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Bushfire: Retrofitting Rural and Urban Fringe Structures—Implications of Current Engineering Data

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Abstract: Since the 2009 Black Saturday bushfires in which 173 lives were lost, two-thirds of whom died in their homes, the question of what a home prepared for bushfire looks like has been repeatedly raised. The 2019/2020 fires saw us not much further advanced. This paper seeks to consolidate what is known about bushfire behavior, its influence upon structures, and, through this data, infer improved standards of practice for retrofitting rural and urban fringe homes. In particular, the prevention of ember and smoke incursion: the data suggesting the prior as the main mechanism of home destruction; the latter as high risk to sheltering occupant health. The article is framed around a comprehensive literature review, and the author's own experiences and observations from fire impacted structures in Victoria's northeast. The article's import lies in demonstrating how embers and smoke may enter homes otherwise seen to be appropriately sealed prior to the fire's approach. Included in the findings are developed hypotheses based on thermal expansion, pressure differentials and backdraft; offering defined paths towards future research. In addition, the work provides practical advice towards mitigating the identified issues using retrofit practices based upon the author's practical experience as a tradesperson and building designer.

Keywords: bushfire; retrofit; ember attack; pressure differential; urban fringe; rural housing; pyro-tornadogenesis; backdraft

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1. Introduction

Prior to the Black Saturday fires of 2009 Australian bushfire policy could be summed up by the phrase 'stay or go'. The premise underlying this approach suggests most homes lost to bush fire succumb to ember attack, not the fire front [1–8]. Received wisdom held, holds today, that ember attack can be defended against, and thus many homes saved. The policy, however, was based upon another premise: that homes were prepared, and residents mentally and physically capable of such defense. The year 2009, and the loss of 173 lives—two-thirds of whom died in their homes—changed that perspective radically [2,3].

Whilst conceptually 'stay or go' still exists, active defense risks to homeowners, discussed by many including state and territory fire authorities [2,3,9–12] have altered the underpinning message. Today, Australians are advised to prepare property before the bushfire season, then leave early should a fire start. In conditions categorized as Catastrophic or Code Red (state dependent categories) the advice is to prepare the home and leave *before* a fire event begins [13,14]. In emergencies, with or without a 'state of emergency' declaration, mandatory evacuations may be ordered, though the legalities of forced removal from a home property are debatable, state specific and unclear [15,16].

Occasionally evacuation is not possible; on others, the indicators of potential fire are low, and communities are taken by surprise. In December of 2015, over 100 homes were lost in the Victorian coastal community of Wye River [6]. On that occasion, the McArthur Forest Fire Danger Index (FFDI)—the measure by which Australia's fire danger levels of High, Very High, Severe, etc., are identified—was only 49 or 'Very High' [6]. Code Red or Catastrophic is 100+. Fortunately, due to the fire's approach direction, no lives were lost.

Both before [17] and after [18] that event, the FFDI as a sole indicator of extreme bushfire risk has been considered questionable. This aside, what remains clear is that homes were not prepared adequately. The 2019/2020 fires again exposed this truth, with fires raging, and homes lost, in all states and territories of the country except the capital. NSW and Victoria took the brunt of losses, with over 2800 houses destroyed in those two states alone. Sadly, on this occasion, 34 human lives were also directly lost [19]. Indirectly, a further 417 lives were lost and 4456 hospitalized due to smoke inhalation [20].

Such deaths give rise to another purpose behind retrofitting: air quality. Occasionally the house is the only shelter available; though Dengate [9] notes that some people decide to stay, others have no such option [2,3,10,21]. Retrofitting will not turn an older home into a bushfire bunker, but it will improve its potential for occupant survival. Much retrofitting discussion is about sealing the home against embers, however as identified above, smoke is just as important, studies also identifying in utero growth restriction of babies through the mother's bushfire smoke inhalation [22,23]. Examples of new homes purposefully built to withstand bushfire attacks without smoke incursion are promising [24]: improving indoor air quality should likewise be a consideration in retrofitting [25].

So what does a home prepared for bushfire actually look like? Specifically, how might we retrofit a home to improve it, and its resident's, preparedness? When constructing a new home in Australia, performance requirements are found in the National Construction Code (NCC) [26] and the standard *AS3959 Construction of buildings in bushfire-prone areas* [27]. However, that standard's veracity is questioned both in this article and by others [28], due to its currently limited interpretation of ember attack mechanisms. Further advice for new and existing homes is given by state and territory fire agency guides on land and property preparedness. Yet, whilst commentary on defensible Australian homes began as early 1945 [1], only recently has discussion focused on retrofitting.

This paper explores the efficacy of these approaches, and AS3959, by drawing upon extant literature, current engineering modeling, reported experiences of homeowners and the author's own experiences. Improved retrofitting actions are proposed based upon these findings; particularly issues arising from potential pressure differentials in extreme bushfire events.

2. Researching Bushfire and Its Influence Upon Structure

What causes a structure to burn is best studied through careful analysis of burnt buildings [1,4–6,29], practical experimentation [30–32], or, when such is problematic (missing evidence, cost, risk), through computer modeling [33,34]. Much of this work has been, or is being, undertaken in facilities around the globe. This article consolidates that material, combining a comprehensive literature review and anecdotal evidence. In reviewing the literature a broad range of terms and phrases were chased through online search engines, academic libraries, Springer, Scopus, Google Scholar and the like. To this was added news reports, blogs, drilled down for quality evidence such as photographs or events witnessed by multiple parties. The main terms used derived from previously understood retrofitting actions and basic bushfire defense systems such as: bushfire sprinklers; intumescent paints; water tanks and bushfire; glazing; ember attack and the like. These terms were followed by those surrounding the hypothesis of pressure differentials, cyclonic winds, pyrogenic winds and such, prior to turning to the specifics of structural components and materials under temperature extremes.

Within this core of articles, the hypothesis of pressure differential was explored; seeking more information as the data exposed questions, potential answers, new terminology: testing the hypothesis in light of known data and reported experiences. Future, targeted, research was thus developed in pursuit of insights to aid retrofitting of older homes, guide the construction of new homes, improve legislated standards and, perhaps, solve mysteries surrounding why seemingly secure homes are destroyed by bushfire, whilst others, much older and more decrepit, survive. To interpret the insights gained from this exploration,

an understanding must first be had of the structure, design and context of the typical Australian home; be it rural, or within the rural-urban fringe interface.

