Development of Fire Fighting Vehicle Crew Protection Systems

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Abstract

The death and injury of fire fighters on fire fighting vehicles during wildfire burnovers occur on a periodic basis in Australia and around the world. Crew safety can be improved in burnover incidents if systems are designed with the sole purpose of protection against radiant and convective heat and prevention of the entry of flame into crew areas.

The paper presents the basis of wildland fire fighting agencies need for performance-based fire fighting vehicle crew protection systems. Crew protective systems for fire fighting vehicles were developed from the analysis of user needs. The Country Fire Authority of Victoria (CFA) and New South Wales Rural Fire Service (RFS) joined with the Commonwealth Scientific and Industrial Research Organisation (CSIRO) Forestry and Forests Products (FFP) and Materials and Infrastructure Technology (MIT) divisions to develop and evaluate crew protection systems for fire tankers. Crew protection systems were evaluated during simulated bushfire burnover scenario experiments.

A bushfire flame front simulator was designed and constructed to allow repeatable and quantifiable testing of fire tankers in a simulated burnover condition. The bushfire flame front simulator was designed to recreate actual bushfire flame characteristics based on measurements of forest fire experiments conducted during the Australasian Fire Authorities Council sponsored Project Vesta. The gas fired bushfire flame front simulator generates bushfire burnover fire intensities for the experiments of 5.0, 7.5, and 10.0 MWm. Tests were conducted on a variety of fire tankers with and without protective water spray systems.

Initial experimental results are reported in the paper.

Background

For some time there has been ongoing research to improve fire fighting crew protection and survivability in case of fire entrapment in a wildfire situation (Bond, 1986, Knight 1988, Budd 1997). Crew protection research on firefighting vehicles has been limited to a few investigations (Mangan 1997, Paix 1999, Cheney 2001).

The use of fire fighting tankers by fire fighting agencies in Australia is an integral practice in the management and suppression of wildfires. Australian fire fighting crews are largely tanker based. Fire fighting tankers are defined as a mobile fire fighting vehicle equipped with a water tank, pump, and the necessary equipment for spraying water and/or foam on wildfires. Various classes of tankers exist including a heavy tanker often on a 4 x 4 chassis equipped with a water tank of 2000 to 3500 litres, a auxiliary pump and a number of lengths of hose, and a variety of fire suppression equipment (AFAC, 1996).

The heavy tanker is the primary tool used by rural fire management agencies in Australia. The typical tanker is a multi-purpose firefighting vehicle that may be at a rural house fire one day, a motor vehicle accident the next, and be sent across the state to a wildfire in a forest or grassland the following day.

As tankers have become the main tool used to suppress wildfires, the risk that a burnover will entrap vehicles has increased. Tankers that are properly designed provide the crew with initial grass fire and bush fire burnover protection against radiant heat and direct flame contact. However, numerous incidents have shown the vulnerability of tankers in high fuel load wildfires, where the fire intensity and flame duration in the burnover is several minutes. The residence time for these types of exposures is generally two to three minutes. Dangerous exposure conditions to fire fighters arise when the fire tanker is exposed to high radiant loads associated with bush or forest fire situations. Fire radiant loads of more than 2000 to 3000 KW per metre and residence times of several minutes create problems for fire fighter safety (Knight, 1988).

Tanker design has evolved over the years to provide crew protection through the use of radiant heat shielding, often a crew roll over protection system (ROPS) area, and the supply of fire blankets for each crewmember. Burnover survival training has been implemented to reduce the risk to personnel in burn over scenarios.

