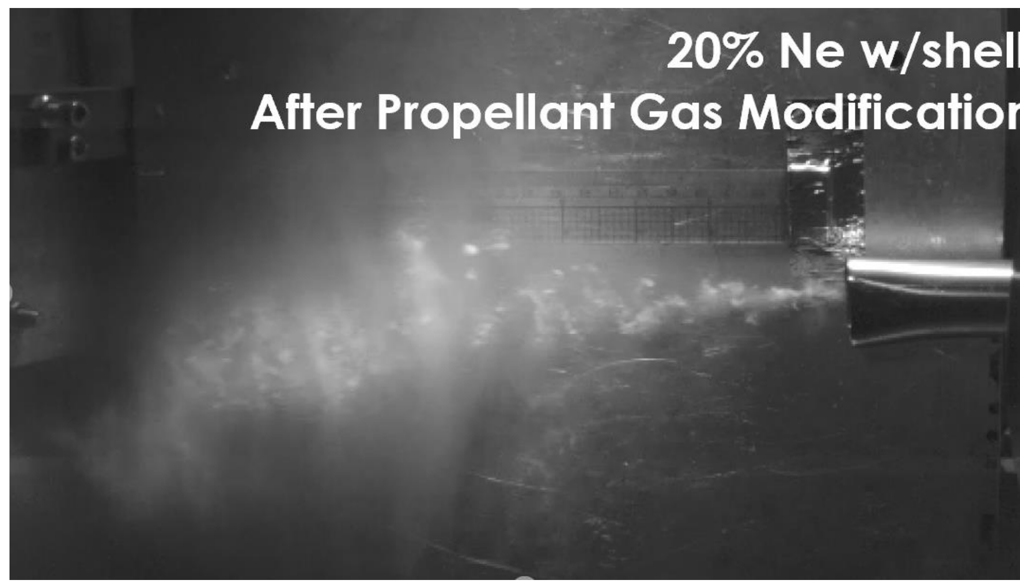
- Before propellant gas modifications with propellant valve (for comparison)
  - 5% Ne w/shell
  - 20% Ne w/shell
  - Pure Ne w/shell

- After modifications
  - Propellant valve
    - 5% Ne w/shell
    - 20% Ne w/shell
    - Pure Ne w/shell
  - Punch
    - 5% Ne w/shell
    - 20% Ne w/shell
    - Pure Ne w/shell

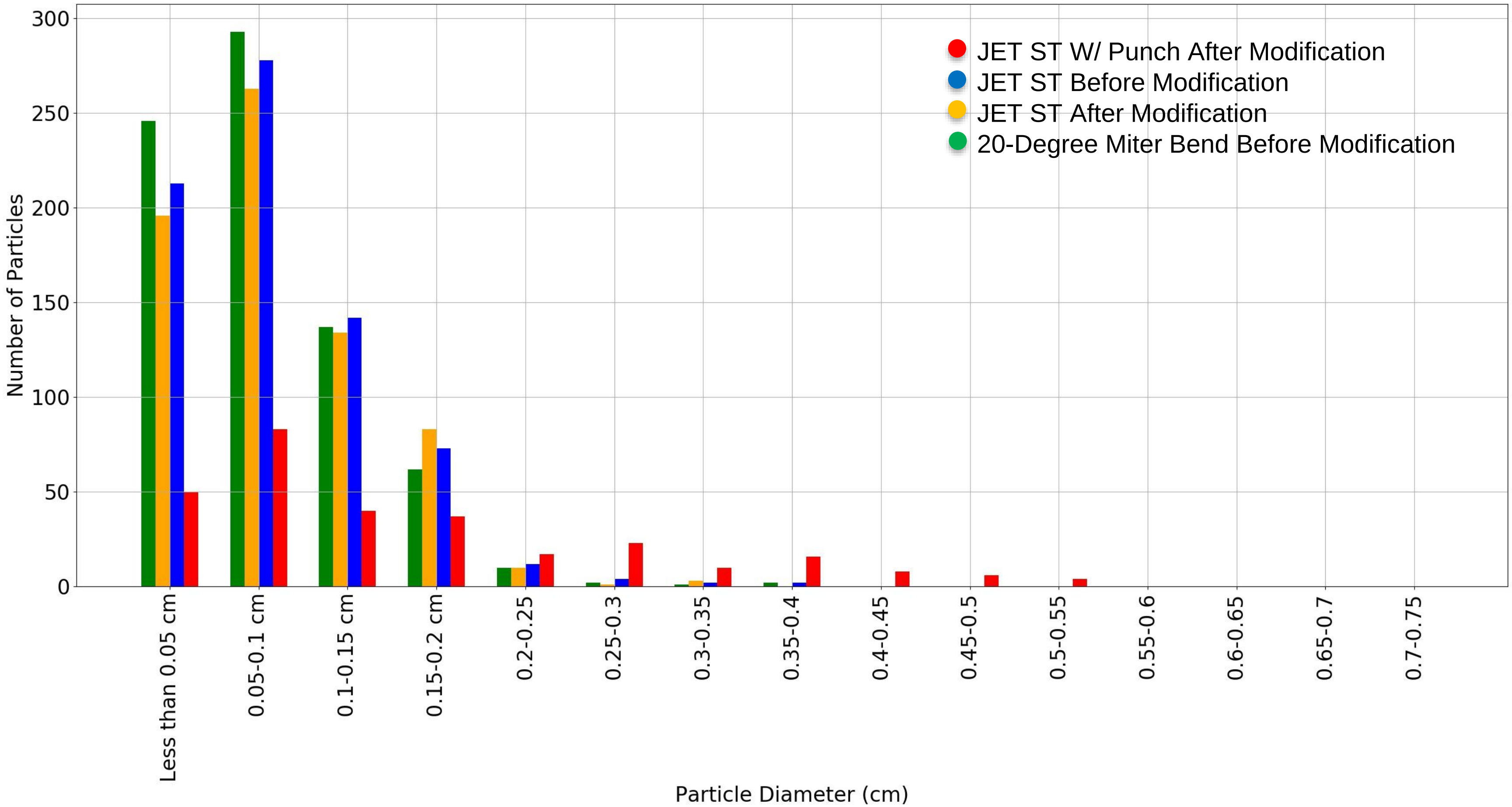
Impact of propellant gas on shatter spray (videos)

- Plume length at ~24 cm from exit of ST is 0.6 ms
- We normally see rotation of the plume with our test setup, but the geometry of the JET shatter tube may negate those effects

- Plume length at ~24 cm from exit of ST is 1.15 ms
- Tail of small particles present
  - Small particles would more easily be accelerated by entrained propellant gas
- Propellant gas is not expected to make an impact on the shattering mechanics, only on the post-shatter fragment acceleration



Measured fragment size distribution for a pure neon pellet w/ 0.5 mm thick D[2] shell

