# Air Toxics Factors and Criteria for Crew Survivability/Tenability in Vehicle Burnover

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## Abstract

The CSIRO, the Country Fire Authority and the Rural Fire Service have been jointly carrying out research into firefighting vehicle crew protection measures for bushfire burnover scenarios. These measures will rely on the crew seeking shelter in firefighting vehicle cabins during burnovers. However, during such shelter the crew should not be exposed to toxic air pollutants affecting (as a minimum) their survivability, and preferably not affecting the tenability of their shelter (i.e. their ability to tolerate the cabin environment and later exit the cabin without harm). Air toxics may arise in the cabin either from ingress of surrounding fire gases (carbon monoxide, smoke particles) due to air leakage paths through the cabin envelope, or from gases emitted from cabin interior materials due to heating (offgassing) or thermal degradation (hydrogen chloride, formaldehyde, volatile organic compounds). Firefighting vehicle cabins were monitored for air toxics relevant to these scenarios while exposed to simulated bushfire burnovers on an LPG gas-fired grid. Significant air leakage paths were identified for many firefighting vehicles, and these were generally rectified before burnover testing. Cabin performances in burnover tests were assessed relative to air toxic criteria for tenability and survivability.

## Introduction

The death and injury of firefighters in firefighting vehicles during bushfire burnovers have occurred many times in Australia and around the world. It is considered that firefighter safety can be improved in burnover incidents if vehicle systems are designed to protect vehicle cabins against radiant and convective heat, and the entry of flame and toxic gases. Experiments with such an aim have been carried out in Australia over 2002–2003 by CSIRO, the Country Fire Authority of Victoria and the NSW Rural Fire Service. Separate papers (Knight *et al*. 2003; Nichols *et al*. 2003) will describe the gas test grid for exposing instrumented firefighting vehicles to simulated bushfire burnover scenarios, systems for protecting the vehicle cabin (generally radiation shields and water sprays), and the protection that resulted against heat and flame. The present paper will describe protection from smoke and toxic gases, from the following perspectives:

- Smoke and gas ingress into vehicle cabins from the external fire.
- Smoke and gas ingress into vehicle cabins from the interior cabin materials.
- Toxic gases and smoke exposure criteria to protect firefighters.
- Measurements from several tests.

Note that this report will include air toxics criteria relevant to tenability of the cabin interior for occupants, which are criteria for comfort and irritation in the absence of irreversible health effects, and also survival criteria for protection of firefighter life. The notion of tenability within the cabin interior is introduced (in addition to survival) since, in the event of untenable conditions being reached, occupants may choose to leave the cabin and face limited survival outside the vehicle. Note also that all of these criteria will be overridden by the loss of cabin envelope integrity (e.g. window breakage) against heat and flame, which includes any flaming ignition of interior materials through heat and radiation transfer.

## Criteria for Cabin Air Toxics

*Smoke and gas ingress into vehicle cabins from the external fire*

Air leaks are expected to exist within the cabin envelope, although the level and significance of such leaks have received little research. Such air leakage is considered to be important to air toxics in the cabin from three perspectives:

- Oxygen depletion.
- Ingress of carbon monoxide.
- Ingress of smoke particles.

In a bushfire burnover scenario, it is expected that firefighters will require a safe haven for a period of 20–30 minutes. The potential for oxygen depletion in this period can be estimated by simple calculation. Assume a cabin volume of 4 $m^3$ occupied by four adults, and the following:

- The cabin is well-sealed and so only its own volume is available for oxygen supply.
- The cabin initially contains 21% by volume oxygen and that this can reduce to 18% without affecting the occupants (e.g. 17% causes respiration to increase and attention/clear thinking requires more effort (Kimmerle 1974)); the volume of oxygen available to occupants is then $4 \times (21–18)/100 = 0.12$ $m^3$.
- Adults at rest consume approximately 0.0004 $m^3$ of oxygen per minute (West 1994).

