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Small-Scale Deflagration Cylinder Test With Velocimetry Wall-Motion Diagnostics

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Abstract. Predicting the likelihood and effects of outcomes resultant from thermal initiation of explosives remains a significant challenge. For certain explosive formulations, the general outcome can be broadly predicted given knowledge of certain conditions. However, there remain unexplained violent events, and increased statistical understanding of outcomes as a function of many variables, or "violence categorization," is needed. Additionally, the development of an equation of state equivalent for deflagration would be very useful in predicting possible detailed event consequences using traditional hydrodynamic detonation models. For violence categorization, it is desirable that testing be efficient, such that it is possible to statistically define outcomes reliant on the processes of initiation of deflagration, steady state deflagration, and deflagration to detonation transitions. If the test simultaneously acquires information to inform models of violent deflagration events, overall predictive capabilities for event likelihood and consequence might improve remarkably. In this paper we describe an economical scaled deflagration cylinder test. The cyclotetramethylene tetranitramine (HMX) based explosive formulation PBX 9501 was tested using different temperature profiles in a thick-walled copper cylindrical confiner. This test is a scaled version of a recently demonstrated deflagration cylinder test, and is similar to several other thermal explosion tests. The primary difference is the passive velocimetry diagnostic, which enables measurement of confinement vessel wall velocities at failure, regardless of the timing and location of ignition.

Introduction

In energetic materials subjected to a fire, predicting the likelihood and effects of outcomes is important to protection of life and property. There have been significant investments in advancing the scientific understanding and modeling capability for cook-off in explosives over the past decades, which have led to a mechanistic understanding of the processes involved for certain explosives.[1-3] For example, the approximate time to explosion for HMX formulations can be predicted with some accuracy. Detailed models, especially in predicting "outlier" events, nonetheless require continued effort. The "tipping points" that divide thermal explosion, steady deflagration, and deflagration to detonation transitions are dependent upon many details, and believed to contribute to the apparent stochastic "anomalous" responses.

If one assumes a particular outcome for a given scenario, however improbable, and dictates, say, that violent, steady deflagration or DDT occurs, the next step is to predict the effects. To do this, one has to construct a model that predicts what the explosive does to its surroundings. For DDT events, this is comparatively simple, since many hydrodynamic models exist to predict detonation events with some accuracy. At the other end of the spectrum, there have been some successes in predicting responses to thermal explosions. Somewhere in the middle, the steady deflagration case presents a challenge. It has been suggested that there would be some usefulness to obtaining parameters similar to a detonation equation of state for steady deflagration conditions which would simply be inserted into existing detonation models. There are flaws with this, since several assumptions inherent to detonation model development are violated in a deflagration; any such pressure-volume relation for deflagration would almost certainly be entirely condition dependent. Nonetheless, a model using the Jones-Wilkins-Lee (JWL) form was successfully used to simulate annular cookoff tests,[4] and this inspired an attempt to capture JWL-like parameters for deflgration in a test based on the detonation cylinder test.

The deflagration cylinder test (DFCT) was developed with the intent to measure parameters to develop a "pseudo equation of state" (pEOS). Several DFCT tests were recently fielded that alluded to "regimes" of outcomes depending on the history and state of the system, and the distinct possibility that useful data for model development could be extracted.[5-7] The windows required for backlighting caused thermal gradients and smoke generation degraded images to varying extents.

Results from the DFCT demonstrated the possibility of capturing steady wave behavior similar to a detonation event. The observed steady-wave deflagration enabled extraction of a pEOS pressure-volume relation for the conditions of the test. In seven fielded tests, steady wave behavior with a propagation speed of 500 m/s was observed once. All of the responses were benign, save one unexplained apparent DDT event at lower temperatures. The test series proved the possibility of capturing pEOS behavior. It also showed that this outcome was improbable.

The DFCT was not suited to fielding many tests to capture the variability of outcomes; it was designed to capture a steady wave event, which proved improbable. The primary difficulty of the test was associated with the camera based diagnostic and required backlighting. These required consistent triggering, and a set of shorting wires near the ignition end failed in the event of autoignition elsewhere in the tube, a probable outcome at conditions of interest.

