FULL SCALE CAR BURNS IN THE SYDNEY HARBOUR TUNNEL

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1.0 ABSTRACT

On the 3rd and 4th of March 2008, a fire exercise was conducted in the Sydney Harbour Tunnel (SHT). Two cars were burnt at different locations in the northern land tunnel segment of the southbound tunnel. The goals of the tests were to provide:

a) A familiarity exercise for the New South Wales Fire Brigade (NSWFB).
b) An opportunity for quantifying smoke duct and tunnel temperatures for car fire incidents.
c) An opportunity to observe and video smoke movement in two particular modes of tunnel ventilation response.
d) Training and familiarity for tunnel operations staff.

This paper provides a commentary on the video footage of the tests and summarises the data collected including smoke duct, tunnel and car temperatures, and radiation in the near vicinity of the fires. Qualitative observations such as smoke movement and deluge effects are discussed.

For the two tests conducted, some of the characteristics of deluge which have been considered in the past as increasing life safety risk were seen not to be so significant. Both the burns were conducted with a low longitudinal air speed at the fire site (less than 1.5m/s). The SHT deluge system was highly effective at suppressing single large car fires and cooling the tunnel environment.

The tests highlighted the value that can be gained, especially by the tunnel operator, from conducting real fire exercises.

2.0 INTRODUCTION

2.1 Sydney Harbour Tunnel

Opened in 1992, the SHT is a twin-tube tunnel with two lanes in each tube. The tunnel incorporates two land tunnels (400m on the south and 900m on the north) and central precast immersed tube structures (960m long). The two tests conducted in March were located in the northern land segment of the south-bound tube.

The SHT is fitted with a deluge system capable of 10mm/min water flow. Each deluge zone is 30m long and two zones can be activated simultaneously. Wormald HV60 nozzles are fitted angled 40° away from the vertical and are installed on the tunnel centreline. The nozzles produce droplets of an average diameter of approximately 200 to 300 microns.

The tunnel has a mechanical ventilation system that can be used in a longitudinal mode or, at some locations, in a "semi-transverse" (supply/exhaust) mode. Supply air plenums located above the roadway for the land tubes, and to the side of the roadway for the submerged

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segments, can be used as smoke exhaust plenums. Dampers are spaced at 60m intervals along the ceiling of the land tubes and to the side of the submerged tubes. Water spray (sprinkler) cooling systems are installed in the smoke ducts to minimise the gas temperature at the exhaust fans.

Incident detection is provided through a combination of manual CCTV monitoring, loop-based traffic detection, video smoke recognition, and traditional thermal detectors spaced at 15m intervals. The SHT was originally designed for a 50MW fire.

The north pylons of the Sydney Harbour Bridge are used as exhaust stacks for the central tunnel fan plant. In terms of total installed fan capacity (both tubes), the SHT has approximately 1700m^3/s of exhaust (can be reversed to provide supply at a lower rate) and approximately 800m^3/s of supply (can be reversed to provide exhaust at a lower rate).

2.2 Tunnel Fire Suppression

Historically, other than in Japan and Australia[4] the installation of fixed fire suppression systems (FFSS) in road tunnels has not been widely supported. Reasoning that has been used against the installation of FFSS include[4,5]:

- Stratification is destroyed, smoke is down-mixed (spreads downwards to the ground), and visibility is lost.
- Suppression has poor effectiveness against vehicle fires because the water is shielded from the fire by vehicle structure (bonnet, cabin structure etc).
- Steam (superheated) is generated which can potentially cause injury.
- Deflagration or flash fire can occur when suppressing liquid hydrocarbon fires.

Various research[2,5] into water-based FFSS (including spray, foam and mist) has shown that such systems, when designed appropriately, can control fires, prevent fire spread, and provide cooling of smoke. The international road tunnel standards of PIARC and NFPA, which are generally accepted to reflect industry best practice, have only recently recognised the role that FFSS can have in protecting life and assets (including business continuity). While asset protection and intervention benefits are clear, the life safety benefits are less clear. It seems possible that deluge could save lives if it prevented a large ultra-fast fire from growing in the middle of a line of stopped traffic. Such a case represents a tiny fraction of all vehicle fire incidents which are already rare events.

The deluge system in the SHT is a manually activated system that is operated as soon as practical. The judgement of practicality is left to the operator, with the guideline that traffic should first have been stopped, in order to avoid the deluge causing a secondary traffic incident. It can be manually shut off by the operator also. This mode of operation is typical for modern Australian road tunnels. Globally, there is no one universal operating policy for FFSS. Bilson et al.[1] concluded that selection of the deluge activation policy is best undertaken on a situation basis and that one critical factor influencing the outcome of any emergency response is operator response time (for all systems). That is; deluge is only one component of an integrated life safety system incorporating egress, traffic, ventilation and suppression that must be activated in a timely manner.

Full scale tests, such as the subject of this paper, assist with improving the ability of an operator to recognise when best to activate the FFSS and also to how best manage the situation once the FFSS has been activated.

3.0 A TUNNEL OPERATOR'S PERSPECTIVE

The importance of conducting real fire exercises cannot be overstated. In addition to regular desktop exercises, the SHT operators perform a full scale exercise, such as the subject of this paper, every three years or so. For all previous SHT full scale drills, tunnel managers and operators have been invited from all over Australia to witness the drills, and to take onboard whatever lessons are relevant to their facility.

Tunnel operators generally spend their time in a control room within a comfortable sterile atmosphere, viewing their domain via a CCTV system without audio. Photograph 1 shows the SHT control room with the SCADA system in the foreground.

The SHT SCADA system includes numerous screens to assist the operator respond to an incident. Photograph 2 shows the main incident screen which displays the fire location and adjacent CCTV camera zones, the pre-programmed ventilation mode for the fire location, and the appropriate deluge zones to be manually activated. Photograph 3 shows the ventilation screen, giving the operator detailed status indication as well as providing a means for manual control of ventilation elements such as fans and dampers.