Thus, four adults in the cabin could survive the following time before oxygen depletion became significant:

$$\text{Time} = 0.12/(4 \times 0.0004) = 75 \text{ minutes}$$

If the breathing rates of the occupants were doubled (e.g. due to stress or exertion), then this time would be halved to 37.5 minutes, still sufficient to provide a tenable environment for firefighters for the duration of the burnover. On this basis, it was considered that there was no need for an oxygen depletion criterion for burnover scenarios.

Bushfire smoke will contain carbon monoxide (CO) gas and smoke particles, though there appears to be no data describing their concentrations very close to or within a bushfire front. If the cabin is considered to be a well-mixed enclosure with a certain level of leakage of its envelope (via body gaps, seals, weepholes), it is expected that the levels of CO and smoke particles ingressing into the cabin ($C_{int}$) will depend on two factors:

- The rate of air leakage $N$ ($h^{-1}$).
- The level of pollutant in the external air ($C_{ext}$).

In the absence of pollutant losses during ingress into the cabin, these factors will change with time ($t$) to the following equation:

$$C_{int} = C_{\mathrm{ext}}\,(1 - e^{-Nt})$$

It can be calculated that the ratio $C_{int}/C_{ext}$ will change during burnover for different levels of leakage, as presented in Table 1.

**Table 1. $C_{int}/C_{ext}$ over time for different rates of cabin leakage**

| Time (min) | $C_{int}/C_{ext}$ for $N$ ($h^{-1}$) | | |
|---|---|---|---|
| | 1 | 2 | 5 |
| 0 | 0 | 0 | 0 |
| 5 | 0.08 | 0.15 | 0.36 |
| 10 | 0.15 | 0.28 | 0.57 |
| 20 | 0.28 | 0.49 | 0.81 |
| 30 | 0.39 | 0.63 | 0.92 |

Thus, a leaky cabin would experience pollutant concentrations of similar magnitudes to external levels within the burnover period, and the lower the leakage, especially below 1–2 $h^{-1}$, the lower the potential for the cabin levels to reach external levels.

While there's little knowledge of CO and smoke particle levels at bushfire fronts, there are exposure–health effect data and criteria that can be used in setting performance criteria for firetruck cabins during burnover (Brown and Cheng 2000). Table 2 summarises these for CO, and shows that there are physiological effects of differing severities for different periods of exposure. For example, Worksafe's short-term exposure level (STEL) is 100 ppm for a 30-minute period, while above 1000 ppm death may occur within short periods.

**Table 2. Relation between carbon monoxide concentration and response in humans**

Physiological effects: reduces oxygen-carrying capacity of the blood, can affect foetal development and exacerbate heart disease

| CO (ppm) | Symptoms |
|---|---|
| 25 | Environmental goal for 1-hour exposure (WHO) |
| 50 | Environmental goal for 30-minute exposure (WHO) |
| 50–100 | Reduced exercise capacity in healthy subjects |
| 100 | Worksafe STEL (30 minutes) |
| 200 | Headache, mental dullness and dizziness after 2–3 hours |
| 400 | Distinct poisoning after 1–2 hours |
| 500 | Hallucinations felt in 30–120 minutes |
| 600 | Headache, mental dullness and dizziness in less than 30 minutes |
| 1000 | Difficulty of ambulation; death after 2 hours inhalation |
| 1500 | Death after 1 hour inhalation |
| 3000 | Fatal in 30 minutes |
| >8000 | Immediate death by suffocation |

Smoke exposure has less comprehensive exposure–health effects information and criteria, partly because of the large variability that exists in the chemical species, particle sizes, dosage definition, exposure periods and health effects for exposure to smoke of any type. Table 3 summarises several occupational and environmental criteria. Note that in the definitions:

- PM10 is the mass concentration of particles smaller than 10 µm in urban air.
- Respirable particles (RP) are those of sizes that are deposited deep in the lung (50% cut-point of 4.0 µm).
- Inspirable particles are those of sizes deposited in the total respiratory system (nose, thorax, lungs).