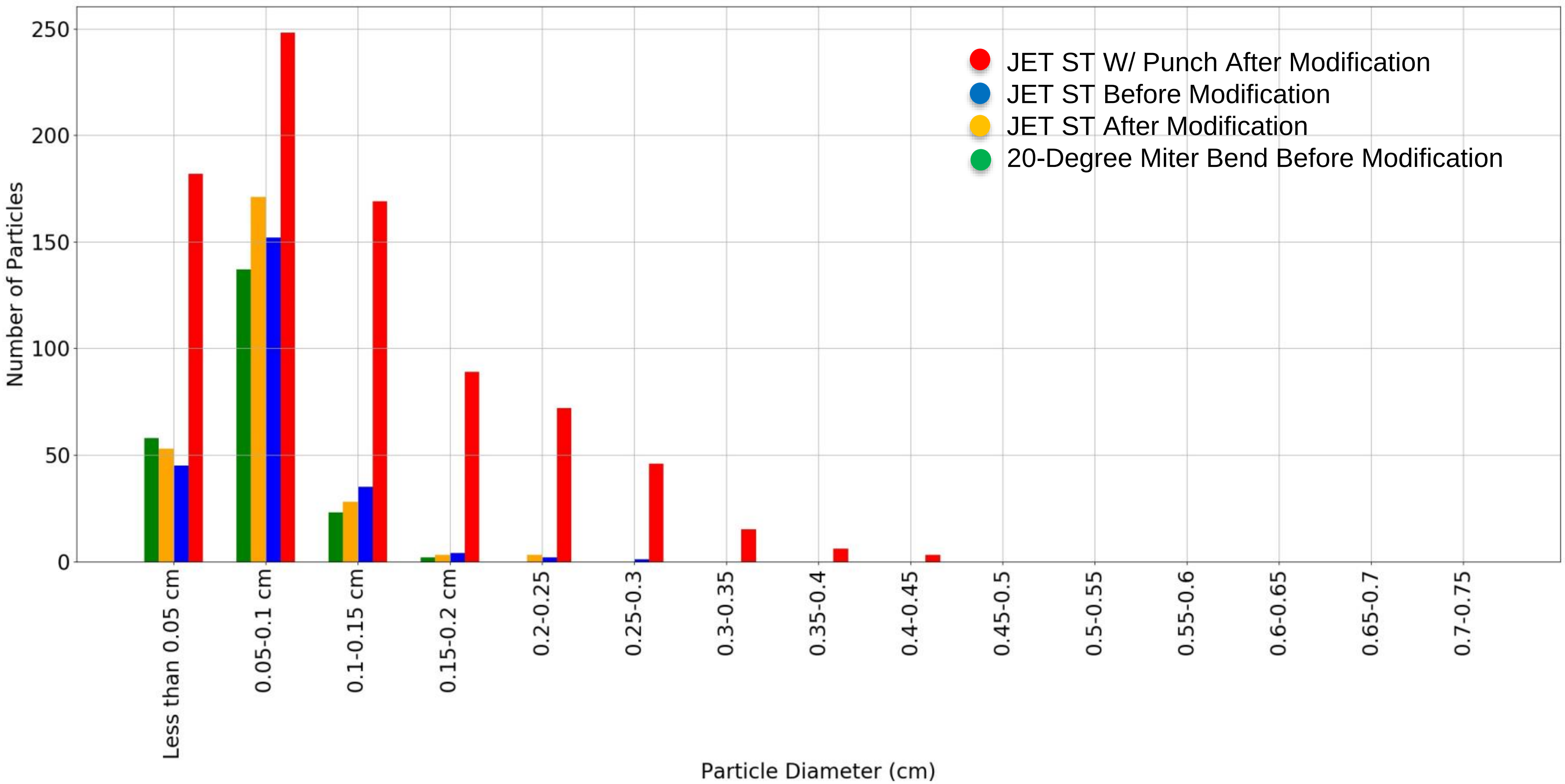


The percent of original mass accounted for in the plume for each case is 25 (before modification), 23 (after modification), and 86 (with punch)

OAK RIDGE National Laboratory

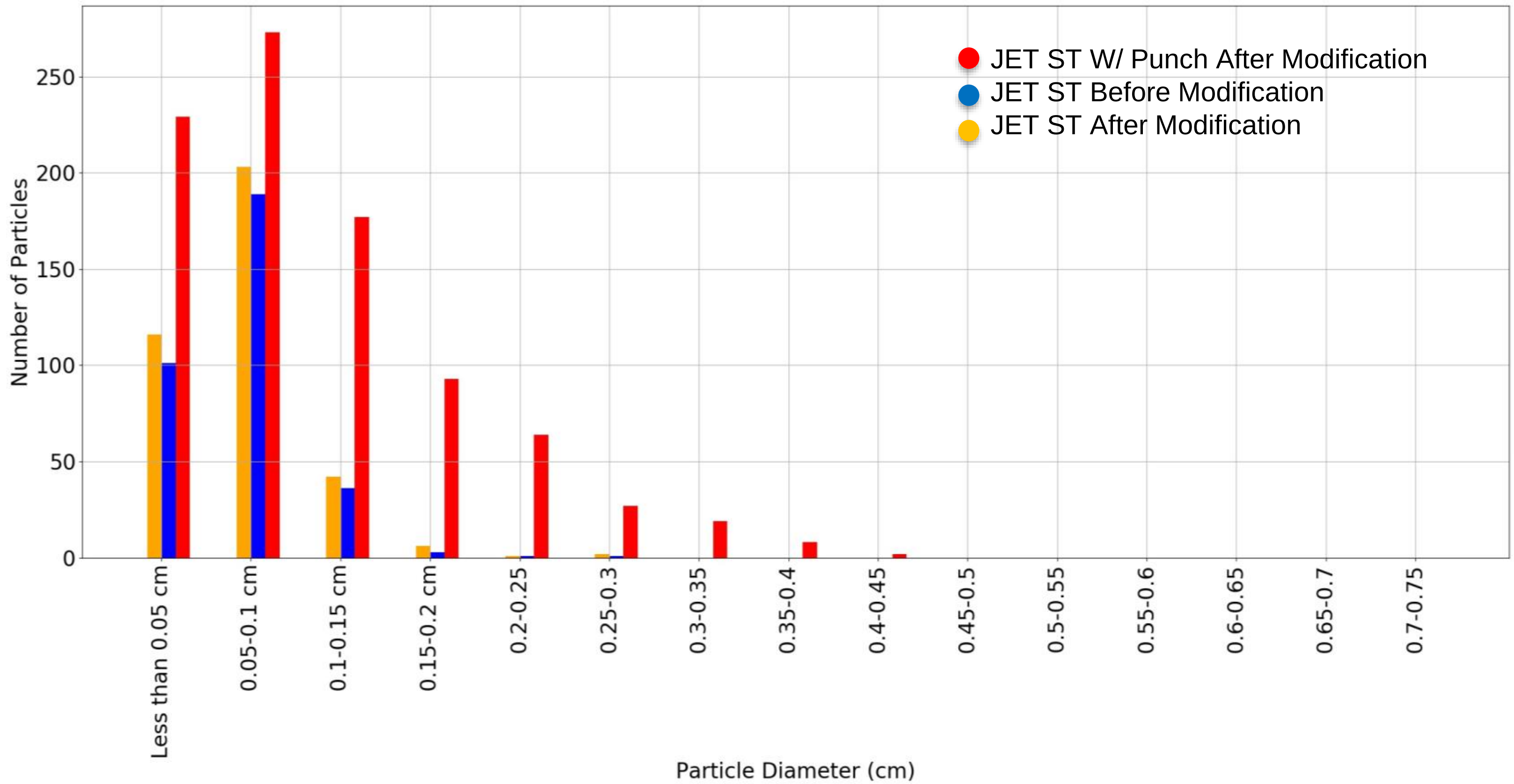
US iter

Measured fragment size distribution for a 20% neon pellet w/ 0.5 mm thick D^2 shell



The percent of original mass accounted for in the plume for each case is 6.6 (before modification), 4.3 (after modification), and 81 (with punch)

Measured fragment size distribution for a 5% neon pellet w/ 0.5 mm thick D2 shell



The percent of original mass accounted for in the plume for each case is 4.3 (before modification), 5.4 (after modification), and 74 (with punch)

