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# Diagnostic Imaging of Detonation Waves for Waveshaper Development

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## **ABSTRACT**

This report details various experimental techniques for imaging the detonation wave in chemically sensitised nitromethane and their application towards developing a rim initiating waveshaper for reliable and symmetric cylindrical convergence of the detonation wave. A Cordin high speed camera was used for the imaging and two successful techniques were developed; direct imaging of the light given off by the detonation wave, and imaging of the pressure wave through adiabatic compression of a small air gap underneath the charge. Modifications to the waveshaper to ensure correct performance are presented and analysed with the imaging techniques developed.

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## Executive Summary

Waveshaping of detonation waves is a method for increasing performance in shaped charge warheads. The simplest waveshaper, an inert disc placed at the top of the charge, provides rim initiation to give cylindrical convergence of the detonation wave and an increase in pressure acting on the liner. The implementation of this waveshaper requires a suitable configuration to ensure that the detonation travels around the waveshaper and not through it and symmetry of the detonation wave is important for optimal functioning.

Various techniques were investigated as diagnostic tools for imaging the detonation wave in sensitised nitromethane with a waveshaper disc. Emphasis was placed on detecting sympathetic detonation through the waveshaper and assessing the symmetry of the detonation wave. These techniques used a Cordin high speed camera for image sampling at two million frames per second.

Direct imaging of the detonation wave was achieved using a glass charge bottom and imaging the light given off by the detonating nitromethane. Various other imaging techniques were explored to provide improved symmetry information, including the use of aluminium foil, sheet explosive, and an air-gap underneath the charge. The most successful of these, the air-gap technique, images the pressure wave through adiabatic compression of a small air-gap underneath the charge. The compressed air emits significant light and indicates a region of high pressure, either due to a detonation or a shock wave in the explosive.

The direct imaging technique used together with the air-gap compression technique provided informative diagnostics for the waveshaper development with the ability to distinguish between a shock and a detonation wave, assess the detonation wave symmetry within the charge and view pressure effects within the un-reacted explosive material.

A modification to the waveshaper disc was developed to ensure correct propagation of the detonation around the waveshaper and to prevent precompression of the explosive underneath. The symmetry information from the imaging tests was used to design a suitable positioning method for the waveshaper assembly to produce a symmetric detonation wave important for optimal collapse of the shaped charge liner.

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GLOSSARY

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## Glossary

<b>DETA</b>	Diethylenetriamine
<b>DSTO</b>	Defence Science and Technology Organisation
<b>EBW</b>	Explosive Bridgewire
<b>HEFC</b>	High Explosive Firing Complex
<b>NM</b>	Nitromethane
<b>WSD</b>	Weapons Systems Division

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# 1. Background

In previous work performed in Weapons Systems Division (WSD), DSTO, waveshaping of the detonation wave to increase the performance of shaped charges devices has been explored [1].

The simplest method of waveshaping for increasing the shaped charge performance is to use an inert disc embedded in the top of the charge [2]. When initiated centrally above the disc the detonation wave travels around the disc resulting in rim initiation of the remainder of the charge below the wave shaper. This causes cylindrical convergence of the detonation waves and an increase in pressure as the wave travels from the outside of the charge in toward the centre. This pressure which is greater than the normal detonation pressure of the explosive causes an increase in energy transferred to the jet and a subsequent improvement in performance. The symmetry is important to produce a symmetrical convergence of the detonation wave to a focal point which is concentric with the charge case. This allows for a symmetrical collapse of the shaped charge liner to give a straight and powerful jet.

For successful charge initiation sufficient explosive energy from the detonator and/or booster is required to successfully detonate the explosive, however too much will cause a strong shock to propagate through the top waveshaper disc and cause sympathetic detonation of the explosive on the other side, resulting in detonation through the waveshaper rather than around it. Additionally the height of explosive above the wave shaper disc is important. Sufficient height is necessary to give an adequate channel to maintain the detonation propagation out to the charge periphery and this is dependent on whether or not confinement, such as a lid, is present.

In order to properly design the charge initiation configuration to provide symmetrical and simultaneous rim initiation, it was necessary to develop suitable instrumentation techniques to differentiate the outcomes from different configurations. This report describes various photoinstrumentation techniques investigated for imaging detonation and shock waves within the explosive material; and their use as diagnostic tools for the development of a successful rim initiation wave shaping system.

## 2. Experimental Setup

All of the tests were conducted in Chamber 1 of DSTO's High Explosive Firing Complex (HEFC). The experimental setup for evaluating the detonation wave imaging techniques is shown in Figure 1 and shows the camera viewing the bottom of the charge via a mirror positioned at 45 degrees underneath.

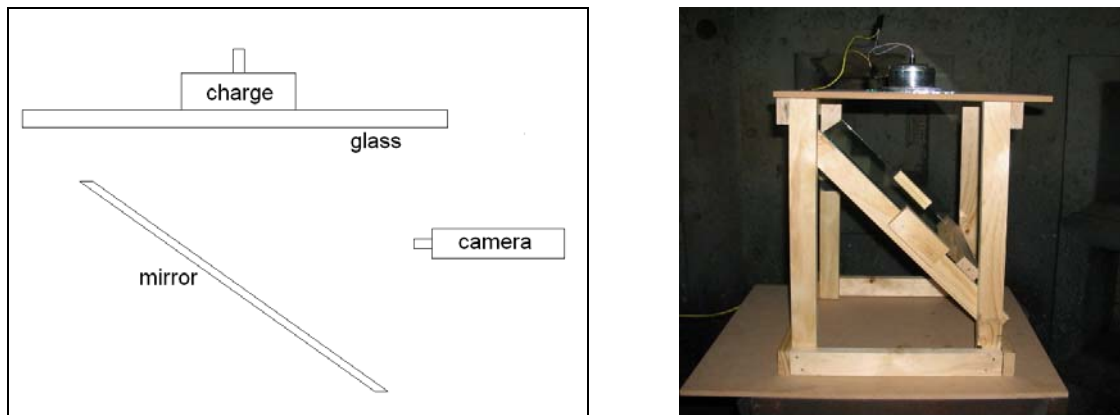


Figure 1: Experimental setup

The camera is a Cordin digital high speed, rotating mirror CCD camera (model 550). It generates 62 frames of 1 megapixel resolution monochrome images at a framing rate of up to 4 million frames per second using a helium driven gas turbine. For this series of tests the camera was run at 2 million frames per seconds to give approximately 31 microseconds duration of image data acquisition.

The liquid explosive used for the tests was chemically sensitised nitromethane consisting of 90% nitromethane and 10% diethylenetriamine (DETA) by volume. This explosive was chosen for its relative sensitivity (detonator sensitive), small critical diameter and ability to uniformly fill a charge with complex geometries without creating voids which would interfere with the detonation wave propagation through the explosive.

The critical diameter for unconfined, uncompressed nitromethane with 10% DETA sensitisation is within the range of  $0.9-1.7 \pm 0.2$  mm [3]. Data was not readily available for the detonation velocity with 10% DETA sensitisation, however, both 3% DETA [4] and 5% DETA sensitisation [5] are reported to have a detonation velocity of 6km/s in the uncompressed state. The 10% DETA mixture was chosen for its small critical diameter, and it is expected to have a similar detonation velocity to the lower DETA concentration mixtures. It is likely that the detonation velocity is slightly less because of the reduced nitromethane content, however it is still expected to be in the range of 5-6 km/s. The explosive was mixed fresh prior to each test and used within 30 minutes to prevent degradation of the explosive performance with time as reported by Cartwright et al. for amine sensitised nitromethane [6].