Exercises, with real full scale fires, enable operators to experience, in the tunnel, the sight, smell and noises generated by a car fire, and, to get an appreciation of the danger and feelings to which motorists would be exposed. They are also able to witness in real time, the results of their actions, that is, the effect of the ventilation, suppression, and dampers on the fire. Only through full scale testing, can operators really gain a practical understanding of the physical interactions between systems such as ventilation and suppression.

The importance of the radio re-broadcast, public address system and evacuation messages also become much more evident when it is experienced firsthand from a tunnel user perspective. The operators gain valuable lessons in the control room as outcomes of their actions are viewed via the tunnel CCTV in real time, and so will suffer the same obscuration by smoke as would occur in a real fire. Any short comings in effective control of the suppression system, fans, pumps and dampers will be immediately obvious.

Real fire exercises provide an opportunity for operators and managers to validate the procedures and systems that keep people safe in their tunnel. Such training empowers the operators with confidence to make appropriate response judgments in what would normally be stressful and distracting conditions.

4.0 INSTRUMENTATION AND SETUP

The instrumentation used included equipment for temperature, thermal radiation and air speed measurement as well as video and still photography. Temperatures in the vicinity of the fire were measured using 'N'-Type mineral insulated metal sheath (MIMS) thermocouples with unearthed tips. These have a temperature rating of approximately 1300°C. The MIMS segments were manufactured in 2m to 6m lengths and were connected back to the data logging equipment using PVC thermocouple cabling. Where temperatures were expected to be relatively low, self contained temperature loggers with integral thermocouples were installed.

Thermopile total heat flux gauges with a range of 0 – 100kW/m^2 were used for all radiation measurements. The radiometers were water cooled and required a 12 volt pump and water supply for the tests.

Radiometer and most thermocouple data were logged on a self-contained 15 channel 'Datataker'.

For the safety of tunnel occupants during the testing, both vehicles were stripped of foam plastics and the fuel tank was filled with foam to minimise smoke toxicity and explosion risk. A gel made by dissolving polyurethane in petrol was smeared around the vehicle interiors for the main fuel load. More gel was applied to the Test 2 car than to the Test 1 car. The fires were initiated with a handheld flare thrown into the cabin, and so the growth rate was exceptionally rapid, and observably unrealistic for a naturally occurring car fire.

The Test 1 car had most of the glazing removed or broken prior to ignition. The Test 2 car had most glazing intact except for the driver's door window, which was left fully open.

For both tests, the car was laterally offset a few metres from tunnel lighting and other services at the ceiling to reduce the chance of fire damage. The asphalt roadway was protected by fibre cement sheeting placed beneath each vehicle.

5.0 TEST 1 – OBSERVATIONS AND RESULTS

Figure 1 demonstrates how Test 1 was conducted. The incident vehicle was placed directly beneath the closest smoke damper to the northern exhaust plant (normally supply) in the southbound tube. The exhaust flow rate was at a practical minimum so as to maximise the gas temperature within the smoke duct and at the exhaust fans.

The following summary identifies key observations against time (minutes:seconds) from ignition.

00:00	**Ignition.**
00:30	Peak heat release attained based on observable maximum plume height.
02:00	Fire observed under the car.
02:54	**Deluge on.**
02:58	Flaring up of the fire caused by deluge. Fire impinging onto ceiling damper. Flame penetrating ceiling damper into the smoke duct.
03:10	Flaring stops.
03:15	Combustion external to the car is suppressed. Combustion still occurring in car.
03:56	Internal fire mainly suppressed.
04:25	**Deluge off.** Remaining combustion attacked by fire crew.
04:43	Limited smouldering combustion inside car.
05:00	**Fire completely out.**

Table 1 in Section 12 shows a series of video frames highlighting key events as seen from the south (downgrade) of the test location. Table 2 shows a series of frames as viewed from the north (upgrade) of the test location.

The fire was ignited at approximately 11.52pm. Deluge was activated at 11:55pm. It took approximately 1.5 minutes for the deluge to practically extinguish the fire (one minute of which was needed to suppress the interior combustion).

Smoke was efficiently exhausted from the tunnel through the damper directly above the fire and there was limited smoke spread upstream and downstream. Because no smoke layer was allowed to develop, activation of the deluge did not cause a complete loss of visibility through the 30m long deluge zone at the fire site (Photograph 4) (i.e. visibility of at least 30m).

It was noted that a deflagration (flash fire) event was initiated within a few seconds of the deluge being activated (i.e. a flaring-up of the fire). This phenomenon, which has been previously observed for misting systems acting on hydrocarbon pool fires[3], is thought to be caused by flash vaporisation and the additional turbulence to stimulate both the pyrolysis / evaporation of the fuel and the combustion reaction. This effect was highly localised and lasted only several seconds. Unless large quantities of liquid hydrocarbons are present at a fire site, it is unlikely that this effect would present any significant danger to persons not in close proximity to the fire.

Figure 3 summarises the temperature data collected for Test 1. The traces shown correspond to the in-car temperature and the two smoke duct temperatures. At its peak, the gas temperature in the car reached approximately 900°C (within three minutes from ignition). A temperature in the car of 800°C was reached in less than 1.5 minutes from ignition. The peak temperature in the smoke duct reached approximately 55°C immediately downstream of the open damper. The temperature increases in the car and within the smoke duct decayed very quickly upon activation of the deluge above the fire.

Figure 4 summarises the radiation data collected for Test 1. Incident radiation 1500mm to the side of the vehicle reached approximately 11kW/m^2. To the front of the car, the value achieved was approximately 6kW/m^2.

From the smoke duct temperatures and measured radiation, it is estimated that Test 1 resulted in a peak heat release rate of approximately 3MW. Despite the flame impingement on the ceiling damper above the car, no observable damage was sustained to the damper nor were any light fittings to the side of the fire site adversely affected.

6.0 TEST 2 – OBSERVATIONS AND RESULTS

Figure 2 demonstrates how Test 2 was conducted. This test was designed to simulate a particular ventilation mode that is being implemented on the new North South Bypass Tunnel (NSBT) in Brisbane (i.e. overhead smoke capture using two downstream dampers). The situation only provided an approximation to the actual mode as the available exhaust rate was very much lower than being provided in the NSBT.