The Australian Home: A Structural Description

The rationale for retrofitting existing dwellings against bushfire attack is clear. Also clear, within the literature, is that ember ingress is the main concern. To understand how ingress occurs requires appreciation of the typical Australian home's structure. Generally, this is a one or two story timber or steel frame building clad with brick veneer, timber weatherboard, cement sheet or rendered panels of autoclaved aerated concrete or polystyrene. Roof cladding is either corrugated metal sheeting or tiles of concrete or glazed terracotta. Windows are usually timber or light aluminum framing, frequently with single panes of glass as little as 3 mm in thickness. More recent homes will have thicker glass (5 mm) and or be double glazed. The whole structure, with rare architectural exceptions, will be constructed upon either timber, concrete or steel stumps or posts, brick piers or a concrete slab. Raised floor structures may have this underfloor space enclosed by a vented brick dwarf wall, be partially enclosed with timber battens, or be fully open.

Common to homes is some form of verandah. In addition, there may be a deck, generally of timber, though on occasions steel-framed, with timber or polymer strip flooring. Eaves of 450–600 mm are typical, though recent trends towards 'eave-less' homes have reduced this to gutters only in many cases. Fascias are frequently timber, or more recently, light steel. Eave soffits are usually cement sheet lined, though older homes may have timber strips venting the roof space. Further roof venting may be available through grills or slats in gables or via static or spinning metal vents. Guttering is usually of galvanized or pre-painted steel, though aluminum and PVC systems exist. Generally, gutters feed to above or below ground water tanks made of steel, fiberglass, plastic or concrete. On occasions, water may be stored under raised floor houses.

In older homes doors and windows seldom seal well, particularly door sills. Weatherboard homes commonly have gaps where external architraves overlap boards. Others may not be flashed correctly at the heads, leaving gaps for embers to settle or be driven into the framework. Some windows will simply not close properly, or have openings in bathrooms or toilets to prevent condensation or odors.

The above demonstrates that most homes under consideration provide ample opportunity for ember ingress. At first glance, retrofitting these homes against bushfire is not a complex task. However, even at a basic level, it requires an understanding of their weaknesses and an appreciation of how bushfires compound these weaknesses through dynamic, high velocity, winds, extreme temperatures and pressure differentials.

3. What Is Known of How Houses Burn in Bushfires

Recent research [4–7] strongly supports Barrow's 1945 [1] suggestion that embers were the most significant cause of house destruction. The fires at Tathra, NSW, in March 2018 furthered this understanding. In that instance, only 32 of the 69 homes destroyed were in a decreed bushfire prone area [35]. The rest were within the seaside township where neither flames nor fire front heat flux had influence. Research has suggested that ember penetration into urban or suburban areas is typically less than 700 m [36], however the Canberra fires of 2003 destroyed homes in the suburb of Lyons over 2 km distant from the fire front [29]. Notably, the Australian Institute for Disaster Resilience (AIDR) Canberra Fires Field Report [29] documents bushfire generated winds damaging homes well before flame arrival; leading to an extremely high percentage (91%) of totally destroyed homes: i.e., once fire took hold, invariably the house was lost.

However, stating ember attack alone is insufficient as it fails to account for the randomization of its effect. In research [1,37,38], news reports [39] and blogs [40], there are multiple examples of homes that 'should' have been destroyed, yet survived intact despite abutting seemingly secure but destroyed homes. Whilst chance must be conceded, there are potentially other factors in play.

During a bushfire, residents are advised to seal homes as much as possible: citing Barrow's proposition ' ... a house should be as air-tight as practicable ... ' [1] (p. 1). Windows, doors, vents, everything should be blocked to prevent ember incursion. With modern homes, this is reasonably achievable: potentially to the point of fault. An untested hypothesis held by this author, to some degree suggested by Ghaderi et al.'s modeling [33], is that of pressure differentials in bushfire contexts: Differentials caused by pyrogenic winds—fire generated winds high in both temperature and velocity—impacting homes incapable of rapid pressure equalization. In such instances at least two things may challenge the integrity of a building: extreme uplift forces; and rapid, potentially destructive, pressure equalization.

The first, uplift, is well understood and engineered for, particularly in cyclonic zones, through AS 1684.3 [41] and AS 4055 [42]. Unfortunately, bushfires also occur in non-cyclonic zones where homes are designed for significantly lower wind pressures. That extreme bushfires can create their own weather systems is also well understood. Pyrocumulonimbus clouds and their associated fire thunderstorms bring about fierce winds, downbursts, and in extreme cases, pyro-tornadogenesis—fire tornadoes generated by the rotating convective winds of the cloud [43]. Video evidence of bushfires assaulting Canberra suburbs Kambah and Chapman in 2003 [43,44] show roof sheeting falling kilometers from the fire front, and the fire tornado's enormity—approximated at 500 m base diameter [45].

Pyro-tornadoes aside, Ghaderi et al.'s investigation [33] into wind-driven surface fires demonstrates that the presence of a structure alters the intensity and dynamics of that fire, supporting earlier work by Honey and Rollo [34]. A range of factors deriving from this study have great import into how homes are challenged by fire, and hence, may be defended. One notable outcome [33] (p. 12) shifts our interpretation of fire behavior from steady heat action (the premise behind AS3959) to dynamic pulsation, uplifting vortices, extremely low pressures and high velocity reverse airflows (reflective of Sharples et al. 2012 wind-terrain modeling [46]).

Figures 1–3 below, evidence these key influences upon a standard flat plane structure (effectively a 6 m × 6 m × 6 m box replicating a house) downstream from an oncoming fire. The main points of interest are as follows:

- The fire produces a low pressure zone immediately downstream from its source which draws the flames forward, (colored red) at velocities significantly greater than the wind (inlet velocity) driving it.
- That ground hugging behavior is significantly foreshortened when confronted by a building, at which point the winds and flames flow upwards.
- Immediately behind the structure, there are fast moving reverse air flows (blue zones) that also drive the plume upwards.
- The fire's momentum immediately in front of the building slows, becomes intermittent; pulsating more rapidly (twice the frequency, P1 circled in Figure 3b 0.93 Hz) than when moving over open ground (P2 & P3 circled at 0.42 Hz and 0.46 Hz respectively).
- This higher frequency raises the convective heat load through increased periods of surface contact, whilst limiting any cooling potential.

