MINING TYRE SOLUTIONS

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Technical Report

CASE STUDY

ON

DIFFUSION TYRE EXPLOSION

DUE TO

WOOD LEFT IN TYRE

Table of Contents

1 INTRODUCTION

A 40.00R57 radial tyre on the left front (position 1) of a 220mt haul truck exploded. The driver of the haul truck was killed as a result of the explosion.

Most, if not all of the damage resulted from the air blast created by the explosion. Both shoulders of the tyre, directly below the cabin of the truck, were ruptured (blown out). However, there was minimal projection of pieces of tyre from the explosion, and the rim remained completely intact.

This case study analyses the causes of the explosion. It also presents recommendations on how to reduce the risk of future tyre explosions.

Definition of terms:

1. Pyrolysis: The decomposition of a substance by heat (usually in the absence of air).
2. Diffusion: The spontaneous mixing of one substance with another when in contact or separated by a permeable membrane or microporous barrier. The rate of diffusion is proportional to the concentration of the substances and increases with temperature. Diffusion occurs most readily in gases, less so in liquids, and least in solids.
3. Auto-ignition: The self-ignition or spontaneous combustion of a substance (usually a fuel) without the help of a spark or flame.

2 SEQUENCE OF EVENTS

A 220mt haul truck had been carting material from a shovel in the mine area to a waste dump. The truck arrived at the dumping area and had stopped in preparation for reversing into the dump. As the truck stopped the left front 40.00R57 tyre exploded, rupturing both shoulders in the upper part of the tyre directly under the cabin of the truck. The air blast from the explosion caused extensive damage to the truck's cabin and areas around the cabin.

3 EXAMINATION

The tyre had ruptured in both shoulders (outer and inner) at the top of the tyre. The tread of the tyre remained essentially intact. The section of inner liner of the tyre diametrically opposite the ruptured area was tacky from heat; this was the point where the explosion initiated. The condition of the inner liner improved (was less tacky) moving away from the initiation point towards the area of rupture. Rupture of the tyre diametrically opposite the point of initiation of the explosion, as occurred in this case, is the most common outcome of tyre explosions.

There were two pieces of wood found inside the tyre[1]. Each was approximately 7cm – 8cm in diameter. One was approximately 29cm long and the other approximately 56cm long. The total surface of each piece of wood was carbonised (refer Figure 1).

There was no visible damage to the rim of the exploded tyre.

The truck was extensively damaged directly around the exploded tyre. The floor of the driver's cabin had been pushed upwards causing major damage to the whole cabin. Sections of the walk platform around the driver's cabin were blown out of place and the left front suspension cylinder had collapsed through the loss of oil/gas due to damage to hoses and piping.

There was no evidence – either eye-witness accounts or examination of the tyre and truck components – that any part of the tyre or truck had caught fire before or after the explosion.

[1] The wood had been used as packing during sea-freight of the tyres from their country of manufacture. During unloading of the tyres, the wood had been placed inside the tyre. This wood had not been removed from the tyre when the tyre was mounted onto the rim.

Figure 1 – One of two pieces of charred wood found in the tyre

4 INVESTIGATION

4.1 *General*

The tyre suffered a chemical explosion following the ignition of a mixture of explosive gases within the air chamber of the tyre. There were several factors that indicated that it was a chemical explosion – not just a blow-out caused by inflation air pressure. Firstly, the condition of the rubber inner liner indicated an explosion. Secondly the structure of the tyre, apart from the two shoulder ruptures caused by the incident, was intact with no evidence of casing or tread separations or other weaknesses[2]; a 40.00R57 tyre in this condition requires a pressure in the order of 700psi to cause instantaneous rupture – many times more than the inflation air pressure range (100psi – 140psi).

Tyre explosions had been known in the industry to be caused by the application of extreme localised heat, which typically sets up pyrolysis[3] of the inner liner of the tyre. These are quite rare occurrences; a process of elimination was used to ascertain the cause of the tyre explosion in this case.

The most common known causes of tyre explosion are as follows:

1. Vehicle electrification through contact with overhead power lines.
2. Lightning strike to a vehicle.
3. Heating of wheel or rim components through the deliberate application of heat, such as oxy-acetylene or arc welding.
4. Overheated brakes (either through a mechanical fault or incorrect operator application).
5. Tyre or truck fire, often fuelled by hydraulic fluid.
6. Internal heating of the tyre due to a separation of the tyre tread or casing.