The following summary identifies key observations against time (minutes:seconds) from ignition.

00:00	**Ignition.**
01:00	Smoke backlayering to the south.
01:51	Combustion external to vehicle. Interior fire under-ventilated.
02:04	Failure of front windscreen.
02:18	Back windscreen fails.
02:23	Failure of most glazing. Ventilation increased to interior fire. Smoke stratified north and south of the fire site.
02:35	Vehicle fully involved. Smoke well stratified to the north and south.
03:45	Involvement of rear tyres and bumper. Smoke has travelled over 100m to the north of the fire site.
04:43	Smoke descends to 3m above roadway to the south.
04:46	**Deluge on.** Local destratification of smoke layer.
04:51	Flaring up of the fire.
05:00	Flaring subsides. External combustion controlled. Combustion suppressed above vehicle.
05:07	Visibility is lost from northern viewpoint locally through fire site.
05:24	Combustion generally controlled within the vehicle. Significant combustion still present externally beneath the car and to the rear of the car.
05:27	Visibility completely lost roadway to ceiling within 100m to the north of the fire site. Beyond 100m to the north the visibility seemed to be tenable.
06:20	Smoke clears to the south of the fire site as smoke is driven to the north with a change in ventilation mode. External combustion present beneath the car and to the rear of the car.

06:41	**Deluge off.** Tunnel to the south of the fire site is clear of smoke. To the north, smoke is destratified within 150m of the fire site. Visibility is poor in this area. Beyond approximately 200m north of the fire site, smoke is generally stratified and visibility at the roadway appears to be greater than 50m (Photograph 5).
07:13	Manual extinguishment commenced.
07:40	**Fire mainly suppressed** except for small localised combustion areas beneath car. Smoke starts to disperse to the north.
08:40	Partial visibility (much better than 50m) restored to the north of the fire site.
14:00	**Tunnel almost completely cleared of smoke.**

Table 3 in Section 13 shows a series of video frames highlighting key events as viewed from the south of the test location. Table 4 shows a series of video frames as viewed from the north of the test location.

The fire was started at approximately 1:11am. Deluge was activated at approximately 1:16am. The deluge took approximately 2 minutes to practically extinguish the fire.

From observation, the Test 2 fire was initially oxygen limited and much of the combustion occurred externally above the driver's window for a period of time until the majority of the glazing failed.

With low longitudinal ventilation velocity along the tunnel prior to activation of the deluge system, smoke readily stratified at the fire site, and remained generally stratified for a few hundred metres upgrade to the north, and 50 or so metres downgrade to the south from the fire site. Later in the test, additional fans were activated in the south to supply into the tunnel. This caused longitudinal movement of the smoke along and then out of the tunnel to the north. A tunnel velocity of approximately 1.3m/s (from the in–tunnel velocity sensor) from the south was not sufficient to prevent slow backlayering upstream and against a 4% grade downhill.

At the commencement of Test 2, dampers DP3174 and DP3173 were open. Relative to the upstream and southern most damper (DP3174), the flow into the northern damper (DP3173) was observed (by smoke velocity) to be low. The smoke duct is relatively restrictive compared to the dampers and so the bulk of the flow entered the smoke duct through the damper closest to the fans (to the south).

The Test 2 fire resulted in much more smoke being introduced into the tunnel environment than the Test 1 fire because the heat release was greater, and more importantly, because the plume had to impinge on the ceiling above the fire rather than immediately enter a damper. This causes significant mixing, increasing the smoke generation rate.

Once deluge was activated, visibility was lost at the fire site. That is, down-mixing of smoke by the deluge was generally limited to the deluge zone. Away from the fire site, the smoke and steam retained sufficient thermal buoyancy to eventually re-stratify downstream, with a low level clear air layer flowing in from behind the smoke providing relatively clear conditions below the smoke layer. This continued after the deluge was turned off (Photograph 5).

Figure 5 summarises the temperature data collected for Test 2. Despite the ceiling above the car being exposed to intermittent flame impingement, the bulk smoke layer temperature reported in the general vicinity above the car was approximately 150°C. It is anticipated that where flame was present locally at the ceiling, intermittent temperatures of the order of 800°C to 1000°C may have been experienced directly above the car. Despite the sporadic flame impingement on the ceiling above the fire car, no observable damage was sustained to the tunnel ceiling or side wall structure.

Fifteen metres upgrade and to the north of the fire, temperatures were measured at several distances below the tunnel ceiling (300mm, 608mm and 2150mm). The peak temperatures measured at these locations were 140°C, 120°C and 35°C respectively. Typically for tunnel design, a tenability criterion of 60°C is used for convected heat and so the area immediately downstream of the fire was tenable for temperature up to a height of approximately 4m. No thermal effects specifically caused by steam liberated from the deluge flow were noted. The ambient temperature in the tunnel at the time was approximately 23°C.

The temperature in the smoke duct immediately upstream of the exhaust fans achieved approximately 27°C for Test 2.

At some point following activation of the deluge a number of thermocouples and radiometers were shorted out causing negative values to be logged. The data prior to and, most likely, immediately following deluge activation were unaffected however.

Figure 6 summarises the radiation data collected for Test 2. Radiation to the side of the vehicle peaked at $33kW/m^2$ and averaged $23kW/m^2$ during the fire. This level of incident radiation would be sufficient to easily ignite most combustible materials in close proximity to the car. In front of the car, the average incident radiation was $6kW/m^2$. Radiation decayed rapidly upon application of the deluge.

It was not possible to estimate heat release for this vehicle fire with the information logged. However on the basis of the high radiation levels in the vicinity of the car it can be concluded that the peak heat release rate was significantly higher than for the Test 1 fire (possibly greater than 5MW). This is consistent with what was visually observed.

7.0 CONCLUDING REMARKS

Exercises and systems testing like that conducted in the SHT in March 2008 are critical for ensuring the best possible life safety outcome in any tunnel emergency situation. In the context of the use of FFSS in tunnels, Dix[4] emphasises the importance of “encouraging an operational culture which prides itself on timely and appropriate responses”. In the context of the whole tunnel life safety package, the owner and operator of SHT has demonstrated how, in part, this can be achieved through real life tunnel exercises.