Additionally, radiative heat flux was determined to focus upon upper wall portions facing the fire, whilst the sides, rear and roof are significantly less affected.

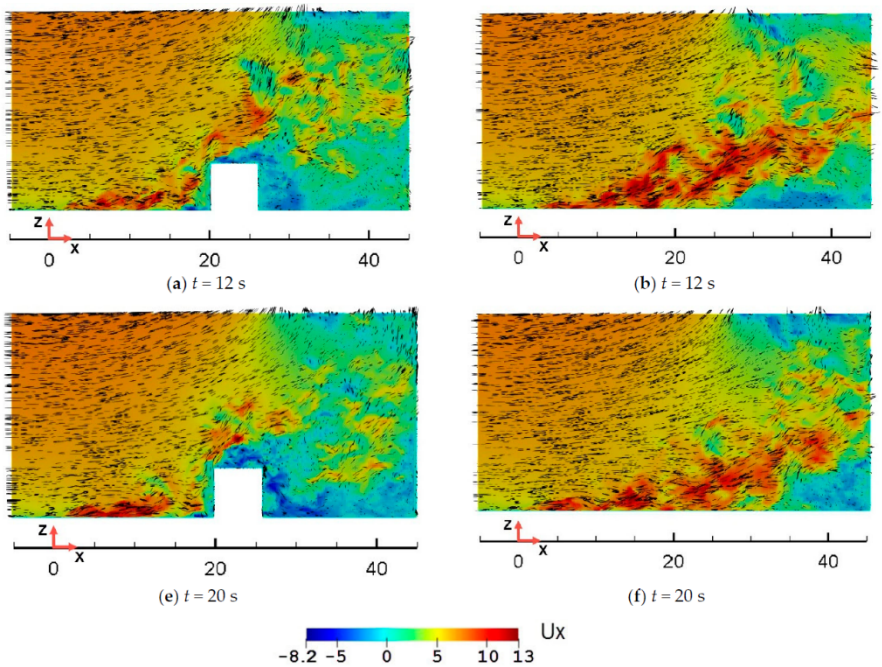


Figure 1. In subfigures (**a**) and (**e**) the white box instances the presence of a 6 m cubic building. Subfigures (**b**) and (**f**) show the fire passing by the building 9 m distance from its center. I.e., 6 m from the side [33] (p. 9). Colorbar represents velocity in m/s along x axis.

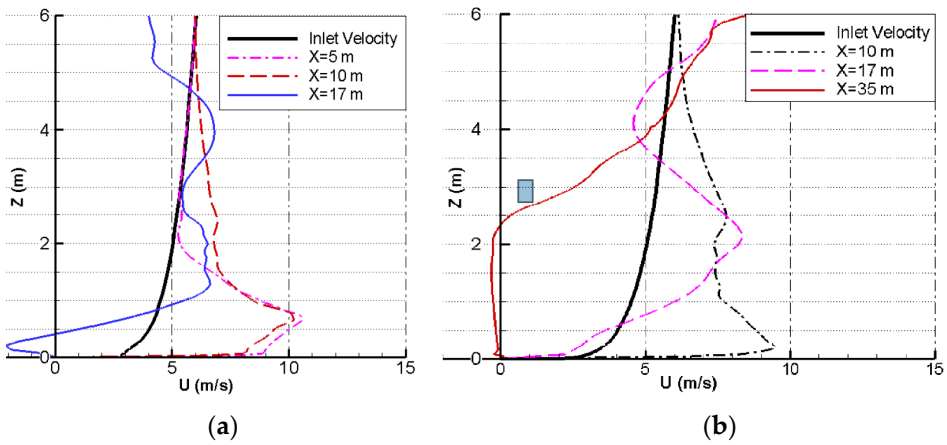
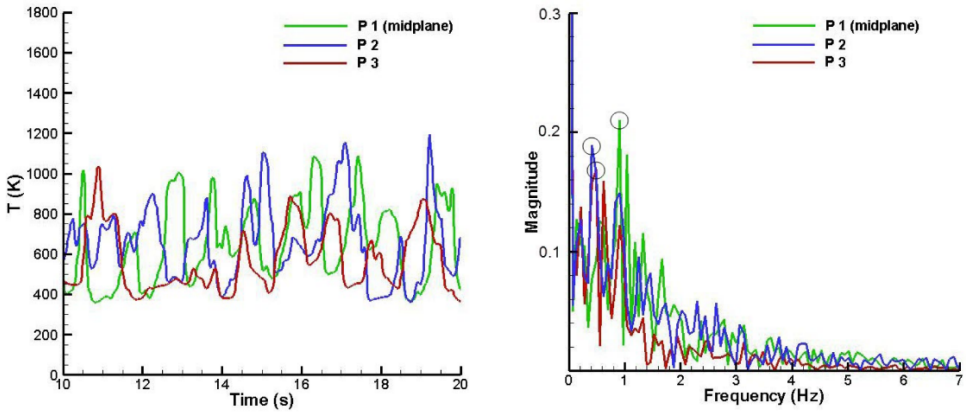


Figure 2. Subfigures (**a**,**b**) show the vertical profile of the airflow's changing longitudinal velocity at different longitudinal positions relative to the inlet location. Subfigure (**a**) shows airflow aligned with the building's center line. Subfigure (**b**) shows airflow passing 9 m on either side of center line [33] (p. 10).

Of particular interest is the identified wind velocities. The fire front wind velocity is seen to be significantly greater than the driving input. I.e., the fire is drawn forward by self-generated low pressures, not simply driven forward by high winds. The input wind velocity in this model is only 6 km/h. Thunderstorms commonly generate wind gusts of 90 km/h, more damaging storms, 160 km/h; cyclones may exceed 360 km/h [47]. The velocity the fire itself travels at in such conditions is discussed in Sharples et al.'s study of the Canberra 2003 fires [46]. Such dynamic low-hi-low heat, wind velocity and pressure fluctuations place inordinate stress upon a structure.