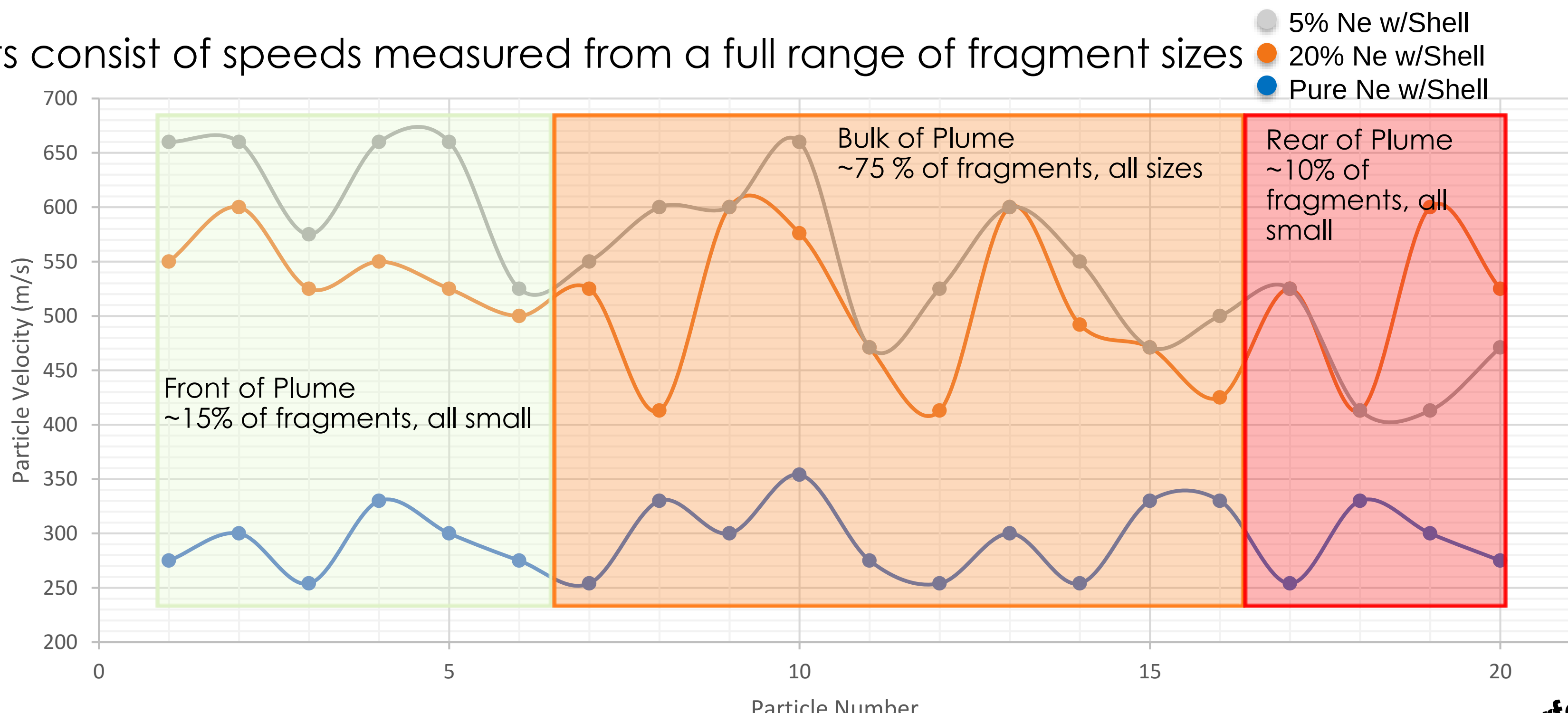
OAK RIDGE National Laboratory
US iter

Shatter plume velocity distribution – No punch, pre modification

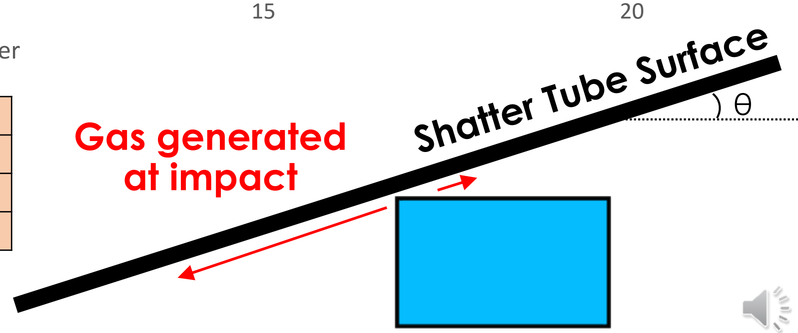
Speeds of 20 random fragments were manually measured at different points in the shatter plume.

~99% of the plume mass is in the bulk of the plume (not 99% of the original pellet mass)

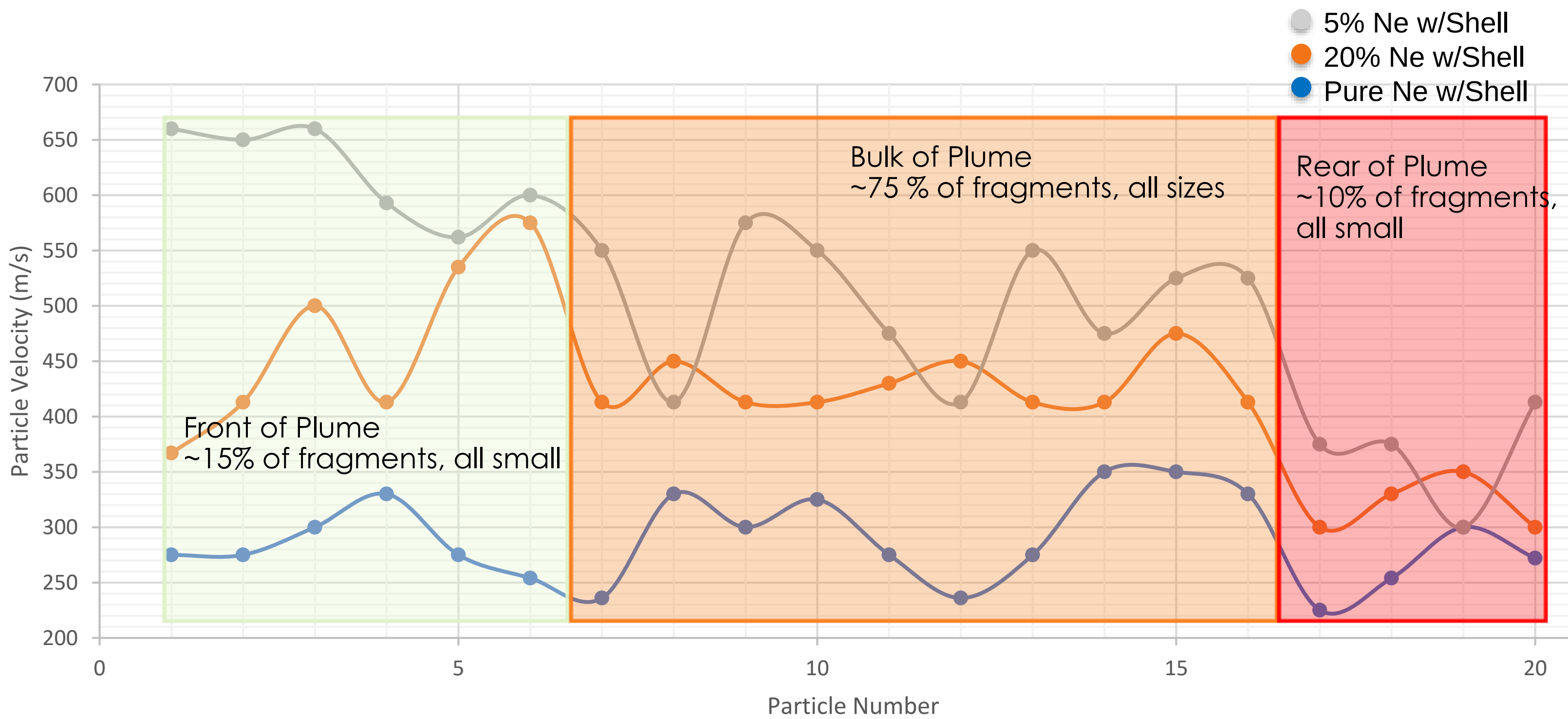
Plots consist of speeds measured from a full range of fragment sizes



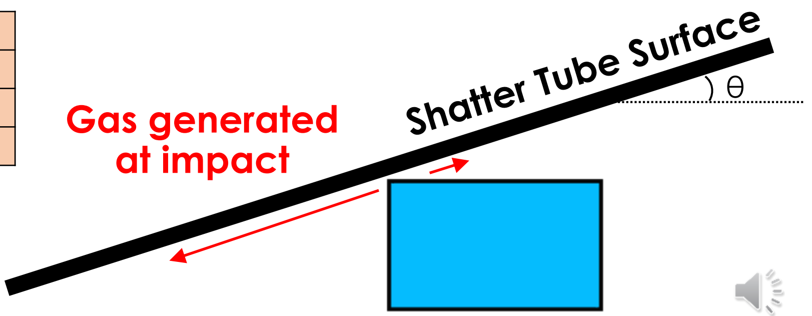
No Punch, Before Mod	Pure Neon W/ Shell	20% Neon w/ Shell	5% Neon w/Shell
Max Velocity	354	600	660
Min Velocity	254	413	413
Average Velocity	293.7	514.95	554.45