There is much that designers can learn from experienced tunnel operators, and particularly from those operators who conduct regular drills and real fire tests. A common theme in all areas of design, not just in tunnels, is the philosophical question around the balance between “safe” automatic responses, and responsibility of an operator to make the most appropriate response. The authors are firmly of the opinion that tunnel life safety systems should be designed and implemented to support the operator of the facility, rather than the operator being there to support the tunnel life safety systems. The designer of any new tunnel should seek input from an experienced tunnel operator as early as possible in the design process.

The 10mm/min deluge system installed in the SHT is effective at suppressing a large car fire within approximately 2 minutes, despite much of the combustion being shielded from the applied water. Because of the higher frequency of use, car fires are a far more probable event than the catastrophic design event of a 50MW fire, representative of a heavy goods truck fire. That is, the installed system has a proven effectiveness in accommodating the most likely fire scenarios to be encountered during the life of the facility.

On the characteristics of deluge which could increase risk, none were an overriding issue for the two tests with low fire site air speed.

There was certainly a sharp decrease in visibility within the deluge zone when discharged through an established smoke layer and fully developed fire (Test 2). Outside the deluge zone, the combination of relatively still air and remnant buoyancy allowed a significant degree of stratification. Where significant smoke was not present in the deluge zone (Test 1), the deluge activity resulted in a situation where visibility was reduced but only to the extent as would be expected in a heavy rain shower. No comment is made here on cases with strong longitudinal tunnel air flow.

The deluge was effective at suppressing the car fires, and no steam could be noted through the deluge. With the low air speed, any hot steam would have risen to the ceiling. The temperature results clearly show the rapid cooling of the tunnel environment on application of the deluge.

Local deflagration (flaring up of the fire) at the fire sites was noted for both tests on the application of the deluge. That phenomenon was local to the incident car and it only lasted several seconds. Tunnel occupants only a short distance away from the fire site would not have been affected by this.

The risk mitigation potential of FFSS should always be explored if the designer of a new facility takes a holistic risk approach to tunnel fire life safety.

8.0 ACKNOWLEDGEMENTS

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The authors wish to thank Dr Conrad Stacey and Dr Matthew Bilson, Maunsell AECOM, for proof checking the draft of this paper.

9.0 REFERENCES

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2. Chiyoda Consultants, “Sprinklers in Japanese road tunnels”, 2001.
3. Cote, A., “Operation of fire protection systems”, Jones & Bartlett Publishers, 2003.
4. Dix, A., “Operational management of fire suppression systems, 13th Australian Tunnelling Conference, Melbourne, May 2008.
5. Liue, Z., Kashef, G., Lougheed, G., and Kim, A., “Challenges for use of fixed fire suppression systems in road tunnel fire protection”, NRC-CNRC, Report 49232, 2007.