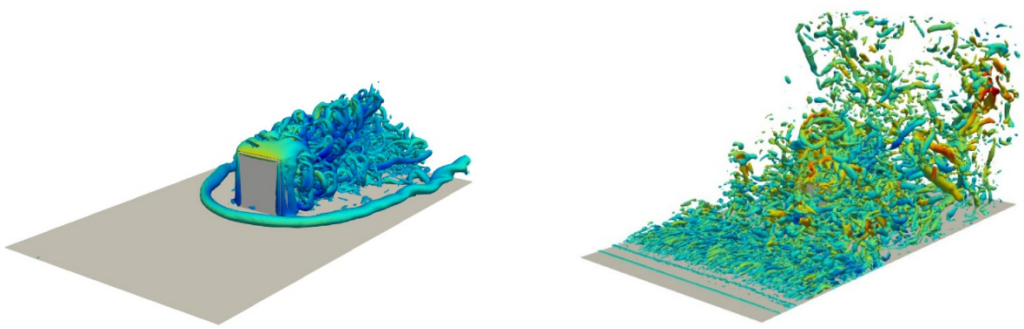


(**a**) (**b**)

Figure 3. Subfigure (**a**) shows the instantaneous surface temperature as measured in Degrees Kelvin at 3 points located on the surface 5 m from the building front. P1 is directly on the building's center line, whilst P2 and P3 are located 9 m on either side of the center. Subfigure (**b**) shows the frequency of peak temperature signals at these same sensors [33] (p. 12).

The significance of the above regarding ember attack is multifaceted: particularly ember disposition being the rear or downstream side of the structure, not the surface facing the fire front. This is concerning for homes with verandahs or other semi enclosed spaces on this side. Also, embers attack both the front and rear of the structure at an upwards trajectory, exposing any weakness under eaves and verandahs.

Figure 4 describes high velocity winds over and around a structure with (b) and without fire (a). Figure 4b demonstrates that in the presence of fire, myriads of small vortices initially hug the ground, then buoyancy inducing forces dominate, creating larger vortices that randomly cross hatch the structural zone generating significant uplift: The structure is attacked simultaneously by embers, heat flux, and wind loads from multiple directions, introducing dynamic loading at numerous points and angles.



(**a**) (**b**)

Figure 4. The vertical airflow structures in the presence of fire (**b**) and without (**a**) [33] (p. 11).

A defensively well sealed building now works against itself as rising temperatures and, to a lesser degree, pressures, occur within the home. What the internal temperature and internal-external pressure differential might be is not addressed in this modeling—nor in any modeling to date. However, it may be assumed that this differential at least adds behind surface loading to uplift forces already existent through high velocity winds.

Coupled with the dynamic fire front heat shock inflicted upon windows, this pressure may suffice to fracture or shatter glass. In either case, cladding and windows of the structure may be compromised: creating gaps and openings, allowing ember ingress and potentially an explosive backdraft action.

The temperatures modeled are also concerning for exposed structural steel elements. It is well argued [48] that at around 600 °C—steel's yield strength drops by approximately

60%, Young's modulus falling by 70%. Given high wind loads, and Figure 3a showing surface temperatures fluctuating between 400 °K and 1000 °K (125 °C to 725 °C), exposed structural steel failure is potentially high. In relation to ember incursion, failure need not involve collapse—columns, beams or lintels need only flex—creating gaps sufficient to allow ember ingress; ingress being considered possible through gaps as little as 2 mm [27].

Understanding the forces affecting structures as dynamic, not stable is therefore crucial to both new homes and retrofitting. Buildings must not be viewed as static entities: rather, as vibrating, pulsating structures attempting to 'breathe', whilst swaying, rocking, being twisted, even if not visibly so.

3.1. Inference: Structural and Cladding Integrity; Ember Incursion

Current modeling does not reflect an actual house with its complexities of form. However, the aforementioned studies provide sufficient data to highlight key areas of risk from ember attack; suggesting useful actions. Rising internal pressures would at first seem a positive defense outcome. I.e., positively pressurizing a room, corridor, or stairwell is a typical fire defense strategy in high-rise buildings [26]. The problem comes, however, with the principles of backdraft and flashover (the latter discussed by Caird Ramsay et al. [37,38]). Flashover occurs when energy trapped within a space cycles upwards such that all materials reach their ignition point—a 'fuel-dependent phenomenon' [49] (p. 55). Backdraft occurs when a closed compartment, bordering on combustion but low on oxygen, is suddenly provided oxygen through an opening—such as broken windows [49]. Add fumes inside a home from furnishings, finishes and fittings [50], frequently volatile organic compounds (VOCs)—Fleischmann et al.'s unburned hydrocarbons [51]—and a rapid combustion event may occur acting explosively outwards.

Not enough is known about VOC off-gassing in homes experiencing extreme bushfire temperatures to state authoritatively that these could amount to an explosive event. Despite multiple anecdotal and media accounts of buildings 'exploding' [52], evidence after the fact is insufficient to support, or refute, such accounts [4,6,37,38]. However, the data above suggests the potential should be conceded. Regardless, the potential for cladding breaches and backdraft remains. Finding means by which to reduce internal air pressures safely, therefore, forms part of the discussion on refitting strategies that follows. Before developing that discussion, an outline of applicable Australian Standards [27,41,42,53] is requisite to understanding contemporary approaches to construction and retrofitting of homes in bushfire zones.

