Firebrand Protection as the Key Design Element for Structure Survival during Catastrophic Wildland Fires

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ABSTRACT

In Southern California in particular, fires that destroy large numbers of structures are inevitably catastrophic, wind-driven events. Characteristics of this class of fire include strong gale-force winds, low probability of professional fire intervention, and the presence of wind-driven firebrands before, during, and after the passage of the fire front. Ignition by radiant heat or direct flame exposure can be prevented by separating the structure from fuels, and this practice is being increasingly disseminated and enforced. Protection from firebrands, however, requires that the structure have no potential ignition points where small wind-driven brands can lodge and pilot structure ignition, or that this ignition be somehow prevented.

We present two new results that point to brands as an ignition source. One of these highlights a new potential threat by showing that there is a possible correlation between "Spanish tile", or curved tile roofs, and home ignition, as observed in the Scripps Ranch neighbourhood of San Diego during the Cedar Fire. The other result consists of a case-study of an interface structure that survived the Cedar Fire through the application of light water spray. This system was designed by one of the authors (Mitchell) to be wind-resilient, and previously disclosed[3] as a "Wind-Enabled Ember Dousing System", or WEEDS. This system used much less water than necessary to protect against peak radiant heat, employed techniques that made it resistant to over-dispersal of spray in strong winds, and was designed and implemented in such a way as to make it independent of external utility and water supplies.

INTRODUCTION

Structure loss in Wildland-Urban Interface (WUI) throughout the world due to wildland fire is and will continue to be a major cause of both of life and property loss. The losses throughout the last decade have been great, and there is reason to believe that the factors driving these losses will continue to worsen. Specifically, the construction of habitations that are intermixed with flammable wildlands continues unabated, regardless of risk, and furthermore it is estimated that climate change will increase the length of the growing season, and therefore increase the likelihood of wildland fire[4].

Reducing wildland fire losses, then, requires that suppression of wildland fires become more effective, or that structures, residents, and fire professionals in the wildland areas be equipped and prepared to withstand severe wildland fires. Achieving these goals requires that the structure ignition conditions and mechanisms in the WUI be causally understood, and that these underlying mechanisms be properly addressed. Fortunately, there has been considerable work in this area, allowing us to make some generalizations regarding the ignition mechanisms.

FIREBRANDS AND STRUCTURE IGNITION

The first data collected regarding factors affecting the survival of structures in a major wildland

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[3] Mitchell, Joseph W.; Wind-enabled ember dousing; Fire Safety Journal; 41:444-458; 2006

[4] Westerling, A.L., et al.; Warming and Earlier Spring Increase Western U.S. Forest Wildfire Activity; Science; 313:940-943; 18 Aug 2006

fire was obtained by the Los Angeles Fire Department[5] following the 1961 Bel Air Fire. This data provided definitive evidence that wooden "shake" shingle roofs had a much higher probability of ignition during wildland fire than structures having ignition-resistant roofs. Brand ignition on shake roofs was listed as a leading cause of structure loss.

The Australian Ash Wednesday Fires

Following the Ash Wednesday fires in Australia of 1983, a forensic study[6] was conducted by Caird Ramsay et al. regarding the primary mechanisms by which structures ignite in wildland fires. This consisted of a forensic examination of damaged areas to determine overall ignition rates of threatened structures as well as the causal elements involved in their ignition. The main data collection mechanisms were on-site inspection, examination of building plans, and questionnaires sent to property owners.

The conclusion reached by this study was that the predominant ignition mechanism appeared to be embers, as determined by eyewitness accounts and forensic examination of structures. The structure destruction probability was 54%, and wooden roofs were not a factor. Probability of damage to the structure was 8%.

In summary, the factors that allow the assumption of firebrand ignition that we can inferred from these studies are:

- Ignitions occurring far from the fire front, beyond the reach of significant radiant heat or flame
- Observed ignitions on the roof or in the attic, or on flammable external structural elements such as fences or decks
- Little correlation seen between exterior cladding material and structure survival, except for brick or concrete block exteriors
- Ignitions that occur significantly before, or more likely after the passage of the fire front
- High probability of "self-saves" by modestly equipped civilians. These would not be possible in the aftermath of a flashover structure ignition by intense radiant heat or direct flame contact
- Forensic evidence of partially ignited elements with little or no radiant heat damage to the surviving elements

The Paint Fire, 1990

Following the "Paint" Fire that struck Santa Barbara County in California in 1990, a statistical analysis was performed by Ethan Foote of the University of California at Berkeley.