10.0 FIGURES

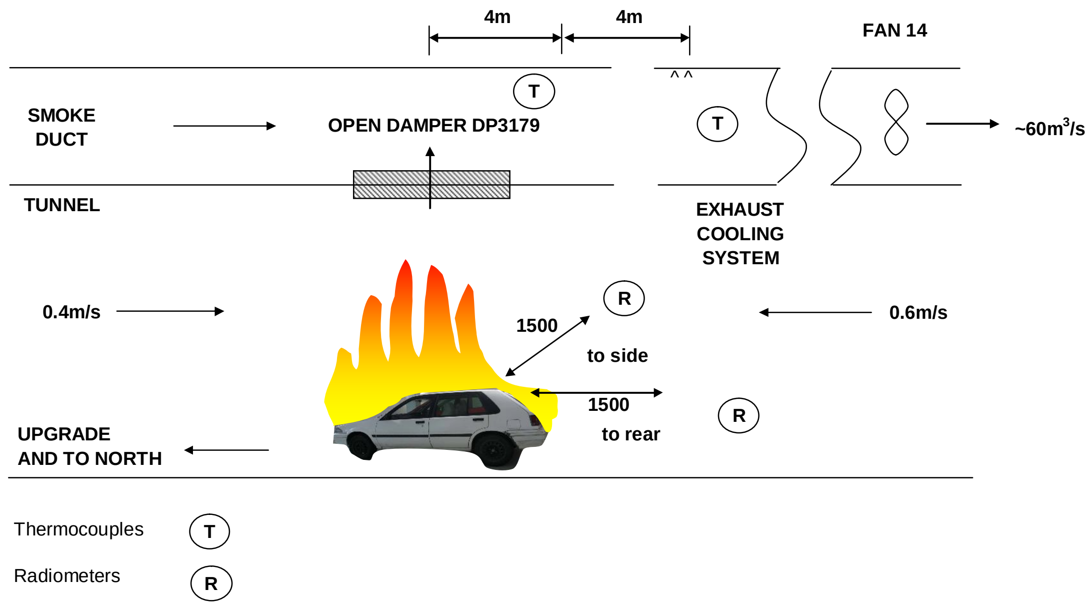


Figure 1 - Test 1 setup

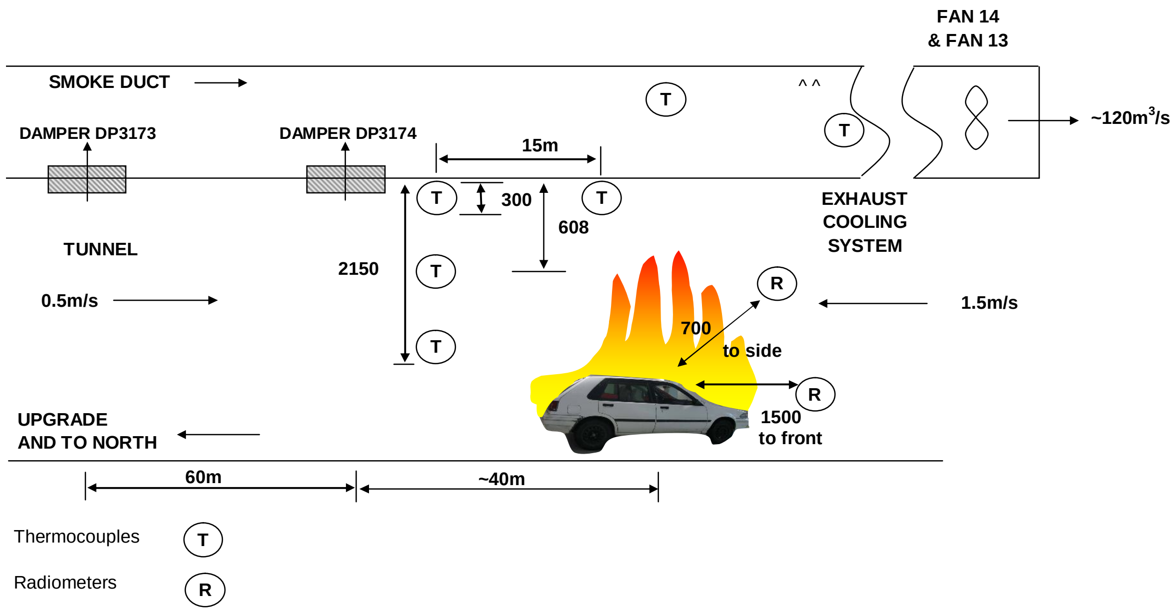


Figure 2 - Test 2 setup

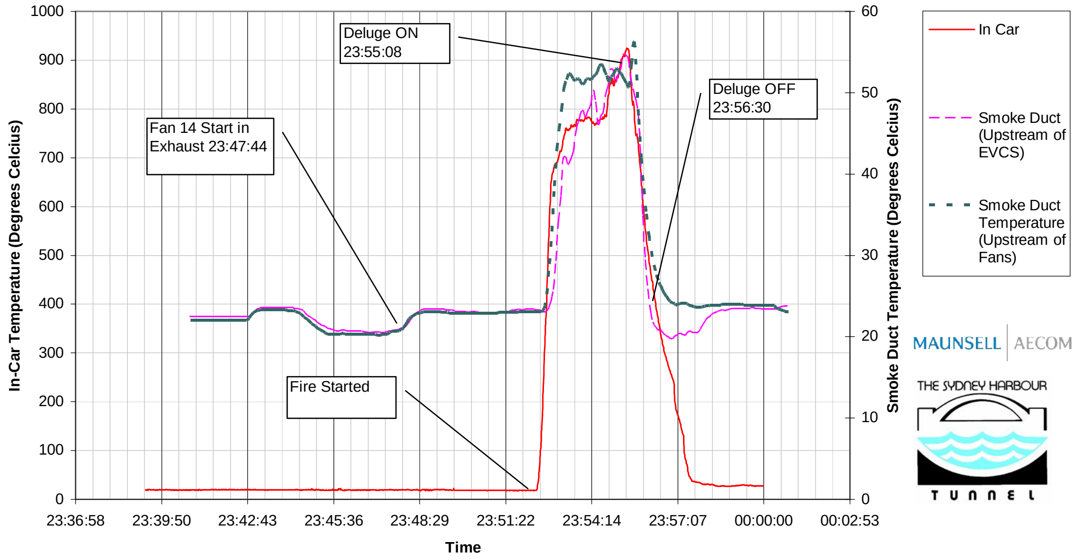


Figure 3 - Test 1 temperature

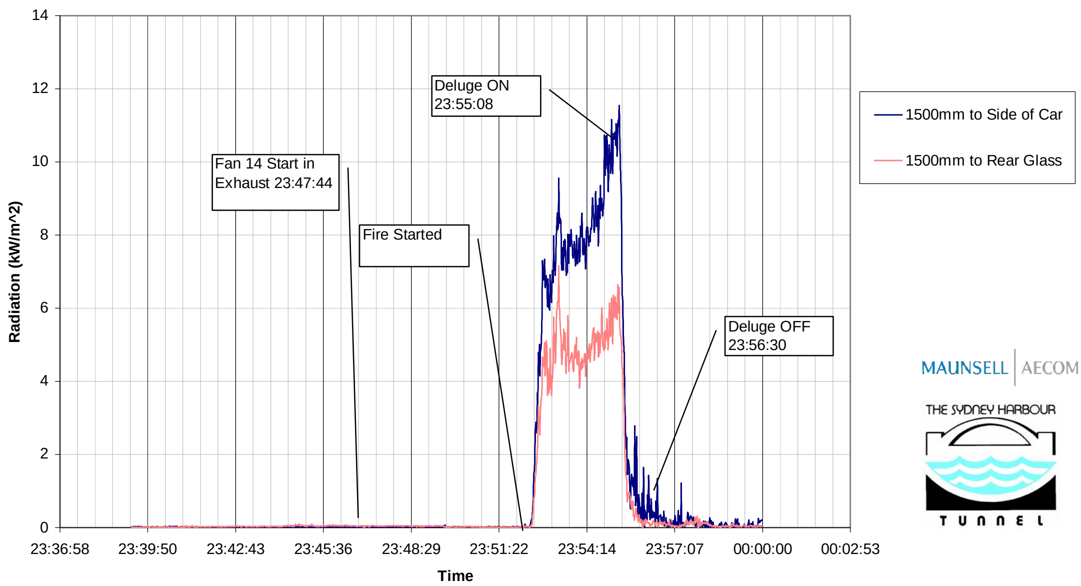


Figure 4 - Test 1 radiation

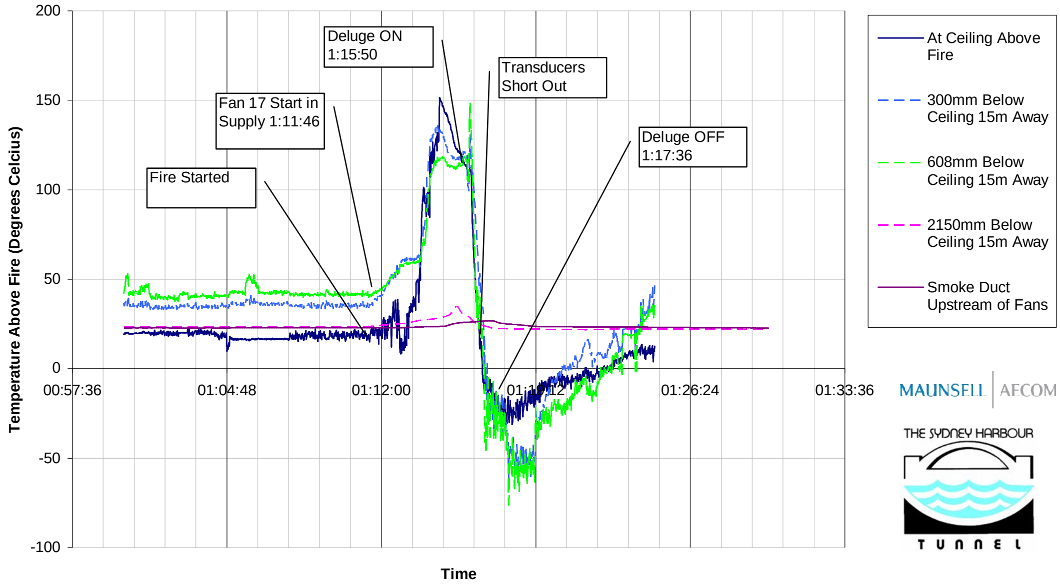