### 3. Imaging Techniques

Four photoinstrumentation techniques were investigated for imaging the detonation wave:

- (i) Direct imaging – light given off by the detonation reaction
- (ii) Aluminium foil – pyrophoric when shocked heated/compressed
- (iii) Sheet explosive – light given off by sympathetic detonation
- (iv) Air-gap compression – ionisation due to adiabatic compression of air gap



### 3.1 Direct Imaging

Direct imaging of the detonation wave in nitromethane was achieved by attaching the charge casing to a piece of glass and filming the detonation from the bottom. It is assumed that significant light is only given off by the detonation wave (not a deflagration or shock), however the main disadvantage of this technique is the lack of depth perception. As the detonation wave travels around the waveshaper and down the charge periphery (see Figure 2) it is difficult to determine the depth of the detonation wave (due to the translucency of the sensitised nitromethane) and when it reaches the bottom of the charge.

The lack of depth perception makes it hard to assess the symmetry of the detonation wave in the horizontal plane. Some degree of symmetry evaluation can be achieved from the concentricity of the images and the image convergence point, however the other techniques discussed in this section, where light is only produced when the detonation wave reaches the bottom of the charge, are better suited for this.

Figure 2 shows a schematic of the charge for a test conducted using the direct imaging technique. The initiation configuration used was a RP80 EBW detonator immersed 10 mm into the sensitised nitromethane, with 20 mm of nitromethane above the waveshaper disc. The images from the camera for this test are shown in Figure 3.

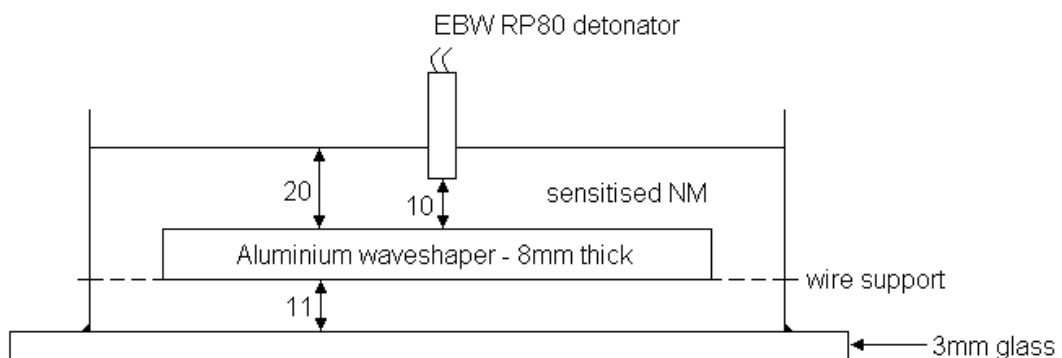


Figure 2: Schematic of charge for direct imaging test

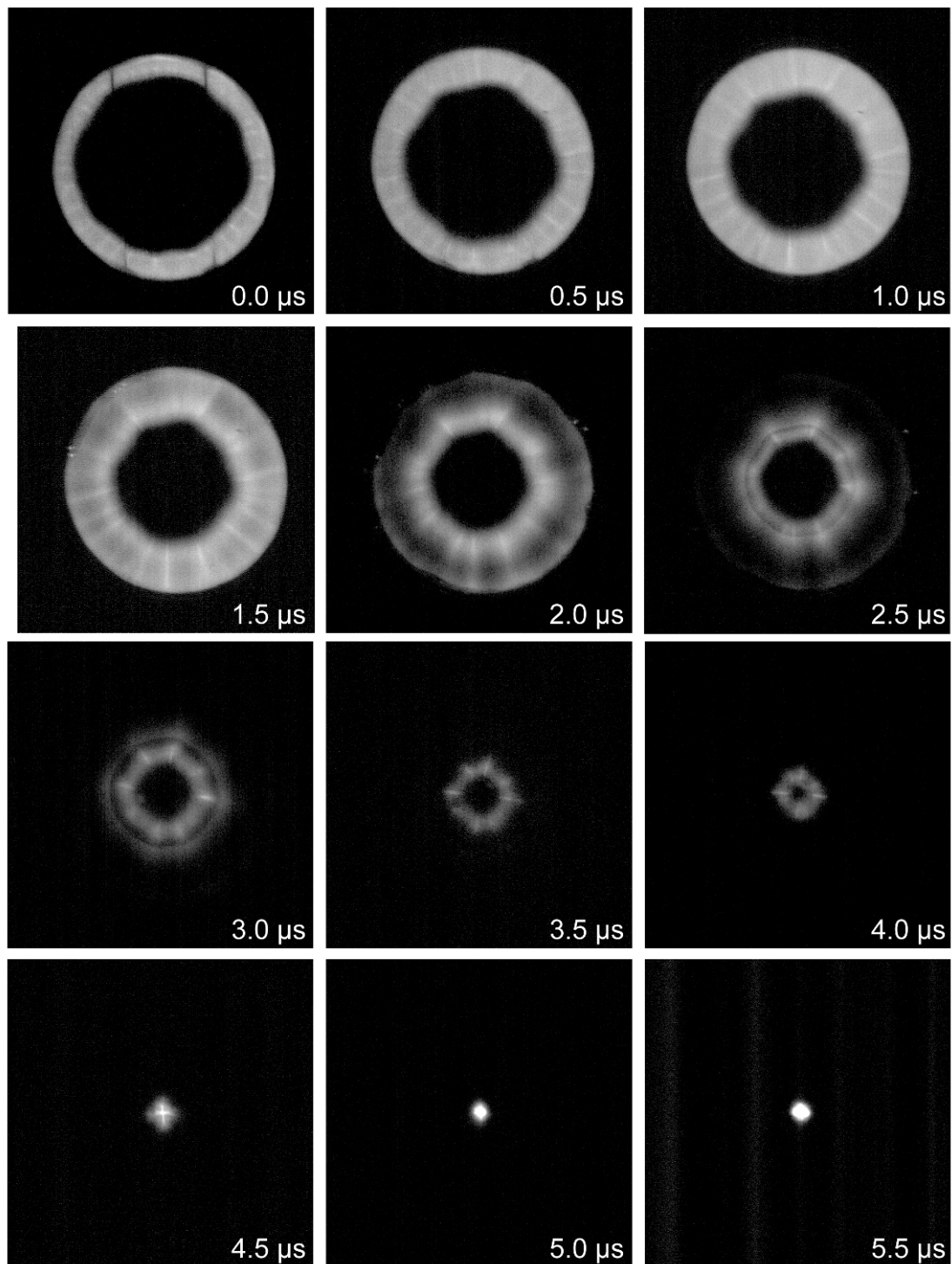


Figure 3: Images from direct imaging technique

In the sequence of images, the times given are relative, in that time zero does not correspond to the functioning of the detonator. The first image (0.0  $\mu\text{s}$ ) in the sequence shows the detonation wave passing down the sides of the waveshaper disc, and the black vertical lines represent the shadow produced by the wires supports used to suspend the waveshaper disc.

In the second image ( $0.5 \mu\text{s}$ ) the detonation wave has progressed past this point. The subsequent frames show the cylindrical convergence of the detonation wave, culminating in a bright spot at the focal point at the end of the sequence. It is clear that the detonation wave has travelled around the waveshaper disc rather than sympathetic detonation through it.

### 3.2 Aluminium Foil

The second imaging technique involved using the pyrophoric nature of aluminium foil for imaging the detonation wave. A sheet of aluminium foil was glued to a transparent plastic base and the charge was assembled and filled on top such that the foil was between the nitromethane and the camera, as shown in Figure 4. The idea was that the aluminium foil would provide a shield from the light while the detonation wave travelled down the charge. When the detonation wave reached the bottom of the charge, the temperature and pressure from the detonation wave would cause the foil to flare and give off light, indicating the position of the detonation wave. Additionally, the initial frame in the sequence would indicate the symmetry of the detonation wave in the horizontal plane.

