Thermal Factors for Human Survival in Fire Tanker Burn-overs

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Abstract

Direct testing of human response under the thermal conditions that will be encountered while sheltering from a bushfire burn-over in a truck cabin is difficult to undertake safely *in situ*. However, radiation and air temperatures occurring within a cabin under such conditions have been measured during unmanned testing utilizing a gas-fuelled bushfire flame front simulator.

Survivability can be limited either by the accumulation of radiative and/or convective heat, which raises the mean body temperature (MBT), or by shorter duration, higher-level heat pulses that cause tissue damage.

We have taken the equations for human response, which had been developed for workers in arduous thermal conditions, and extrapolated them to the extreme conditions expected during a bushfire burn-over. MBT is predicted while sheltering for the 20 minutes typically required for safe egress on to burnt ground. The point at which radiation causes tissue damage is a complex intensity vs. time question and limits selected are based on consideration of several contradictory reports.

Application of these equations to the survival situation requires allowances for other factors – such as existing heat stress in preceding conditions, extreme radiation pulses and contained humidity.

The results have been used as the basis for predicting the intensity of bushfire that can be survived in a truck cabin.

Background

Australian firefighting crews largely work from water carrying tankers. Current tankers are based on a cab chassis of twin cab, dual axle, and 4WD configuration, generally around 5 – 6 tonne capacity. They carry 3000 – 3500 litres of water and the associated water delivery systems.

The sequence of events surrounding a bushfire burn-over varies widely. In a typical scenario, there can be a period of high radiation load as the fire front approaches a stationary truck or as a truck passes along a track flanked by flame while attempting to escape worsening firefighting conditions. The highest thermal impact occurs in the first seconds of the burn-over, as tall flames, associated with the rapid combustion of the fine surface fuels envelope the truck. After 15-30 seconds, the fine fuels become depleted and flame heights subside as the combustion of larger fuels become dominant. After 20 to 30 minutes, only large logs and stumps remain burning and are usually scattered sufficiently to enable a safe exit on foot if the truck is disabled.

The transition from normal operations to recognition of imminent danger and the need to take refuge can occur in a matter of seconds. Once inside the cabin, the crew must quickly deploy available safety systems. The systems currently being employed are water spray systems and roll-down radiation curtains.

Research is in progress to develop and improve these tanker protection systems to maximise the chances of survival of an accidental bushfire burn-over. Testing has so far been carried out using unmanned trucks placed in a 12-m-long liquid propane-fuelled bushfire flame front simulator. The propane is distributed to an array of burners in a sequence designed to replicate the approach, immersion and departure of a flame front. The rate of fuel release, the total quantity released and the spacing of the jets have been designed to simulate the combustion of surface fuel, the burnout times and the flame geometry of natural bushfires.

The testing of such a system necessarily takes place as unmanned experiments and survivability assessments of a protection system must be made based on remotely recorded cabin conditions. This paper describes the method used to predict survivability from these measurements.

Human tolerance and response to heat

Setting limits for radiation pulses

The pulse of radiation associated with the passage of the fire front and the burning of fine fuels presents an immediate short-term hazard to tanker occupants. The nerves just below the skin surface respond to temperature rather than radiation itself. The limit, when expressed as radiation, is thus a general guideline. A determination of the exact radiation levels required to damage skin would require consideration of the total heat flow to the sensitive layers just below the insensitive surface epidermis. Important factors are the initial skin temperature, and the temperature and velocity of air movement taking place.

Beuttner (1950) and Stoll and Greene (1959) found that pain occurs when skin temperatures reach between 42°C and 45°C. Pain occurs when peripheral blood flow in the skin is unable to remove heat arriving on the surface of the skin and damage to cells begins. The level of thermal radiation required to cause pain is dependant upon the incident radiation and the period of exposure. Arnold *et al* (1973) as cited by Backer *et al* (1976) note that burn damage to skin is caused by input radiative heat fluxes in excess of approximately 2 kW/m^2 and that it takes above 84 kJ/m^2 of accumulated heat to cause partial thickness blistering (second degree burn). Budd *et al* (1997) used the value of 2 kW/m^2 to define the thermal radiation pain threshold on bare skin. Lower levels of radiation, while not damaging the surface tissue, will be absorbed into the body and contribute to potential incapacitation by heat stroke. These lower levels of radiation are allowed for in the calculation of mean body temperature.