Figure 5 - Test 2 temperature

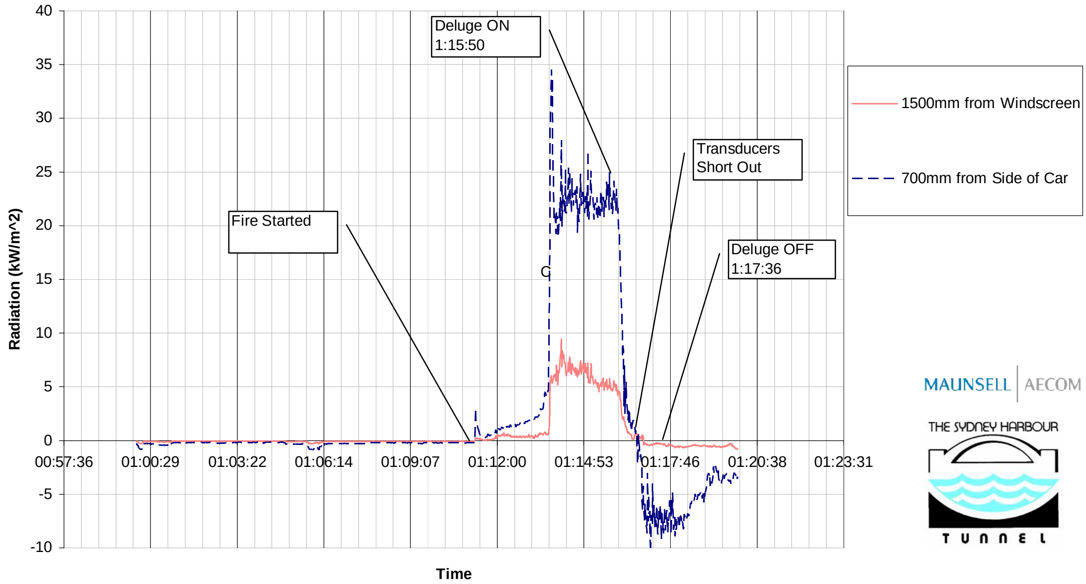
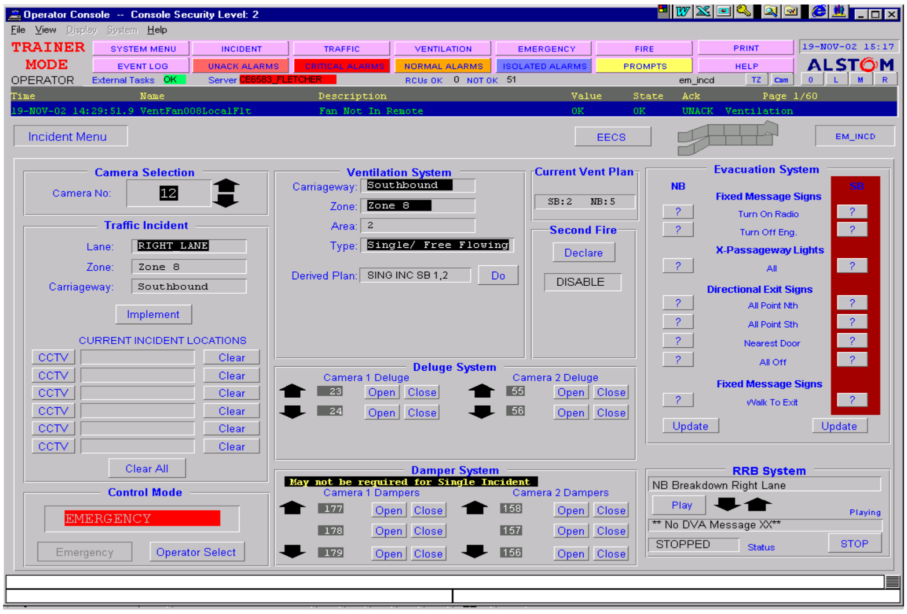


Figure 6 - Test 2 radiation

11.0 PHOTOGRAPHS

Photograph 1 SHT control room.



Photograph 2 - SCADA incident management page.

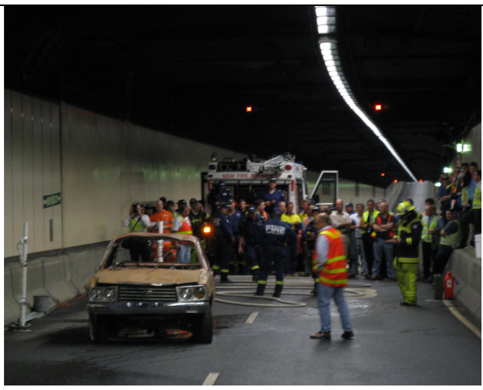
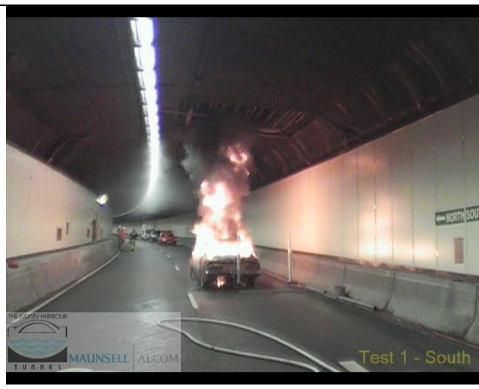
Photograph 3 - Fan SCADA control.