Unfortunately this technique was unsuccessful in imaging the detonation wave. While the foil was most likely ionised when it interacted with the detonation wave, due to a lack of oxygen around the foil it was unable to burn and give off light. This may be different for an explosive with a positive oxygen balance this however was not tested.

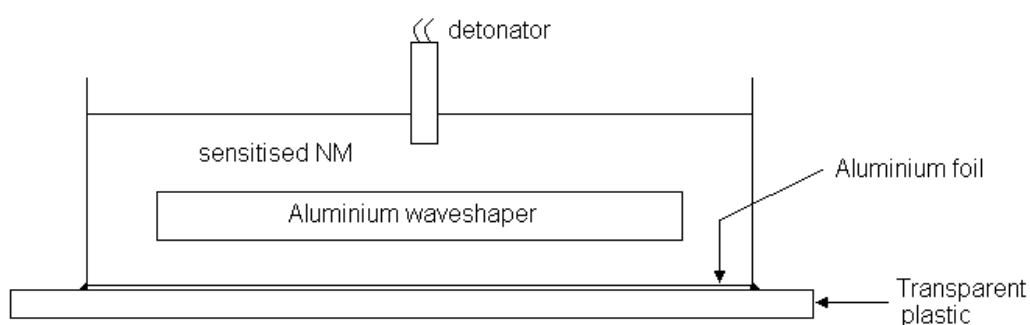


Figure 4: Schematic of charge for aluminium foil imaging technique

### 3.3 Sheet explosive

The third imaging technique involved using sheet explosive in a similar way to the aluminium foil. The sheet explosive was sandwiched between a piece of glass and the bottom of the charge as shown in Figure 5. To allow the detonation wave to initiate the sheet explosive without being in direct contact with the nitromethane (to avoid possible incompatibility issues), a thin sheet of aluminium was glued to the bottom of the charge case. This isolated the two explosives from one another and provided a medium to transmit the shock from the detonating nitromethane to the sheet explosive.

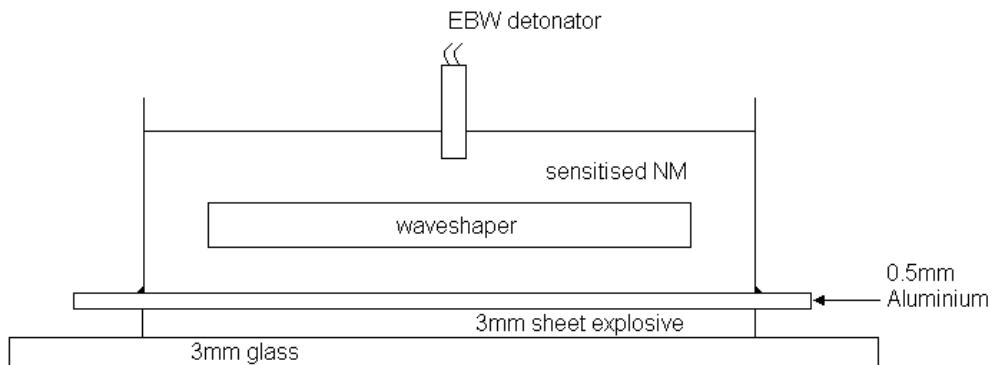


Figure 5: Schematic of charge for sheet explosive imaging technique

It was expected that the light given off by the detonating sheet explosive would form the basis for imaging the detonation wave in the nitromethane. However, it was discovered that the main source of light using this technique was not due to the sheet explosive but rather from small air pockets between the sheet explosive and the glass. The detonation pressure caused the air gap to undergo adiabatic compression and give off light. This effect is clearly illustrated in Figure 6 which shows the sheet explosive sandwiched between the glass before the test and the resulting image captured by the high speed camera. A small groove in the sheet explosive corresponded to a bright line in the camera image. The areas where there was very good contact between the glass and the sheet explosive there was actually very little light given off, indicating a comparatively low amount of light given off by the detonating sheet explosive.

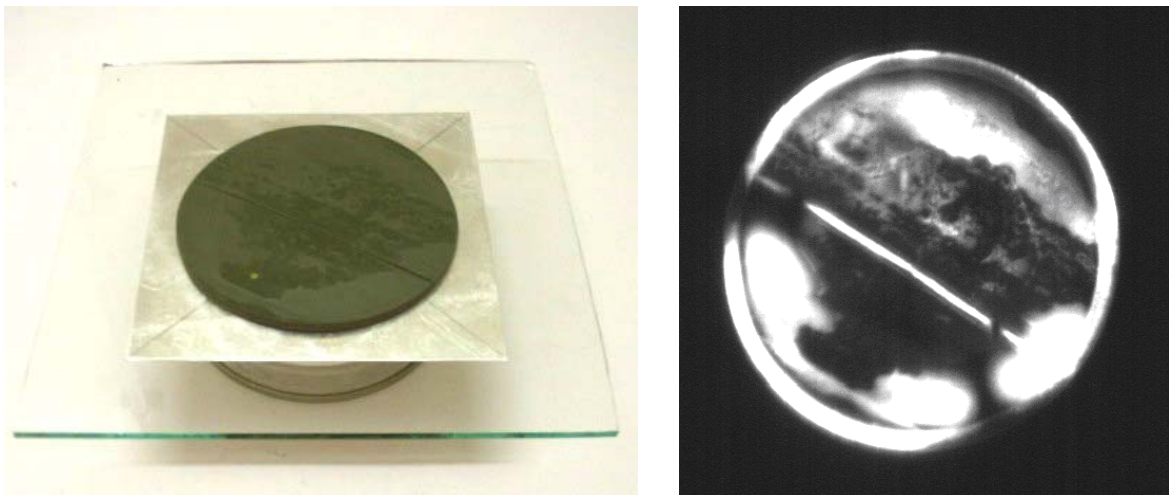


Figure 6: Contact between sheet explosive and glass (left), and resulting high speed image (right)

A significant disadvantage of this technique is that the detonation velocity of the sheet explosive is higher than the nitromethane. Consequently, subject to the approach angle of the detonation wave in the nitromethane onto the charge base, the detonation wave in the sheet

explosive may overtake that in the nitromethane. If the detonation in the nitromethane stopped, this would also not be recognised by this technique as the sheet explosive detonation would continue regardless. The initial image of the detonation wave reaching the bottom of the charge gives information on the wave symmetry, however, past this point the images are difficult to interpret using this technique.

### 3.4 Air-gap compression

In the sheet explosive tests the detonation pressure was seen to adiabatically compress the air trapped between the glass and the sheet explosive, causing an emission of light. This observation was exploited for the air-gap imaging technique by replacing the sheet explosive with common plastic flyscreen mesh. The flyscreen mesh provided an air-gap with constant thickness between the charge bottom and the piece of glass.

This technique allows for information on the symmetry of the detonation wave as light is only produced when the detonation wave reaches the bottom of the charge. However, because this technique is a measure of pressure, light is produced not only for a detonation wave, but also for a shock wave travelling through the nitromethane. The pressures associated with these different events may be quite similar and thus care is required in interpreting the results. The relationship between the pressure magnitude and level of light emission is not known and may not be linear. Timing analysis can be used to help distinguish the source of the pressure and this technique used in combination with the direct imaging technique can be used in determining the detonation wave propagation. The direct imaging technique provides less symmetry information, but its light output is restricted to a detonation.