Data was collected by Foote and a slew of fire investigators from different agencies for threatened and destroyed structures, and it covered dozens of possible causal variables. A multivariate logistic regression analysis was conducted on these variables to ascertain which characteristics were correlated with structure survival during wildland fire. Numerous "shake" roof structures were in the fire area, and as in the previous Bel Air Fire, these showed a very high loss rate when compared with previous fires. The large number of structures lost in this fire allowed a statistically significant sample to be taken (800 structures). There was a 40% survival rate of exposed structures, but a large fraction of destroyed structures had shake roofs, and these drove the statistics.

One less-publicized conclusion was the effectiveness of human intervention during or after the fire, with civilian intervention being at least as if not more effective than professional intervention. Intervention led

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[5] Greenwood, Capt. Harold W.; Bel-Air – Brentwood and Santa Ynez Fires: Worst Fire in the History of Los Angeles; Official Report of the Los Angeles Fire Department; Los Angeles Fire Department Historical Archive; http://www.lafire.com/famous_fires/611106_BelAirFire/110761_belair_LAFDreport.htm

[6] Ramsay, G.C., N.A McArthur,. and V.P. Dowling,; Preliminary results from an examination of house survival in the 16 February 1983 bushfires in Australia. Fire and Materials, 11:49; 1987

to an order of magnitude improvement in the survival odds[7]. Once again, this can be taken as evidence for brand-induced ignition, since ignition by direct flame contact or radiant heating would be expected to affect entire structure fascia, and not to be amenable to attack by poorly equipped civilians.

Vegetation clearance distances in the affected area tended to be small, and a strong correlation of structure survival with vegetation clearance distance was seen. This could be consistent with ignition by radiant heat exposure or flame contact. However, one anomalous and bizarre correlation suggests that this is not necessarily the primary ignition mechanism. It was observed that non-flammable wall cladding had an *inverse* correlation with structure survival. The statistical significance of this result is high (Yule Q = -0.45 ± 0.07)[8]. This suggests that there maybe correlations between some of the variables (such as housing styles, location, or construction period) which would link wall cladding to other variables more likely to be associated with ignition. However, it also makes the hypothesis that structures are primarily ignited by radiant heat or direct flame contact less tenable.

The Oakland Hills (Tunnel) Fire, 1991

The Oakland Hills Fire of 1991 was the most costly single wildland fire in US history in terms of property loss, with losses calculated at $2.1 billion (2004 $US)[9]. Once again, wood-shake shingle roofs were a major contributor to structure loss. Due to the dense construction in the area, this fire progressed more as an urban conflagration, with structure-to-structure ignition playing a large role[10]. Hence, external cladding of structures took on a much larger role in structure survival in this fire, since separation from external fuels was not possible.

Canberra fires, 2003

Keping Chen and John McAneney[11] did an analysis of the 2003 Como-Jennali and Duffy (Canberra) fires. The methodology for this study was to use satellite photos of the affected areas before and after the fires and to determine the probability of structure survival as a function of distance from the forest boundary. The distance corresponding to a 50% survival rate for these fires was 145m and 45m, respectively. This distance is far too great to allow the possibility that direct flame or radiant heat were the causes of ignition, and the conclusion reached was that most structure ignition was due to wind-driven firebrands.

Analyses by fire scientists[12,13] that span these and other fires, as well as laboratory experiments have also concluded that firebrands are a leading cause of structure ignition. There has been little published data so far from the 2003 California Fire Siege. However, some new data highlights an undocumented structure vulnerability and further implicates firebrands.

