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USING AN ULTRA-HIGH SPEED CAMERA TO CAPTURE A TUBE EXPANSION TEST

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Computational analyses of explosive events became commonplace over the last twenty years or so. The input parameters used by these computational tools to calculate the material response requires extensive testing in most cases. One set of such parameters is for the JWL equation of state that models the detonation of an explosive. Tube or cylinder expansion tests are a standard way to determine the JWL parameters of such an explosive. A streak camera normally captures the copper tube expansion as the explosive detonates, resulting in a high-resolution continuous expansion at a fixed position.

This paper discusses the test set-up and the use of the Cordin ultra-high-speed camera for capturing the results of the expanding copper tube. The camera captured the expansion of the cylinder at a frame rate of one million frames per second and produced 32 digital images. Firstly, the velocity of detonation is approximated by noting the onset of swelling of the tube on each of the 32 images. Secondly, the expansion of the tube was estimated by viewing each image and extracts the expansion position in terms of pixels at specific locations, using the PFV software from Photron. Fifteen of the 32 images were used for this exercise.

1 BACKGROUND

The tube test was developed at LLNL to directly compare the dynamic performance of explosive compositions or to obtain empirical equations of state of their detonation products (Gibbs and Popolato, 1980). An OFHC copper tube with a typical inner diameter of 25 mm and length 300 mm is filled with the explosive composition under scrutiny. The copper thickness is controlled to produce a nominal loading of the tube of 4.03 g of copper per cubic centimetres of explosives.

The normal procedure for recording the expansion characteristics of the copper cylinder is that the tube is planar initiated at one end while a rotating mirror camera records the expansion via streak photography at a slit in the horizontal plane approximately 200 mm from the initiation end. The streak speed of the camera is typically in the range of 2 mm/µs to yield high spatial and temporal accuracy over the approximately 20-50 µs time duration of the event. The test is also normally performed in a helium atmosphere to reduce shock refractions.

The wall position of the copper tube is analysed at typically 500 positions and the data is fitted with a seventh order polynomial or various spline functions. The data is complicated by the fact that the early acceleration of tube is driven by successive compression and reflective shocks and the motion is affected by non-uniform pullback. Because the position data is differentiated to obtain velocity and twice differentiated to obtain acceleration, it is imperative to obtain accurate recordings of the position with time during the expansion procedure. The expansion is typically followed to 12-15 times the original diameter of the copper tube and LLNL quote their procedure to be accurate to 0.5% in spatial in temporal coordinates (Gibbs and Popolato, 1980).

Another pre-requisite for the application of the tube test procedure is the accurate measurement of the detonation velocity of the explosive. In the standard LLNL tube test procedure, the detonation velocity is measured simultaneously with the expansion by fitting fine enamelled copper wires in accurately measured positions around the circumference of the tube. It is claimed that this non-intrusive method does not influence the tube expansion and provides adequate accuracy of the detonation velocity down the tube.

The standard infrastructure at the DBEL test range includes a Cordin Ultra High Speed Camera that produces framing records (between 20 to 30 frames) of up to 2 Mfps. It does not have a streak capability. In principle, the expansion of the tube can be captured at different positions and time within the range of the frames and then used in a fitting routine to deduce the continuous motion of the tube wall. However, if 20-30 points are used in comparison to the standard 500 points usually obtained with the streak-facilitated test, a pre-requisite for sufficient accuracy is some knowledge of the functional form of the expansion. Elek et al 2015, proposed a methodology that uses such pre-knowledge.

This paper discusses the test set-up and the use of the Cordin Ultra High Speed Camera for capturing the results of the expanding copper tube. The camera captured the expansion of the cylinder at a frame rate of one million frames per second and produced 32 digital images. Firstly, the velocity of detonation is approximated by noting the onset of swelling of the tube on each of the 32 images. Secondly, the expansion of the tube was estimated for one of the tests by viewing each image and extracts the expansion position in terms of pixels at specific locations, using the PFV software from Photron. Fifteen of the 32 images were used for this exercise.

2 DESCRIPTION OF TESTS

A number of OFHC copper tubes of 25.4 mm outer diameter had been procured and filled with various explosive types such as TNT, Composition B, and 50/50 TNT/NTO. The tests described below used one tube filled with TNT and three tubes filled with TNT/NTO.

2.1 Test Setup

The primary diagnostic tool to be used to quantify the expansion of the copper tube will be the Cordin Ultra High Speed Camera at the T7 firing range at DBEL. The conceptual layout for the test was devised by Olivier 2015 and is shown in Figure 1.