This case was very unusual in that none of the above 'common' causes had triggered the explosion. They were eliminated as follows:

[2] A separation within the tyre can cause friction between internal tyre components generating heat that, in some rare cases, has led to an explosion.

[3] Pyrolysis of the inner liner is essentially heat decomposition of the inner liner. In can start at temperatures of around 200°C – 250°C creating combustible and explosive gases; if the temperature is high enough, typically in the order of 400°C – 450°C, then auto-ignition of these gases may occur, resulting in an explosion.

1. Although the haul truck did pass under 23kV overhead power lines during its haul between the shovel and the dump, there was no evidence at all that any part of the truck had contacted these power lines causing vehicle electrification. The distance between the top of the truck and the power lines was more than 5 metres, precluding any possibility of electric current arcing between the power lines and the truck.
2. There was no electrical storm activity at the time of or prior to the explosion.
3. There was no evidence, from maintenance records for the whole period that the tyre had been fitted to the truck (a period of three weeks), of any heat being applied to the tyre, wheel or hub by means of oxy-acetylene torch, arc welding or any similar form of heating/welding.
4. The truck did have brake problems with the left front wheel, but there was nothing in the maintenance records to suggest that this resulted in overheating of the wheel or tyre. There was also no physical evidence on the tyre itself of heat being transmitted from the wheel to the beads of the tyre[4].
5. There was no tyre or truck fire.
6. The tyre had been fitted new to the truck three weeks prior to the explosion. The tyre was in good condition (apart from the damage caused by the explosion) with no evidence of any internal separation that may have led to overheating of the tyre. The tyre and rim were correctly matched by size and both were correct specification fitments for the truck and for the haulage operation.

The investigation found that there had been no application of heat to the tyre or wheel assembly, internal or external, due to any of these usual causes. The investigation was also able to eliminate[5] the bead lubricant or oil (or other inflammable substance) contamination of the inflation air as causes of the explosion. There was also no evidence of the wood found inside the tyre having been contaminated by any form of petroleum or other flammable substance. The investigation therefore had to look for another reason for the explosion.

4.2 Main hypotheses investigated

4.2.1 Initial theory – pyrolysis of rubber inner liner

After eliminating the above possible causes of tyre explosion, the investigation began to concentrate in earnest on the role of the two pieces of wood found in the exploded tyre.

The investigator's initial hypothesis, based on his previous experience with tyre explosions, was that pyrolysis of the tyre's rubber inner liner may have occurred creating explosive gases which subsequently ignited – either by auto-ignition or some other process. He postulated that the action of the wood rolling around within the tyre generated heat, through friction (wood on wood, and wood on inner liner), allowing pyrolysis of the inner liner to occur.

However there were several factors that worked against this theory. Firstly, while the section of inner liner around the initiation point of the explosion (180° away from the rupture zone) had undergone noticeable degradation from the effects of the explosion, the inner liner material in the rupture zone appeared to be in near normal condition[6]. If the wood friction had caused the inner liner to pyrolise, then one would have expected the effects of pyrolysis to be observed around the whole inner liner circumference. Secondly, there were doubts that the wood friction could generate

[4] Based on the investigator's past experience with tyre explosions, the fact that the truck had left the workshop only some 17 minutes before the incident led him to examine this matter, and the previous point regarding the deliberate application of heat, in considerable detail. However, he found no evidence – physical or documentary – and was able to eliminate both as possible causes.

[5] Through laboratory analysis conducted on samples of inner liner.

[6] Although subsequent microscopic analysis showed that even this section of inner liner had levels of porosity not found in other worn tyres of similar specification.

sufficient temperature to cause pyrolysis of the inner liner (at least 200°C to 250°C)[7]. Finally, laboratory analysis of the inner liner found that its decomposition through heat produced combustible but not necessarily explosive gases[8].

4.2.2 Subsequent theories

The mining company subsequently commissioned combustion experts from a renowned university to assist with the investigation.

4.2.2.1 Pyrolysis of wood

The university initially considered that incomplete combustion or pyrolysis of the two pieces of wood may have produced the explosive gases. It is generally considered that chemical decomposition of wood can occur at temperatures[9] as low as 120°C at a pressure of 1 atmosphere[10] (atm.), and at lower temperatures when the pressure is considerably higher[11].