Vehicle entrapments from burnovers that have occurred usually involve several contributing factors. Wildfires occur in a variety of vegetation types including grassland, scrub such as heath and shrubs, to dense forest. The topography the Australian rural fire fighters are confronted by can range from flat plains to rolling hills to rugged mountains. The vehicle entrapment incidents can be characterised by aggressive fire fighting under dangerous conditions, usually in forested areas with extreme fire behaviour conditions and tanker crews taking unnecessary risks to suppress the wildfire. In most cases the burn over incidents occur when the crews are in forests or heavy scrub and often have heavy fuels between the vehicle and the fire front (Cheney, 2001). A sudden change in conditions can lead to a rapid increase in the fire behaviour and often a rapid increase in the rate of spread of the fire front. Fire behaviour changes can be associated with alterations in wind speed, changes in wind direction and topographical influences. The lack of capability to retreat from the area or the failure to recognise the potential for these changes in fire behaviour can result in the crews becoming entrapped.

The sequence of events surrounding a burnover vary widely. In a typical scenario there can be a period of high radiation loads as the front approaches a stationary tanker or as a tanker passes along a track flanked by flame while attempting to escape escalating conditions. The highest thermal impact occurs in the first seconds of burnover as tall flames associated with the fine surface fuels burn rapidly. After 15-30 seconds fine fuels are depleted and flame heights will subside rapidly as progressively larger fuels take over. After 20 to 30 minutes only large logs and stumps remain burning and are usually spaced sufficiently to enable a safe exit.

The transition from normal operations to recognition of imminent danger and need to take refuge can occur in a matter of seconds (Cheney, 2001). Once inside the cabin when a burnover occurs, the crew must quickly deploy whatever safety systems available.

The effects of radiant heat damage on fire appliances involved in fire fighting has been examined in laboratory experiments carried out to duplicate the damage effects to give a measure of the radiant heat exposure required to generate such damage (McArthur, 1999). Damage will occur to various components at differing rates given various radiation profiles and exposure times (McArthur, 1999).

Vehicle Protection System Project

A project to analyse current crew protection and develop a more effective vehicle crew protection system was proposed following deaths of firefighters in New South Wales and Victoria in recent years. The project became a joint venture between the Victoria Country Fire Authority (CFA), NSW Rural Fire Service (RFS) and Commonwealth Scientific and Industrial Research Organisation (CSIRO). The project will establish a scientific basis for evaluating vehicle and crew protection systems in an effort to reduce the risk of injury and/or death to wildland fire fighters in a fire entrapment situation when exposed to conditions that exist during a fire burnover. The project objectives are to identify and define burnover conditions, establish test parameters, develop test methods and a fire burnover simulator facility, identify and test existing water spray systems, develop and test prototype crew protection systems, validate results through field experiments, and report the project outcomes. The project will advance the knowledge of wildfire entrapment protection systems for wildland fire fighters.

The project will be conducted in four defined stages and commenced in 2001.

The focus of Stage 1 was the laboratory assessment of CFA and RFS existing crew protection spray systems assessed on a laboratory mock-up of a fire tanker cabin, in a wind tunnel at various wind velocities. The effects of wind direction on the spray systems were also examined.

Stage 2 involved the development and assessment of an effective crew protection system that will provide adequate vehicle protection coverage in high wind velocity. The performance of the material and the survival capability of the vehicle under various conditions were studied and evaluated.

Stage 3 of the project consisted of the development and implementation of a large-scale gas fired flame simulator test to evaluate tanker protection systems under varying fire intensities. The stage assessed the integrity of the external and internal features of the tanker cabin when exposed to radiant heat and direct flame immersion.

Stage 4 involves field experiments to validate the large-scale simulator results under a variety of real life burnover scenarios at controlled fire burn sites.

Bushfire Flame Front Simulator

A bushfire flame front simulator was constructed to allow repeatable testing of fire tankers in simulated burnover conditions. The simulator was constructed in the open at the NSW Rural Fire Service Hot Fire Training Facility south of Mogo, NSW, Australia. The simulator is 12-metres wide (sufficient to fully immerse a 7 – 8-metre-long fire tanker) and 3 metres deep. The bushfire flame front simulator was designed to recreate actual bushfire flame characteristics (e.g. flame temperature profiles and radiant heat flux) based on measurements in forest fire experiments conducted during Project Vesta (Gould, 2000).