**Table 3. Criteria for 'smoke' exposure**

| Smoke level | | Basis of criteria |
|---|---|---|
| $mg/m^3$ | Definition | |

| | | |
|---|---|---|
| 0.05 | PM10 | National Environmental Protection Measure (NEPM) for particles smaller than 10 μm in urban air |
| 3 | Respirable particles | Worksafe Occupational Exposure Standard (OES) for respirable particulates ‘not otherwise classifiable; |
| 10 | Inspirable dust | Worksafe OES for inspirable ‘nuisance’ dust |

*Smoke and gas release within vehicle cabins from the interior cabin materials*

During a burnover, the interior materials may reach elevated temperatures such that they smoulder, emitting smoke and thermal degradation products. For example, PVC products can emit large quantities of hydrogen chloride (HCl) gas (pure PVC can emit 58% of its weight as HCl) and nitrogen-containing products (wool, nylon, polyurethane) can emit hydrogen cyanide (HCN). In addition, there may be volatile organic compounds (VOCs) offgassed from interior cabin materials such that irritating or toxic levels of these VOCs or the total VOC (TVOC) are reached (Brown and Cheng 2000). The toxic effects and human responses to VOCs and combustion gases are summarised in Tables 4–10 (Brown 2001).

**Table 4. Relation of hydrogen cyanide concentration in air and symptoms of humans**

Health effects: inhibits enzymes required for the respiration of cells in the body

| HCN concentration (ppm) | Symptoms |
|---|---|
| 0.2–5.1 | Threshold of odour |
| 10 | Worksafe peak limitation |
| 18–36 | Slight symptoms (headache) after several hours |
| 45–54 | Tolerated for 0.4 to 1 hour without difficulty |
| 100 | Death after 1 hour |
| 110–135 | Dangerous to life, may be fatal after 0.5 to 1 hour |
| 135 | Fatal after 30 minutes |
| 181 | Fatal after 10 minutes |
| 280 | Immediately fatal |

**Table 5. Inhalation effects of hydrogen chloride on humans**

Health effects: extremely discomforting to upper respiratory tract and may cause mucous membrane damage and aggravate asthma and inflammatory pulmonary disease

| HCl (ppm) | Symptoms |
|---|---|
| 1–5 | Limit of detection by smelling |
| 5 | Worksafe peak limitation |
| 5–10 | Mild irritation of the mucous membranes |
| 35 | Irritation of the throat on short exposure |
| 50–100 | Barely tolerable |
| 1000 | Danger of lung oedema after short exposure |

**Table 6. Inhalation of hydrogen fluoride and its effects on humans**
Health effects: may cause occupational asthma, extremely discomforting to upper respiratory track/lungs, may aggravate pre-existing respiratory conditions, fatal at high levels

| Hydrogen fluoride (ppm) | Symptoms |
|---|---|
| 0.04 | Odour detection threshold |
| 1.0 | No significant change to pulmonary function from occupational exposure |
| 3.0 | Burning and irritation of eyes, nose and skin (reddening) |
| 3.0 | Worksafe peak limitation |
| 4.3 | Threshold for minimal increases in bone density (fluorosis) over time |
| 4.7 | Repeated exposures for 6 h/day tolerated without severe adverse reaction |

**Table 7. Inhalation of hydrogen bromide and its effects on humans**
Health effects: lack of exposure data, expect similar to chemically related substances

| Hydrogen bromide (ppm) | Symptoms |
|---|---|
| 3.0 | Worksafe peak limitation |
| 5 | Nose and throat irritation to volunteers |

**Table 8. Inhalation of nitrogen dioxide and its effect on humans**
Health effects: suspected reproductive toxin, highly discomforting to upper respiratory tract and lungs; presents hazard (including death from single acute exposure, with serious effects (pulmonary oedema) slowly evolving 5–72 hours following exposure)

| Nitrogen dioxide (ppm) | Symptoms |
|---|---|
| 0.09 | Occupational reproductive guideline (8 hours) |
| 0.1 | WHO Environmental goal (1 hour); odour threshold |
| 3 | Worksafe TWA (8 hours) |
| 5 | Worksafe STEL (15 minutes) |
| 25–38 | Physiological response by workers from short exposure |
| 80 | Tightness of chest |