Incomplete combustion of the wood would produce carbon monoxide (CO) that can combine with oxygen (O2) and water vapour (H2O) to produce an explosive gas mixture. However a high temperature would be required to ignite this mixture.

Pyrolysis of the wood would have required a temperature in the order of 180°C so pyrolysis was also discarded as the main chemical process associated with the explosion.

Notwithstanding this, one or other of these processes may have contributed to the generation of volatile gases before or during the explosion, although neither is considered as a primary factor.

4.2.2.2 Diffusion from wood & generation of combustible materials

4.2.2.2.1 Diffusion

The university in conjunction with the laboratory finally hypothesised that the wood pieces had undergone diffusion[12] creating wood alcohol. Wood alcohol consists of 95% methanol (CH3OH), also known as methyl alcohol, which is flammable and explosive.

Diffusion, in this case, was essentially a drying-out process of the wood pieces. At least 15% moisture is needed within the wood to allow the chemical process that produces the methane to occur. This level was entirely consistent with the circumstances, with the wood readily absorbing moisture from both the surrounding air and from condensation that forms as temperatures drop at night. As the water migrates from inside the wood to the air contained within the tyre inflation chamber, it transports the methanol with it. The amount of methanol produced by the process is in the order of 2% of the initial weight of the wood.

Methanol has a boiling point of 64.7°C (a temperature routinely reached in an operating tyre[13]) at 1atm (with this temperature reducing as pressure increases[14]) so would exist in vapour form in a normal operating tyre. Methanol vapour is 11% more dense than air so it would collect in the bottom of the tyre, significantly increasing its percentage volume (%V) within the surrounding air mixture.

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[7] In addition, investigations of past explosions suggests that a temperature in excess of 400°C would be required to cause auto-ignition of any explosive gases produced by pyrolysis of the inner liner rubber.
[8] This result differed from that obtained, for another brand and size of tyre, in a tyre explosion fatality investigation conducted in 1981. In that case pyrolysis of the rubber inner liner did produce explosive gases – styrene and butadiene. These gases were produced at a temperature of approximately 250°C and exploded at a temperature of around 430°C.
[9] Note that 100°C is insufficient to cause surface carbonisation of the type of wood found in the exploded tyre; i.e. if the wood had undergone pyrolysis, it possibly could have done so without any carbonisation of its surface.
[10] 1 atmosphere is equivalent to 14.7psi.
[11] There is conjecture in the scientific community about this – some sources suggest that wood pyrolysis requires temperatures of 400°C – 600°C at 1atm pressure.
[12] The diffusion process is based on a difference in the chemical concentration of elements present.
[13] Based on actual recorded tyre pressures taken through the tyre's life, the operating temperature of the air contained within the air chamber of the tyre would have had a minimum range of from 10°C – 75°C. At times the air temperature was almost certainly cooler than 10°C, and at times it may have exceeded 75°C.
[14] The normal operating inflation pressure within the tyre ranges from approximately 7atm – 9atm.

4.2.2.2.2 Generation of combustibles

The friction between wood–wood and wood–inner liner would have generated a substantial quantity (probably in the order of several kilograms) of small particles of combustible dust particles with carbon as their main element. These particles came from both the inner liner and from the wood. This combustible dust would have contributed significantly to the explosion process due to the considerable area of total surface area of contact between these particles and the methanol/air gas mixture.

4.2.2.2.3 Auto-ignition of gas mixture

The critical factors for auto-ignition of a methanol/air mixture are concentration and pressure, not temperature[15]. Auto-ignition can occur in a methanol/air mixture ranging from 6% – 36.5%V of methanol, and at a temperature lower than that necessary to produce the methanol vapour, i.e. a temperature considerably lower than 64.7°C (and within normal operating tyre temperature range). Because of the density of methanol vapour, a concentration of only 4% of the total air volume of the tyre's inflation chamber would have been required to become an explosive concentration.