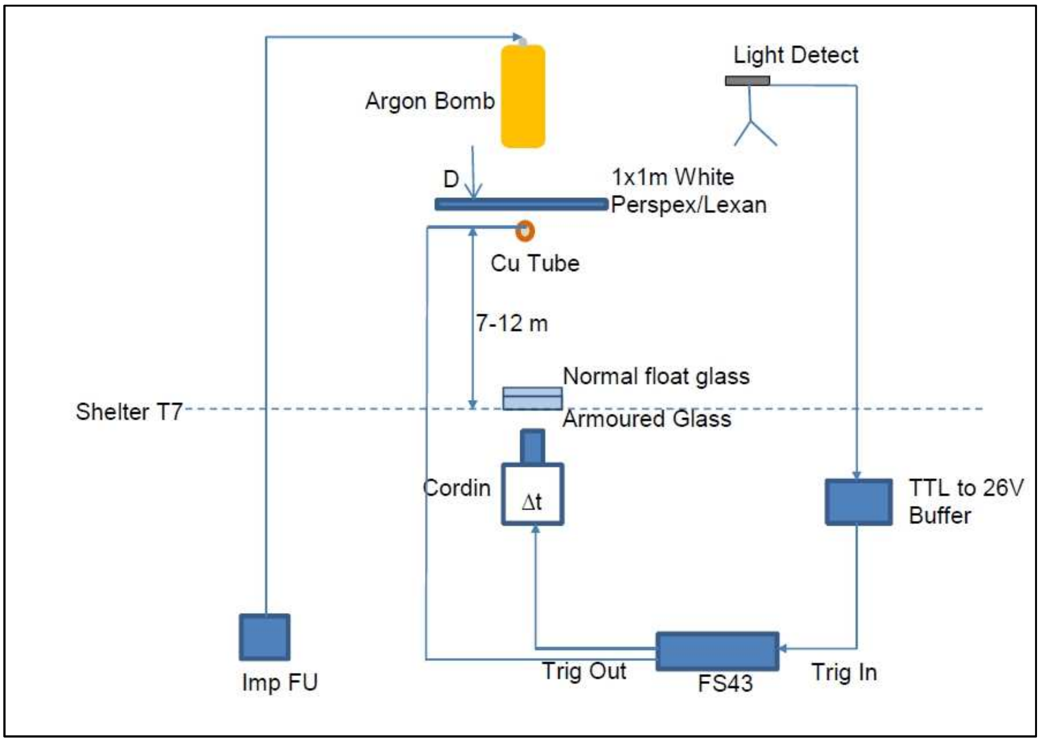


Figure 1: Conceptual layout of the tube test setup in front of the Cordin camera

The Cordin camera is installed in the right hand front cubicle of the T7 shelter with the viewing axis of the camera on a fixed height of approximately 1.5 m above ground height. The viewing port of the camera is covered with a 50 mm thick laminated ResistoGlass as built-in that protects the direct line of sight to the camera. Due to the complexity of introducing geometric aberrations with non-optically flat mirrors (optically flat mirrors are expensive items to write off on every test), it is decided to view the event directly into the line of sight. This naturally introduces a serious hazard of fragments that can impact, penetrate and possibly perforate the glass and cause damage to the camera.

The way of handling the fragmentation hazard is to place a sacrificial float glass pane of 8 mm thickness on top of a 2 mm thick transparent Lexan plate directly in front of the armoured glass pane in the view port of the camera. By firing the copper tube in the downward direction on the same level as the view port and between 7-12 m away, the hit probability of the main fragment spay is drastically reduced. However, there is still a distinct chance of a fragment hit on the glass frame from the top section of the copper tube. Estimated maximum velocity of the fragments from that section is 1700 m/s. Mass of the fragments are difficult to estimate because of the uncertain metallurgical condition of the tube, but 2-4 g are typical estimates. The penetration of a 4 g fragment at 1700 m/s initial velocity is estimated to be 12 mm of steel at 7 m standoff distance. Scaling up with the density ratio to glass, approximately 33 mm penetration capability is expected. This implies that the fragment will be stopped by the combined glass protection in the event of a hit on the view port.

A close-up schematic description of the line of sight view on the camera plane of the setup is shown in Figure 2.

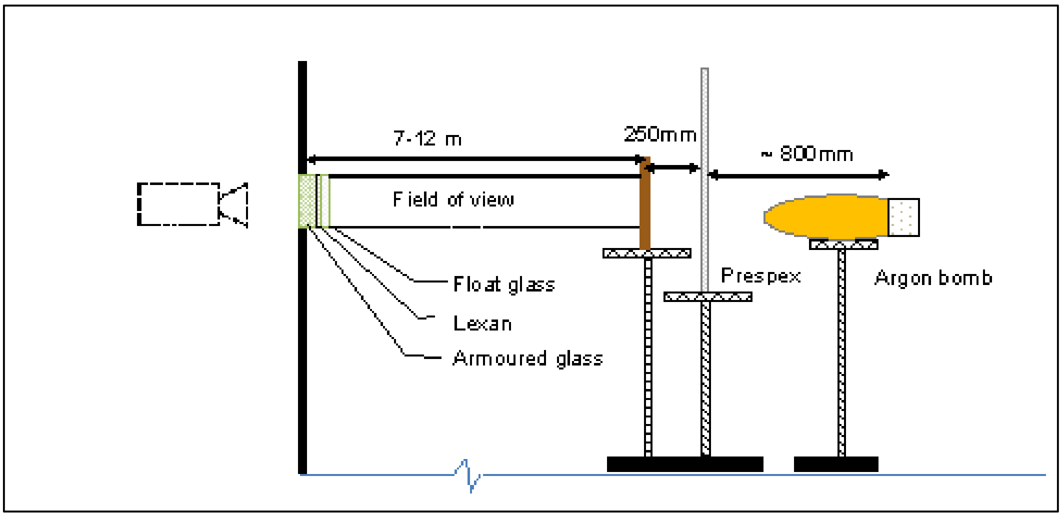


Figure 2: Schematic representation of the setup, line of sight, in the camera plane

Figure 3 shows a typical test set-up of the Argon bomb, diffusing screen and the Cu tube with its frame. Detonation was from the top down to direct the flying fragments downwards.