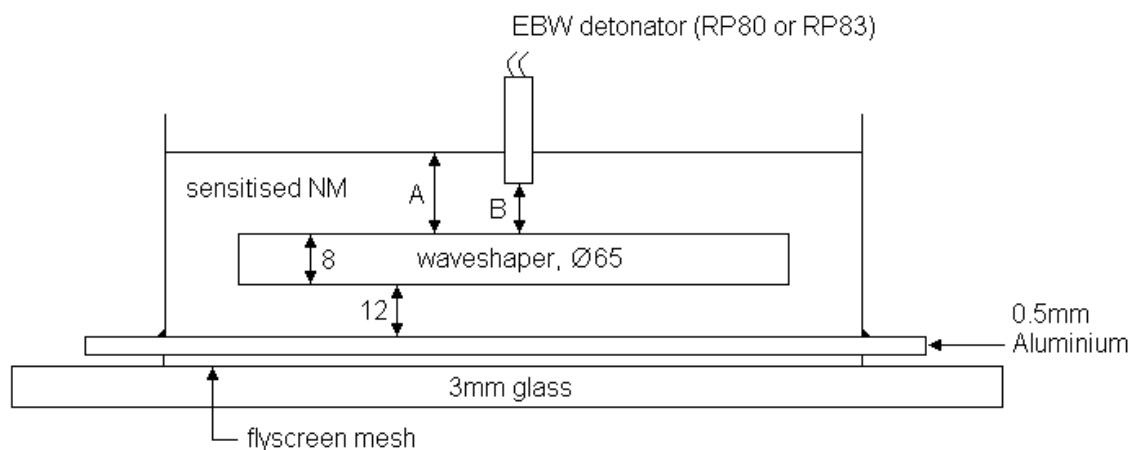


Figure 7: Schematic of charge for air-gap imaging technique

Figure 7 shows a schematic of the charge for the tests conducted using the air-gap imaging technique. The results from two tests using different initiation configurations are presented here and the parameters are summarised in Table 1.

Table 1: *Air-gap imaging tests: charge initiation configurations*

Test #	EBW Detonator	NM above waveshaper, A	Detonator to waveshaper, B
1	RP83 (large)	30 mm	25 mm
2	RP80(small)	20 mm	10 mm

The RP80 EBW detonator contains approximately 200 mg of explosive and has an end directional output. The RP83 detonator is a larger, stretched version of the RP80; it contains approximately 1100 mg of explosive and is less directional in its output.

The first test used the larger RP83 detonator with a 30 mm channel of nitromethane above the waveshaper for initiation of the nitromethane and sustained propagation out to the periphery of the charge. The images from the camera for this test are shown in Figure 8.

In Figure 8, the first (0.0  $\mu\text{s}$ ) and second (0.5  $\mu\text{s}$ ) images show a high pressure region in the centre which propagates outward in subsequent frames. A high pressure area is present at 2.0  $\mu\text{s}$  at the periphery, which begins at the top due to some asymmetry in the detonation wave, and converges to meet the expanding central pressure region. The missing frame at 2.5  $\mu\text{s}$  is a characteristic of the camera. There are always two blank frames present in the 64 frame record which may occur at any position depending on the time the camera was triggered.

It is likely that the initial high pressure at the centre indicates detonation of the nitromethane through the waveshaper. The relative brightness of the initial central dot and an absence of a converged bright focal point at the end of the sequence suggests that the pressure corresponds to a detonation through the waveshaper and not a shock. This is also supported by the timing of the events.

For the charge geometry of the first test (Table 1), the time for the detonation wave (velocity  $\sim 6 \text{ mm}/\mu\text{s}$ ) to travel from the detonator, around the waveshaper, and reach the charge bottom at the periphery is estimated at 10  $\mu\text{s}$ . For sympathetic detonation through the waveshaper (aluminium shock speed  $\sim 6 \text{ mm}/\mu\text{s}$ ), the path length is shorter and the time for the detonation wave to reach the charge bottom at the centre is estimated at 7.5  $\mu\text{s}$ . This means a sympathetic detonation through the waveshaper will reach the charge bottom before the arrival of the detonation wave at the periphery. However, for a shock through the waveshaper that only transmits a shock into the nitromethane below, without creating a detonation, the shock speed through the nitromethane is substantially lower (approximately  $1.5 \text{ mm}/\mu\text{s}$ ). In this scenario, the time for the shock to reach the charge bottom at the centre is estimated at 13.5  $\mu\text{s}$ . This means a shock through the waveshaper will reach the charge bottom after the arrival of the detonation wave at the periphery. Consequently, for the images shown in Figure 8, the central high pressure dot before the arrival of the detonation wave at the periphery indicates sympathetic detonation through the waveshaper and not a shock.

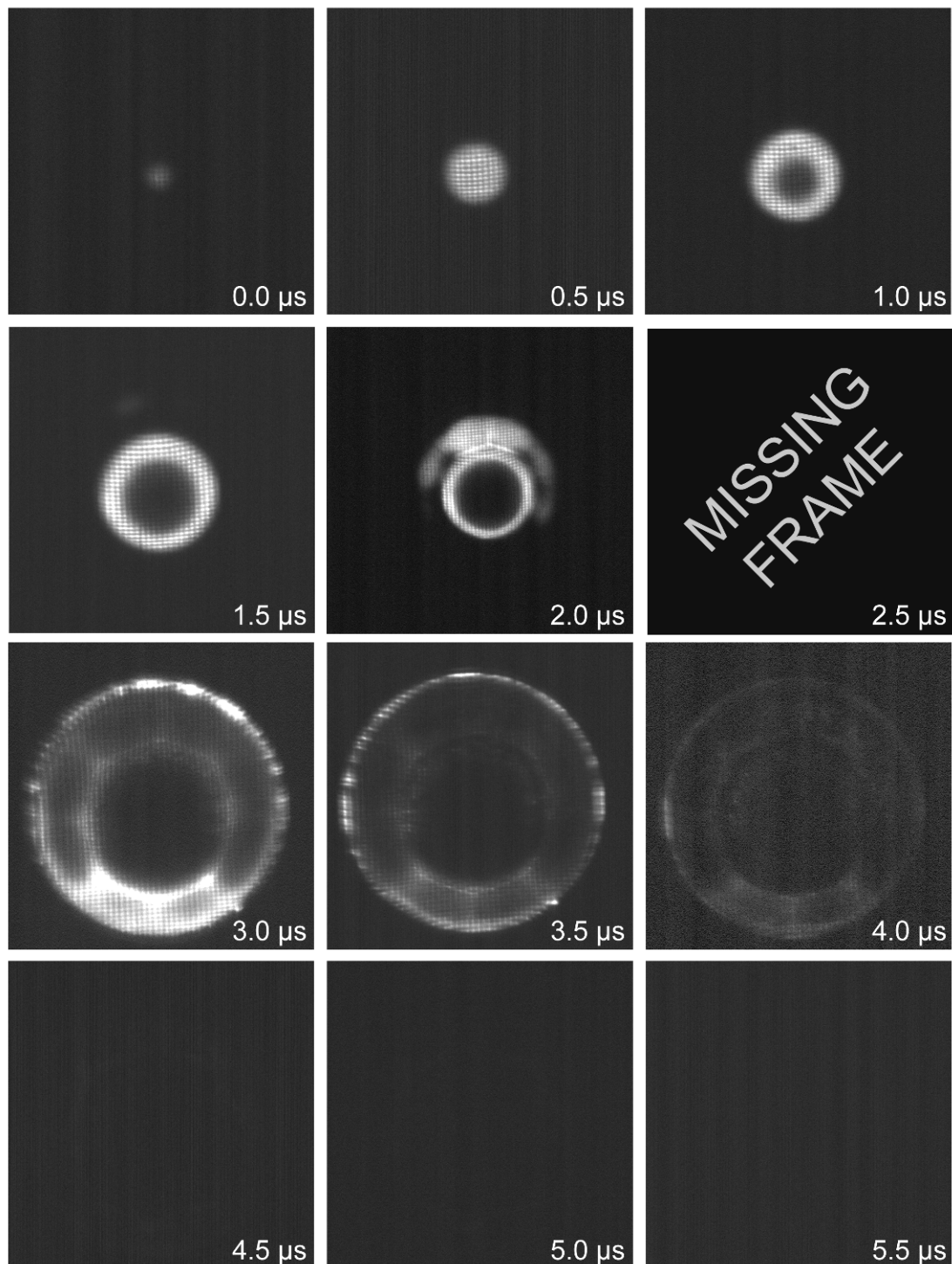


Figure 8: Images from air-gap imaging technique – Test #1

The sympathetic detonation of the nitromethane through the waveshaper negates the effect of the waveshaper and represents a failed initiation configuration. This can be addressed by increasing the shock attenuation through the waveshaper (thicker waveshaper, or different material) or decreasing the amount of explosive above the waveshaper. In the second test the