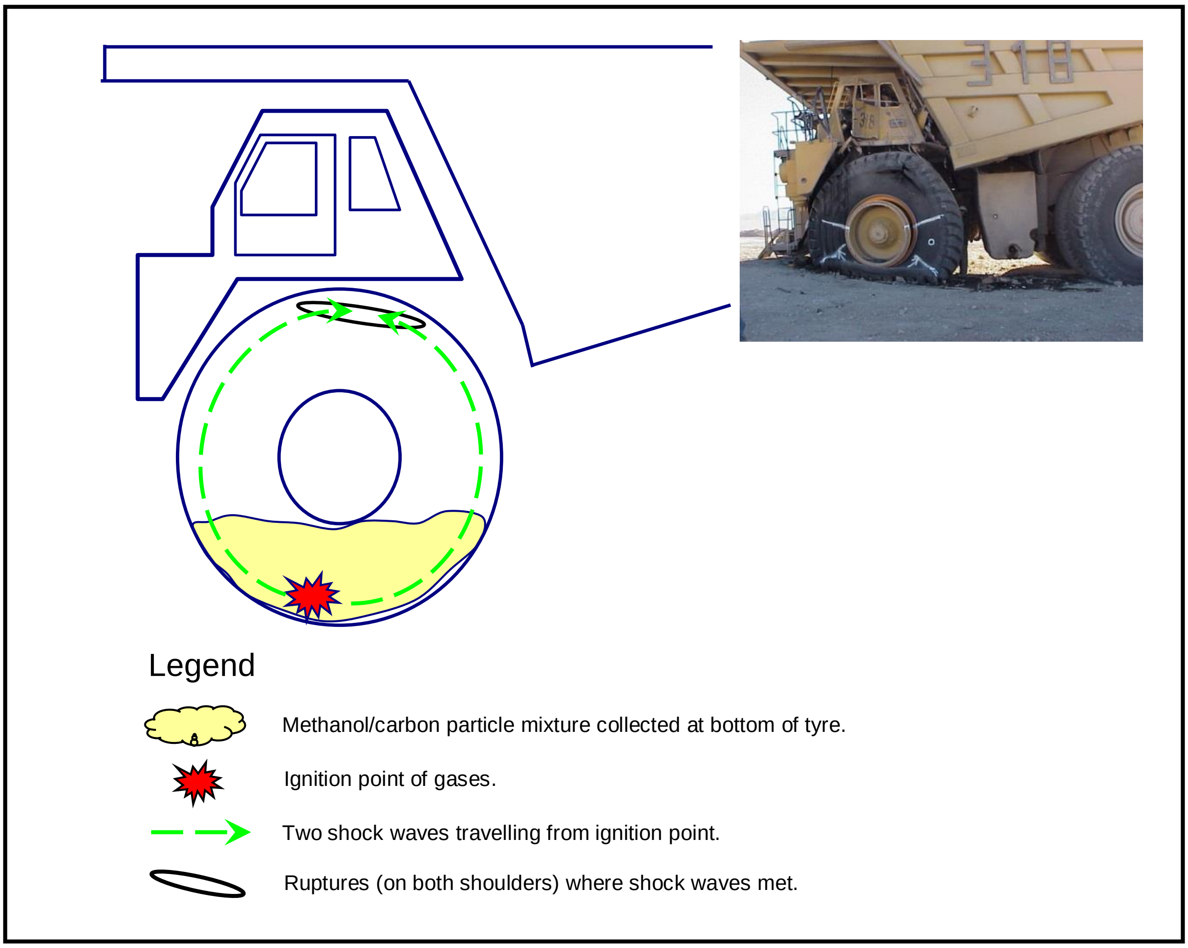


Diagram 1 – Schematic of the exploded tyre on the haul truck showing the collection of gases at the bottom of the tyre, the ignition point of the explosion (slightly forward of the very bottom of the tyre), the two shock waves moving away from the ignition point – meeting 180° away and rupturing the outer and inner shoulders (slightly behind the very top of the tyre) under the driver's cabin of the truck.

[15] The 'pressure' factor is why enclosed wood storage boxes containing wood do not routinely explode in peoples' houses.

The fact that the tyre exploded just as the truck braked to a stop while in a right hand turn indicates that the sudden load transfer to the left front tyre (through a combination of braking and turning) may have produced a zone of local compression (with an associated increase in energy) in the methanol vapour mix creating the thermodynamic conditions for auto-ignition.

5 CONCLUSIONS

The tyre suffered a chemical explosion due to the diffusion, and subsequent auto-ignition, of methanol from two pieces of wood that were in the tyre.