We set out to create an economical version of the DFCT such that we could capture a range of behaviors over a range of conditions. The scaled design we describe advances this test in several specific ways. It can deliver pEOS data if steady combustion is observed, and is inexpensive enough to map outcomes by fielding many tests.

We performed several experiments on the HMX-based explosive PBX 9501 with a copper confiner, employing off-the-shelf, high material and dimensional consistency parts and signal-triggered multi-point photon Doppler velocimetry (PDV) to effectively reduce cost in materials and labor for both assembly and fielding. We chose PBX 9501 because background work in this configuration has been performed with this material, and it holds promise to demonstrate the richness of the response range due to the phase change in HMX. Explosive parts were pressed to shape and the overall test size was reduced to less than 10 mm in diameter. The only diagnostics were thermocouples to ensure temperature uniformity and PDV to capture wall motion.

The PDV technique allows triggering on signal, which captures flow events in the event of auto-ignition anywhere in the tube. This eliminates both camera triggering needs and insulation complications arising from lighting requirements. PDV is also quite adaptable and forgiving; PDV points can be added to a density which approaches that of a camera diagnostic, can be positioned radially around the tube to give information on symmetry of response, and remains effective even when signal is degraded due to alignment, surface reflectance, and the presence of smoke.

The addition of an ignition element at one end of the cylinder, and the wall motion diagnostic are all that differentiate this test from many similar tests.[8-12] However, the pEOS goals are unique, and this dictated the use of a confiner that exhibits large extensions prior to failure. This requirement works as a disadvantage since such materials not ideal for pressure vessels, and premature confinement failure favors non-violent explosive response.

Although a range of conditions were observed for the original 7 DFCT experiments, the 14 scaled DFCT experiments described here delivered consistent outcomes. All were thermal explosions described by a thick-walled pressure vessel failure, and small variations observed are ascribed to confinement conditions and temperature. None exhibited steady wave behavior.

Experiments are planned for the future to address several variables including diameter, explosive porosity and preparation method, confiner material and thickness, and heating profile.

Experimental

A rendered drawing of the experimental fixture and a photo of an experiment in an insulated heating enclosure is shown in Fig. 1. Four 3/8" diameter, 3/4" tall PBX 9501 pellets were loaded into a 0.1" thick C101 Cu tube. Total length of the explosive was 3". The Cu tube was annealed to dead soft temper to achieve maximum elongation prior to failure. The tube was supported on either end by 304 stainless steel flanges, which were connected by three stainless rods, to fix the length dimension with temperature. Stainless end caps with 2 o-rings each were inserted into each end of the tube and bolted to the supporting flanges. One of these flanges contained a diesel glow plug (Honeywell, Autolite #1103) to be used as an igniter if desired. When utilized, a 12V, 5A power source was connected to the igniter (or "stinger").

PDV probes (AC Photonics, part no. 1CL15P20LCC01) were inserted into 2 of the supporting rods, such that there were 2 rows of 4 probes, 120° from each other. The probes, spaced at 3/4" in each of the 2 rows, were interleaved; probes 1-4 were located near the pellet edges at distances (from the igniter) beginning at 3/8" from the igniter, while probes 5-8 were approximately centered on the pellets at distances beginning 5/8" the igniter. The PDV itself was constructed in-house, employing an IPG Photonics 1550nm source laser. Signals were recorded on 6 GHz Tektronix digitizers for a total duration of 1ms.

A plywood box with external dimensions 11.5"L x 9.5"W x 8"H was insulated with 2" thick Fiberfrax Duraboard®. Into the bottom insulation was inserted a resistive (Watlow ceramic fiber). Exterior seams were sealed with aluminum duct tape.

The heater was controlled by a LabView program connected to a power supply, with reference to a control thermocouple placed in the enclosure near the heater. Thermocouples were placed inside the flange containing the igniter and affixed to three locations across the confinement tube with Cu tape. Heating rates were set to about 8°C/min as measured by the control thermocouple, actual heating rates of the fixture were markedly slower, and actual temperature achieved in the fixture was lower than the set point. Typical heating profiles showing both the control thermocouple and the 4 thermocouples on the fixture are shown in Figure 2. Temperature uniformity was about 1°C across the 4 fixture-mounted thermocouples for all experiments.