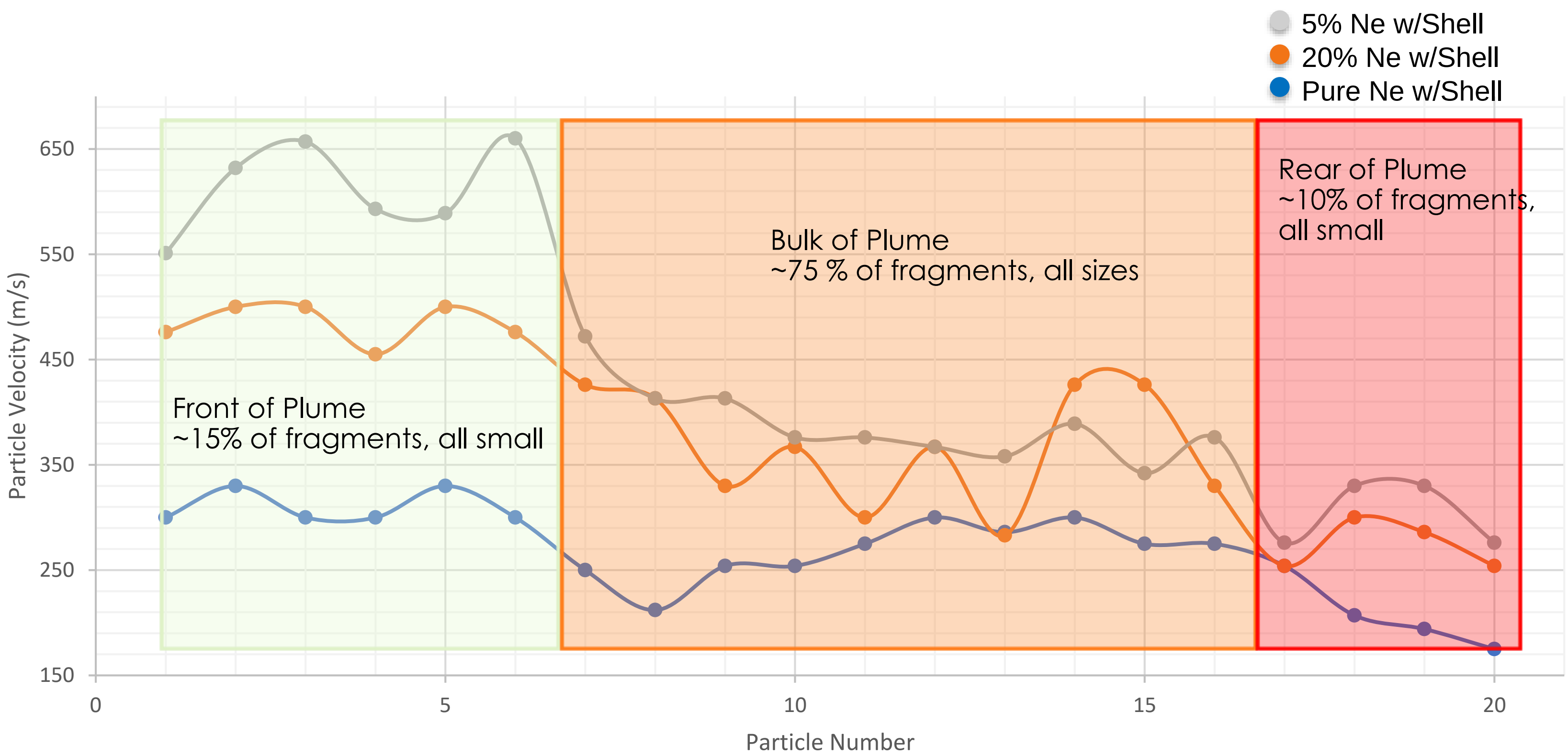
Shatter plume velocity distribution – No punch, post modification



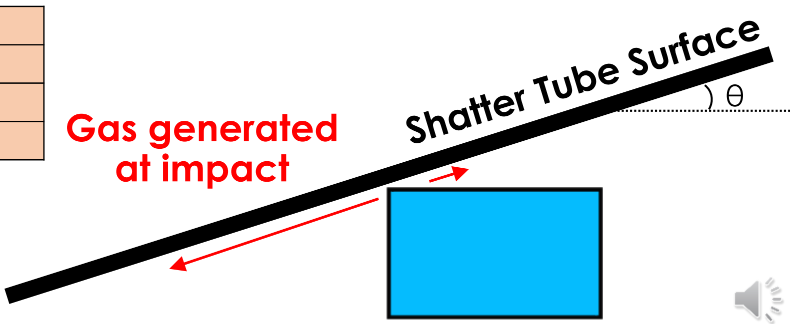
No Punch, After Mod	Pure Neon W/ Shell	20% Neon w/ Shell	5% Neon w/Shell
Max Velocity	350	575	660
Min Velocity	225	300	300
Average Velocity	288.35	418.3	511.95



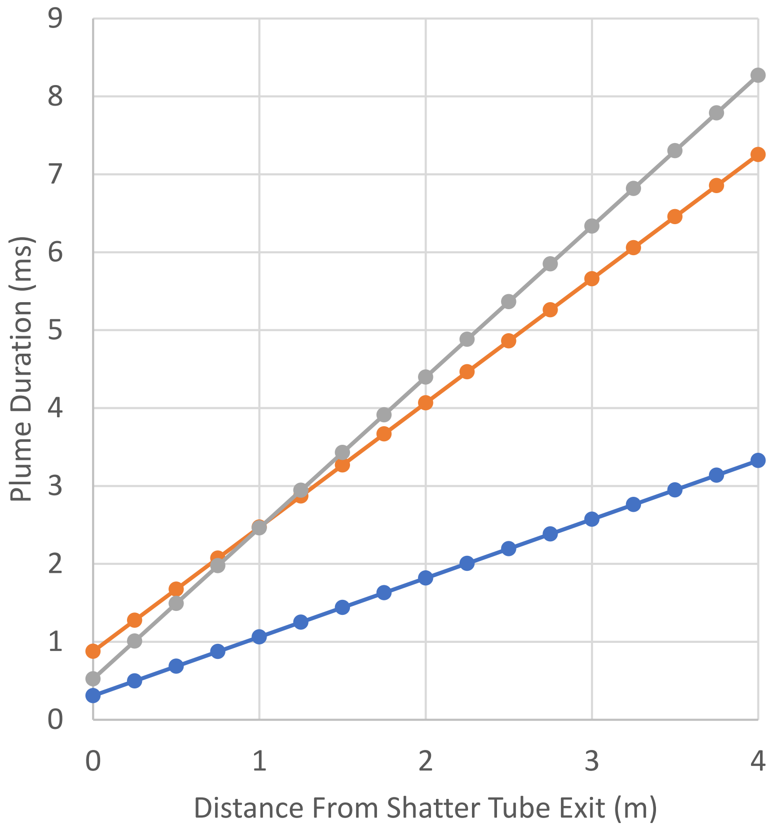
Shatter plume velocity distribution – With punch, post modification

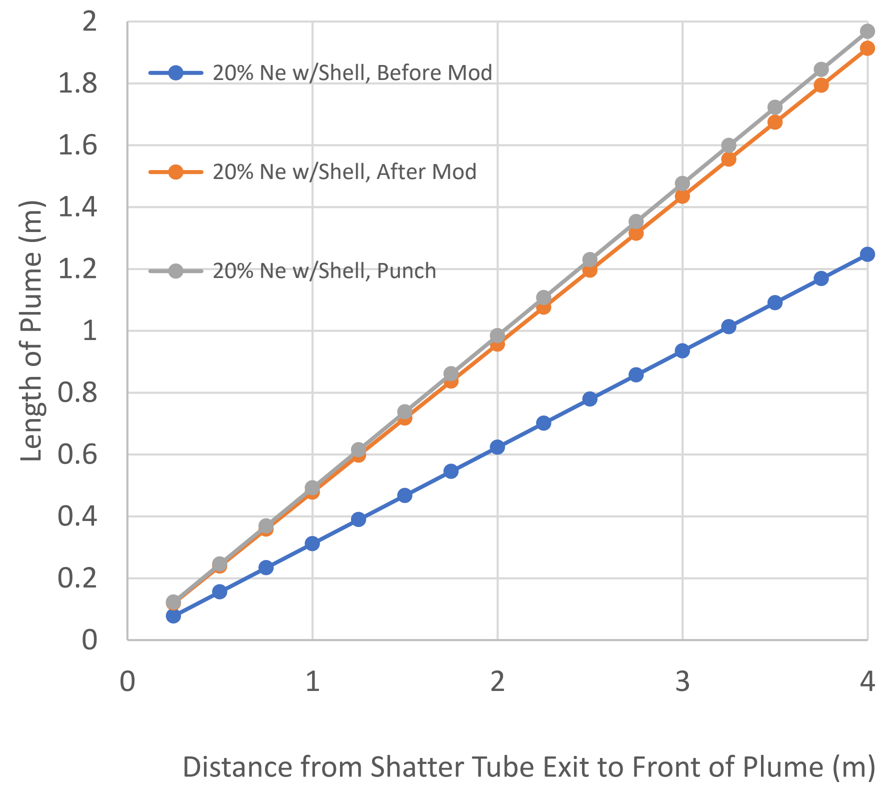


W/ Punch – No Prop Gas	Pure Neon W/ Shell	20% Neon w/ Shell	5% Neon w/Shell
Max Velocity	330	500	660
Min Velocity	175	254	276
Average Velocity	268.55	383.45	438.8