The investigation postulated that the following series of events took place:

1. The tyre was delivered new to site with the two pieces of wood inside.
2. The tyre was mounted onto a wheel rim with the two pieces of wood still inside.
3. The tyre/wheel assembly was fitted to haul truck in question.
4. During operation the inflation air within the tyre's air chamber heated up due to normal flexing and heat build-up of the tyre. The air temperature would on occasion have reached 75°C, possibly higher.
5. The operating temperature and pressure of the inflation air within the tyre produced conditions suitable for diffusion of methanol from the wood into the air chamber of the tyre.
6. Production of methanol continued over time with the methanol vapour, being denser than air, accumulating at the bottom of the tyre.
7. Minute particles of carbon were generated from both the pieces of wood and the rubber inner liner of the tyre, due to wood on wood and wood on inner liner interaction.
8. The carbon particles mixed with the methanol vapour to produce an enhanced explosive mixture.
9. At the time of the incident, the conditions necessary for the auto-ignition of the methanol/carbon particle mixture (together with, possibly, other explosive gases[16]) occurred – that is, the necessary concentration of explosive mixture for the prevailing condition of pressure and temperature. The braking of the truck as it turned at the dump may also have contributed by producing a zone of local compression in the gas mixture. The vapour mixture exploded.
10. Two shock waves, followed by flame fronts, emanated from the initiation point of the explosion, near the bottom of the tyre. The shock waves travelled in opposite directions circumferentially around the air chamber of the tyre. The flame fronts followed, carbonising the surface of the wood pieces and scorching the inner liner of the tyre (particularly near the initiation point, becoming less severe as the flame front moved away from the initiation point depleting the supply of oxygen required to sustain the flame).
11. The shock waves met near the top of the tyre, generating a very high pressure sufficient to rupture the steel carcass cords on both the inner and outer shoulders of the tyre at this point.
12. The explosion air blast emanated from the two ruptures in the tyre. Probably most of the air blast that emanated from the outer shoulder of the tyre was dissipated into the atmosphere (although it still could have caused serious ear damage to anyone in the vicinity). The air blast that emanated from the inner shoulder of the tyre probably did almost all of the structural damage to the truck, including the extensive damage to the driver's cabin.

An explosion of this nature is not a more common event because it involves two unusual circumstances that rarely occur together:

[16] While other gases may have contributed to the explosion the investigation considered that the methanol/carbon particle mixture was the key element, and that the explosive could have occurred solely with the methanol vapour/carbon particle mixture.

a. There were two pieces of wood in the tyre. Their volume provided the required amount of methanol for an explosion to occur (a certain critical mass quantity of wood is necessary), and interaction with each other, through friction, increased the production of carbon particles necessary for an explosion of sufficient energy to rupture the tyre.
b. The pieces of wood had not been removed from the tyre when it was being mounted onto a rim.

Had the tyre been properly checked prior to fitment to the rim, and the wood removed, this explosion would not have occurred. It is an industry accepted procedure that tyres are cleaned out prior to fitment to a rim for the following reasons:

a. To prevent damage and injury from projectiles that can be expelled from a tyre that suffers an impact failure (blow out).
b. To prevent damage to the inner liner could result in premature tyre failure.
c. To minimise the incidence of blocked or partially blocked valves.

Nitrogen inflation, properly implemented, would almost certainly have prevented the explosion. The diffusion of methanol gas may still have occurred; however – providing that the amount of oxygen in the inflation medium was less than 5% by volume – auto-ignition of the methanol gas mixture would not have ensued.

6 RECOMMENDATIONS

The investigation produced the following recommendations in relation to the tyre explosion:

1. Properly inspect the inside of a tyre before mounting it onto a rim to ensure that the tyre contains no foreign objects. If it contains foreign objects, remove them.
2. Recommend to all tyre companies that wood spacers not be used in their tyres (even though a wood spacer had not been used in this case).
3. Recommend to the appropriate shippers and port authorities that wood, or other objects, not be placed inside tyres.
4. Increase the awareness of site personnel – both maintenance and operations staff – regarding tyre fires and explosions and their causes. In particular ensure that people know the difference between a tyre blow-out and a tyre chemical explosion, and the dangers of heating a wheel rim or hub while the tyre is fitted (irrespective of whether the tyre is inflated or deflated).
5. Produce a set of site emergency procedures to be used in the event of a tyre fire, vehicle electrification or any other event that has the potential to lead to a tyre explosion.
6. Consider nitrogen inflation of earthmover tyres.