**Table 9. Inhalation of formaldehyde and effects on humans**
Health effects: sensitiser, may aggravate existing respiratory conditions (asthma, bronchitis etc.), Category 2 carcinogen (probable human carcinogen)

| Formaldehyde (ppm) | Symptoms |
|---|---|
| 0.05–1 | Odour threshold (range) |
| 0.1 | Low level of mucous irritation for eye/nose/throat |
| 0.3 | ACGIH occupational exposure standard (peak) for USA |
| 1.0 | Worksafe TWA (8 hours) – under review |
| 1–2 | Typical threshold of irritation |
| 2 | Worksafe STEL |
| 2–5 | Increasing irritation of eyes/nose/throat, pungent odour |
| 10–20 | Profuse tear production, severe burning, coughing |
| 50 | Serious bronchial and alveolar damage |
| 100 | Induced chemical pneumonia and death |

**Table 10. Short-term exposure limits (15 minutes) for some VOCs (Worksafe 1995)**

| VOC | Exposure standards (ppm (mg/m$^3$)) |
|---|---|
| Acetaldehyde[1] | 50 (91) peak |
| Acetone | 1000 (2400) |
| Acrolein[1] | 0.3 (0.69) |
| Benzene[2] | 5 (16) |
| 1,3-Butadiene[2] | 10 (22) |
| 1-Butanol | 50 (150) peak |
| Crotonaldehyde | 2 (5.7) |
| Ethylbenzene | 130 (540) |
| Ethylene glycol butyl ether[1] | 25 (120) |
| n-Hexane | 20 (72) |
| Isocyanates[2] | – (0.07) |
| Isopropanol | 500 (1200) |
| MIBK | 75 (310) |
| Phenol | 1 (4) |
| Styrene[2] | 100 (430) |
| Toluene | 150 (570) |
| 1,2,4-Trimethylbenzene | 25 (120) |
| m,p-Xylene | 150 (660) |
| o-Xylene | 150 (660) |
| (TVOC) | (envir. goals 0.5–2) |

[1] Classified as carcinogens.
[2] Classified as reproductive toxins.

*Toxic gas and smoke exposure criteria to protect firefighters*

Exposure criteria within the firetruck cabin during fire burnover experiments need to be based on two considerations:

- Tenability – the fire crew will be able to occupy the cabin for the bushfire burnover period without experiencing non-tolerable irritation, significant loss of alertness, or irreversible health effects.
- Survival – the fire crew will be able to occupy the cabin for the bushfire burnover period without loss of consciousness or loss of life.

Tenability is the ideal performance target for the firetrucks, but survivability is considered as the essential target for acceptable performance. Based on the criteria and toxicity information presented above, the exposure criteria listed in Table 11 were utilised for assessment of firetruck performance during burnover experiments, though it was not considered essential to measure all of these pollutants during burnover experiments (e.g. if a source of the pollutant was absent).

## Measurements from Several Tests

*Air leakage of cabins*

Initially, all cabin vents and windows were closed and visible gaps to the exterior in the cabin body were sealed. However, early experiments showed that the CO level in the cabin responded rapidly to gas burner phases, raising concerns about excessive leakage of the cabin envelope. As a result, a procedure was developed by which leakage could be characterised prior to simulation testing, and if it was found to be high then it was rectified to reduce it to a minimum practicable level.