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[7] Foote, E.I.D.; Structure survival on the 1990 Santa Barbara “Paint” fire: A retrospective study of urban-wildland interface fire hazard mitigation factors. MS thesis, University of California at Berkeley, p. 129; 1994

[8] Ibid., p. 97

[9] National Fire Protection Association; Research Report “25 largest fire losses in U.S. history (in 2004 dollars)”; http://www.nfpa.org/itemDetail.asp?categoryID=954&itemID=23352&URL=Research%20&%20Reports/Fire%20statistics/Deadliest/large-loss%20fires

[10] National Fire Protection Association; Fire Investigations; Oakland/Berkeley Hills Fire, Oakland/Berkeley CA; October 21, 1990

[11] Chen, Keping and John McAneney; Quantifying bushfire penetration into urban areas in Australia; Geophys. Res. Lett. 31:L12212; 2004

[12] Cohen, Jack D.; Preventing disaster: home ignitability in the wildland-urban interface; Journal of Forestry 98(3):15-21; 2000

[13] McArthur, N.A. and P. Lutton; 1991; Ignition of exterior building details in bushfires: An experimental study; Fire and Materials; 15:59-64

ROOFING MATERIAL RESULTS FROM THE CEDAR FIRE

This section looks at the correlation between roof type and house survival during the October 2003 Cedar Fire in the Loire Valley, Phase 1 (LVP1) neighborhood of Scripps Ranch, in the City of San Diego. LVP1 turned out to be a nice neighborhood for statistical study, because it had a mix of destroyed and surviving houses -- there are no meaningful statistics in neighborhoods with all houses destroyed (a floor effect), or no houses destroyed (a ceiling effect). The two-part conclusion is that (a) houses with a wood-shake shingle roof did poorly, confirming old results, but also that (b) houses with a Spanish curved-tile roof fared significantly worse than houses with a newer, fire-resistant roof, which is a novel published result[14].

The Cedar Fire hit LVP1 quickly, about 8:00 Sunday morning, October 26, 2003, roughly 15 1/2 hours (including an hour for the Daylight Saving Time change) after its late-afternoon start about 22 miles away, near Cedar Creek between Ramona and Julian. Driven by strong Santa Ana winds, it forced residents to evacuate with little or no notice. When residents were allowed to return, about 54 hours after evacuation, 28 of 68 houses (41%) had been destroyed. Additionally, many of the houses that survived sustained tens of thousands of dollars of smoke damage, much of it due to open windows and chimney flues.

It was evident that a house's having a wood-shake shingle roof was a very good predictor of whether it survived. To document that observation, two residents, Amy and Oren Patashnik (a computer scientist/mathematician), on Sunday, November 16, 2003, walked through the entire neighborhood, gathering the data used in this section. Each house was classified by roof type: wood-shake shingle (W), curved tile (CT), stone-covered steel (S), flat-tile/concrete (FT), or tar-paper/no-roof (T). Note: "curved tile" is also known as, among other things, Spanish style, Mexican style, and Mediterranean style; this section uses the more descriptive "curved tile" (Figure 1).

The houses in LVP1 were built starting in 1981 and first occupied in 1982 and 1983, so were over 20 years old when the fire hit. Initially, 22 of the 68 had curved-tile roofs; the remaining 46 had wood-shake shingle roofs. During the 6 years or so preceding the fire, 33 of the 46 wood roofs had been converted to fire-resistant roofs: either flat-tile/concrete or stone-covered steel. One of the 33 (the tar-paper roof) was still in the process of conversion when the fire hit – it survived. (The last page of a preliminary report on these Cedar Fire roof statistics[15] gives the roof type, general location, and survival status of each of the 68 houses in LVP1.)

Table 1 breaks down by roof type the 28 of 68 houses destroyed (all LPV1 column). The most obvious conclusion is that all houses with wood-shake shingle roofs in LVP1were destroyed. And that conclusion is very statistically significant: The probability that 28 houses chosen at random from among 68 would include all 13 W houses is given by

$p = \binom{13}{13}\binom{55}{15} \Big/ \binom{68}{28}$ which is about 0.0000012.

All probabilities in this section come from a formula like the one below, which is a sum over the tail of a hypergeometric distribution:

$$p = \sum_{k=0}^{m} \frac{\binom{t}{k}\binom{n-t}{s-k}}{\binom{n}{s}} \qquad [1]$$

Here n is the number of houses in a population N under consideration, t is the number of houses of type T

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[14] Anecdotes involving curved tile roofs are noted in an unpublished U.C. Berkeley report used to support the funding of the analysis contained in the Foote thesis (Foote, E.).