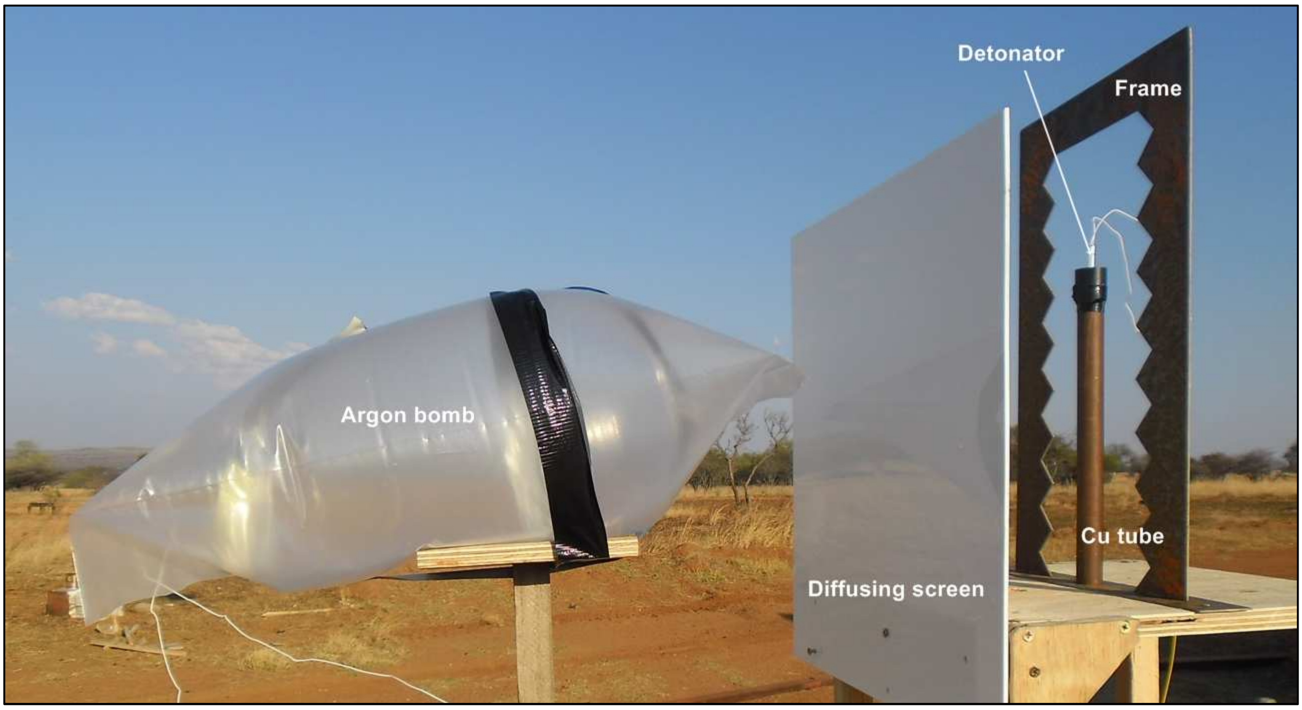


Figure 3: Test set-up showing the Argon bomb and Cu tube

2.2 Argon Bomb Requirements

Figure 4: The Cu tube with light sensors and ionisation probes

The Lexan screen between the argon bomb arrangement and the copper tube is aimed at reducing direct luminosity into the Cordin recording, but simultaneously providing adequate contrast lighting for a clear definition of the tube shadow. The time of the event is approximately 25 µs which implies that an effective lighting time for the argon bomb should be between 20-30 µs of uniform illumination. The preferred arrangement is a cylindrical argon bomb balloon with a restricted illumination signature that does not extend beyond the Lexan screen. The explosive charge could be PE4, Composition B or TNT but with a mass not exceeding 0.5 kg. The argon bomb must be as close as possible to the Lexan screen but the explosive charge cannot be closer than 200 mm due to fact that the shock may then interfere with the last phase of the tube expansion. It will be on the safe side to extend it further out to 800 mm if possible to minimise the forward projection of the tube fragments.

2.3 Detonation velocity measurements

Provision is made for velocity of detonation measurements in the tube in separate tests. In these setups, either ionisation probes or photodiodes will be used to record arrival times down the side of the tube (Figure 4). Plane wave generators are also required for these tests or, alternatively, phase velocity corrections need to be made for the detonation curvature.

3 VELOCITY OF DETONATION MEASUREMENTS

BPW34 light sensors and Ionisation Probes measured the VOD. The holes in the tubes were 3 mm in diameter and spaced 50 mm apart. Table 1 gives the measurements of the detonation velocity. The average velocity over 4 distances and 10 time intervals was calculated and the values are given in column 4. Eliminating the highest and lowest value, give an average shown in column 5. Eliminating the two highest and two lowest values, give an average shown in column 6.

Table 1: The VOD measurements (in km/s)

Shot	Explosive	Light sensors	Ionisation probes	Average velocity over 4 distance and 10 time intervals		
				Average	Elimination 1	Elimination 2
1	TNT	No data	6.736	6.751	6.736	6.728
2	NTO/ TNT	7150	7.110	7.147	7.130	7.125
3	NTO/ TNT	6800	6.971	6.927	6.886	6.876
4	NTO/ TNT	No data	7.221	7.203	7.221	7.219

Note that during shot 1 the light sensors were affected by some light coming through the hole in the tube and the results are ignored. The problem had been overcome by fitting neoprene rings to shield the light. The results for shot 4 are inconclusive as the selection of the pre-trigger of the oscilloscope was incorrect.

The one-millimetre diameter ionisation probes were mounted in 3 mm diameter holes, 50 mm apart from centre to centre. This implies a separation distance of 48 to 52 mm between probes and may explain the lower detonation velocities.