A series of 24 tests were performed with and without spray systems to determine their effectiveness. Tests were conducted between April 2002 and November 2003. Two generic test vehicle types were used. Bedford fire tankers supplied by the NSW RFS and International ACCO fire tankers provided by the CFA.

The characterisation of flame temperature and radiant heat from the gas-fired flame of each test fire is of prime importance in evaluating the survivability of a fire tanker with or without protective spray systems. While every effort has been made to accurately simulate every aspect of a bushfire, there remain fundamental assumptions and limitations associated with trying to simulate a moving fire on a stationary grid and the use of propane gas to simulate bushfire flames.

Characterisation of natural fires

The Byram fireline intensity is the most common single parameter used to characterise and compare natural fires. It has proven very useful as a measure of fire behaviour and suppression difficulty. Although it is used to describe each level of testing in this series of experiments, it is worth reviewing its use in terms of fire behaviour.

In a forest fire, the actual Byram fireline intensity is defined as the energy released behind each metre of fire front. However, in practice, the Byram fireline intensity is calculated using the estimated weight of fine surface fuel (i.e. fuels < 6mm diameter) multiplied by the rate of spread and the heat yield per unit weight:

$$I = Hwr$$

Where H is the heat yield in kilojoules per kilogram, w is the measured weight of fine fuel per square metre and r is the forward rate of spread (metres per second). The actual and calculated fireline intensities of a bushfire may differ because the amount of fine fuel actually consumed may not equal that estimated, and also fuel elements larger than 6 mm will not be accounted for but will contribute to the energy released.

The calculated intensity thus assumes that all the fine fuel burns and that energy contributions from coarser fuels are ignored. While this may not be an accurate representation, the energy released by these larger fuels does not contribute significantly to the flame front characteristics, nor does it affect suppression difficulty or heat transfer over distances greater than 2 or 3 metres. However, in the case where a fire tanker remains stranded in close proximity to these fuels, these fuels can represent a significant source of danger to the fire crew.

The extent of involvement of the fuels in a fire will affect the Byram fireline intensity. At lower Forest Fire Danger Indices (FFDI) the total fine fuel load will not be completely consumed, possibly over estimating the actual fireline intensity. At higher FFDI, the fine fuel will be completely consumed but the combustion of additional fuel elements (such as shrubs, bark and larger material) will result in an underestimation of the actual fireline intensity.

Characterisation of simulated fires

While the fire in the simulator does not have a rate of spread, the concept of the Byram fireline intensity can still be applied. By going back to the original definition, the measure of the amount of propane consumed and the fact the simulator is of fixed depth (i.e. 3 m) is used to calculate the rate of energy released by the simulator. The fireline intensity as energy released per metre width of simulator can be calculated as the simulator is of fixed width (i.e. 12 m).

Because of the precision in measuring the amount of gas consumed during each test, the calculation of the Byram fireline intensity of the gas-fired flames is more accurate than can expect measured from an actual bushfire. Due to the high degree of variation in fuel loads and local rates of spread experienced during actual bushfires, local intensity will vary widely. The simulator, however, does not have such variation and its calculated fireline intensity will also not vary. The flame front simulator schematic is depicted in Figure 1.

The limitations in matching the simulator to natural fires are due to the step-wise limitations of the simulator and the equivalent area over which fuel consumption comparisons are made.