7 PHOTOGRAPHS

Photograph 1 – Haul truck at the dump after the explosion of the left front tyre, the tyre directly below the operator's cabin. The right front tyre was deflated for safety reasons after the explosion. The broken windscreen from the truck is in the foreground.

Photograph 2 – The orientation of the exploded tyre (the truck had momentarily stopped immediately prior to the explosion). The explosion initiation zone is at the bottom of the tyre, and the two rupture zones (one on each shoulder) are near the top of the tyre.

Photograph 3 – Rupture, near the top of the tyre and on the outer shoulder, caused by the explosion.

Photograph 4 – Rupture, near the top of the tyre and on the inner shoulder, caused by the explosion.

Photograph 5 – Looking down at the exploded tyre from the driver's cabin.

Photograph 6 – Damage to the driver's cabin caused by the explosion air blast (there was very little debris expelled from the exploded tyre, and the tyre itself did not contact the cabin).

Photograph 7 – The first piece of charred wood found when the exploded tyre was removed from its wheel rim.

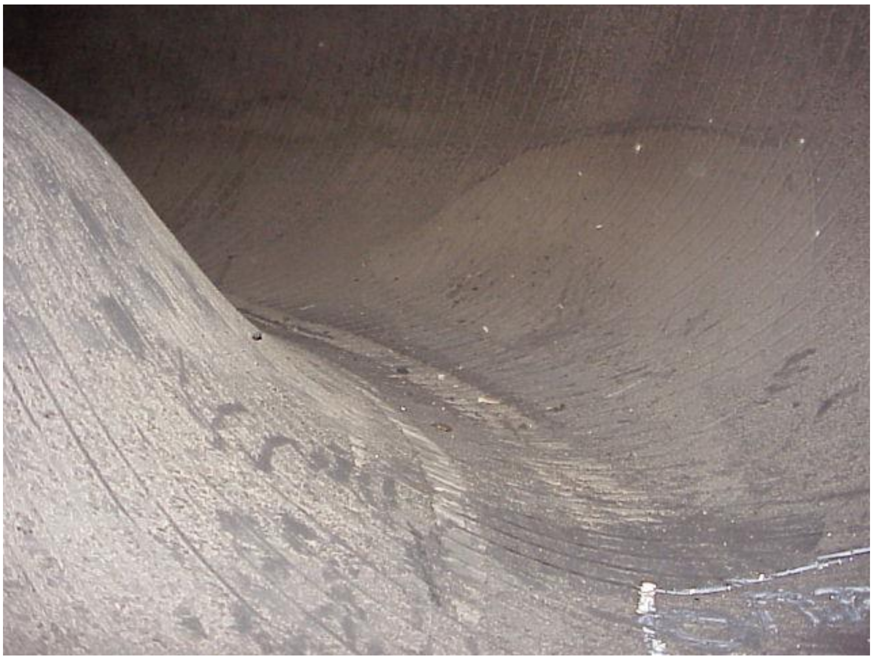
Photograph 8 –The second piece of charred wood found when the exploded tyre was removed from its wheel rim.

Photograph 9 – Burst steel carcass cords at the rupture zone on the outer shoulder of the exploded tyre. These cords showed no indication of fatigue failure, only tension failure.

Photograph 10 – Residual material found inside the exploded tyre, including uncharred pieces of wood.

Photograph 11 – Circumferential crease marks observed in the shoulders of the exploded tyre near the explosion initiation zone.

Photograph 12 – The crease marks shown in Photograph 11 were caused by the tyre folding onto itself after it had exploded.



Photograph 13 – Inner liner of the tyre around the explosion initiation zone. The white chalk marks border the area from which scrapings of inner liner material were taken for laboratory analysis.

Photograph 14 – The rim components showed no visible evidence of damage or of the explosion.

Photograph 15 – Pieces of wood removed from a batch of new tyres that had been delivered to the mine site. The wood is used as a packing material during the sea-freight, and appears to have been placed in the tyres when the tyres are unloaded at the port.

Photograph 16 – A section of the tyre's shoulder was cut out at the explosion initiation zone to determine if there was any failure or separation in the internal structure of the tyre that may have contributed to the explosion. There was no evidence of any damage to the tyre's internal structure.

Photograph 17 – Cut section of one of the two pieces of wood found in the exploded tyre. Along the length of the wood the depth of carbonisation was very shallow (it was a little deeper at the ends).

Photograph 18 – Initial set of samples sent for laboratory testing.