In the present study, a limiting level of 2 kW/m^2 was taken as the limit of radiation during the initial stages of burn over when external radiation loads were highest. This is a conservative limit appropriate to a tanker cabin where air temperatures will be high with minimal air movement. Under cooler, breezy conditions, an unstressed person can endure slightly higher levels without intolerable pain for periods of up to a minute. The radiation limit may be higher for clothed skin, but the bare skin limit was chosen because there will always be patches of skin (e.g. face, neck) that will not be covered and will limit the amount of radiation that can be tolerated.

Setting limits for convective pulses

Air temperatures of up to 200°C can be endured without skin damage provided that the air is relatively dry and evaporative cooling occurs at the skin and airway boundary layers. In-cabin temperatures of greater than 200°C would occur under two possible scenarios:

- a window fails and air directly from the flames enters, or
- thermal transfer through the cabin walls is sufficient to raise the air above this level.

Cabin integrity under flame immersion is a design objective for the project so the first scenario is not considered. If, in the second scenario, air temperature in the cabin rose to this level by means of conduction, the cabin walls would have similar if not higher temperatures. Under these circumstances, black body radiation from the walls would be 2.8 kW/m^2 and of a duration of several minutes. Air temperatures of 200°C, even if survivable, would thus be associated with excessive radiation and excessive rises in mean body temperature (MBT).

Specific determination of the maximum short duration pulse in air temperature is thus not relevant to our considerations and will be ignored.

Setting limits for mean body temperature rise

When working at a physical task (e.g. rake hoe fireline construction), the core body temperature has been shown to rise by one half to a full degree (Budd *et al.* 1997). If a person's MBT rises to 40°C, body function is severely handicapped and self- rescue is unlikely. At temperatures approaching 40°C, heat stress is critical, the body's thermo-regulation system is in danger of breaking down and physical and mental performance is impaired. Experiments, in which core body temperatures of firefighters working on a rake hoe line were measured, showed that peak temperatures of 38.5°C were commonly reached (Budd et al 1997). We have allowed for tanker crews to be under a similar degree of thermal stress and have thus set a maximum limit for the rise in mean body temperature of 1.5°C.

Effect of occupants on cabin environment

Occupants will have a significant influence on the temperature of the air within the tanker cabin. The energy required to raise the body temperature of a 70 kg person by 1°C is equivalent to the energy needed to raise 1 cubic metre of air by 340°C. In an empty cabin, most of this energy would be redistributed elsewhere, but to test a cabin without simulating the thermal mass of the occupants could result in air temperatures that are artificially high by several degrees.

Drums of water (initially at body temperature) were placed in the cabin to simulate the thermal mass of the occupants. The temperature absorption of a drum was measured in a laboratory oven and, on an equal mass basis, was found to closely match that of a clothed person.

Calculating the rise in mean body temperature

The accumulated effects of radiation and hot air--at levels below those that cause rapid injury to surface tissues--are well described in the equations of Brief and Confer (1976). The equations, called the MBT equations, estimate the rate at which energy enters the body based on surrounding air temperature, air movement and wall temperatures. The rate of energy absorption can be integrated over the duration of refuge to obtain the total sum of the energy absorbed. The energy absorbed is easily related to the rise in MBT (the specific heat of a 70 kg person is 253 kJ/°C, very close to the specific heat of the equivalent mass of water).

The rise in MBT during refuge in the cabin was calculated by tracking the heat inputs and outputs to the occupant using the conditions recorded during the nominal 20 minutes of occupation.

Internal Metabolism

The calculations include an allowance for an internal metabolism of 150 watts per person. This is a resting metabolism.