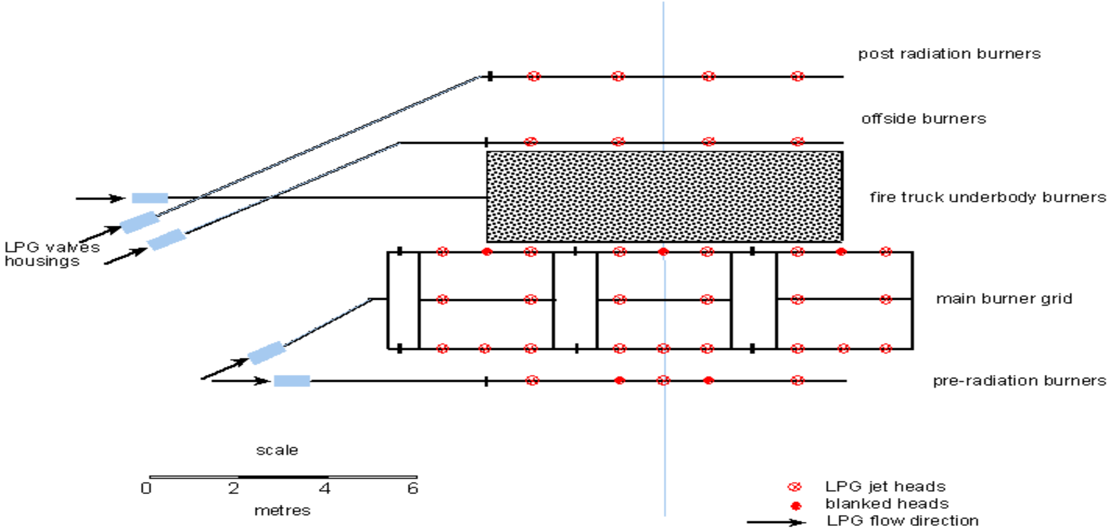

Figure1. Schematic of the manifolding and jetting layout for the gas-fired bushfire flame front simulator at NSW RFS Hot Fire Training Facility at Mogo, NSW.

Testing of Fire Tankers Using the Simulator

Three phases of a bushfire burnover were identified in the Definition of Bushfire Burnover Conditions (Knight, 2003). These are:

1. The approach phase, where radiation loads from the approaching fire are the main threat;

2. The flame immersion phase, where heat transfer and ignition may occur by direct flame contact both on the windward, leeward sides and beneath the fire tanker; and
3. The receding phase, where the bushfire has passed the fire tanker and radiant heat loads subside.

The energy release and duration of each phase of a burnover were matched to simulate different burnover scenarios. The burnover simulation was achieved by adjusting the volume delivery rate of liquid propane to the bushfire simulator.

Instrumentation Measurements

The fire tankers were instrumented with over 60 various data collection devices. Internal air and surface temperatures were measured using over 50 thermocouples positioned at various heights within the cabin on all materials and glass surfaces and in the Roll Over Protection Area.

Radiation was measured using water-cooled radiometers with a sensing range of 0 to 100kW/m^2. The radiometers were mounted externally on the vehicle facing the fire front and the leeward side. Internal radiometers were placed in the cabin above the passenger seat facing the windscreen and the side window to measure internal cabin radiation. The output from the external radiometers was used as feedback to the simulator controller who then adjusted a control valve so that the measured radiation matched the predetermined values.

All thermocouples and radiometers were logged at 5-second intervals via a Data taker 505 with an expansion module data logger. The data logger and module were placed in a steel fireproof box located on the vehicle cabins. The data logger had an onboard power supply, which was recharged between tests. A single lead was taken from the truck via the RS 232 port to a PC in the control room. Data collection was observed in real time and was simultaneously recorded on the data logger's internal memory and the PC to minimise the potential for data loss. All power, data transmission leads and radiometer-cooling lines exited the cabin through a hole drilled in the cabin's rear wall. All above ground, exposed leads were wrapped together with kaowool and over wrapped with aluminium adhesive tape to protect against direct radiation and flame contact.

Air sampling from the cabin during testing was conducted to determine the tenable nature of the cabin for occupants. Real time toxic gas samples were also taken within the occupied spaces of the fire tanker. Respirable particles, hydrogen chloride, formaldehyde, volatile organic compounds, carbon monoxide and carbon dioxide were all measured. The test procedures and toxic gases analysis is described in detail (Brown, 2003).