**Table 11. Exposure criteria for firetruck cabins during fire simulation experiments**

| Pollutant | Exposure criteria for | |
|---|---|---|
| | Tenability | Survivability |
| Carbon monoxide | 100 ppm | 1,000 ppm |
| Carbon dioxide | 30,000 ppm | 50,000 ppm |
| Respirable particles | 6 mg/m$^3$ | Unknown |
| Hydrogen chloride | 50 ppm | 1000 ppm |
| Hydrogen cyanide | 45 ppm | 135 ppm |
| Hydrogen bromide | 3 ppm | Unknown |
| Hydrogen fluoride | 4 ppm | Unknown |
| Nitrogen dioxide | 5 ppm | >80 ppm |
| Formaldehyde | 5 ppm | 50 ppm |
| TVOC | 50 mg/m$^3$ | Unknown |
| Benzene | 2.5 ppm | 8000 ppm |
| Toluene | 150 ppm | 2000 ppm |
| Styrene | 100 ppm | 1000 ppm |
| Acetaldehyde | 50 ppm | Unknown |
| Acrolein | 0.3 ppm | 10 ppm |

This procedure was:

- All visible gaps in the cabin envelope, including the seal around openable windows and decayed rubber boots, were sealed with aluminium tape.
- The cabin was filled with artificial smoke and then viewed from outside to identify other leakage points, usually less visible gaps and weepholes, that were similarly sealed.
- Due to difficulty in ensuring a good door seal, usually the door perimeter was also sealed with aluminium tape.
- The cabin was filled with ~200 ppm CO as a tracer gas, and the decay of CO concentration with time $t$ ($C_t$) was monitored for 30–60 minutes; this decay was fitted to the equation:

  $$C_t = C_o\, e^{-Nt}$$

  to determine the air change rate (or leakage) $N$.

Generally the air change rate was measured on the morning of firetruck testing and provided a characterisation of the firetruck cabin leakage for that day of tests. With experience, this was progressively reduced, especially in later tests, where it became apparent that the minimum practicable level was ~2 $h^{-1}$ c.f. levels of 5–7 $h^{-1}$ that were observed initially for some firetruck tests. Table 12 presents the air change rates determined in one test series.

*Overview of firetruck test results*

A summary of several firetruck tests is presented in Table 12. Air sampling employed an air pump which delivered cabin air to a mixing vessel remote from the firetruck. Air toxics analysis procedures were the same as those reported in Brown et al. (2002), except for formaldehyde and hydrogen chloride, which were sampled using colorimetric tubes. It was found that leakage of the cabin interior was a significant factor to the air toxics measured in the cabin, even with the significant sealing of the cabin that was undertaken. Usually CO and smoke levels increased rapidly with the flame immersion phase (a period of 20–30 seconds when the gas burners operated at their highest outputs, providing flames that fully engulfed the truck) of the simulation, even without thermal degradation of interior materials. The CO levels in cabins increased to peak levels of 200–400 ppm following flame immersion and, if a window failed, it exceeded 1000 ppm almost instantly.

**Table 12. Summary of air toxics results for firetrucks during burnover testing**

| Test no. | Firetruck | Fire (MW/m) | Air leakage rate ($h^{-1}$) | Water spray/ shields/blankets | Maximum concentrations in cabin |  |  |  |  | First fail time in cabin (minutes/pollutant) |  |
|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  | CO (ppm) | RP ($mg/m^3$) | HCl (ppm) | Formaldehyde (ppm) | TVOC ($mg/m^3$) | Tenable | Survival |
| 15 | Acco2a | 5 | 4 | Y/Y/Y | 310 | 180 | 0 | 1 | 140 | 7(RP) | P |
| 16 | Acco2a | 7.5 | 2.7 | Y/Y/Y | >1000 | 300 | 50 | 1 | 180 | 6(Bz) | 9(CO) |
| 17 | Acco3 | 7.5 | 2.1 | Y/Y/Y | 370 | 22 | 0 | 4 | 33 | 8(CO) | P |
| 18 | Acco3 | 10 | 1.2 | Y/Y/Y | 230 | 16 | 0 | 0.3 | 13 | 8(RP) | P |
| 19 | Bedford3 | 5 | 1.8 | Y/Y/Y | 120 | 20 | 0 | 2 | 47 | 8(RP) | P |
| 20 | Bedford3 | 7.5 | 1.2 | Y/Y/Y | 460 | 5.1 | 0 | 2 | 37 | 7(CO) | P |
| 21 | Bedford3 | 10 | 1.2 | Y/Y/Y | 190 | 39 | 0 | 3 | 60 | 7(TVOC) | P |
| 22 | Bedford3 | 7.5 | 2.5 | Y/N/N | 39 | 6.2 | 0 | 3 | 16 | 7(RP) | P |
| 23 | Bedford3 | 10 | 2.5 | Y/N/N | 97 | 5.1 | 0 | 2 | 8.2 | P | P |