4 PROCESSING THE IMAGES OF THE CORDIN

4.1 Introduction

Figure 5: The view of the Cu tube from the Cordin

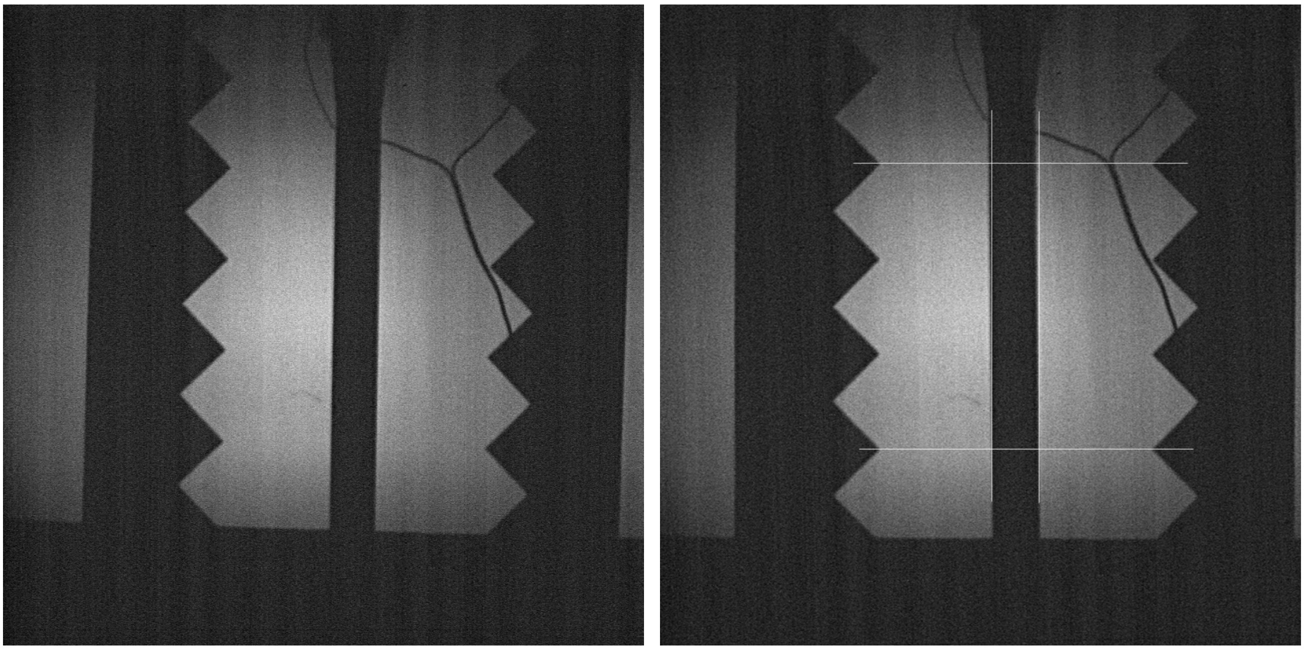
The images captured by the Cordin Ultrahigh Speed Camera for test 3 were useful and the processing of them is discussed below. The Cordin captured the expansion of the tube in 32 images at a frame rate of one million frames per second. Figure 5 shows the Cu tube as viewed by the Cordin.

These images are analysed to assess the usefulness and coherence of the extracted data. Firstly, the velocity of detonation is approximated by noting the onset of swelling of the tube on each of the 32 images. Secondly, the expansion of the tube was estimated by viewing each image and extracts the expansion position in terms of pixels at specific locations, using the PFV software from Photron. Fifteen of the 32 images were used for this exercise.

4.2 Cordin ultra high speed images

The images were quite dark and Photoscape was used to enhance the contrast and sharpen the images Figure 6(a). Thereafter they were rotated to align the measuring indicators that are the serrated objects left and right of the tube shown in Figure 6(b). To convert the pixels to millimetres a ratio of 0.336 ± 1.2% mm/pixel is used (in both horizontal and vertical direction).

It is evident that the tube is slightly tilted towards the left hand side (about 0.6°). The effect on the horizontal line through the thickness of the 25.4 mm tube is less than one pixel. The distance between the horizontal lines is 150 mm and the tilt delivers and offset of 1.7 mm in the vertical direction.



(a) The image altered by Photoscape

(b) The rotated image and lines to show the area of interest

Figure 6: An unprocessed and processed image from the Cordin

The frame rate of the Cordin was 1032258 fps, giving a time of 0.969 microseconds between the images. According to Coneely *et al*, 2011a, there is an average discrepancy in the frame rate measurement of 0.66 ± 0.48%, with a maximum difference of 2.33%. The same group developed an approach to reduce this error (Coneely *et al* 2011b). The error was not corrected for this analysis.

4.3 The detonation velocity

The swelling of the tube is extracted from the 32 images by locating the point on the surface where the expansion commences. This axial position (in millimetres) starts at zero on the top horizontal line and ends at 150 mm on the bottom horizontal line in Figure 6(b). Figure 7 shows the axial distance over time with a linear fit, giving the detonation velocity as 7.29 km/s. The horizontal error bar is ±0.2 microseconds and the vertical error bar is ±1.37 mm (4 pixels). Note that the units of velocity in the graph correspond to km/s.