latter was tried; the smaller RP80 detonator was used and the nitromethane above the waveshaper was reduced to 20 mm. A confining lid on the charge would have allowed this top channel to be reduced further, however previous experiments showed difficulties with bubble formation between the nitromethane and the lid which resulted in problems for the radial symmetry of the detonation wave propagating out along the channel. The images from the camera for this second test are shown in Figure 9.

In Figure 9, the partial ring in the first image (0.0  $\mu\text{s}$ ) shows some asymmetry in the detonation wave, however the emphasis with these early tests was on establishing whether detonation occurred through the waveshaper or around it. As such, the charge assemblies were not constructed with highly toleranced parts, and this affected the charge symmetry.

Again there is a pressure at the centre which begins on the second image (0.5  $\mu\text{s}$ ) in the series. However, this occurs after the detonation wave has travelled around the waveshaper and arrives at the periphery of the bottom of the charge, as represented by the partial ring in the first image (0.0  $\mu\text{s}$ ) and full ring in the second image. The shorter path length through the waveshaper, yet longer time indicates that the high pressure at the center after the peripheral breakout is due to a shock and not a sympathetic detonation. This is supported by the reduced brightness of the central dot and the convergence to a central focal point later in the sequence.

The images suggest that the air may be shocked several times in the event however will only give off light during the first shock (for the time intervals of interest here). As a result, the light from the converging ring disappears around 2.5  $\mu\text{s}$  because the air in the centre has previously been shocked earlier in the sequence. The bright spot at the focal point (3.5  $\mu\text{s}$  onwards), is the result of the converging detonation wave, with increasing pressure and temperature, which may result in other sources of illumination.

The charge initiation configuration used in this test (RP80 detonator and 20 mm nitromethane above the waveshaper) is the same as that reported for the test using direct imaging of the detonation wave (section 3.1). The images of the light given by the detonation wave of Figure 3 clearly show the detonation wave converging from the periphery and collapsing to central focal point for this configuration.



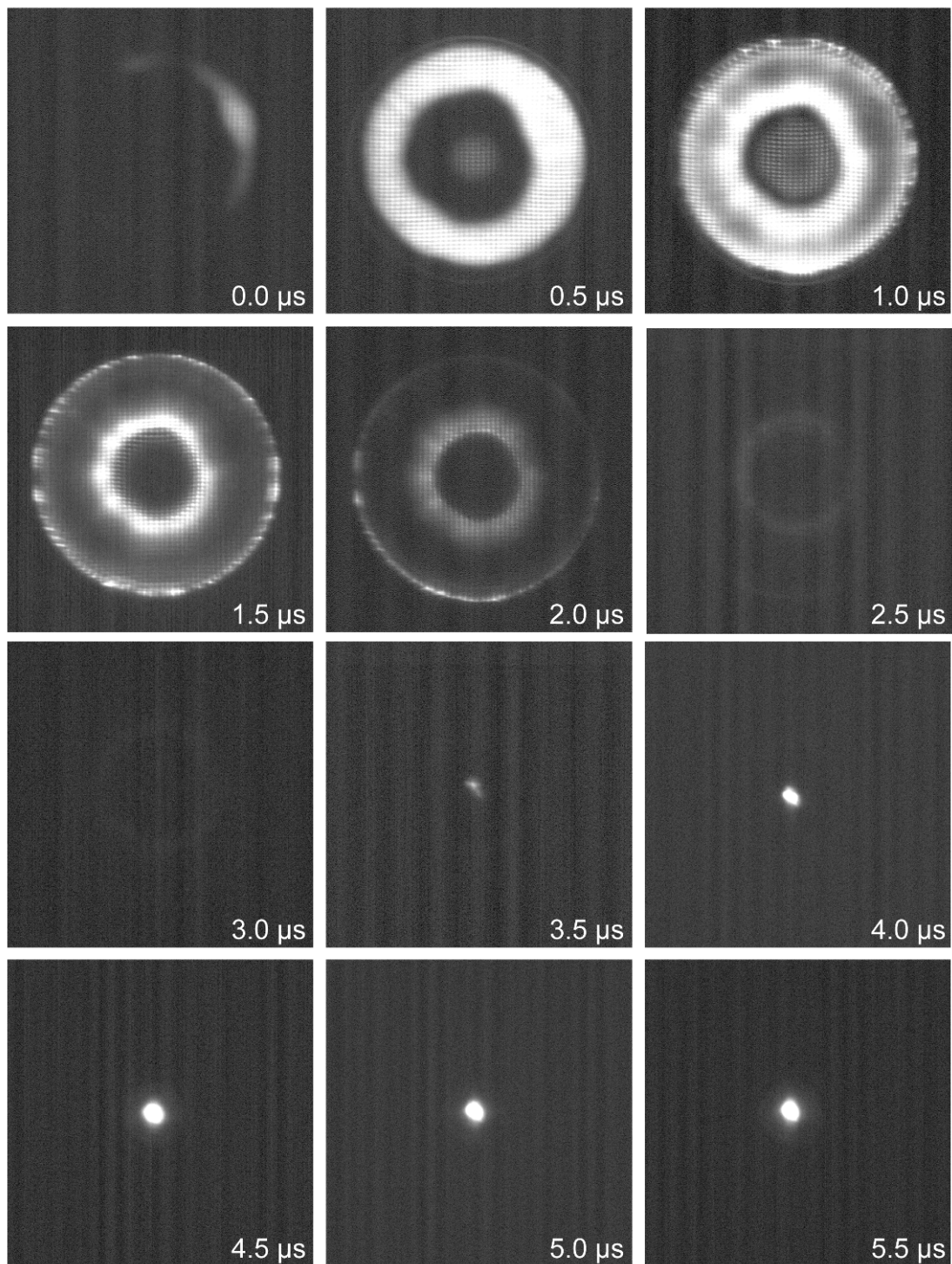


Figure 9: Images from air-gap imaging technique – Test #2

## 4. Waveshaper Modifications

The air-gap imaging technique, because it is sensitive to pressure from detonation and shock waves, drew attention to the shock wave travelling through the waveshaper into the unreacted explosive beneath. For insensitive solid explosives using the simple disc waveshaper design this may not be a problem because the precompression may not significantly alter the detonation velocity of the explosive. However, for nitromethane the precompression results in a significantly higher detonation velocity compared to its uncompressed state; 7.5 km/s vs 6 km/s as reported in [4]. For the simple disc waveshaper design this changes the shape of the converging detonation wave. It also presents further issues, particularly timing, for more complex waveshaping designs which require rim initiation as part of the design.