Direct radiation

Direct radiation is treated separately from the indirect radiation associated with the temperature of the walls of the cabin. The energy absorption was calculated from the radiation measured by full-hemisphere radiometers, which were located in the cabin looking out the side and front windows of the cabin. The radiation load was integrated over the 20 minutes allotted for refuge.

The energy absorbed by a 70 kg person as a result of direct radiation is given by:

$$Q_d = I_d \times 0.656 \times 0.35$$

where Q_d is the energy transfer to the person as a result of direct radiation (W) and I_d is the instantaneous radiation passing through windows (W/m^2).

The factor 0.656 allows for the attenuation of radiation by clothing. This factor was derived by Brief and Confer (1976) for clothing typical of workers in hot environments. It is assumed that the proban-treated overalls worn by Australian firefighters fall into this category.

The second factor of 0.35 allows for the projected area (m^2) of a sheltering occupant in the direction of radiation.

Convection/indirect radiation

Brief and Confer (1976) combine the effects of convective transfer and indirect radiation on the absorption of heat by a clothed person in the following pair of equations:
$Q_w = 7.9(T_w - 35)$
$Q_c = 8.2v^{0.6}(T_a - 35)$

where Q_w is the background radiant heat transfer to the person (W), Q_c is the convective energy flow to the person (W), v is the air velocity (m/s) and T_a and T_w are the air and wall temperatures respectively (°C). Note that a linear approximation to radiation transfer has been made (Knight 1988).

Brief and Confer assumed that the air temperature followed the wall temperature/surface temperature in the cabin fairly closely. This was accepted as a reasonable assumption for the 20 minutes of refuge.

Thermocouples placed on surfaces within the cabin were found to show wide variations but a more precise method was not attempted. The temperatures used in the equation were taken from thermocouples measuring an air temperature within the cabin volume at a position likely to be taken by sheltering firefighters.

Perspiration

We have allowed 2 cubic metres of dry air per person for the dissipation of energy through perspiration. A total of 183 kW is lost due to evaporation--at this point the cabin's moisture content would be at the saturation level of the boundary layer against a person's skin (at approximately 40°C).

Results

To determine the heat accumulation over the refuge period, it is necessary for the measured air temperatures, radiation levels and airflows during the test to be applied to the equations at frequent sub-intervals.

Figure 1 shows a typical test and the application of the MBT equations. The steady rise of MBT under the changing cabin air temperature and direct radiation load is shown as a dotted line. In this example, MBT rises by almost 1°C, even though maximum temperature and radiation load are not excessive.