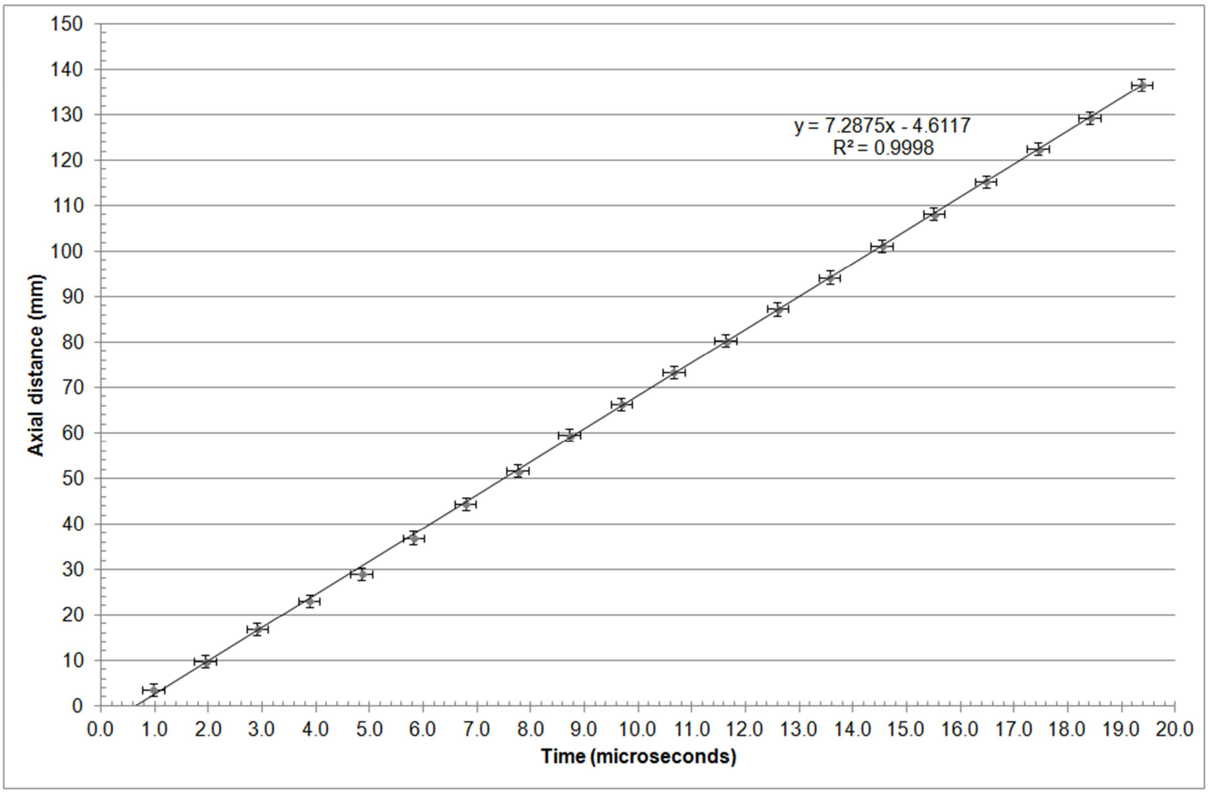


Figure 7: The velocity of detonation obtained by extracting the swelling of the tube from the Cordin images

The graph in Figure 7 uses only 21 points in succession to determine the velocity of detonation. Comparing all points with one another provides one with 231 pairs of distance and time, smearing out the variance in the data. This gives a velocity of detonation as 7.3 ± 2% km/s. Table 2 shows the velocity of detonation obtained by applying the two methods to the Cordin images, the average from ionisation probes (Table 1, column 4) and a published value from Smith and Cliff, 1999.

Table 2: Velocity of detonation

	Units	Cordin		Ionisation Probes	Smith and Cliff, 1999
		Method 1	Method 2		
Average detonation velocity	(km/s)	7.233	7.299	7.073	7.340
Standard deviation	(km/s)	0.509	0.134	0.177	-
	(%)	7%	2%	2.4%	-

4.4 Expansion results

The images used for this exercise is shown in Table 3. The zero time is taken at frame 11, where the expansion is just below the top white line marker. Due to the tilt, the thickness of the tube was measured in pixels, converted to millimetres and divided by two to get the radial expansion. Due to the vibrations induced by the rotating mirror, the pixel position of the tube and markers varies somewhat from image to image. This affects the axial location of the radial expansion.

The axial locations were determined in Section 4.3. Suppose we want to find the axial location as given by image A, on image B (Figure 8). Use the vertical distance (in millimetre) on image A for the location and convert it to pixels on image B (by dividing with the mm/pixel ratio). The location in image B is then found by adding this number of pixels to the vertical pixel number of the white line. The horizontal expansion at this vertical pixel number is then recorded.

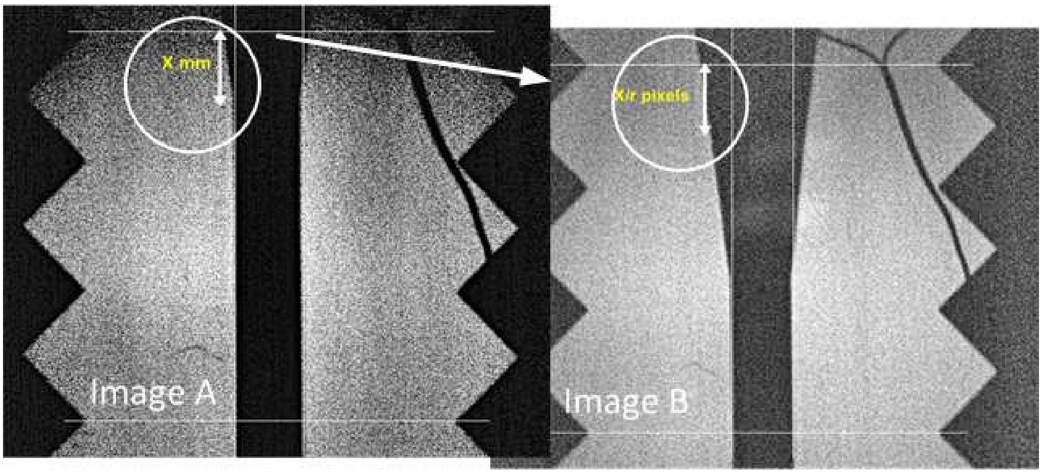
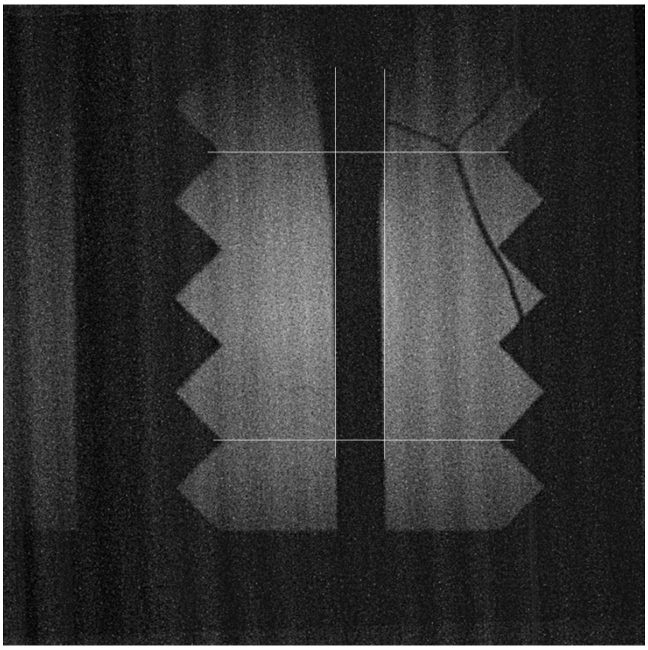