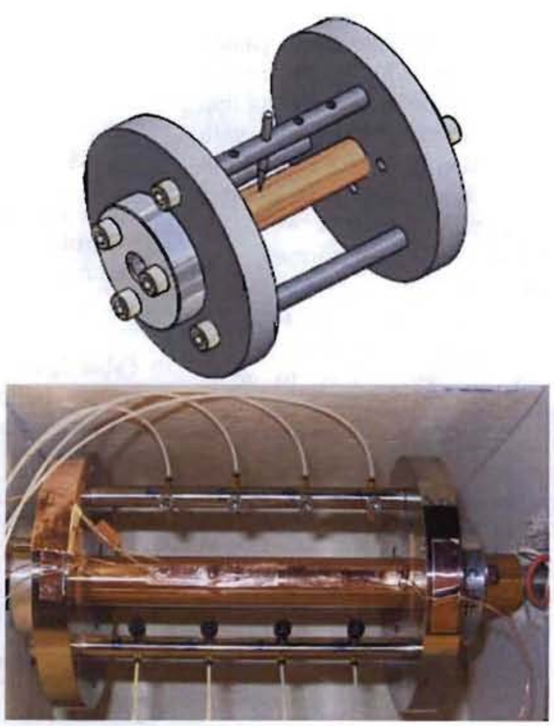

Fig. 1. Rendering of the shot fixture (top) and photo of a shot in the insulating box. The igniter is on the right, and the 8 PDV probes are mounted to the fixture rods, with probes 1-4 on top.

The explosive pellets were pressed to shape, and tubes were machined such that their internal diameter was within ~0.001" of the diameter of a set of pellets, which were chosen in matched dimensional sets. To the limits of assembly, we allowed for no ullage within the tube. Explosive porosity of 6% at 190°C was targeted. There was no effort to make porosity uniform across the range of conditions tested. Ultimate porosity depends on tube strain, which was not measured. Densities were measured by dimensions and mass for each pellet, and were in the range of 1.814 and 1.823 g/cc. Since the pellets were chosen by dimensional consistency for each test, the density follows, and the typical variation of densities for pellets in a single experiment was +/- 0.001 g/cc. The density of the pellets was below specification density of PBX 9501, but the cost savings of pressed-to-shape parts was considered an acceptable compromise since the parts are damaged by heating and tube strain prior to ignition is not measured; the precision gained from a machined part would be lost to these other factors. It was the below-specification density that enabled reaching approximate 6% porosity with no ullage. Of course, density gradients and overall porosity may vary from a machined part, and this comparison will be made in future work.

Fourteen experiments were performed. The first four were scoping tests, and employed only 4 PDV probes. Their primary purpose was to set up a self-triggering threshold for the PDV probes and compare the utility of doing this to more traditional triggering devices (shorting and PZT pins, shorting wires, etc.). We found that auto-triggered PDV was most reliable, especially for autoignition cases, since the location of first motion is not known ahead of time.

For the remaining 10 experiments, heating profile and ignition characteristics were varied as outlined in Table 1.

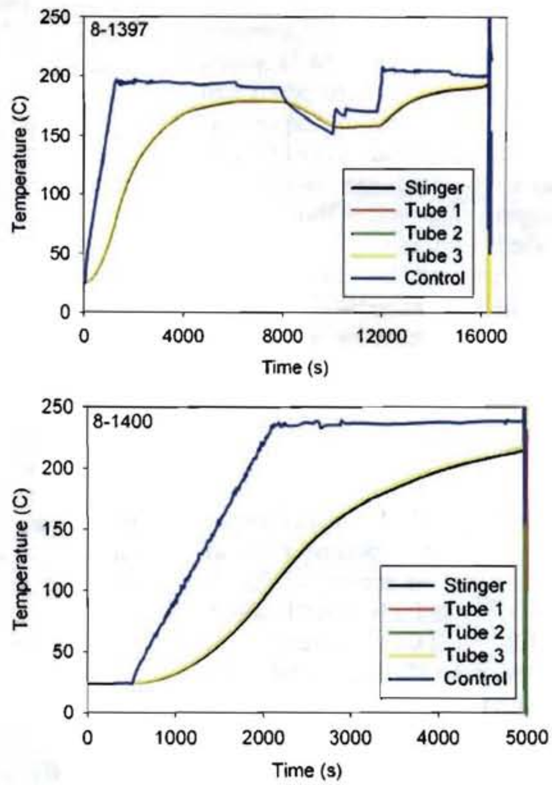

Fig. 2. Sample heating profiles for two experiments showing the typical lag between fixture temperatures and control set points.