[15] Patashnik, Oren; http://www.scrippsranch.org/special/FireDocuments/RoofDamageReport.pdf

(for example, W houses) within *N*, and *s* in the number of houses in a subset *S* of *N* -- where *S* will be either the surviving or the destroyed houses within *N*, determined from context. Then *p* computes the exact probability, in a randomly chosen subset *S* of *N* of size *s*, that *S* contains at most *m* houses of type *T*. This is inherently a one-tailed probability – here the left tail. The corresponding right-tail range of summation is $m <= k <= t$, to compute the probability that the randomly chosen *S* contains *at least m* houses of type *T*. In the example above, *N* is all LVP1 houses, *S* is all destroyed houses, *T* is the W houses, and we have n=68, s=28, t=13, and the range of summation is the right tail 13<=k<=13.

Table 1 gives the statistics for LVP1 as a whole. But LVP1 actually consists of two loops -- a front loop and a back loop, connected by Rue Finisterre. Several residents/firefighters indicated that the firefighters, during the initial firestorm, made their stand where the front loop meets Rue Finisterre, because it was too hazardous to go into the back loop. Thus they devoted most of their resources to the front loop, so it makes sense to analyze the two loops separately (Table 1, last two columns). The boundary between the two loops is along that Finisterre connection, at the farthest reach of firefighter protection during the initial firestorm.

Table 1. Houses destroyed, by loop

	All LVP1	Front loop	Back loop
wood-shake shingle (W)	13/13	2/2	11/11
curved tile (CT)	10/22	0/7	10/15
stone-covered steel (S)	5/19	0/4	5/15
flat-tile/concrete (FT)	0/13	0/11	0/2
tar-paper/no-roof (T)	0/1	0/1	0/0
total	28/68 (41%)	2/25 (8%)	26/43 (60%)

This table shows the fraction of (destroyed/total houses) for each roof type in the Loire Valley Phase 1 neighborhood (LVP1). Columns indicate all houses in sample and also divided into areas that received (front loop) and did not receive (back loop) firefighter protection during the initial firestorm.

Two comments regarding wood-shake shingles (W) are in order here. First: The poor W-house survival throughout LVP1 is so statistically significant (even in the front loop, with just two W houses, *p* is about 0.0033) that the rest of the section spends no further time analyzing the W data. Additionally, any analysis would merely reproduce known results. (LVP1 isn't the only area of Scripps Ranch in which the W houses did badly; for example on nearby Grainwood Way, where there was a 100% correlation between wood roofs and house destruction: of 22 houses on Grainwood Way, all 20 W houses were destroyed, while both non-W houses survived.) And second: Firefighters generally consider a W roof to be a bad roof, so in some sense their poor survival is partly a self-fulfilling prophecy. When firefighters have limited resources, they will concentrate their efforts on saving houses they think have a better chance of survival. But there is no such bias against, for example, the CT roofs ("that's a good roof" according to one LVP1 firefighter), so firefighter bias doesn't explain any poor CT survival.

The third column of Table 1 shows that in the firefighter-protected front loop all houses were saved except for the two W houses. Thus there's no statistical difference among the non-W houses' front-loop survival, due to a ceiling effect (all such houses survived). Incidentally, it might appear in the “All LVP1” column of Table 1 that there is a difference between S and FT survival; but after the front-loop ceiling effect of Table 1 is stripped away, leaving just the data in the back-loop column, there is no statistical significance – the 5/15 destruction rate for the S houses is not significantly different from the 0/2 destruction rate for the FT houses (*p* is 0.49). So there is no evidence of a survival difference between stone-covered steel (S) and flat-tile/concrete (FT) houses in LVP1, and the rest of this section combines them into a single S/FT category.

In the back loop, 10 of the 15 CT houses (67%) were destroyed, whereas only 5 of the 17 S/FT (29%) were; and that's moderately statistically significant (*p* about 0.039). But the difference between the CT and S/FT survival is more pronounced when viewed a little differently. The main idea is that the performance difference between the houses that do well and those that do poorly shows the most in those houses that were most in harm's way – houses presumably facing higher firebrand densities and also greater exposure to radiant heat, convective heat, and flame.