Extrapolated shatter plume time duration and length from exit of shatter tube – 20% neon with shell





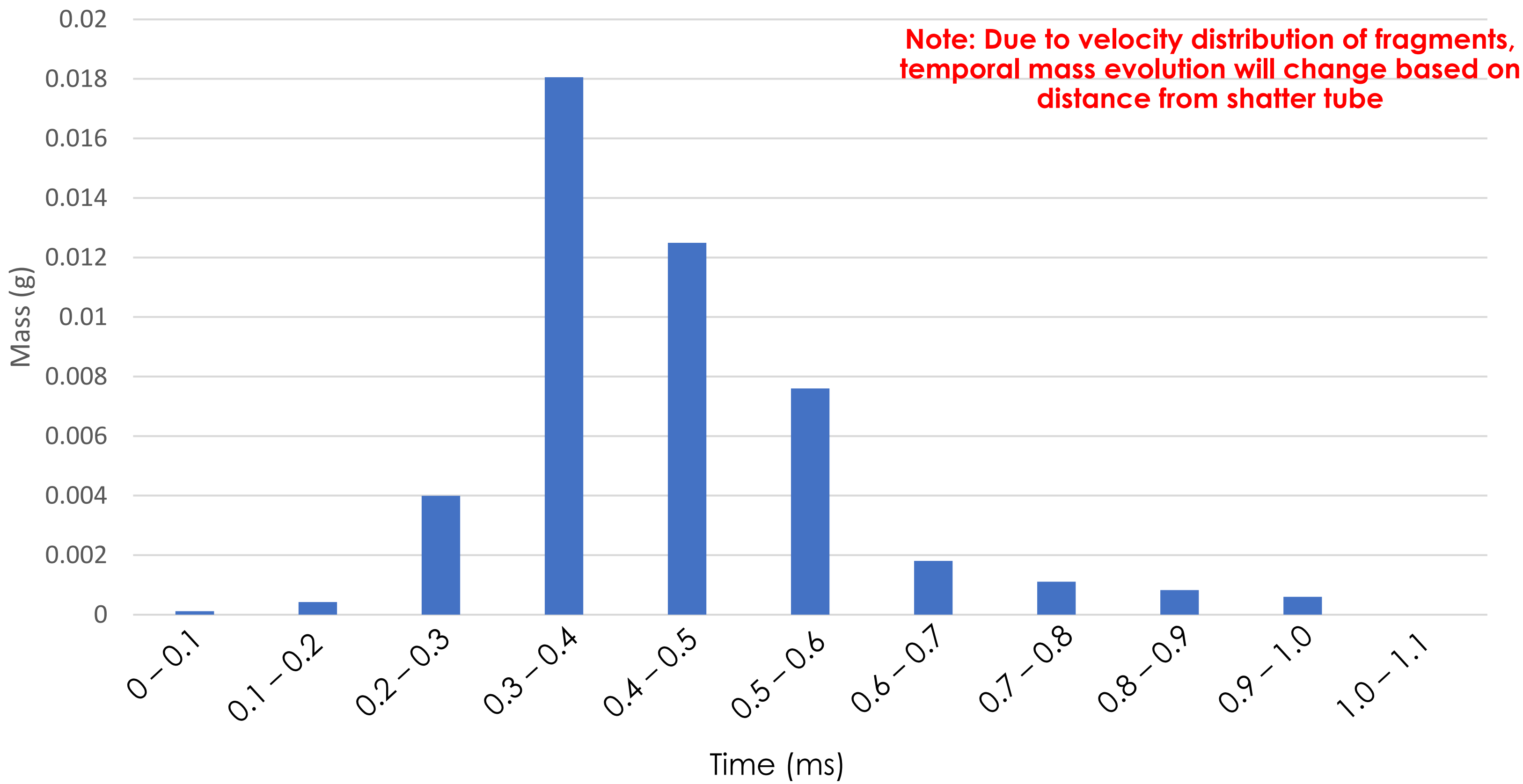
Plume lengths and durations were calculated based on the measured velocities from the fastest and slowest fragments measured in the shatter spray

OAK RIDGE National Laboratory

US iter

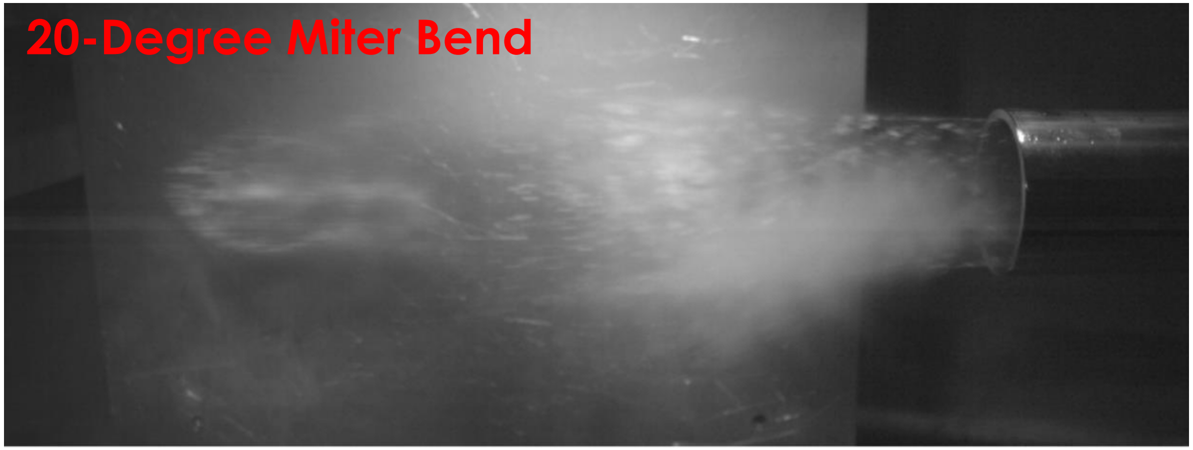
Temporal mass evolution results of a 20% neon pellet (w/shell), post modification

This histogram was generated by counting the number of particles in each size range that pass through a point ~0.15m from the shatter tube exit between set time increments. The total mass of fragments is 0.047 grams (~4.3% of original mass)



Comparison of JET S-bend and 20-degree miter bend, with entrained propellant gas

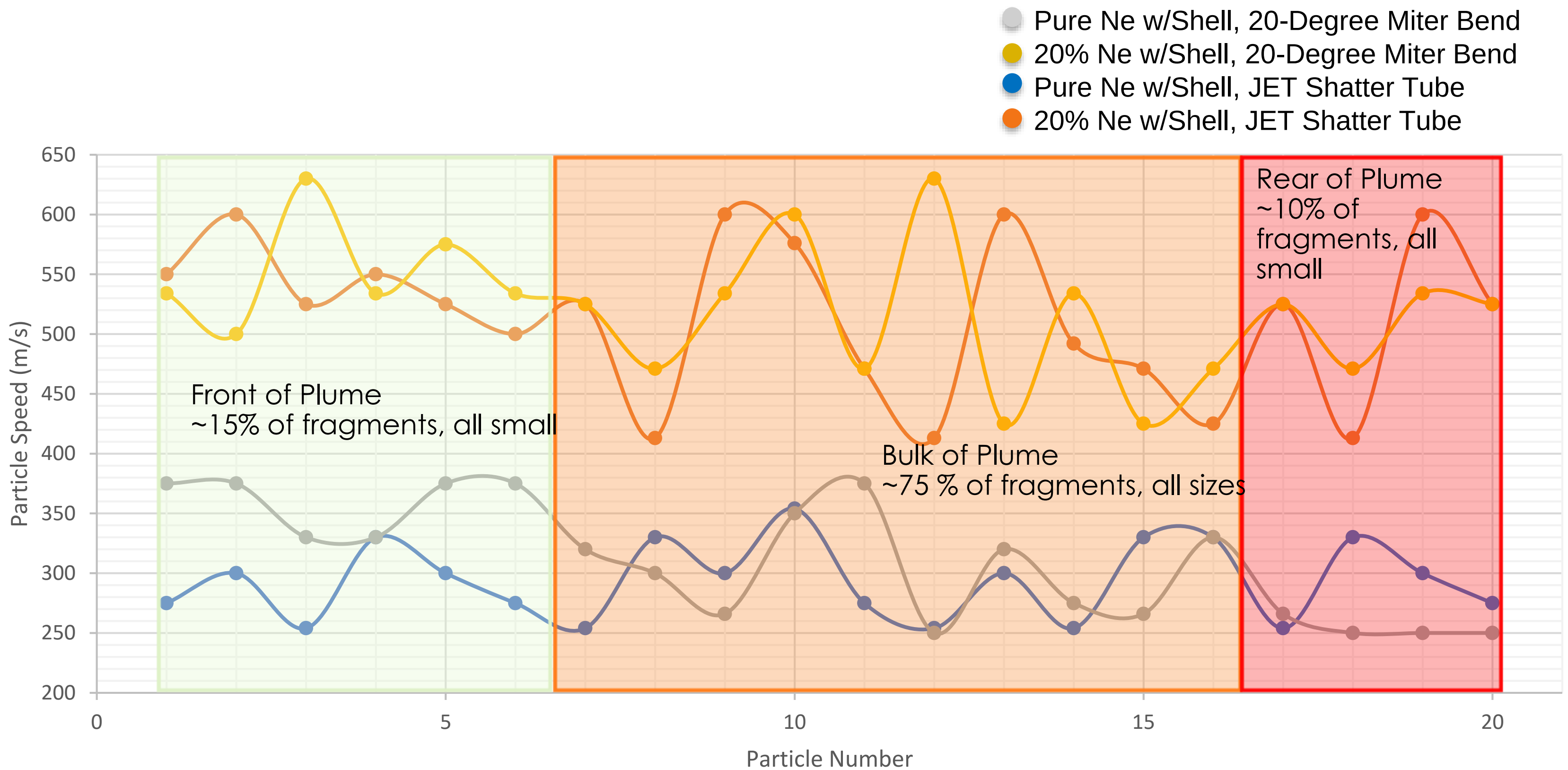
VS.