Table 1. Heating profiles: temperatures are in °C, arrows indicate ramping, dashes indicate soak periods, shading indicate temperature cycling, asterisks indicate use of the ignition element.

Shot #	Heating profile
8-1390, 91, 92	↑180 –30 min. ↑205
8-1394, 95	↑180 –30 min. ↑190
8-1398, 1400	↑225
8-1399	↑180 –30 min. ↓160 –30 min. ↑225
8-1396*	↑180 –30 min. ↓160 –30 min.
8-1398*	↑180 –30 min. ↓160 –30 min. ↑190

Results and Discussion

The first 4 proofing experiments served as a test of the triggering and data capture scheme. Three of these were deliberately ignited at the ignition end, where several redundant triggers were located. Although the PDV system triggered at the approximate explosion time, the records contained no velocity data. The fourth experiment autoignited, and relied completely on the PDV to sense motion for trigger. This experiment did capture wall motion velocities as expected. The observed wall velocities of a few 100m/s and observable damage to the enclosure were consistent with the shots that followed, but since there were only 4 probes on this shot, they have been excluded from comparison with the rest of the series. All of these events were relatively non-violent pressure bursts occurring at about 190°C, followed by a fire lasting a few minutes. There was the appearance of unburned explosive residue on the fixture, but this proved to be remnant insulation.

The DFCT was conceived as a means to measure a pEOS for a specific set of deflagration conditions. In three of these first four scaled DFCT experiments, forcing ignition from one end of the tube failed to generate a violent event, or even a steadily propagating deflagration prior to tube failure. This may be partially due to the fact that surface ignition is fundamentally different than a volume ignition. Forced ignition experiments approximating volumetric ignition have been demonstrated, but this was not achieved here.

Autoignition was accidentally achieved on 1 of the original DFCT experiments, and was observed to be more violent than all of the forced ignition events. It also occurred accidentally on the 4th scaled DFCT proofing test, and had the appearance of increased violence (although we had no velocity records to compare with). Therefore, we sought to achieve autoignition in many of the remaining experiments. However, the observed outcome was very non-violent in all cases. The tube wall velocities reached just a few 100 m/s at most with associated expansions estimated from a few mm to more than 10 cm, depending on probe location. The insulated wooden enclosure was scarcely damaged, and in most cases the event was neither heard nor seen on camera from the control room 10 meters away. Those that were visible were only so due to the subsequent fire that presumably consumed the explosive remaining after burst.

Of the remaining 10 experiments, with temperatures ranging from about 160°C to 220°C, 8 achieved autoignition and 2 were deliberately ignited, but all yielded pressure burst responses. None showed steady wave behavior.

Three experiments (8-1390, 8-1391, and 8-1392) autoignited after a heating profile that included ramping to 180°C, soaking 30 minutes, and ramping to approximately 205°C. Two experiments (8-1394, 8-1395) displayed very similar behavior after a similar profile that ended at about 195°C. Prompt autoignition occurred at about 215°C for two experiments (8-1398, 8-1400) when a ramp profile direct to a target of 225°C was applied. Finally, three experiments (8-1396, 8-1397, 8-1399) were performed in which a temperature cycle above and below the phase change; one autoignited and two were deliberately ignited with the "stinger." The purpose of this cycle was to inflict a work-hardening effect on the confiner tube. Although more energy was apparently released – the damage to the shot enclosure was greater – these were still just pressure bursts. In contrast to the others, the failure profile of the tube was notably different. These results, and the analysis approach, will be discussed in more detail in the following.