3.2. Australian Standards and the Bushfire Attack Level (BAL)

Whilst not required for all home retrofits, AS3959 [27] remains the preeminent guide for Australian housing in bushfire zones. Integral to this standard is the Bushfire Attack Level (BAL) rating system. Briefly, the 'BAL' is a statement of the likely severity of a site or building's exposure to bushfire and ember attack. A radiant heat flux range statement in kW/m^2, it is an evaluation of a structure's context. The evaluation includes:

- Identified Fire Danger Index (FDI) for a given location in Australia
- Vegetation classification
- Slope of the land under this classified vegetation
- Distance the classified vegetation is from the building

Derived ratings are either BAL-LOW, 12.5, 19, 29, 40, or FZ (Flame Zone). The higher the BAL, the more threatened a structure. Once identified, guidance on acceptable construction is given to each BAL level through the major sections of the standard. A typical visual guide is given in Figure 5 below:

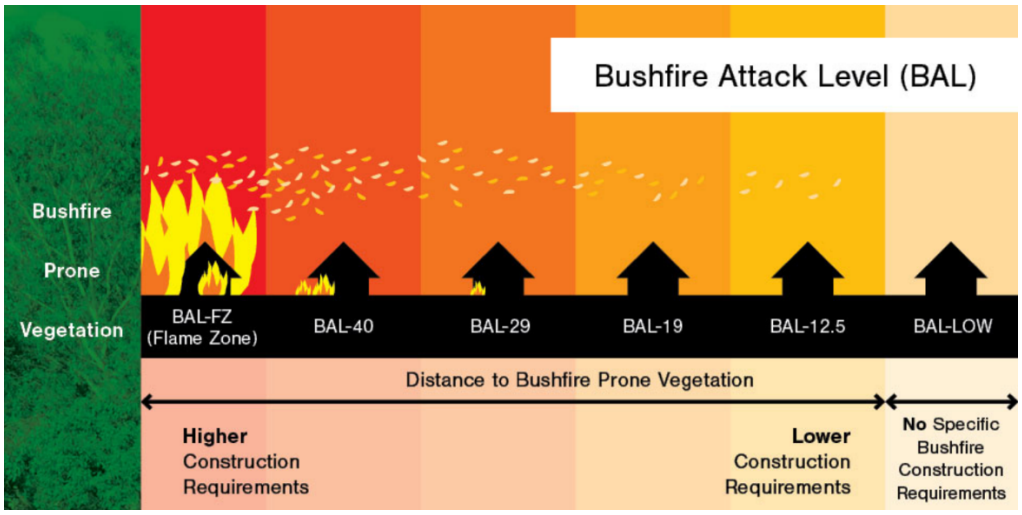


Figure 5. Pictorial description of Bushfire Attack Level (BAL) ratings [54].

AS3959 becomes challenged when dynamic, not static, heat flux is considered. As others have found [55], even these static values are questionable when detailed modeling is applied. Add the previously identified vortices, uplift and negative pressure loadings and the construction provisions lose relevance. This does not negate the standard's total relevance, however, BAL must now be understood as indicative rather than definitive—potentially a significant understatement. When retrofitting or designing and constructing new buildings far greater attention to detailing, hold down and material choices should apply.

The BAL system of identifying risk is further challenged when Figure 5 is reflected upon in light of documented home losses; many destroyed despite BAL-LOW ratings. It fails to account for ember attack many kilometers ahead of the fire front, frequently within town or urban fringe areas many streets back from classified vegetation. Yet the BAL system remains valuable in identifying radiant heat and flame proximity for given locations. It allows homeowners, when considering retrofitting, to better prepare land around buildings to reduce heat and flame levels. But with regards to embers, distance from the flame front is not a safeguard.

3.3. Australian Standards and Wind Ratings

Wind ratings for Australian houses are defined by AS 4055 [42], or AS1170.2 [56]. For the purposes of this paper, outlining AS4055′s rating system will suffice for exampling wind speeds in a later discussion. Ratings within AS4055 are given as either N1 through to N6, or C1 through to C4. N or C ratings depend upon regional location; 'C' referencing areas likely to experience cyclonic conditions. The individual ratings suggest limit state (serviceability and ultimate) design wind gust speeds. Stated in m/s, classes N3 through to N6 have the same design gust speeds as C1 through to C4, being: 32 (50 ultimate), 39 (61), 47 (74) and 55 (86) respectively. The difference between the N and C becomes evident when calculating positive and negative pressures applicable to given surfaces or building elements (roof, walls or the like). For example, a C2 rated roof surface has a general ultimate limit state pressure of −3.21 kPa (a net uplift), whereas N4, with the same gust speed of 61 m/s, is deemed to have a net uplift pressure of only −2.21 kPa. These derive from a table of pressure coefficients recognizing the dynamic low-hi-low pressures sustained in cyclonic events. Ghaderi et al.'s [33] study suggests that such dynamic pressures evolve from bushfires as well.

4. Retrofitting: Applied Implications

Conceding that embers cause most bushfire home losses, the ambition of retrofitting is to prevent their ingress and eliminating or reducing ember deposition zones of high

ignition risk. The previous section's guidance support's most government or fire authority recommendations. However, the material allows review of existing retrofitting publications more informatively, several of which are outlined briefly below. The following then discusses key areas of bushfire attack—pressure differentials, uplift, angles of attack, counter flowing winds and the like—relative to those structural elements most influenced, seeking to mitigate such attack and inhibit ember and smoke ingress. In making recommendations it is conceded that retrofit activity is framed by what is 'reasonably practicable'. Available time, financial resources, structural element access and emotive connection to home and contents, all influence perceptions of achievability.

A recently published bushfire resource for the construction and retrofitting of homes in Queensland [57], has relevance beyond that state. Particularly useful is the Level of Protection system that informs builders/owners of the protection achievable with a particular range of actions. An extensive document, it also directs builders to particular sections of the relevant standards [27,41,58].

Another developing Queensland publication [59] lays the ground work for retrofitting against extreme winds. Yet despite being a Geoscience Australia and James Cook University's Cyclone Testing Station (JCU CTS) collaboration, under the banner of the Bushfire and Natural Hazards CRC, there is no linkage between bushfires and high wind loads. Despite this lack, it promises to be a valuable resource in identifying levels of protection gained against 0.2 s peak wind gusts gained from different actions undertaken [60].

The Victorian Building Authority (VBA) and Country Fire Authority (CFA) have also produced valuable guides specific to retrofits [61,62]. One deals with domestic homes whilst the other focuses upon commercial buildings defined as Class 9 under the NCC—those that might be used as last resort shelters for vulnerable communities—it holds advice relevant to domestic structures, particularly subfloor venting, piping and roof penetrations. As with the recommendations being promoted here, these documents frequently promote methods exceeding AS3959.

Reflecting on these documents in light of research implications presented earlier, the following frequently references Australian Standards and building codes to higher than 'normal' standards.