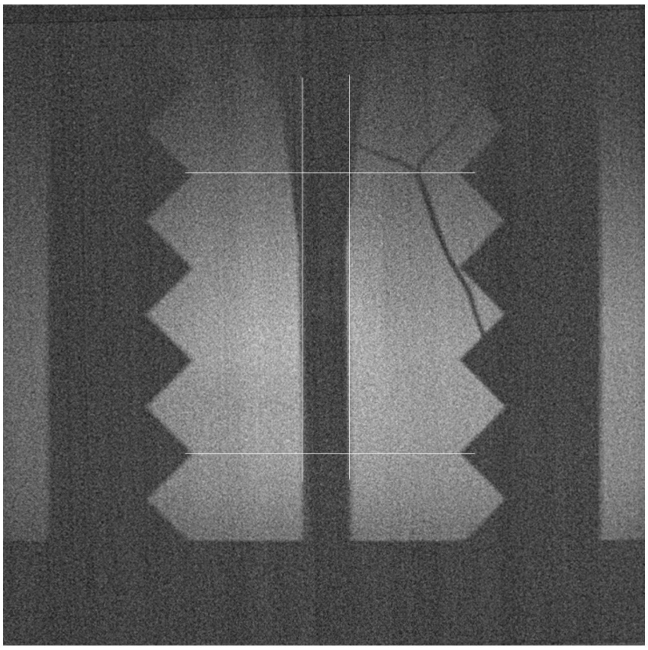
Figure 8: The location on image A measured on image B

Table 3 shows a few of the processed images used for extracting the radial expansion at the various locations along the tube.

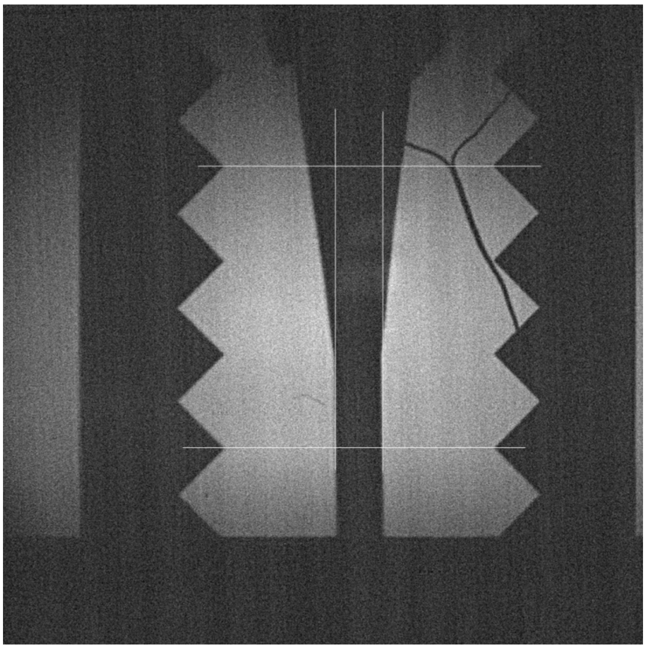
Table 3: a selection of images of shot #3, 9 September 2015