From the interference fringes measured by the PDV, a Fourier transform generates an image which represents velocity. From this image numerical velocities are extracted. Velocity profiles are integrated to estimate the tube expansion. To this point, all of the analysis was performed using the Java application for this purpose written by Steve Pemberton.

The expansion profiles located to their respective positions on the initial tube geometry give a time-dependent picture of the location, nature, and rate of expansion at thermal runaway. Using these time-dependent positions, a reconstruction of the tube is made by interpolation. This reconstruction assumes perfect symmetry; the 8 PDV records are assumed to originate from a single line, and this interpolated profile is assumed to be rotationally symmetric around the tube. This is just an estimate. As the tube expands the reflector is turning away from the PDV probe and the velocity measured is only one component of the copper velocity. Velocity measurements at large expansions could easily be underestimated by 50% or more, and symmetry of expansion and failure may be a poor assumption.

Increasing the number of PDV points would allow reconstruction of shapes of varying complexity. Increased density of points along each line would decrease the errors in interpolation, and increased density of point along many radial locations would provide asymmetric expansion information directly.

The phase velocity can be extracted but is time dependent and can be misleading. At early times, the apparent phase velocity approaches infinity and decreases as a function of time.

All shots displayed similar behavior. They were categorized by the specific heating profile. The most striking differences occurred between those shots that were temperature cycled and those that were not, and those that autoignited vs. those one which the stinger was applied.

Fig.3 shows the measured velocities for shot 8-1398. This experiment was ramped directly to autoignition at about 215°C. Symmetric tube failure is evident in the velocity records. The apparent position of ignition is indicated in the scale diagram included above the plot. Fig. 4 shows the tube expansion obtained by integration of the velocity records in Fig. 3. The other experiment with this temperature profile was nearly identical, the three experiments that ignited at 205°C, and the two that ignited at 195°C were very similar; they simply took slightly more time to expand to failure.

Fig. 5 shows the tube wall expansion record obtained from the velocity data from shot 8-1396. This record (and those of 8-1397 and 8-1399) is remarkable in that the duration of expansion was much longer than the rest of the shots. A very long duration linear expansion preceded a more rapid expansion, followed by a slower expansion near failure. The duration of the failure event in these cases approached about a millisecond; the other experiments took about 10 to 20% as long. The primary difference in these three experiments were the temperature cycling heating profile, which served to stretch the tube. This stretching possibly opened increased volume for reaction products at runaway and work hardened the tube to a small degree. The supposition of work hardening is corroborated by the three expansion regimes observed. These compare directly to the stress-strain behavior of copper in annealed vs. hardened states.

Typical fixture remains are pictured in Fig. 6, again using shots 8-1398 and 8-1396 as examples. The supposition of differing failure mode as a function of hardening state is consistent with these fixtures. Ductile failure with large fragments was observed on all shots, except those that were temperature cycled, wherein tubes remained connected with tears down the length of the tubes.

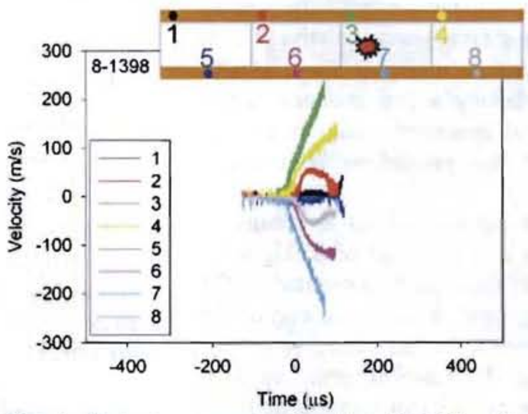

Fig. 3. Velocity records for shot 8-1398 with a scale diagram of probe locations, explosive pellet positions, and apparent ignition point.