The initial analysis showed that the entrained propellant gas had little effect on the plume, a comparison of a 20-degree miter bend and the JET shatter tube, with entrained propellant gas was conducted

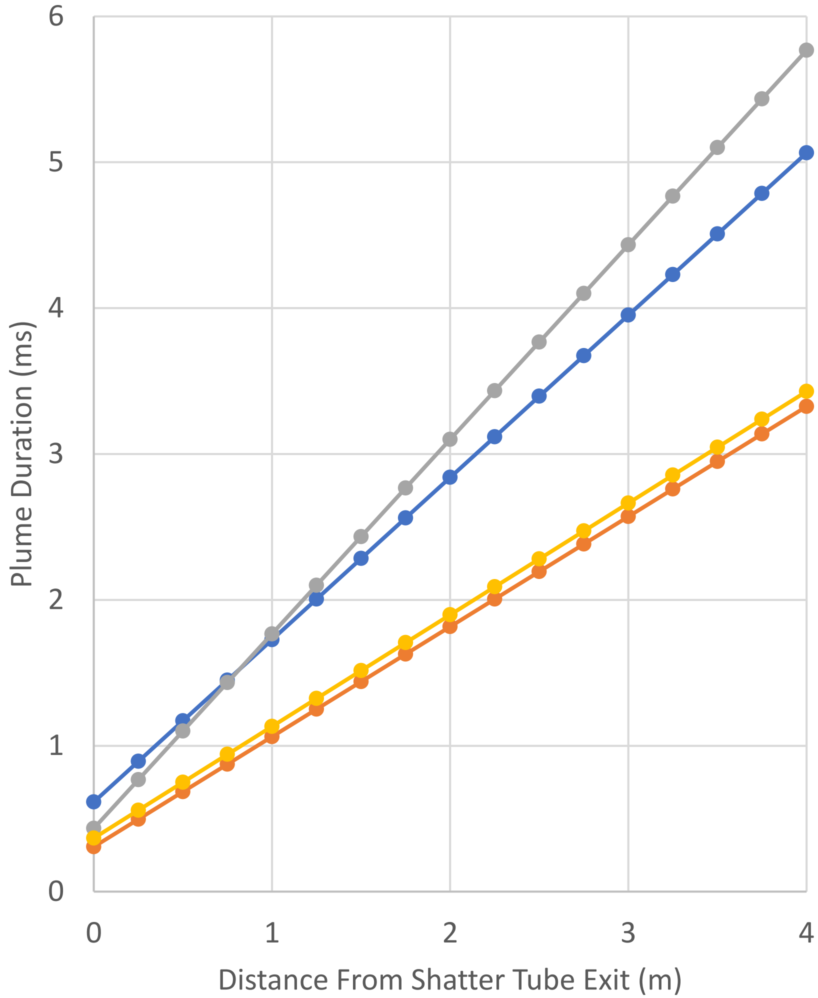
The gas cloud in the top picture disburses slightly after the frame shown. The miter bend pipe diameter is larger, and the impact happens farther back in the tube leaving the gas with more time and volume to expand. Making it much easier to see the fragments earlier in the flight.

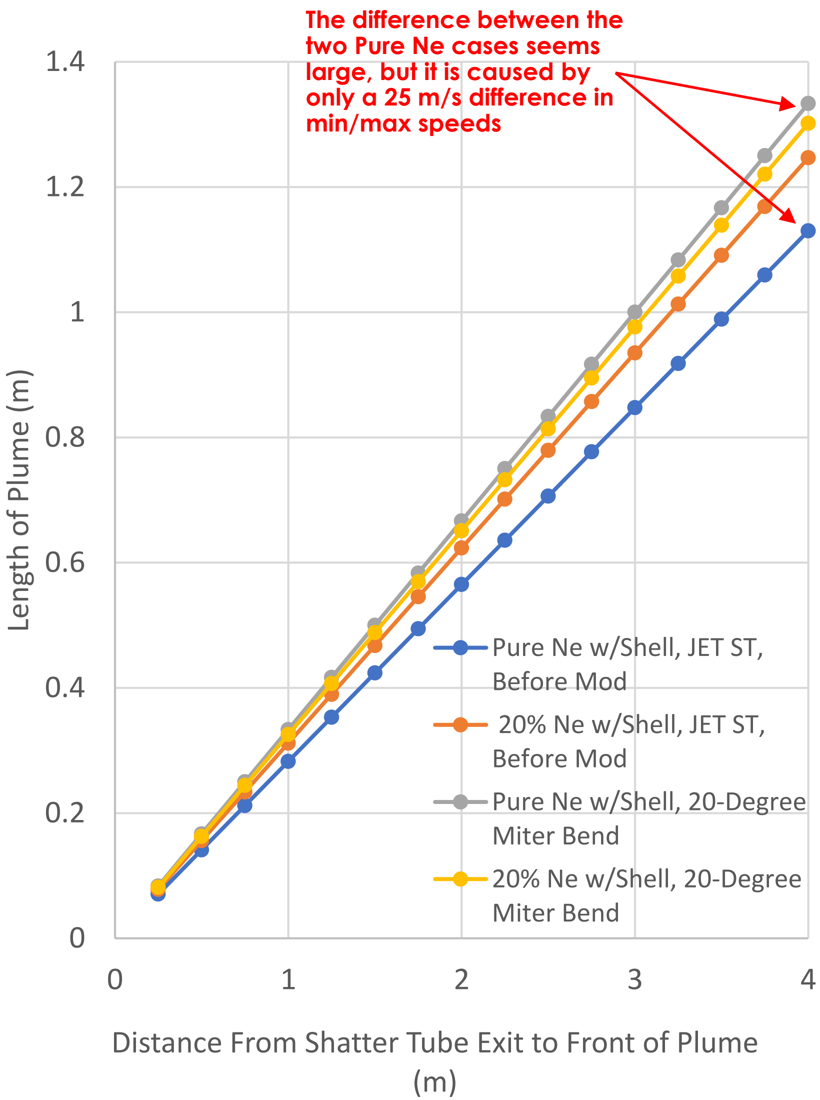
Velocity distribution comparison of JET S-bend and 20-degree miter bend, with entrained propellant gas



	20-Degree Miter Bend		JET Shatter Tube	
	Pure Ne w/Shell	20% Neon w/Shell	Pure Ne w/Shell	20% Neon w/Shell
Min	375	630	354	600
Max	250	425	254	413
Average	311.4	522.4	293.7	514.95