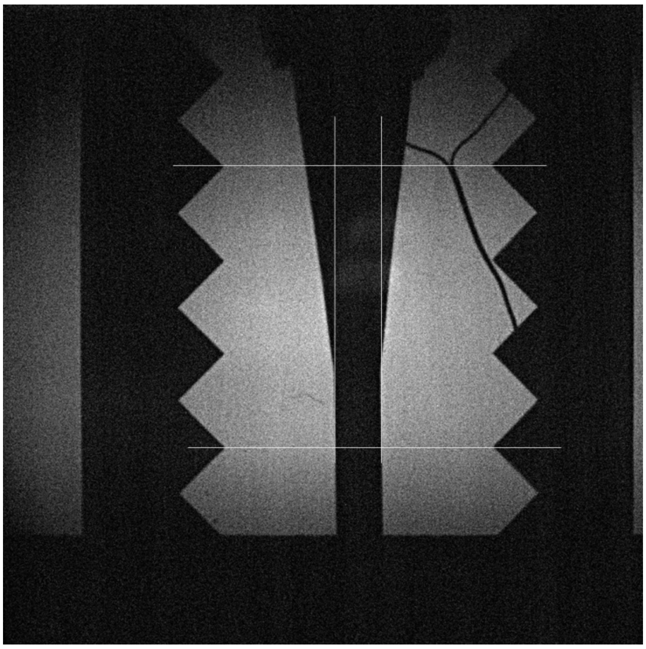
Frame 15 – time 3.875 µs



Frame 16 – time 4.844 µs



Frame 25 – time 13.563 µs



Frame 26 – time 14.531 µs

The radial expansion at the various locations where the swelling commenced (Section 4.3) was extracted from the images. Figure 9 shows the radial expansion at selected times along the axis of the tube. The linear fit yields a coefficient of determination R^2 between 0.98 and 0.99. The gradient of these linear fits ranges from -0.13 to -0.11, giving an average angle with the tube axis of 6.98° ± 5.3%. Note that the radial expansion at the various locations on the axis of the tube lies on a perpendicular line. If lesser points are used per time (thus eliminating the expansion after the tube has fractured) a slightly larger angle is found, namely 7.06° ± 5.5%.

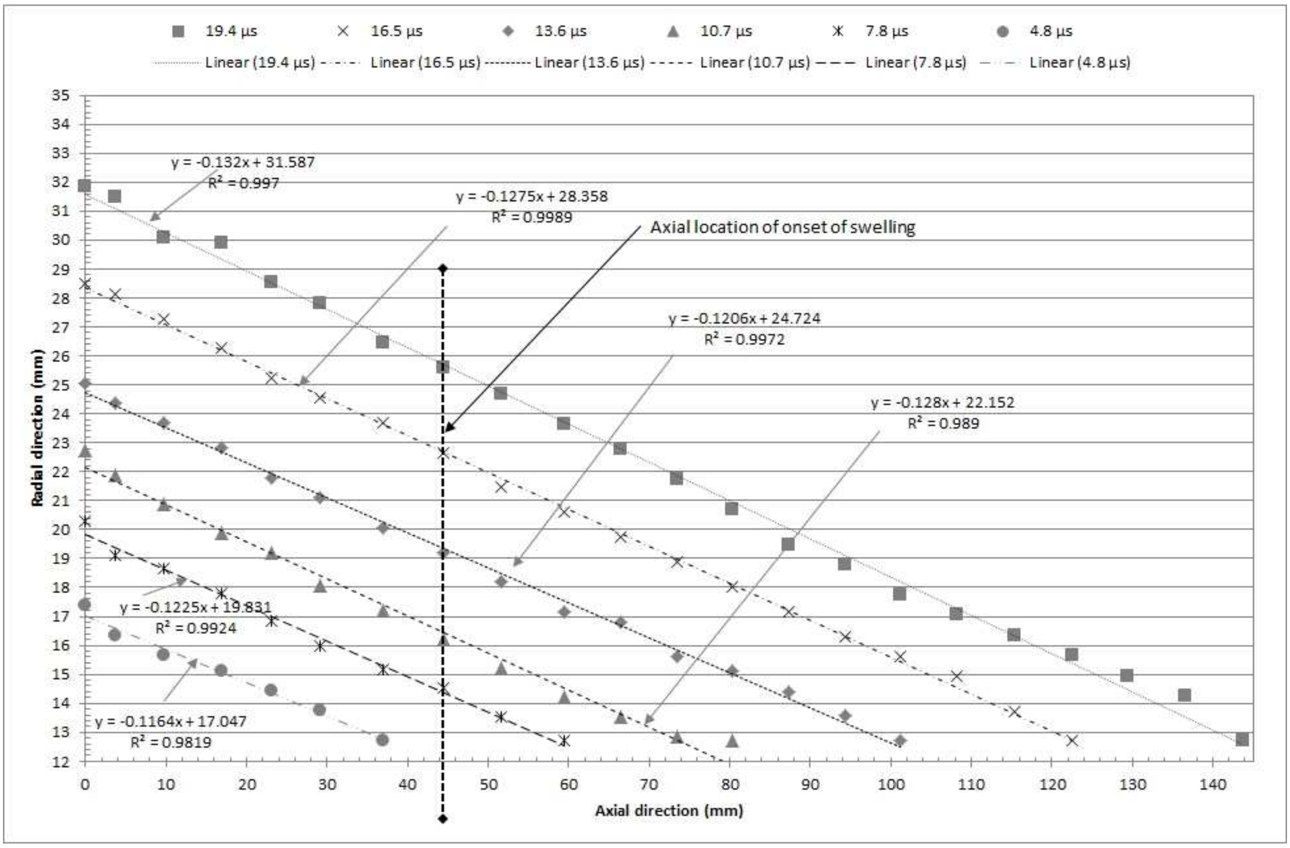


Figure 9: The radial expansion of the tube along its axis at various times

The streak image used for the computation of the JWL equations in publications such as for example, Elek *et al* 2015, gives a continuous expansion at one of the axial locations. Using the individual images, a discrete expansion can be given at each of the axial locations above. Table 4 shows a selection of these values.