Note:

- The rapid increases in concentrations before and after flame immersion (~6 minutes).
- The presence of some VOCs specific to the cabin or ROPS interior materials, e.g. 1-butanol and hexanal in the cabin may have been emitted from the paint, and styrene in the ROPS from the glass-reinforced fibreglass (GRP) construction material.
- Several VOCs within the cabin may have been external combustion products (of LPG or firetruck components, especially tyres, e.g. benzene, toluene, xylene, styrene).
- No VOC concentrations in the cabin or ROPS exceeded Worksafe occupational exposure standards.

In several tests, an infra-red CO detector was used to monitor air sampled outside the firetruck during the simulation, and external CO concentrations were found to rise sharply only during the flame immersion phase, reaching 5,000 ppm to 35,000 ppm, with higher concentrations being observed for higher radiant loads. Clearly, the significance of our findings for CO and smoke ingress into cabins will depend on what external levels will be experienced with actual bushfire burnovers relative to the simulation grid – an unknown factor at present.

Generally, the firetruck cabins remained within survivability criteria unless there was a window failure, as in Test 16, where a malfunction of the truck's external water spray protection system occurred and a side panel window failed, resulting in a rapid rise of CO and thermal degradation of vinyl seating such that HCl reached 50 ppm. However, most firetruck cabins did not remain within tenability criteria, generally because of CO and smoke levels that rose rapidly during flame immersion, as described above. Tenability criteria were also exceeded for other pollutants, as indicated by high benzene and TVOC levels, and these were considered to be associated with both gas ingress and thermal degradation of interior components. For example, Table 13 provides some VOCs determined within the cabin and roll-over protection system (ROPS), in this case for a moderately severe test of a fully protected International Acco firetruck.

**Table 13. VOCs in firetruck during Test 17.**

| VOC | Concentration (mg/m$^3$) | | | |
|---|---|---|---|---|
| | Cabin | | ROPS | |
| | 5.5 min | 7.5 min | 5.5 min | 7.5 min |
| Acetaldehyde | <0.03 | <0.6 | <0.3 | <2.4 |
| 2-Propenal(acrolein) | 0.06 | 0.23 | 0.1 | 0.4 |
| Benzene | 0.24 | 0.7 | 3.6 | 15 |
| 1-Butanol | 0.82 | 23 | <0.01 | 0.13 |
| Toluene | 0.11 | 1.5 | 0.57 | 1.7 |
| Hexanal | 0.04 | 0.9 | 0.02 | 0.08 |
| m,p-Xylene | 0.02 | 0.17 | 0.22 | 1.8 |
| Styrene | 0.05 | 1.1 | 4.5 | 57 |
| TVOC | 1.7 | 33 | 16 | 150 |

## Conclusions

A protocol has been developed for assessing firetruck cabins for their tenability and survivability for firefighters during bushfire burnover. This protocol considered the potential air toxics and levels of exposure to the firefighters. Using burnover simulation experiments, it was found that:

- Firetruck cabin envelopes have many air leaks.
- There was a primary role of air leakage into the cabins in determining firefighter exposures to carbon monoxide and smoke particles from external fire gases.

The significance of these findings for real burnovers will depend on levels of carbon monoxide and smoke particles at the fire front – an unknown factor at present. In addition, some air toxics appeared to arise within the cabin due to offgassing, thermal degradation and ingress from outside. Tenability criteria were exceeded in many tests, but it was uncommon for survivability criteria to be exceeded in protected firetrucks.

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