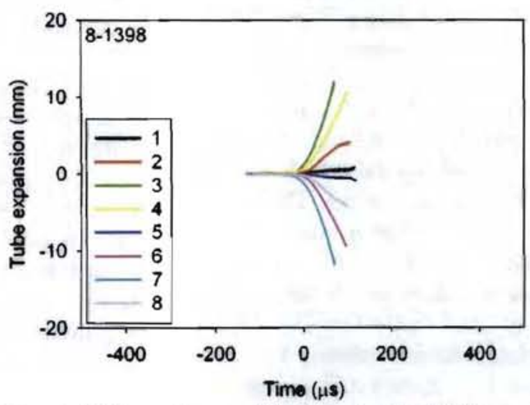

Fig. 4. Wall motion profiles for shot 8-1398.

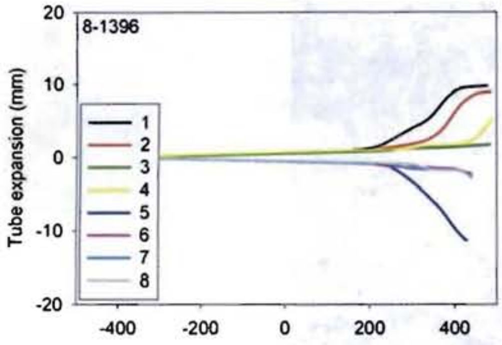

Fig. 5. Wall motion profiles for shot 8-1396.

Fig. 7 shows tube reconstructions for shots 8-1398 and 8-1396, depicting the last apparent tube shape prior to failure. In this comparison, the limitations of interpolation are evident as expansions greater than measured and artificial contractions. The differences between autoignition and forced ignition are apparent in the location of failure and the time duration to failure.

Continuing to use the mechanical properties of the copper, it is possible to estimate the energy released at failure. There is a wealth of data on yield and ultimate tensile strength for copper, including with temperature and hardening state. The tube fixture, a thick-walled pressure vessel, fails when the hoop stress at the outer wall exceeds the ultimate tensile strength. Using interpolated values of ultimate tensile strength from the ASM Handbooks, internal pressures to achieve failure were calculated from initial dimensions. The pressures were combined with the last apparent volume prior to failure from the tube reconstructions to estimate energy. Table 2 summarizes the measured and calculated values from all experiments.

While energy from the temperature cycled experiments approaches twice the value of the others, the energy density of all was of order 0.1 kJ/cc. This is an order of magnitude lower than estimates of energy density expected from deflagration.

The thick walled cylinder can be modeled with high fidelity so long as materials properties are known, including as a function of temperature and strain rate.[11] This approach will be useful, especially in designing future tests with increased confinement strength.

Gurney velocity for detonation of PBX 9501 in this configuration is 3.5 km/s by the relation

$$\frac{V}{\sqrt{2E}} = \left(\frac{M}{C} + \frac{1}{2}\right)^{-1/2} \quad (1)$$

where E ~ 2.8 for HMX, M ~ 10g, and C~ 66g in this experiment. Maximum velocities of a few hundred m/s were observed in all of the experiments, clearly inconsistent with detonation.

In the original DFCT series, there was one apparent DDT event that remains unexplained. Given that the failure of the copper tube occurs at such low pressures, it is remarkable that a DDT-like event occurred at all, and reproducing this result seems highly improbable. Inertial confinement may have been more important in the larger test,[13] but the ratio of confiner thickness to explosive volume was less than the current tests.

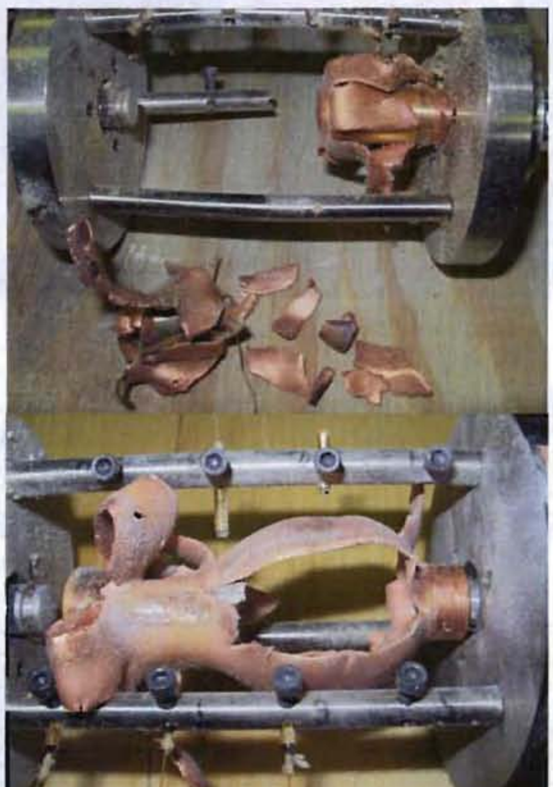

Fig. 6. Typical fixture remains: shots 8-1398 (top) and 8-1396.