The next two analyses use two different methods to examine the data with that idea in mind. One method looks at the area of the neighborhood with the most destruction, to see what houses in that area were left standing. In the back loop, hardest hit was an area herein called the "semi-ring of fire" – about half the outer perimeter of the back loop. It's characterized by proximity to large, open-space hillsides and also to Pinecastle, which was the hardest-hit street in Scripps Ranch, with 46 of 47 houses destroyed. (The last-known resident to leave the back loop says that the worst part of the firestorm came from the Pinecastle area; it was a "50-foot-plus cascade of hot air and embers that felt like it was sucking the oxygen out of the air.") Of the 22 houses in the semi-ring of fire, only 4 survived – all S/FT houses (in fact, all S houses). Not a single CT house survived

When considering just the 16 S/FT and CT houses, this is only moderately statistically significant (*p* about 0.038), because the sample size is getting too small.

Table 2. Back loop houses (destroyed/total)

	SRF	Extreme
wood-shake shingle (W)	6/6 (100%)	11/11 (100%)
curved tile (CT)	8/8 (100%)	10/11 (89%)
stone-covered steel (S)	4/8 (50%)	5/13 (38%)
total	18/22 (82%)	26/35 (74%)

This table shows a breakdown of the SRF "semi-ring of fire" (most affected area) houses and the "Extreme" exposure sample (adjacent destroyed home).

The second method for looking at houses in harm's way has a bigger sample size, giving better statistical significance. The idea is simple: A house has extreme exposure if a house next to it is burning. (When the houses in LVP1 were built, the building codes required just a 5-foot setback; that is, the house proper had to be at least 5 feet from the property line, although the eaves could extend closer. Therefore many of the houses in LVP1 were just 10 feet away from each other, with their eaves often just 5 feet apart. Building codes now require at least a 6-foot setback.) So a house is defined to have *extreme exposure* if one or more adjacent houses were destroyed, where two houses are *adjacent* if they share a property line and that line is (roughly) perpendicular to a street they're both on.

By this definition, each house in LVP1 was adjacent to either one or two other houses. The last column in Table 2 gives the destruction data for all extreme-exposure houses in the back loop.

The CT houses performed significantly worse than the S/FT houses, with

$$p=\frac{\binom{11}{0}\binom{13}{9}+\binom{11}{1}\binom{13}{8}}{\binom{24}{9}}$$

which is about 0.011, and the CT houses did not perform significantly better than the W houses, with $p = .5$, due to a floor effect.

So the general conclusion from Table 2 is that, in the extreme parts of the neighborhood, the houses with a newer, fire-resistant roof did better than the houses with a curved-tile roof, while the curved-tile houses showed no significant difference from the houses with a wood-shake shingle roof, due to a floor effect.

The results of this section suggest that future fire analyses separate Spanish/curved-tile roofs from other roofs currently in the category of fire-resistant roofs. They also suggest that there be an effort to understand the poor behavior of the CT houses. Unfortunately, we don't know the source of ignition for any destroyed house in LVP1. We do know the source, however, for one house in an adjoining neighborhood

(Chantemar). That house had a CT roof, and was one of the first houses in Scripps Ranch to start burning, so received immediate firefighter attention and was ultimately saved. The resident observed that it started burning in two places: in an attic air vent facing a canyon, and at the junction of two beams near the apex of the roof, where there were gaps in the curved tiles. So for that house we do know that the curved-tile roof was implicated in the ignition.

It's also worth examining the current status of the CT roofs in LVP1. These roofs are now 25 years old and therefore maintenance is an issue. Many have cracked tiles, missing or dislodged "birdstops", and gaps between tiles that small firebrands could infiltrate. Figure 1, a picture taken in November 2006, shows one such LVP1 roof. Notice in particular the sizeable gap behind the farthest birdstop, easily big enough to allow firebrand entry. One such birdstop in a different part of that roof was found earlier this year to be harboring a bird's nest. In general the gaps can be significant.

Figure 1. Curved Tile Roof

This figure illustrates the firebrand vulnerabilities introduced by poor construction or maintenance of curved tile roofs. Note the missing and displaced "birdstops" that provide an entry path for firebrands.