As a consequence, it was desired to modify the simple waveshaper disc to allow the detonation wave to travel around the waveshaper and converge at the focal point before a shock wave travelling through the waveshaper could interfere. A plate separated by an air gap above the waveshaper disc (top hat arrangement), as shown in Figure 10, was investigated. The top plate would be accelerated by the explosive and travel through the air gap, while the detonation wave travelled around the outside. The detonation wave would converge underneath the assembly before the top plate impacted the bottom plate. The velocity of the top plate is dictated by the amount of explosive above it, and the thickness and density of the top plate material. From a simple 1D analysis using the CTH hydrocode, a 5 mm thick aluminium top plate with 20 mm nitromethane above gave a plate velocity of less than 2 km/s. This is significantly less than the 6 km/s detonation velocity of the nitromethane travelling around the waveshaper assembly, which allows time for the additional distance the detonation wave has to travel.

This arrangement is better than just an airgap by itself (separated with a thin membrane in the case of a liquid explosive), because the top plate mass provides resistance to the expanding detonation products. Without the top plate, the expanding detonation products would travel faster and a taller cavity would be necessary to achieve the same result. Another option would have been to use a solid waveshaper made from a low density material, however it would be difficult to get the material shock speed below 2 km/s and there are chemical compatibility issues with many low density materials and nitromethane.

The CTH hydrocode was used to design the top hat using a 2D axisymmetric model. The resulting pressure plots are presented in Figure 11 and show the detonation wave travelling around the top hat assembly as it collapses. The final image in the sequence shows the detonation wave converging to a point underneath the waveshaper, prior to impact of the top plate of the assembly with the bottom plate.

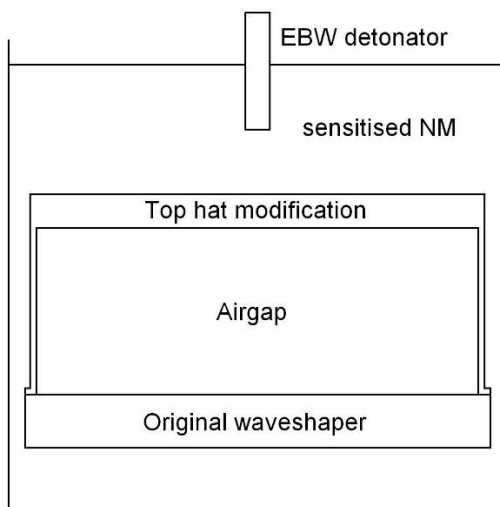


Figure 10: Top hat design

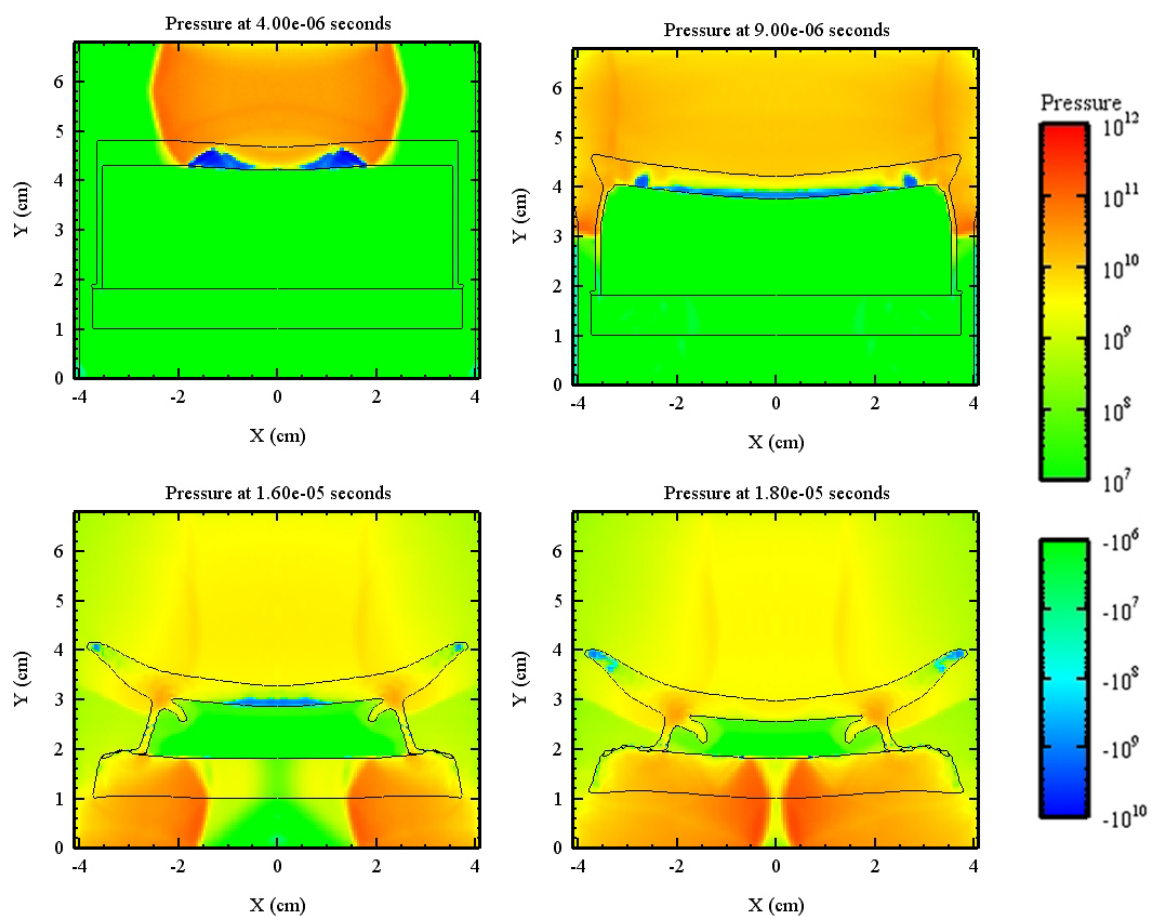


Figure 11: CTH pressure plots of detonation wave propagation around top hat assembly

The waveshaper top hat modification was tested experimentally using both the direct imaging and air-gap compression techniques to provide maximum information about the propagation of the detonation wave and its symmetry. The images produced using the air-gap imaging technique are shown in Figure 12. They show some asymmetry in the detonation wave, as shown by the partial ring in the first frame and dual convergence points later in the sequence (3.5  $\mu$ s), however, importantly there is no pressure in the centre prior to the detonation wave convergence, indicating no detected precompression of the nitromethane. The images produced by the direct imaging technique are shown in Figure 13 and Figure 14. They show the detonation wave travelling down the sides of the waveshaper and then the progressive convergence of the detonation wave to a central focal point along the bottom.

The asymmetry of the detonation wave associated with these tests was attributed to the positioning of the top hat assembly in the charge cylinder and the long thin channel down the length of the top hat. Screws were used to position the assembly and these did not allow accurate concentric positioning within the cylinder. The top hat diameter was also made the same as the bottom original waveshaper disc, which resulted in a long thin channel for the detonation wave to travel down between the top hat and the inside of the charge cylinder. The detonation velocity in the nitromethane is related to the channel width and this effect is more pronounced when close to the critical diameter for the explosive. For a channel width close to the critical diameter, a small change in channel width can give an appreciable change to the detonation velocity, whereas for a much larger channel width, the effect is less noticeable. Consequently, the combination of positioning inaccuracy and a strong dependence between channel width and detonation velocity led to the detonation wave travelling faster in some regions of the charge and hence asymmetry in the detonation wave.