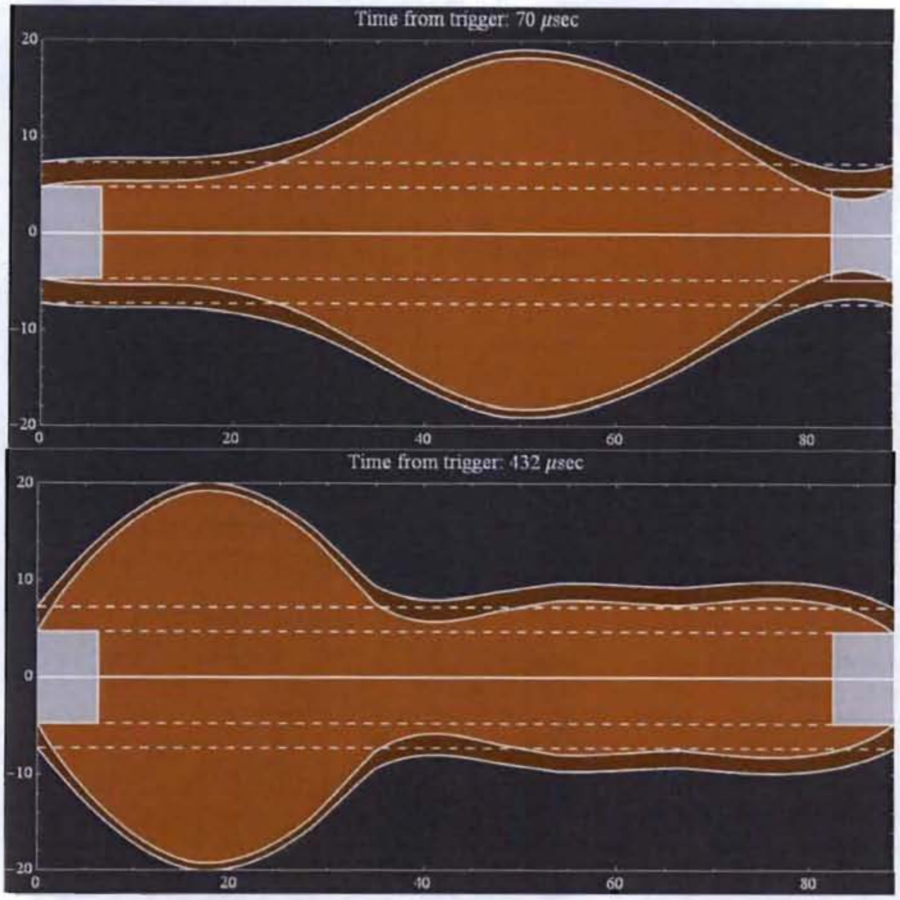

Fig. 7. Tube reconstructions: shots 8-1398 (top) and 8-1396. Axes indicate dimensions in mm.

Table 2. Summary of experimental results grouped by similar conditions. Shaded items were temperature cycled, asterisks indicate use of the ignition element, all others autoignited. Temperature and time for shot 8-1395 indicated by † are estimated from shot 8-1394.