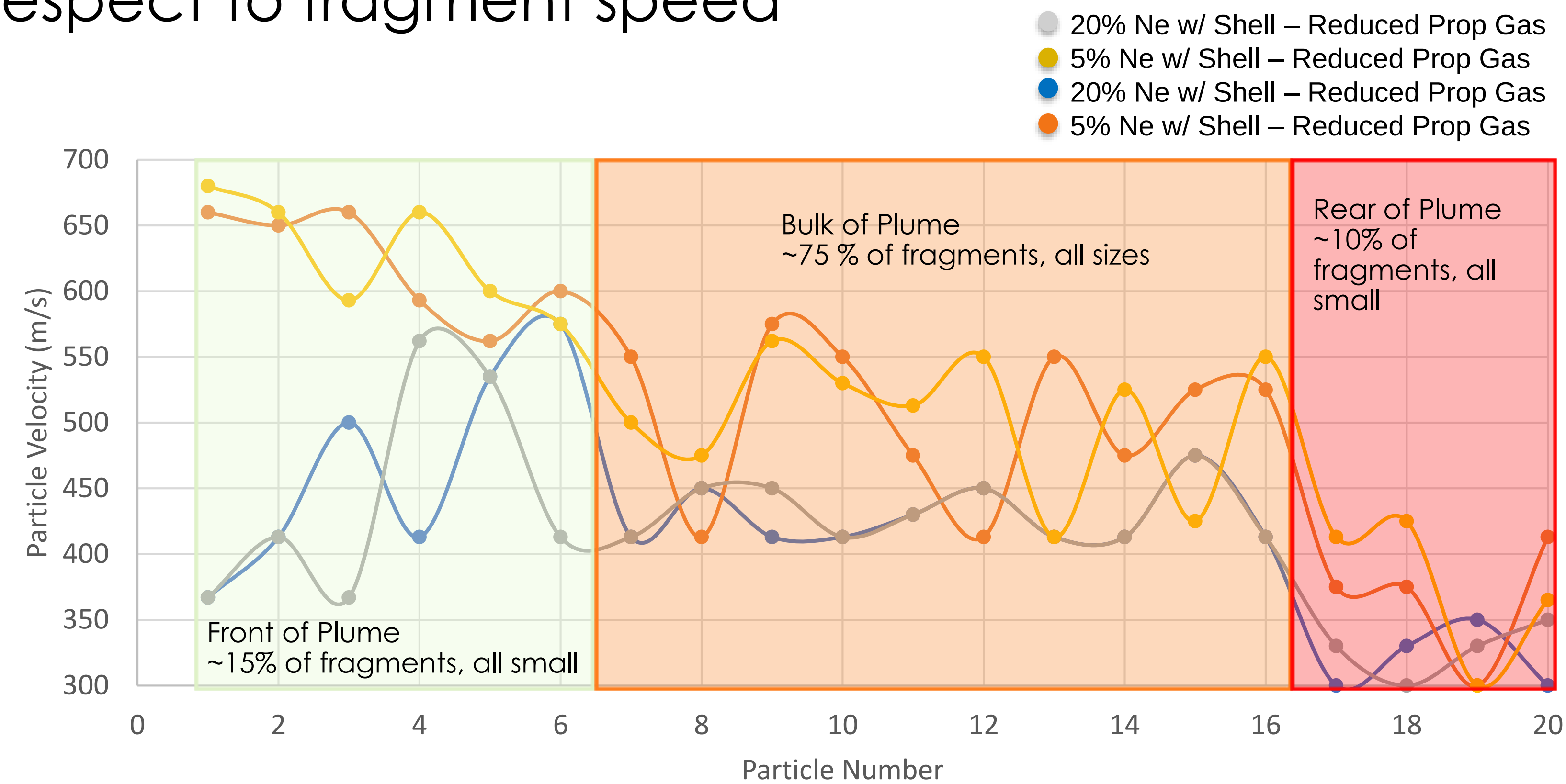
Plume length and duration comparisons of JET S-bend and 20-degree miter bend, with entrained propellant gas





Additional Analysis – Comparison of similar shots post-modification and more on temporal mass evolutions of different pellets

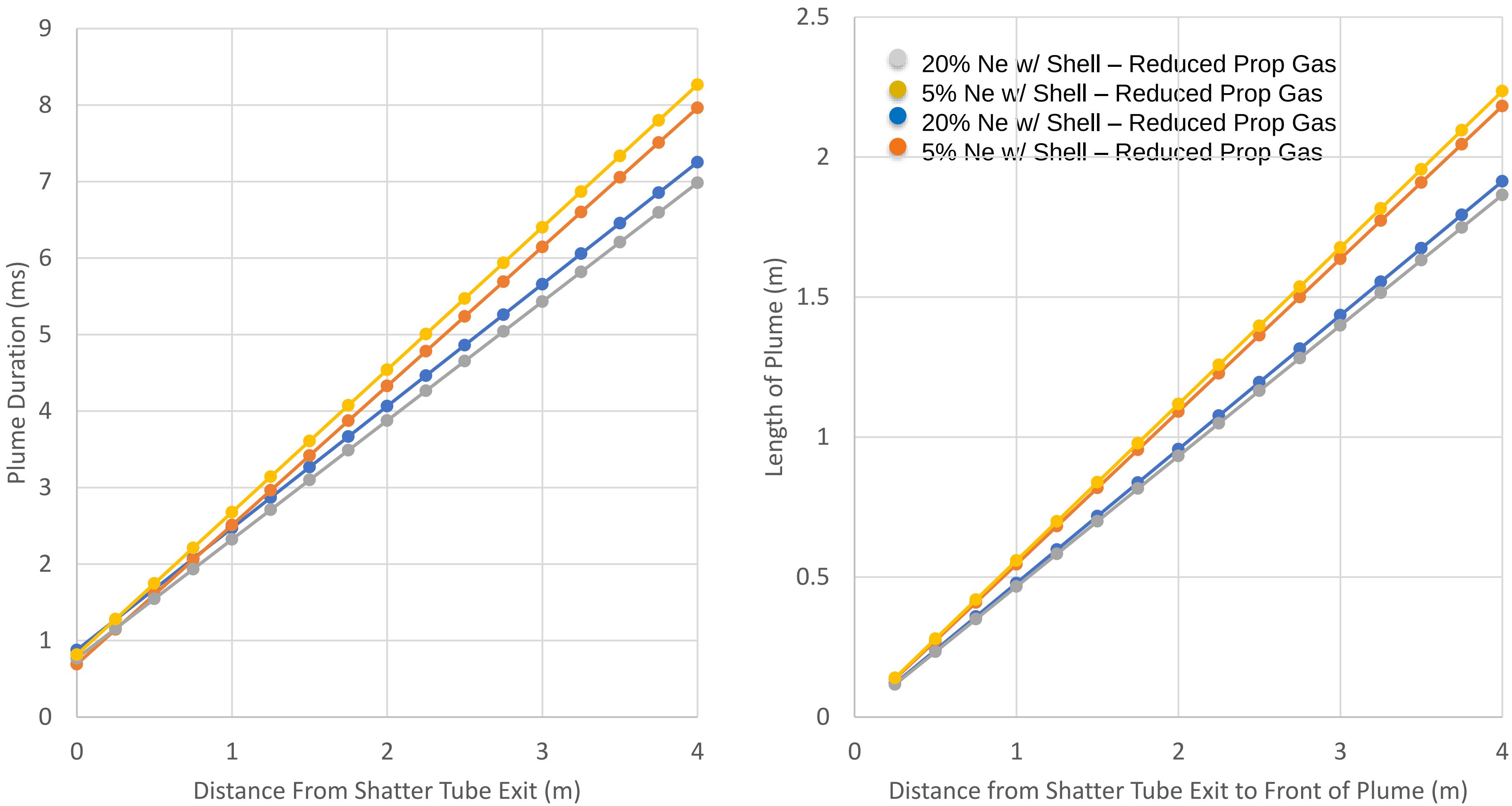
Comparison of similar shots (5% and 20% Ne) with respect to fragment speed



	20% Neon w/ Shell (Blue)	5% Neon w/Shell (Orange)	20% Neon w/ Shell (Gray)	5% Neon w/Shell (Yellow)
Min	575	660	562	680
Max	300	300	300	300
Average	418.3	511.95	414.35	515.7