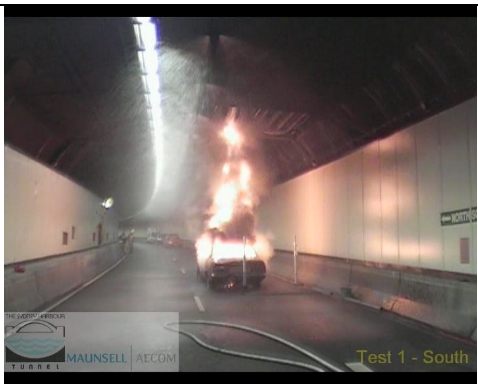
Photograph 4 - Test 1 - visibility after deluge activation (better than 30m). There is no smoke as the damper is directly above the fire.

Photograph 5 - Test 2 - stratification of smoke 200m away downstream (to the north) from fire immediately after deluge was shut off.

12.0 TEST 1 VIDEO SERIES

Table 1 - Test 1 view from south (approximate time from ignition shown in minutes : seconds)

 Setup	 1:00
 0:1	 2:00
 0:10	 2:30
 0:30	 2:54 Deluge activated



3:00

3:03

3:10

3:30

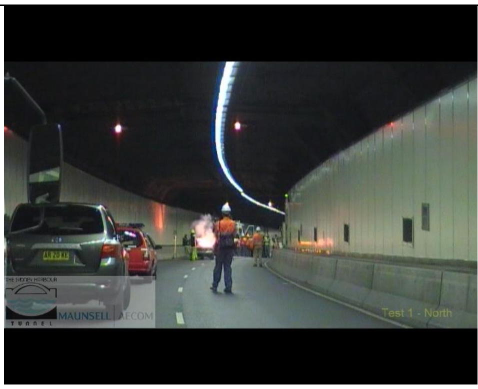
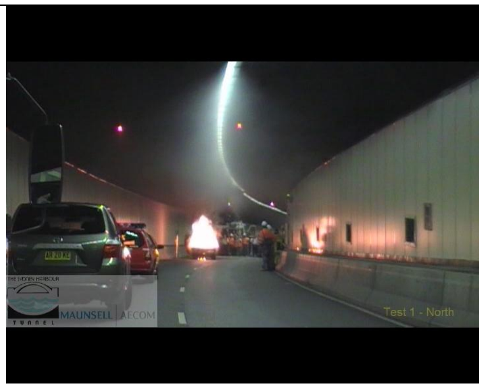
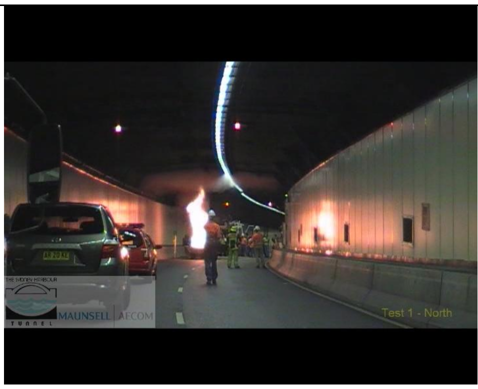
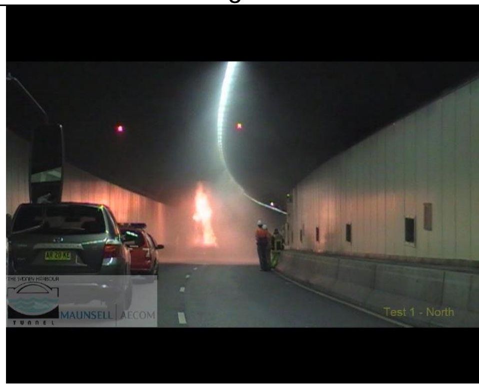
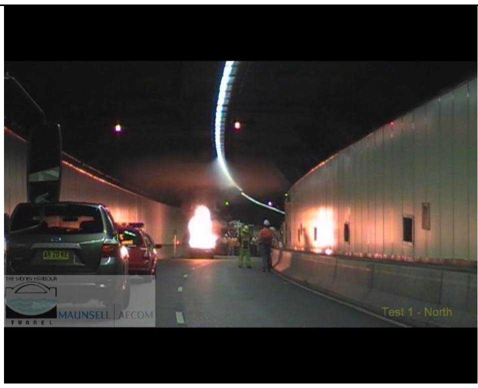
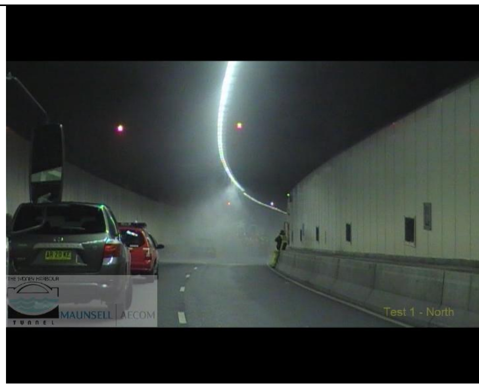
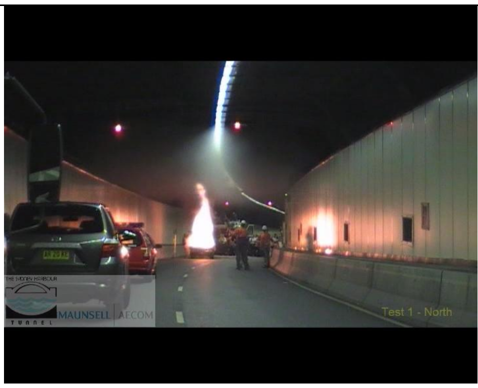
3:34