Shot #	Temp. (C)	Time (min)	Velocity (m/s)	Expansion (mm)	Volume (cc)	Pressure (MPa)	Energy (kJ)
8-1390	204	230	208	12.6	33.4	80	2.7
8-1391	209	188	223	11.4	37.2	79	3.3
8-1392	204	195	221	12.2	30.7	80	2.5
8-1394	195	156	383	10.7	16.6	82	1.4
8-1395	195†	156†	267	12.5	23.1	82	1.9
8-1398	214	91	242	11.9	36.2	78	2.8
8-1400	218	83	267	12.5	35.5	77	2.7
8-1399	210	244	216	12.5	26.5	92	2.4
8-1396*	164	178	91	12.5	33.7	110	3.7
8-1397*	196	272	130	12.4	39.0	98	3.8

Energy dissipation follows strain to failure for the temperature and hardening state of the tube. Cu was chosen for its ability to undergo a large amount of plastic strain prior to failure. Where and when it fails relies on localization, and its strength and rate dependent plastic response depends on temperature. Transitions to steady deflagration and DDT likely are very sensitive to small heterogeneities in the system.

Small charges will DDT with sufficient mechanical confinement, as demonstrated with heavily-confined cylinder tests.[14] Versions of this test have demonstrated not only repeatable DDT, but also measurement of deflagration rates and run distances to steady deflagration and DDT.[15] Thus, with confinement somewhere between these heavily-confined tests and that used in the current scaled DFCT experiments, steady deflagration might be achieved to return the needed pEOS data. The degree of confinement between the two experiment designs, and the overall size effect, needs to be explored systematically and statistically.

Previous large scale annular cookoff tests[4] bear some similarity to the current results. If the annular tests are "unrolled" the motion profiles are quite similar to the tube reconstructions presented here. Although these were larger charges, most exhibited analogous pressure burst responses. The modeling of these tests employed a JWL-form pEOS for the deflagration. It is interesting that in order to match experimental results a slow burn propagation velocity with full detonation energy was required. This is consistent with thermal explosion outcomes and with what has been described previously.[10] High confiner velocity can result from thermal explosion, and propagation velocities can appear high depending on the time they are extracted, but the confiner acceleration is far less than what is expected from detonation.

Confinement, explosive porosity, damage, and similar system variables are really just contributing factors to the ability of the system to generate and dissipate energy. A key variable is pressurization rate, which is related to confinement. In most experiments temperature and pressure are also linked. A completely vented system dissipates energy rapidly at runaway, while a completely sealed system leads to increased pressure as the temperature is increased. Static pressure decreases the propensity for autoignition.

In order to transition to steady deflagration, the rate of energy generation must be similar to the rate of dissipation. For DDT, the explosive needs to generate energy faster than it is dissipated from the system. There are essentially three regimes: low generation/dissipation ratios will lead to extinguishing (benign deflagration), intermediate generation/dissipation ratios will lead to steady deflagration (the particulars of which are almost certainly condition dependent), and high generation/dissipation ratios will lead to DDT. The dissipation of energy from the system is linked to many parameters, which include confinement and explosive porosity, and the rate of dissipation needs to be compared to a region of reaction kinetics undergoing rapid change.

The occasional very violent event at lower temperatures might be rationalized to some degree by considering details of confinement failure mechanisms. While the pressure may be lower in the tube at lower temperatures, the strength of the tube will be higher because of the lower temperature while the pressurization volume increases slightly. Although the explosive is less likely to run away at lower temperature, more violence may result because the system is not capable of dissipating energy as rapidly as is needed for failure prior to critical runaway than at higher temperature. There have also been cases where a violent autoignition is observed at low temperatures after reduction from higher temperatures. In this case, increased volume for initial pressurization and potential hardening effects must be considered.

Autoignition at lower temperatures, with ample volume to pressurize rapidly prior to system dissipation increases the probability of violent system response. Defining critical inertial and mechanical confinement values leading to the transitions from thermal to steady deflagration to DDT will remain a subject of research. For steady deflgration, pEOS measurements might be achieved by a passive PDV diagnostic as demonstrated.

Conclusions

The experiments described demonstrate the utility of the scaled DFCT configuration. Signal-triggered PDV is a very useful, accurate, and simple technique suited to cookoff experiments. A key variable in cookoff violence is confinement. Fielding tests of this nature allows behavior mapping in engineering-relevant scenarios.

Planned parametric studies will vary length and diameter, explosive manufacturing technique (machined vs. pressed-to-shape), explosive porosity, temperature, temperature history, and soak duration, and most crucially, confiner material and thickness to achieve steady deflagration.

Acknowledgements

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