4.1. Pressure Differentials, Dynamic Loadings and Cladding

These are issues least addressed by current retrofitting advice and AS 3959 generally. Of particular import is the dynamic loading bushfires impose: loads suggesting cyclonic standards (such as cladding fixing AS 1562.1 [63]) whereby materials must satisfy a Low-Hi-Low testing regime that 'rattles' elements over a seven stage sequence of varying pressures. The only guide to this procedure, and any claims of compliance, is a draft document published in April 2009 by JCU CTS [64].

The following 'grounds' this discussion in practice: i.e., how does the preceding data inform the typical Australian home retrofit? Though only common building elements are addressed, the principle of increased attention to tie down may be applied more generally. At the section's end, the discussion turns to idealized means by which internal-external pressure differentials may be alleviated.

4.1.1. Metal Sheet Roof Cladding

In older homes roof sheeting is commonly nailed, not screwed; whilst capping and flashings to many relatively new homes are pop-riveted rather than screwed—Australian standards [63] only requiring screws from 2018. Both are problematic regarding tie-down—the identified potential for high uplift pressures and dynamic wind loadings is likely to exceed their withdrawal capacity. Even if sheeting or capping is not torn away, sufficient gaps may be created at sheet ends and overlaps allowing ember ingress. Sheet roofs should thus be check and fixings upgraded to screw fastenings using cyclonic fixing patterns following AS 1684.3. Gaps between flashings and corrugated profiles should be filled with non-combustible material such as rock wool.

4.1.2. Tile Roofs (Terracotta or Cement)

In low wind areas (AS 4055 ratings N1, N2, N3), tiles tend to be tied down minimally or not at all. Given higher and dynamic wind loads associated with bushfires, tiles should be mechanically fastened to a minimum of N4 or C2 wherever there is the possibility to do so. Appropriate sarking should be provided under the tiles, though this may be considered impractical in many instances due to the costs associated. When retrofitting incorporates new cladding, appropriate sarking must be installed, and sheeting rather than tiles considered.

4.1.3. Further Roofing Considerations

In the above cases, the tie-down has only been achieved for the cladding. This remains inadequate if tie-down of battens to rafters, rafters to wall plates and studs, is inadequate. Hence the concept of 'reasonably practicable'; i.e., it depends upon owner willingness or financial capacity. Yet, where possible, tie-down fixings should be upgraded at these points. AS 1684.3 provides appropriate guidance in this area. It is important to work to these higher wind loads, not standard contextual loads which may be as low as N1—which the previous information has shown inadequate in extreme bushfire scenarios.

4.1.4. Wall Cladding

Fixings to sheet cladding (steel, ply, cement sheet), should be checked for security and upgraded anywhere movement is detected. Gaps and cracks should be filled. Likewise for weatherboards; replacing damaged boards. Older homes may have no sarking, with the upward trajectory of embers, gaps in board overlaps become susceptible, allowing embers to settle within the wall cavity. Eave/wall junctions, re-entrant and external wall corners, should be carefully inspected; loose or damaged stops or cover straps replaced, gaps filled. Intumescent paints may be considered to protect against fire front heat flux, or low areas were embers may settle, however, the service life of such coatings remains doubtful [65]. Closing gaps to prevent ember penetration is the main aim.

4.2. Subfloor Protection

As per existing retrofitting guides, these areas should be shielded by steel mesh and close fitting battens. In the case of brick dwarf walls, gaps or cracks should be filled, vents should be upgraded if vent openings are greater than 2 mm. The junction between dwarf walls and main wall cladding should be inspected and gaps filled.

4.3. Fascia, Eave, and Guttering

This area is particularly open to ember attack due to wind approach angles—upwards at 45–60 degrees from horizontal. Generally, soffits are non-combustible cement sheet, and gutters of galvanized or painted steel. However, fascias are frequently either light steel or timber. Under heat loads, steel may deflect, allowing soffit sheets to drop from groves; joiners between sheets are generally light PVC which may melt, gaps for embers now becoming present. The soffit/wall cladding junction should also be inspected. Fixing should be checked as per previous elements.

4.4. Gutter Guards

This is an area of contention amongst homeowners, builders and suppliers/manufacturers. This author's experiences and anecdotal reflections of homeowners and architects, suggests that no available system works effectively. Metal guards are considered the most effective in being less susceptible to damage from birds and small marsupials, however, the mesh tends to trap leaf ends and grass still grows under the guard. Many such guards cannot be easily removed for cleaning. When installed, systems for flushing gutters without removal should be integrated, and regularly used.

4.5. Sarking

Sarking has been listed in several of the above recommendations. Leonard et al. [57] recommend against conventional sarking, even flammability index 5 rated (NCC requires 5 or less). That document recommends the use of flame resistant sarking, but fails to identify what that actually means. Kempster [66], however, describes bushfire roof and wall systems incorporating fireproof blankets, sarking and insulation elements tested to AS 1530 [67] offering a flammability index of 1. The materials within these systems can be individually applied as part of a retrofit program but require cladding removal to do so.

4.6. Structural Steel

Structural steel is common to Australian homes as beams, columns and light gauge wall and roof framing. In normal conditions, these elements are stable, serviceable and non-combustible. However, suffering extreme bushfire temperatures components may buckle under load having lost potentially 60–70% structural capacity. Alternatively, tie-down capacity of joints may become compromised or gaps in cladding generated: the latter through steel's linear expansion coefficient of 1.2×10^{-6}, meaning with a temperature rise of as little as 60 °C (from 40 °C ambient to heat flux induced 100 °C material temperature), a 2.4 m or 2.7 m steel wall will gain height by approximately 2 mm.

Exposed posts and beams undergo greater elongation. An 8 m long beam, may expand linearly when raised by 100 °C, as much as 10 mm. Though non-failure temperatures, issues arise when components are restrained, either by other steel components, or elements such as brick or concrete columns. Baetu et al. [48] demonstrate that constrained structural steel is more likely to fail early—before yield temperatures and loads are reached—due to constrained liner expansion causing premature buckling. This was particularly notable amongst lightweight steel components. The import here is not that structural steel will inevitably fail in bushfire conditions, rather that it may, due to even minor deflection, be a factor in exposing the internal elements of walls and roofs to ember ingress through the generation of gaps as the fire front passes.