Oak Ridge National Laboratory
US iter

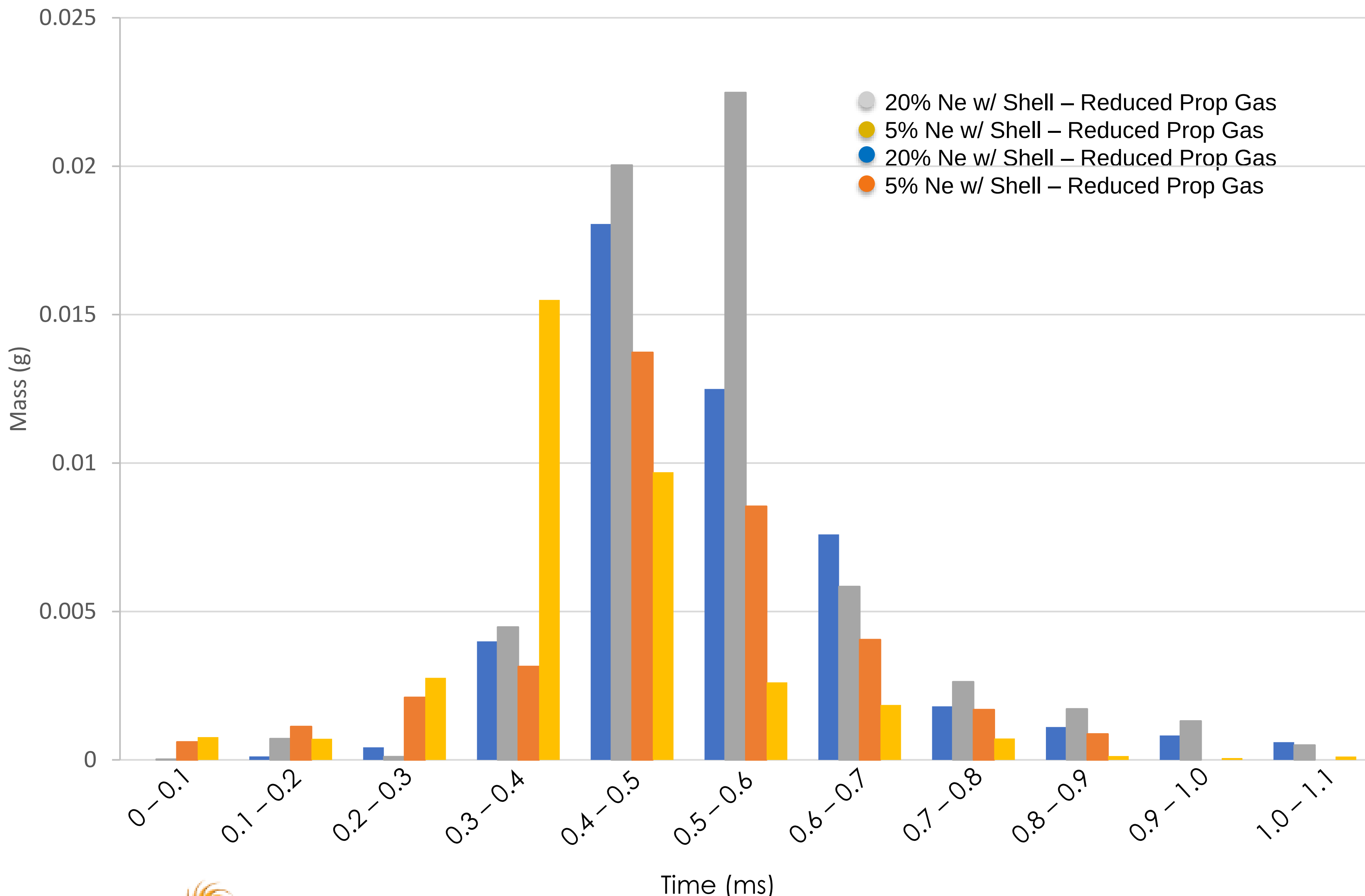
Extrapolated shatter plume duration and length from exit of shatter tube for similar pellets



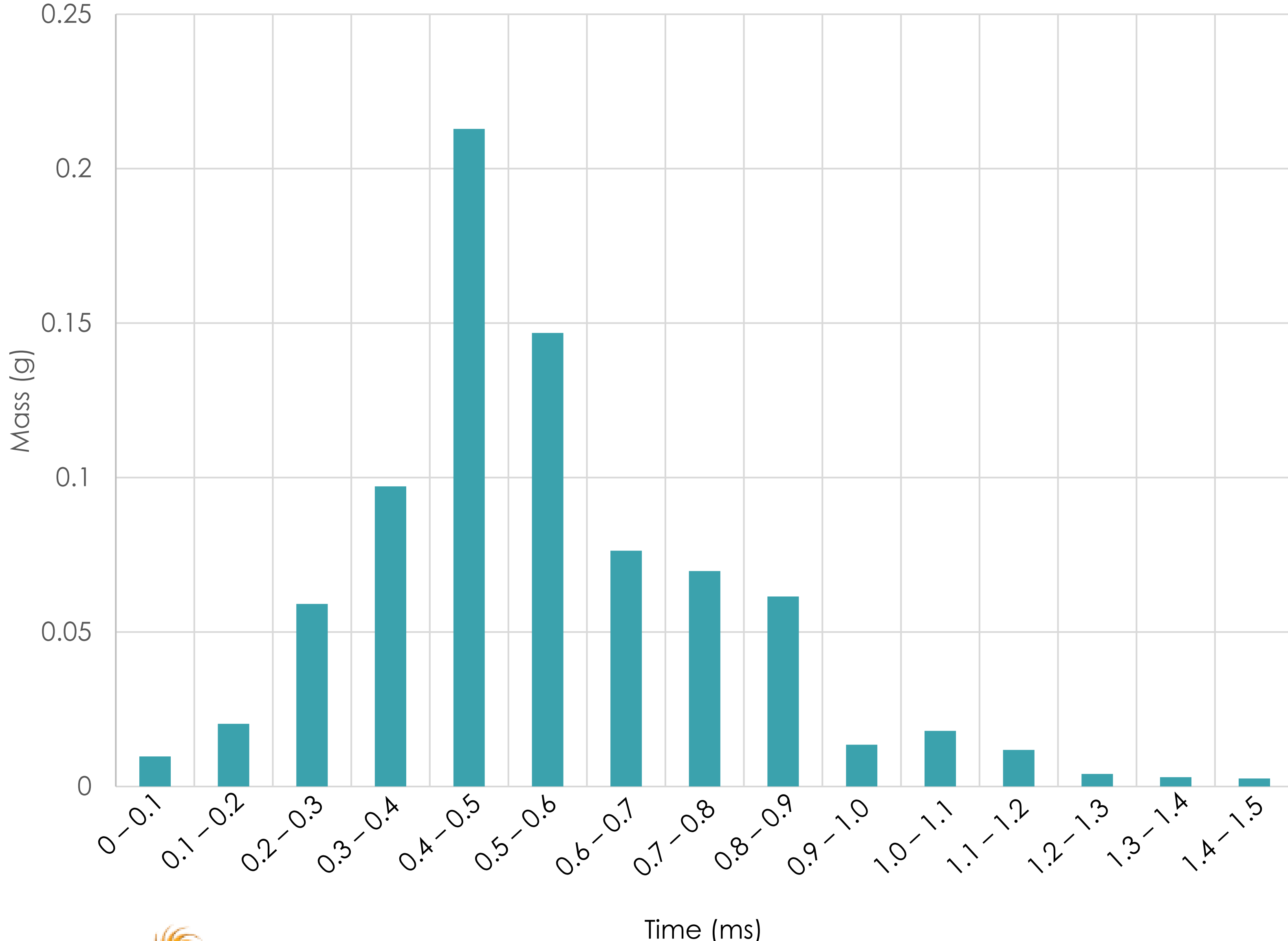
Oak Ridge National Laboratory

US iter

Temporal Mass evolution of 5% and 20% neon mixtures



Temporal Mass evolution of a pure neon pellet



OAK RIDGE National Laboratory

US iter

Conclusions/General Thoughts

- The modifications made to reduce propellant gas down stream resulted in a significant change in plume dynamics
  - Smaller particles at the rear of the plume stretch out over a longer time than without gas, previously accelerated by excess gas (hypothesis)

- No statistical difference in fragment size distribution between gas and reduced-gas cases, also no difference between 20-degree miter bend (similar to DIII-D and KSTAR) and JET shatter tube

- Fragments at the front of the plume are traveling significantly faster than the fragments at the end, resulting in a possible large spread over a long distance
  - Forces (or gas) generated during shattering process accelerates small fragments at front of plume and slows fragments at rear of plume (hypothesis)

- The bulk of the mass is located after a very small initial segment of plume, which consist of very small fast fragments

- The initial pellet speeds were not measured, but the speeds of the bulk of the plume seem to somewhat coincide with the assumed nominal speeds of these pellets

- The comparison of the JET ST with the 20-degree miter bend shows that with the propellant gas entrained, there is no significant difference in fragment size distribution, plume spread, or plume duration