Table 4: The radial expansion at selected locations as the time evolves

Time (µs)	Radial expansion at selected locations (mm)					
	23.1	29.1	37.0	44.4	51.7	59.5
2.91	12.7	-	-	-	-	-
3.88	13.2	12.7	-	-	-	-
4.84	14.4	13.7	12.7	-	-	-
5.81	15.2	14.2	13.4	12.7	-	-
6.78	16.1	15.4	14.6	13.4	12.7	-
7.75	16.8	16.0	15.2	14.5	13.5	12.7
8.72	17.6	16.8	16.1	15.2	14.4	13.5
9.69	19.1	18.0	17.0	16.3	15.6	14.4
10.66	19.2	18.0	17.2	16.2	15.2	14.2
11.63	19.3	18.6	17.6	16.8	15.8	15.0
12.59	20.9	20.1	19.1	18.4	17.2	16.3
13.56	21.8	21.1	20.1	19.2	18.2	17.2
14.53	23.3	22.3	21.4	20.4	19.7	18.6
15.50	24.2	23.2	22.7	21.6	20.6	19.6
16.47	25.2	24.5	23.7	22.7	21.5	20.6
17.44	26.6	25.4	24.4	23.5	22.8	21.4

Time (µs)	Radial expansion at selected locations (mm)					
	23.1	29.1	37.0	44.4	51.7	59.5
18.41	27.1	26.3	24.9	24.2	23.3	22.1
19.38	28.5	27.8	26.4	25.6	24.7	23.7

Figure 10 presents these data points in another way, namely by radial expansion over time. This shows that the velocity of expansion varies between the locations. Due to the experimental set-up, the linear fits should be parallel with one another. This has not been achieved and the reason for this remains unclear.

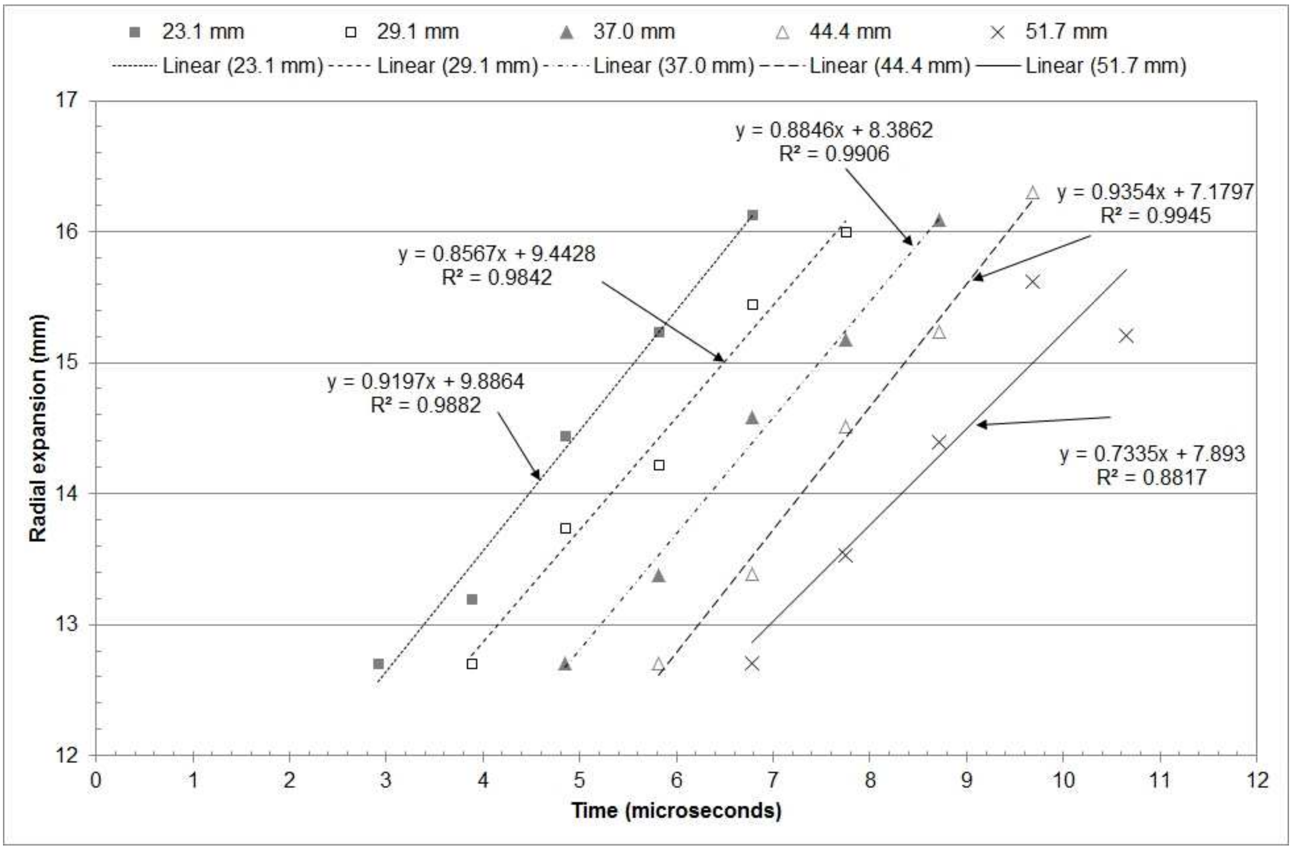


Figure 10: The radial expansion over time at specific locations on the axis of the tube

5 DISCUSSION

Extracting the expansion from the images in Table 3 was not an easy task. The uncertainty of the location of the expansion radius is three to four pixels, translating into 1.0 to 1.3 mm. This uncertainty may be too large for what is required for determining the JWL parameters from these images. The error made in terms of expansion going from one frame to the next is of the same order (or larger) as the expansion! From Table 4 the average expansion from frame to frame is 0.89 mm ± 44%. This error can be reduced if the smearing of the image is taken into account.

The angle with the tube axis of the expanding radius (6.98° ± 5.3%) can be used for determining the JWL constants with ANSYS AUTODYN. The input parameters are those obtained by EXPLO5 and then adjusted to obtain the angle with the tube axis of the expanding radius.

The accuracy of the data depends on selecting the exact pixel that represents the expanding radius. If this could be attained (for instance by dedicated software), the uncertainty reduces to ± 1 pixel, or ± 0.34 mm. To decrease the uncertainty further, one needs to increase the pixel count.

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