Retrofit actions to counter the issue of steel's expansion may be in the form of:

- Intumescent coatings to exposed steel elements (columns and beams).
- Fireproof mastic sealants with high (40% or greater) expansion characteristics to any areas where expanding steel elements may lead to gap generation.
- Fireproof mastic at junction of metal fascia and soffit lining to limit lining sag should the fascia buckle outwards.
- For steel frames, similar mastics around window and door frames where they meet claddings, particularly at window heads.

4.7. Of Pipes and Penetrations

Contemporary plumbing invariably involves PVC components, often with long exposed lengths under suspended subfloors. Rigid PVC's flash and sustained ignition temperatures of approximately 400 °C and 450 °C respectively [68] are achievable in a fire front. Though unlikely to carry fire directly through a wall, roof or floor element, PVC components will melt, droop or compact as the melting range is only 115–245 °C (manufacturing process dependent) [69]. It is by this mechanism that embers and flame may gain entry into or through structural and protective elements either during the initial assault or after the fire front has passed.

Fireproof collars are available for retrofitting that hinge around PVC piping. Likewise, there are metal fittings that couple around a pipe and backfilled with fireproof mastics. Where piping is more exposed, consideration should be given to applying intumescent coatings or flameproof insulating wrap, shielding the PVC from heat to prevent unnecessary replacement.

4.8. Windows and Doors

Glazing represents a weak point in the defense against ember attack and the bushfire front itself. Many early homes may have large panes of ordinary annealed gas only 3 mm thick: totally inadequate against a fire front. Likewise, they are easily shattered by flying debris from trees or neighboring properties. More modern homes may have thicker glass, though still generally ordinary annealed.

Upgrading of windows against bushfire needs careful consideration outside the scope of this article as solutions must be highly contextualized; reflecting requirements of AS 3595, the NCC, and through this code, multiple further standards. However, Bowditch et al.'s [32] research offers some guidance. Though reporting on a range of glass and framing types exposed to bushfire temperatures, the simulation was of steady heat flux as against the rapid fluctuations observed by Ghaderi et al. [33]. Likewise, no high velocity winds were brought to bear and the glazing units stood in an open frame. The latter factors meaning that internal-external pressure differentials were not considered. These issues aside, the findings suggest that improved glazing should include 5 mm toughened glass as a minimum (particularly the exterior pane is part of a double glazed unit).

A cheaper, or more easily applied, means of upgrading window security against heat, flame and impact, is shielding. Multiple systems are available, from proprietary roller shutters to cost effective hinged panels, shutters or screens [70]. In either case, 'non-corrosive steel' (generally taken to mean stainless steel) or bronze should be used and installed such that no gaps greater than 2 mm remain.

Doors and windows, designed to open, mean small gaps are common to ensure free movement. It is imperative that these gaps have high temperature resistant seals that will prevent smoke ingress, not just embers. Standard rubber seals are generally inadequate for this purpose, likewise brush seals. High quality neoprene seals should be installed wherever possible.

5. Pressure Equalization Strategies—Requisite or Not?

Notably lacking attention, this area needs applied research and theoretical modeling. The modeling previously discussed [33] is suggestive of pressure differentials affecting bushfire attacked homes but does not confirm it. After the 1983 Ash Wednesday fires this author noted examples of untouched weatherboard homes beside destroyed brick dwellings. Similarly, following the 2008 Black Saturday fires, a grass fire destroyed a new, seemingly secure but evacuated, brick veneer home and steel shedding. Nearby, stood an old weatherboard house unscathed. This difference between the two outcomes could be 'chance': Alternatively, old cottages leak air with little resistance; whilst the new home, appropriately closed and sealed against ember incursion, failed to quickly equalize the internal-external pressure. Barrow's [1] documenting of timber clad homes with mesh covered windows and vents surviving bushfires led to our understanding of ember attack. Potentially there is another message here too.

Whilst awaiting further research it is worth considering potential remedies, particularly from a retrofitting perspective. One solution is release valve venting. Associated with every room, they must allow rapid release of pressure but disallow incursion of embers or smoke. Notably, the hypothesis is less about high pressures forming suddenly within the house, and more about sudden low pressures—relative to the interior—becoming dominant outside the structure. It is about reducing that pressure differential sufficiently to limit structural flex and component creep, or the fracturing of already heat shocked glazing, either of which may allow ember incursion and destructive backdraft ignition.

6. Defense through Water

Dousing a structure with water before a bushfire arrives has long been considered a reliable defense strategy. Several studies have been undertaken [71–74] reporting on the effectiveness of bushfire defense sprinkler systems. To this may be added news reports and testimony of those who have saved or lost homes where sprinkler systems have been

deployed [40]. However, discussion remains as to its potential for heightening risk through over expenditure of water—leaving inadequate supply for fire front defense.

Water storage and supply are crucial to active fire defense systems; particularly for those who remain and defend a property believing themselves equipped to do so. Wilkinson & Eriksen [75] outline water scarcity, pump failures, power outages and melting componentry—pipes lines, hoses, fittings and even water storage tanks—as the 'weak link' in seemingly well prepared systems. They also note that reticulated supply cannot be guaranteed due to power cuts to pumping stations, or through drought depleted reserves being drawn down prior to fire front emergence. Some cities or towns may impose restrictions on reticulated water supply to conserve storage, small town or farm homes use tank or bore water and are not required to comply, making conservation discretionary.

Current water storage policy, though varying state to state, requires maintaining dedicated firefighting reserves of between 10,000 L to 22,000 L to be maintained on site depending upon block size [76–78]. This raises the question of what a viable storage container looks like. Previous research [4,6,79] suggests that polyethylene (PE) tanks are inadequate in the face of significant heat sources, even when full. However, when appropriately sited, shielded or installed underground, they may offer low cost alternatives. No data is available regarding the effectiveness of intumescent coatings to such tanks. Concrete or metal tanks were shown to have no such limitations. Of importance in all cases, however, is that connections and above ground piping should match those of the local fire authority and be of metal.