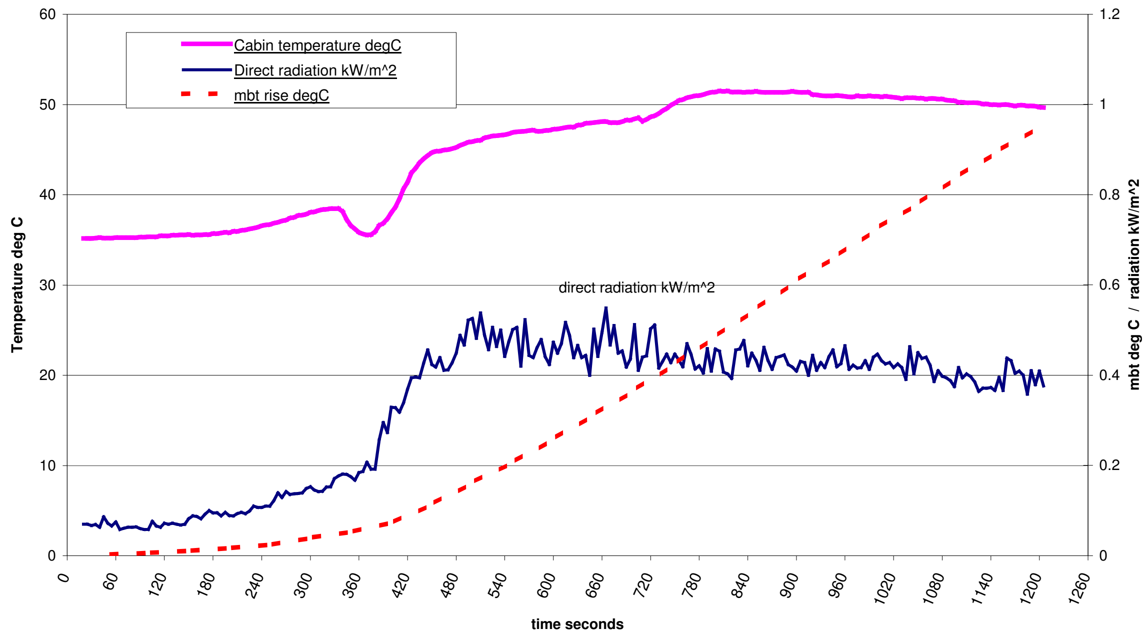

Figure 1. Test 18: ACCO tanker, fire intensity 10 MW/m , radiation shields deployed, water spray system engaged.

Table 1 summarises the tests so far on several fire tankers. Note there is still a wide range of results within each intensity range. The variation is a result of the open location of the simulator and the strong influence wind gusts at the time of burn over have on flame angle.

Table 1. Summary results of fire tanker testing.

Test No.	Simulated fire intensity (MW/m)	Truck configuration^	Direct Radiation (kW/m^2)	Time to MBT limit (mins)	MBT rise @ 20 mins (°C)	Pass/ Fail*
1	2.5	S		-	.45	P
2	2.5	D		-	1	P
3	5	S	3.5	17	1.7	F
4	5	W	3.5	9.5	3.3	F
5	5	D		9	4.5	F
7	7.5	S	4.3	11	2.5	F
9	7.5	D	7.4	9	5.1	F
10	5	S	6.0	10.5	2.2	F
11	7.5	D	7.2		1.2	F
12	10	S	4.9	13	1.8	F
13	7.5	D	5.0	10.5	3.8	F
14	5	S	5.7	8	2.8	F
15	5	S	5	19	1.6	F
16	7.5	S,RF	2.0	15	2.5	F
17	7.5	S,RF	0.5	-	0.9	P
18	10	S,RF	0.5	-	1.0	P

19	5	S, RS *	3.5	-	0.9	F
20	7.5	S,RS*	1.2	-	0.8	P
21	10	S,RS*	10	-	1.3	F
22	7.5	S	8	17	1.8	F
23	10	S	9.5	17	2.0	F

^ D = dry, S =sprays, RF = full rad^n shields, RS = side shields
* These are passes on thermal considerations, in some instances toxic gases rendered survival unlikely.

Discussion

The application of the MBT equations provided a means for comparison of bushfire burn-over protection systems. The equations used were extrapolated from those developed for workers in hot workplaces. Refinement of the equations, using volunteers prepared to undergo the rigorous test conditions, would be a major task. The method has provided a suitable basis for comparison of simulator-based tests to date. A rapid cycle of test and development resulted in a much-improved prototype fire tanker protection system. Hazards presented by toxic smoke and gas emissions, from both within and outside the tanker cabin, are discussed in an associated paper (Brown et al. 2003).

Conclusions

A method for predicting occupant survival in a bushfire burn-over from unmanned fire truck 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 fire line intensities up to 10 MW/m and equivalent fuel loads to 20 tonnes per hectare. We have found that standard truck cabins have sufficient thermal robustness to provide the basis for an effective burn-over protection system up to these levels of intensity and fuel load. Testing showed that spray systems must be carefully designed for full, even coverage of the cabin and other exterior surfaces, and that an allocation of 500 litres of water should be sufficient. Radiation shields were an essential design feature to prevent both short-term injury and accumulated heat stress over the 20 minutes of refuge.

The simulated phase of testing has now been completed and the prototype tanker is considered ready for field-testing in forest fuels. The field tests will take place next summer and aim to expose any tanker weaknesses that are unique to forest fires, and to verify the above predictions against the equivalent forest fire estimates.

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