Wind speed was recorded at 2 metres above ground in clear locations approximately 30 metres to the northeast of the simulator and 60 metres west of the simulator. The anemometers are used to determine the average wind affecting the fire during the approximately 20 minutes of testing.

Audio-visual recording was conducted extensively throughout each of the tests. Cabin internal and external digital video cameras were used to record each test. During the initial 12 tests, one internal and two external digital video cameras were protected in fireproof boxes on loan from the United States Forest Service. From test 13 on the internal and external digital video cameras were protected in fireproof boxes built by CSIRO based on the United States Forest Service design. Additional roaming digital camera footage was shot during the tests as well as still digital photos. All video has been filed and catalogued for future access.

Experimental Procedure

Each truck was positioned in the centre of the grid with the cabin to the SE such that the left side faced the pre-radiation and on-side burners. Flames were simulated to approach from the NE with the prevailing wind.

During each test six 20-litre polypropylene water containers were placed in the cabin to approximate the heat sink effect of 2-3 occupants. Testing of the heat absorption in a temperature-controlled oven has shown that the energy absorption of a water-filled 20-litre container is similar to that measured for clothed occupants on a watt absorbed per degree temperature difference per kg per minute basis.

The main component of the spray system, a ring main, was installed around the roof of the cabin and sprayed water over the exterior surfaces of the cabin. Wheel sprays were incorporated and in later tests additional sprays were installed to protect the rest of the truck body. The basic parameters for the water protection system assumes that there is a minimum of 500 litres on hand and that the water spray needs to be active for a minimum of 5 minutes.

Drop down radiant protective curtains were used in the latter tests to protect the interior from the effects of radiant heat.

The simulator parameters are displayed in Table 1. The sequence of each test simulation phase is:

1. *Pre-radiation*. The duration and radiant intensity given by test schedule is based on information presented in Definition of Bushfire Burnover Conditions. The spray system was activated when radiant intensity reached 30 kWm^{-2}.
2. *On-side immersion phase.* Six seconds before scheduled immersion, the dump valve was activated and main valve opened to allow rapid priming to burner jets. The dump valve was closed at the scheduled immersion time and, on visual confirmation of the main grid achieving full power, a secondary timer was started. Once the nominated duration of immersion was achieved on the secondary timer, a call was made to the simulator controller to reactivate the dump valve and close the main valve. At this stage the main grid rapidly de-powered.
3. *Under body phase*. Commenced immediately after on-side immersion phase finished. This phase simulates the release of energy from a track with a light (2 t/ha) fuel load. This phase operates on a separate supply of gaseous propane. The required fuel load is released in 1 minute.
4. *Offside immersion phase*. Commenced 15 seconds after under body phase commenced. The offside phase has only a single row of burners and hence a lower manifold volume to charge up. Response is quicker than on the main on-side grid and correct timing is achieved by operating the on/off valve according to the schedule.
5. *Post fire radiation*. Commenced 3 seconds after offside immersion phase completed. The post radiation sequence operates in a similar manner to the pre-radiation.

Fireline Intensity (MW/m)	Equivalent fuel loading (t/ha)	Flame depth (m)	Flame residence time (s)	Total propane consumption on-side immersion (l)	Propane consumption Rate (l/s)
2.5	15	1	11	13.9	1.27
5.0	15	2	11	27.9	2.54
7.5	15	3	11	41.9	3.81
10.0	20	4	14	71.0	5.07
12.0	24	4	14	84.7	6.05

Table 1. Simulator parameters used to achieve required Byram fireline intensity
Imposed radiation on passenger (upwind) side of vehicle

A peak in excess of 100kW/m^2 is indicative of direct flame immersion of the radiometer and only occurs briefly in each. The period following the main peak is the time where the passenger side of the vehicle receives low level (5 MW/m) radiation from heavy fuels that remain burning after the main flame front has passed. Leaving the pre-radiation burners on at a low-level following main burner operation simulated this condition. There is significant variation in received radiation during this time.