Thus, two problems with the initial design were highlighted; positioning accuracy and the channel width being too small. The positioning accuracy was addressed by using locating tabs machined onto the top hat and ledges within the charge cylinder to position the assembly (Figure 15). The top hat diameter was reduced to increase the channel width, thereby reducing the impact on the detonation velocity for variations in channel width.

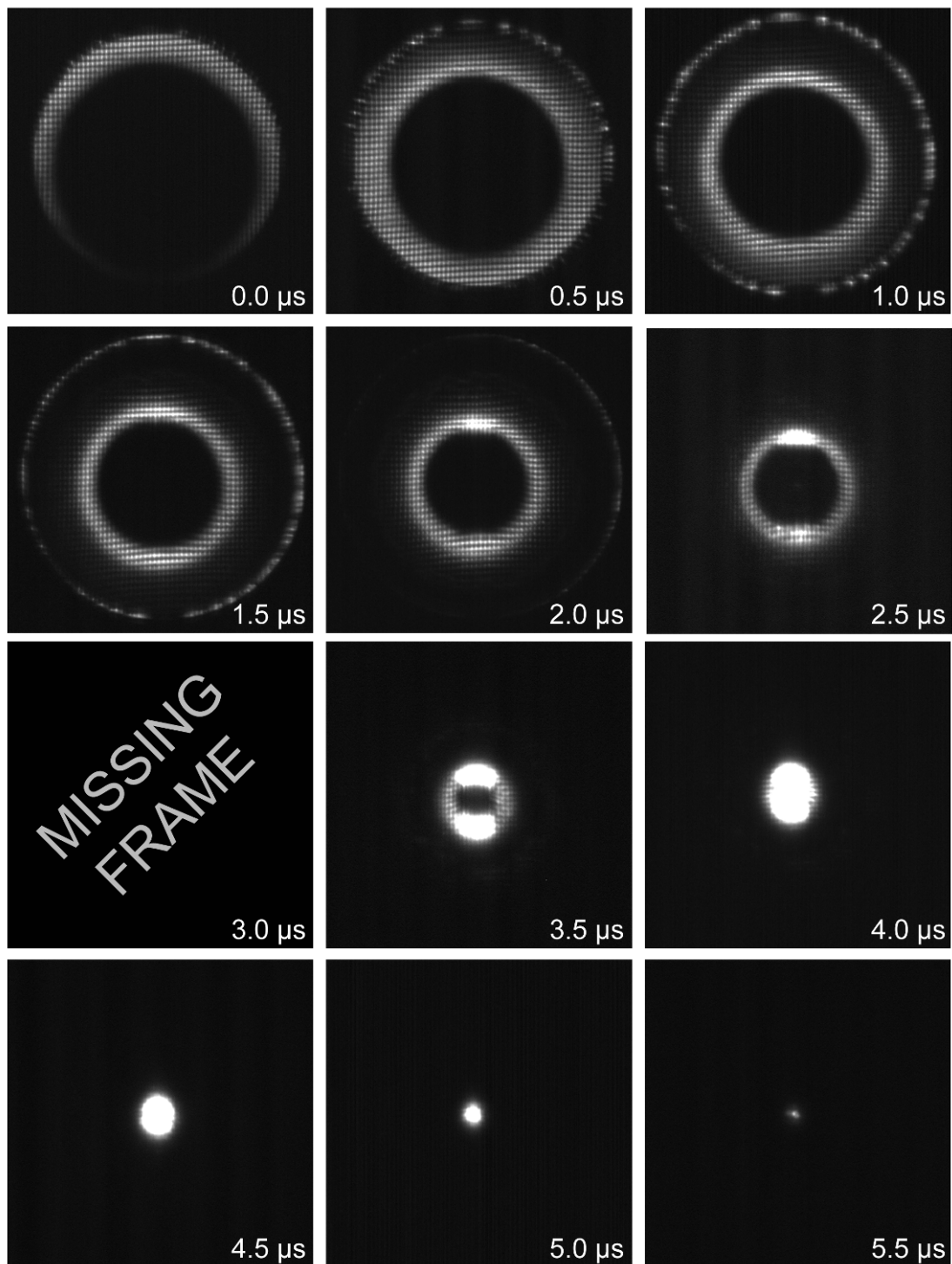


Figure 12: Air-gap compression imaging technique – waveshaper with top hat modification