3:56

4:25 Deluge Stopped

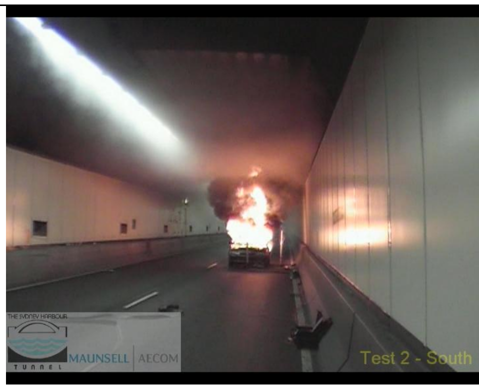
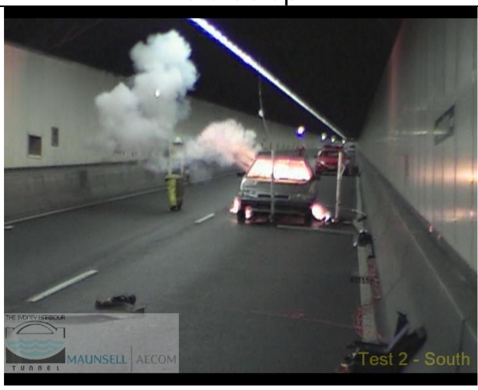
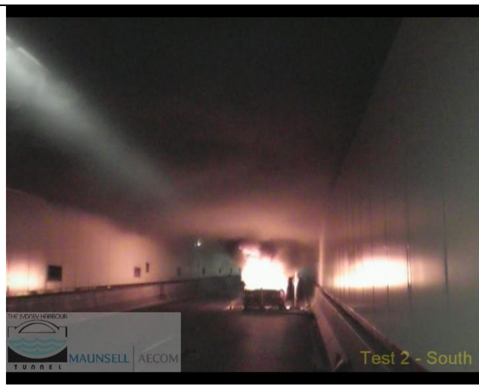
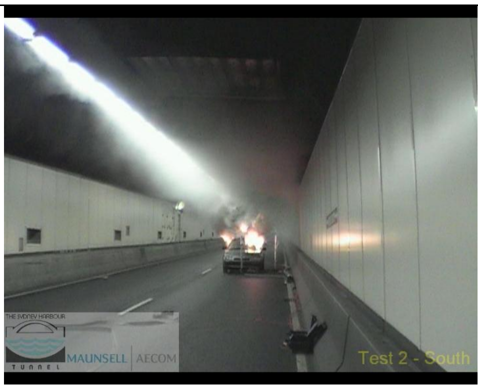
4:43 Extinguished

Table 2 - Test 1 view from North (approximate time from ignition shown in minutes : seconds)

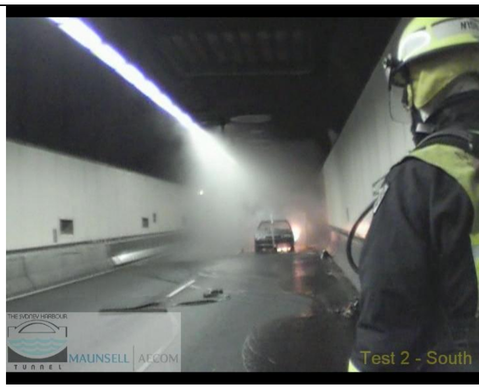
 0:01	 2:54 Deluge activated
 0:30	 3:03
 1:00	 4:25 Deluge off
 2:00	 4:43 Extinguished

13.0 TEST 2 VIDEO SERIES

Table 3 - Test 2 view from south (approximate time from ignition shown in minutes : seconds)

	
0:0 Setup	2:35
	
0:2	3:45
	
1:51	4:43
	
2:23	4:46 Deluge on

4:51

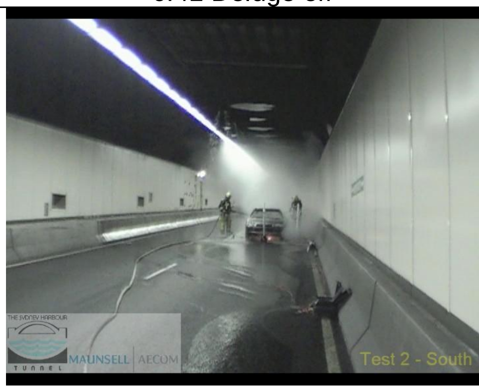


6:20

4:58

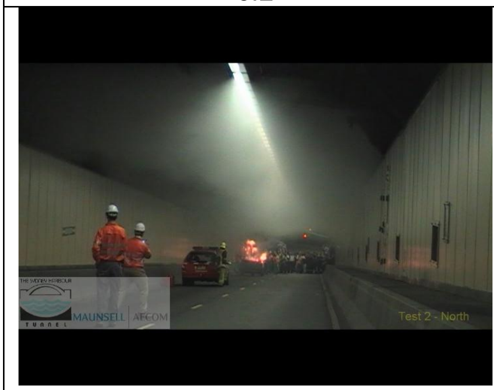
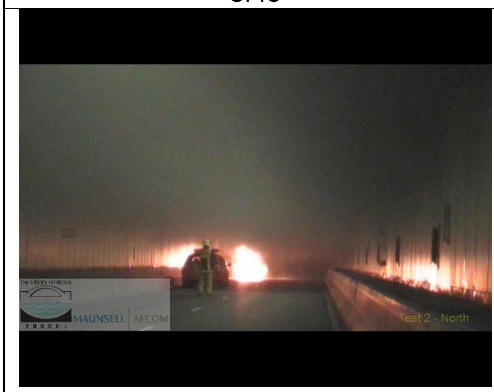
6:41 Deluge off

5:24



7:40 Extinguished

Table 4 - Test 2 view from north (approximate time from ignition shown in minutes : seconds)

 0:2	 4:58
 2:23	 5:27
 3:45	 6:44 (Deluge off at 6:41)
 4:46 Deluge on	 7:40 Extinguished

	
8:40 Smoke clearing	14:00 Tunnel clear