Results

The tests resulted in the following observations:

- Radiant heat entry into the cabin is the most critical factor limiting the survival of the fire fighting vehicle crew.
- Cabins are structurally sound yet they could perform better with minor modification to the make them less susceptible to outside air intrusion.
- Total vehicle protection is required to promote tenable conditions for crew survival.
- Well-designed spray systems are shown to provide useful gains in firefighter safety at low to moderate fire burnover scenarios.
- Tenability limits for toxic gasses are exceeded when the vehicle in unprotected from fire intensities of 5 MW/m or more.
- Toxic gas concentrations are tenable in the cabin and ROPS areas up to 10MW/m with the heat curtains and spray system in operation.
- Radiant heat curtains are effective in reducing inside cabin and ROPS radiant heat and temperatures.
- Survivability inside the fire tanker cabin without some kind of radiant heat protection is unlikely in the simulated burnover fire intensities of 5 MW/m or more.
- Radiant heat loads inside the fire tanker cabin peak above the pain threshold and burns to the skin are likely in fire intensities of 5 MW/m or more.
- Mean body temperature increase by more than 1.5 degrees C occurs in fire intensities of 5MW/m or more due to direct radiation from flames directly outside the windows.
- An efficient spray system will consistently reduce glass surface heat load and the inside cabin temperature at all intensities tested.
- Windows are quite durable under radiation and flame contact up to 10 MW/m.
- External tanker fittings cause considerable toxic smoke emissions.

- The prototype crew protection system was an effective protection system at medium fire intensities.
- The prototype crew protection system internal cabin temperature reduction was considerable when compared to external temperatures.
    - Outside air temperature 500 to 950 degrees C, inside cabin air temperature in refuge positions 45 to 50 degrees C.

Conclusions

A method of predicting survival in unmanned fire tanker testing has been developed. The method has formed a basis for a cycle of test and development using a simulated bushfire flame front at equivalent fireline intensities up to 10 MW/m and equivalent fuel loads to 20 tonnes per hectare. The project has found that standard tankers equipped with specially designed protection systems have sufficient thermal robustness to provide the basis of an effective burnover protection system up to the levels of intensity and fuel loads simulated. Testing showed that spray systems must be carefully designed for full even coverage. Radiation shielding for critical components and crew areas are essential design features to prevent both short-term injury and accumulated heat stress over the longer refuge interval.

The multiplicity spray protection systems installed on fire fighting vehicles before the start of this project have proven to be ineffectual when exposed to a wildfire burnover conditions. The risk in allowing the use of ineffectual systems to continue is that the fire fighters may experience a false sense of security, resulting in injury and/or death.

The testing program has shown that a well-designed spray protection system in combination with radiation shields successfully prevents the glass breaking and lowers temperatures inside the cabin sufficiently for the fire crew to survive the extreme heat generated when a fire tanker is overtaken by fire of moderate intensities.

The simulated phase of testing is now completed and the prototype tanker judged ready for field-testing. The field tests will take place in January 2004 with the aim to expose the vehicle crew protection system to any potential weaknesses in actual forest fire conditions and to verify the results from the simulator tests.

The development of a vehicle spray protection system can be utilised to augment the improvements in training, equipment and communication implemented within fire management agencies. These improvements should greatly reduce the risk to fire fighters by ensuring that they are not exposed to a wildfire burn over. An effective vehicle protection system is a final precautionary step for crew protection in the event that improved training, equipment and communication initiatives fail to ensure that the vehicle and crew are not exposed to a burn over scenario.

Fire fighting tanker entrapment incidents will occur no matter how well tanker crew protection systems are designed. Crew protection systems can only be designed for protection in low to moderate intensity fire entrapments or burnover situations. Fire fighting tankers, which are useful in normal conditions, are not designed to provide crew survival in high intensity wildfire burnover situations.

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