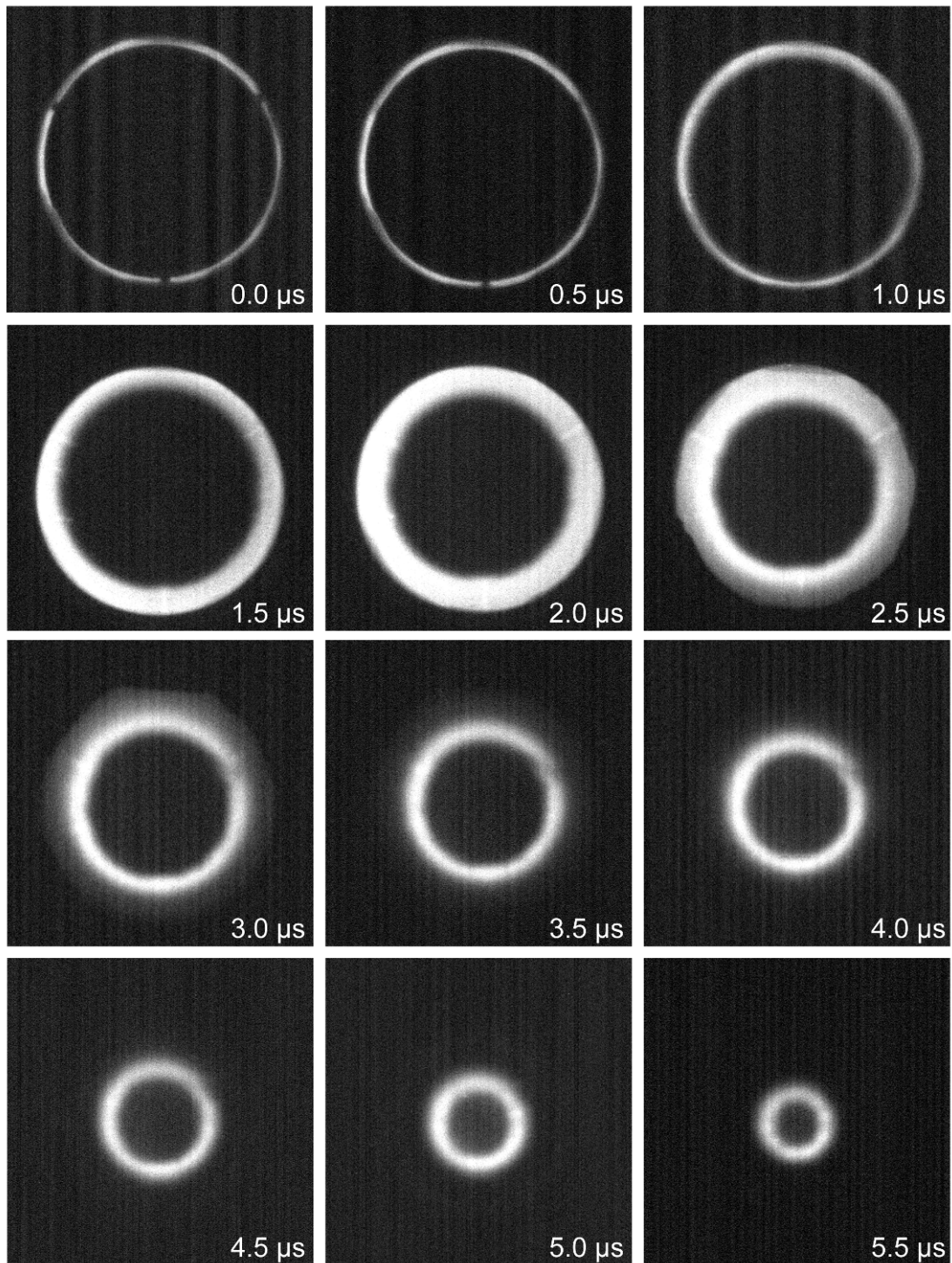


Figure 13: Direct imaging technique – waveshaper with top hat modification

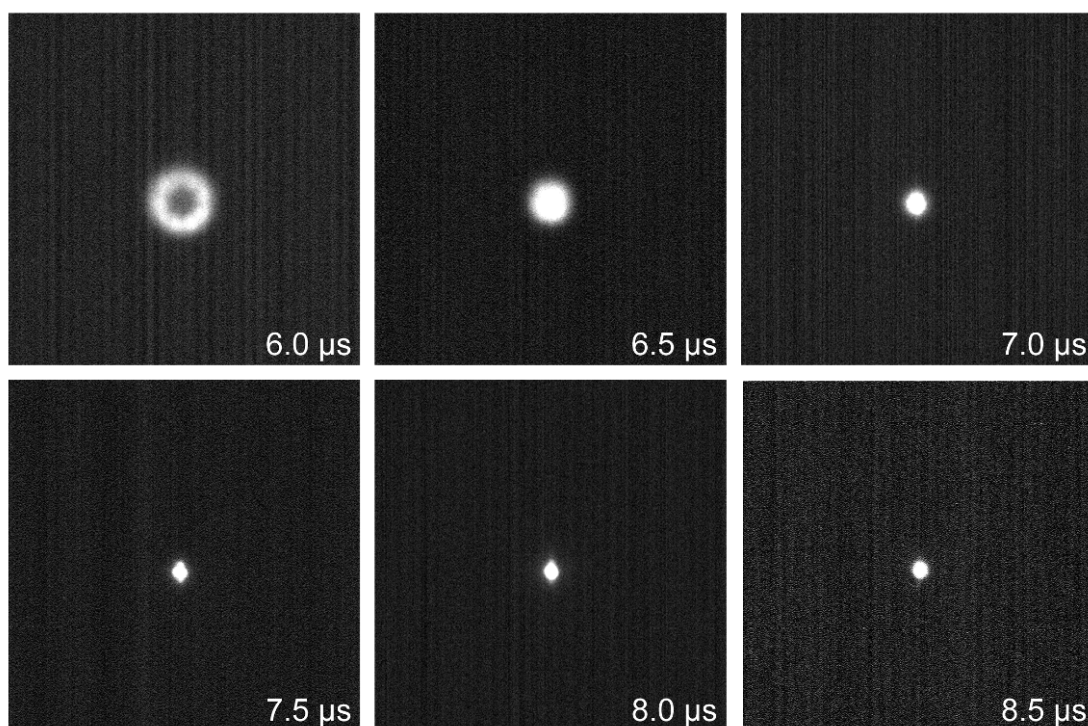


Figure 14: Direct imaging technique – waveshaper with top hat modification



Figure 15: Top hat with reduced diameter and machined locating tabs

These two changes resulted in success for the waveshaper system with good symmetry achieved. In subsequent shaped charge tests using the top hat rim initiation design [7], the symmetry of the detonation wave was measured using piezo pins. Four pins were positioned equally around the circumference of the charge casing at the height of the shaped charge liner apex. An example from the piezo pin output is shown in Figure 16 which shows excellent temporal simultaneity. Good symmetry of the charges was also indicated in the straightness of the holes produced by the shaped charge jets into the targets.

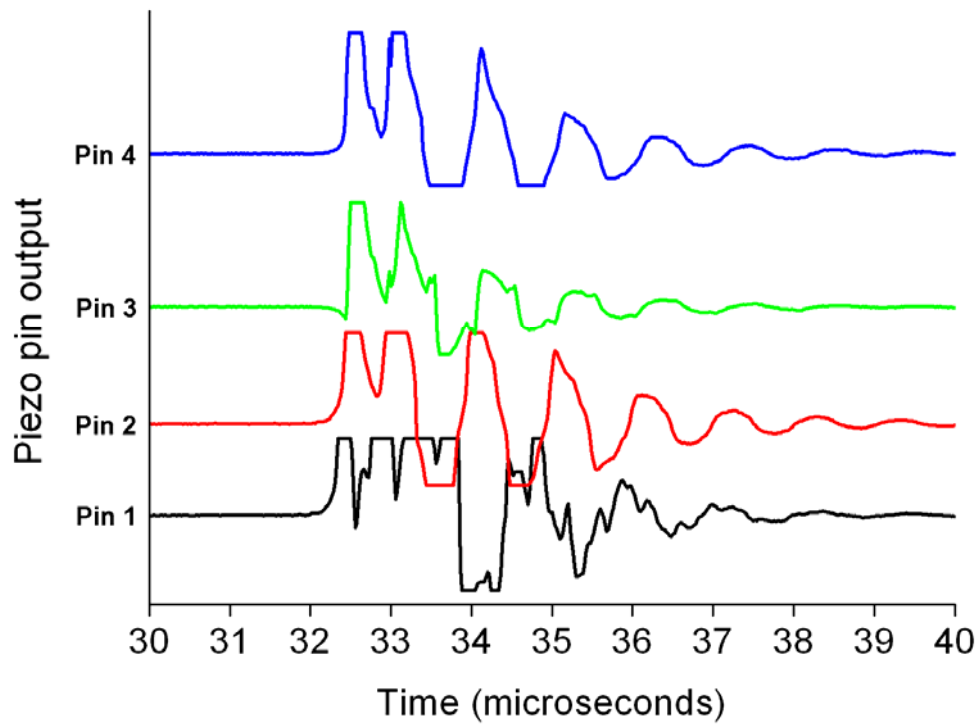


Figure 16: Piezo pin traces from waveshaper shaped charge experiments



## 5. Conclusions

Two successful imaging techniques, the air-gap compression and direct imaging technique, have been established for imaging detonation and other high pressure waves. Each provides different information, such that they can be used together to provide maximum information on the detonation wave propagation and pressure effects within the un-reacted explosive material.

The air-gap compression technique provides information related to the detonation wave pressure. It is sensitive to pressure from the detonation wave as well as shock waves and can provide information on the detonation wave symmetry. The direct imaging technique is less useful for symmetry information, however it is only sensitive to the detonation wave. Consequently, by combining the two techniques it is possible to distinguish between a shock wave and detonation wave.

These imaging techniques have allowed the development of a systematic process for designing a cylindrically converging waveshaping system for use in shaped charges. The benefits of which include:

- correct initiation configuration to ensure detonation around the waveshaper and not through it;
- top hat waveshaper modification to prevent precompression of the explosive, which is particularly important for nitromethane based shaped charges and complex waveshaping designs based on rim initiation;
- waveshaper positioning method, to produce a symmetric detonation wave important for optimal collapse of the shaped charge liner.

This body of work has successfully addressed problems encountered with the engineering aspects of achieving cylindrically converging/rim initiating waveshaping and provides an important foundation to undertake the experimental assessment of other more complex waveshaper designs.

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19. ABSTRACT This report details various experimental techniques for imaging the detonation wave in chemically sensitised nitromethane and their application towards developing a rim initiating waveshaper for reliable and symmetric cylindrical convergence of the detonation wave. A Cordin high speed camera was used for the imaging and two successful techniques were developed; direct imaging of the light given off by the detonation wave, and imaging of the pressure wave through adiabatic compression of a small air gap underneath the charge. Modifications to the waveshaper to ensure correct performance are presented and analysed with the imaging techniques developed.					