Spray and Sprinkler Systems

When appropriately designed and deployed, spray systems have shown high value in protecting homes [40,80]. What is appropriate remains widely discussed in a range of reports in Australia and internationally [40,57,61,71–75,81]. A recent study into the efficacy of airborne droplets for attenuating the effects of bushfire offers useful insights, whilst raising further doubts [73]. The key findings from these studies show that:

- Water sprayed directly onto upper wall surfaces are more than twice as effective at lowering heat flux than spraying way from the building.
- Air flows significantly influence the sprinkler effectiveness (varying almost 40%).
- Sprinklers are effective when using very high flow rates, but these rates were beyond the storage capacity of most domestic settings.
- Further investigation required to determine the efficacy of small droplets (0.1 mm) at moderate flow rates.

Post bushfire blogs and news reports tell of sprinkler efficacy in some instances, and failure in others [40,80]. The main questions arise around spray head location, pressures, flow volumes and spray direction. In the 2020–2021 Australian fires, a rural property was actively defended by the occupants with the aid of preinstalled sprinkler systems [80]. The design of the home and immediate landscape aiding their success (a green roofed structure). However, the most important asset was the water supply: more than 200,000 L held in concrete tanks. Saving the property took over 150,000 L, most expended through the sprinklers. Such volumes of water are seldom available. Arguments against sprinklers have focused on this expenditure of water prior to fire front arrival. Yet another commentary [40] argues that sprinklers did little to prevent the destruction of the home despite plentiful water supply.

Most researchers and manufacturers concur that spray head type and location are the keys to a system's success [71,82,83]. Recommendations include static low volume, high pressure, spray heads that generate a 'screen' of fine water droplets. Others use rotating heads to similar effect, deploying heads around eaves and fascia. Systems located on the roof ridge line are considered ineffective due to the high uplift winds taking the water away from the property: a premise supported by the modeling discussed earlier [33]. The modeling of Green [71], suggests spray systems should be close to a structure's walls

for efficacy, directed in such a manner that water is carried back to the upper walls, wall bases and under eaves by the encroaching winds and vortices.

Most importantly, spray systems and service lines must be fireproof. Whilst CPVC piping is fire resistant and has been successfully tested for unshielded interior fire suppression systems, questions remain about their resilience after extensive exposure to UV [84,85]. The recommendation for metal systems thus remains.

7. Retrofitting and the Context: Landscaping

In 2011 Honey & Rollo [34] analyzed the influence of structural form, proximity, and the arrangement and alignment of multiple structures upon the transport, passage and deposition of embers. They also investigated the significance of air pressure and velocity, with findings not dissimilar to Ghaderi et al.'s modeling. In dealing with the form they experimented with alignment and, through raising structures off ground, introduced interrupting airflows limiting ember build up on the lee side. Potentially the most important aspect of this study is their observationally derived hypothesis concerning land sculpting in front of buildings in order to confuse wind flows and dictate preferred ember deposition [34].

A useful CFA [86] document speaks to appropriate landscape design for bushfire, however, the focus is upon materials, layouts and plant/tree selection. Sculpting of the landmass itself is not raised. In practice, such sculpting may be problematic for many homes due to block size restrictions, suggesting collaborative sculpting across multiple blocks, or council-assisted sculpting of government or state forest lands. Further studies need to be undertaken, however, before such works could be assured of success; particularly in light of Sharples et al.'s modeling and experimentation demonstrating powerful reverse airflows driving fires laterally upon ridges and rapidly up the lee sides of hilly terrain in extreme bushfire contexts [46].

Controlled burning, another landscape strategy, also needs further research having received varied commentary. A recent publication, whilst questioning clearing burns deep within the forests, strongly promotes burns proximal to infrastructure: Arguing that lower fuel loads near housing reduces heat flux levels and fire spread, making fringe control more achievable [87]. Indigenous burning and land care practices have recently been acknowledged as effective through changing the density and species of forestation: opening the landscape, slowing down encroaching fires and reducing their intensity [88–90]. Only this latter approach would appear to have a broader influence upon ember attack reduction from extreme bushfire events—through potentially limiting the likelihood of such events. It is suggested here that these practices should be promoted as part of resilient and regenerative communities: as retrofitting beyond the boundaries of structure and personal land holdings.

8. Conclusions and Retrofitting Limitations

As most previous writing on retrofitting suggests [57,59,61,62], such actions have their limitations: many alluded to, or boldly stated, in the sections above. Not least is the cost. In 2017 Penman et al. [91] found that preparing occupants and homes for bushfires ranged from AUD 8500 to as high as AUD 47,000. With 2020 construction industry annual price growth being 3.6% [92], and CPI averaging 2% over the past 4 years [93], a rise of approximately 10% on these prices is reasonable: i.e., the contemporary cost for retrofitting approximates AUD 9350 to AUD 51,700. To which end of that spectrum any retrofit comes from being totally dependent upon the depth of actions taken.

Cost, however, is not the only limitation. Retrofitting is about working with what is, towards a frequently unobtainable ideal. In many cases, gaps will remain, likewise timber window frames and walls, and the tiles will remain tiles. Installing sarking behind existing cladding is a major exercise at which many will balk. Fitting out a house with appropriate spray heads, fire pumps and adequate water storage is full of complexities—and for some, it can be as simple as a question of aesthetics on a heritage home, foolish as that may sound.

This paper has sought to consolidate existing knowledge surrounding retrofitting actions for Australian homes facing bushfire threats: augmenting that knowledge through inferences drawn from otherwise uncorrelated fields. Additionally, the concept of retrofitting has been expanded beyond singular structures, conceptualizing its role in resilient communities and collective defense strategies. In offering directions for further research, the influence of the immediate landscape and other structures has been included. The purpose of retrofitting has also been broadened to consider sheltering occupant's air quality in light of recent evidence showing significant mortalities, hospitalizations and in utero risks from smoke inhalation. More significantly, the work expands our knowledge of why homes are open to ember attacks in the first instance. In so doing, a pressure differential hypothesis has been explored using the existing engineering and modeling data. This data suggests that such a hypothesis has a level of merit that should be pursued through detailed engineering modeling and practical testing. At a minimum, the existing data strongly suggests attention to retrofitting actions that may counter the influences, however minor, of these potential pressure differentials upon glazing, claddings and openings. This, because such influences, coupled with component movements brought about by extreme temperatures and wind forces, may create small openings through which embers and smoke may encroach upon a structure's interior, leading to its demise.

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