Although it's hard to know for sure that the curved tiles contributed to house destruction in LVP1, since other variables like style and period of construction could conceivably be involved, the statistics in this section, along with the tiles' current condition, certainly suggest a curved-tile role. If further studies corroborate the results here, and if the curved tiles are shown to be a factor, then it stands to reason that if curved-tile roofs require a tar-paper underlayment for water protection they should also require analogous protection for wind-blown firebrands that can infiltrate the gaps during a firestorm like the one that struck Loire Valley, Phase 1.

FIREBRAND DEFENSE

There are three approaches to preventing firebrand-induced structure ignition:

1. Prevent the entry of firebrands into the structure
2. Remove all flammable materials on or in the immediate vicinity of the structure
3. Extinguish the live embers before they can pilot ignition of the structure

The first two remove ignition points from the structure, while the third reduces the ember density at the structure. Current building codes, guidelines and recommendations for preventing firebrand ignition fall into the first two categories. Measures requiring wire mesh over vents, requiring tempered or double-paned glass in windows, or sealing of gaps under roof tiles all are aimed at preventing ember entry into the structure. Reducing exterior flammability is usually divided into two parts: flammability of external components (decks, roofs, and fences) and flammability of the surrounding landscape (type, density, and placement of vegetation around the structure). Having non-flammable external facia and additions is one way of reducing firebrand ignitions, while planting & proper maintenance of relatively inflammable vegetation is another. Many American and Australian sources provide detailed guidelines – for instance see Ramsay & Rudolph[16]. An example of firebrand defense being incorporated into building code can be found in the 2005 Wildland-Urban Interface code from the California Office of the State Fire Marshal[17]. As California State Fire Marshal Ruben Grijalva states in the letter announcing adoption of the code changes:

> *"The main components of these regulations address all types of exposure, but focus primarily on preventing ember-caused ignition loss. They do not require fire-resistive construction, but rather ignition-resistant construction is utilized. This is a new paradigm that uses mostly existing materials and methodologies for construction."*[18]

Structural solutions are sound, but there are two reasons that they are not a panacea for the wildland-urban interface structure loss problem. The first is that they are dependent on proper design, construction, inspection, and maintenance. Failure in any of these can lead to the introduction of ignition points and the potential for structure loss. During the Cedar Fire, for instance, recently constructed homes following the most current building standards and brush clearance requirements were still lost at a significant rate in severely-impacted areas. The testimony of one homeowner[19] who thought that he had a fire-safe house makes this point most poignantly:

> "*What effort did I take before the fire? It was a new home there were no vents on the east side of the house. The eves were entirely stucco, tile roof, I had the vents in the roof plugged on the east side of the house in case any hot gases got into that house from the windward side of the house. I grew the groundcover which worked, it got singed but it's still there, it's alive. The fire did not reach my house…*
>
> *I've grown up in California, I know what Santa Ana winds are, I know what fires are. The architect came back from a trip that next week and my wife, a realtor, wanted to take him on a tour to show him what happened and his comment was, I know one house that didn't burn, it was my house. She said when they got there his jaw hit the floor because everything was done to protect that house from fires."*

The second reason that structural solutions are difficult to implement is that structures currently built and at risk may require significant modifications to the structure. These may be too expensive for homeowners, too invasive, or may result in aesthetic changes to the structure that homeowners find unacceptable.

The third strategy, extinguishment of the brands before they can ignite the structure, can be implemented either by

1. Extinguishment of the brands and induced spot fires by firefighter actions.
2. Extinguishment of the brands and induced spot fires by civilian actions.
3. Extinguishment of brands and wetting of fuels by automated spray systems.

The first is accepted by fire agencies, but in the case of a massive wind-driven wildland fire completely impractical. Neither of the latter two is favoured by fire agencies in the United States. The second, civilian self-saves, has become accepted practice in many Australian jurisdictions, and as mentioned in an earlier section, leads to significantly lower structure loss rates. However, it is not currently (with rare exceptions) favoured by American fire services, who recommend that all civilians leave the area of the wildland fire so

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[16] Ramsay, Caird and Lisle Rudolph; Landscape and Building Design for Bushfire Areas; CSIRO Publishing; Collingwood, VIC; 2003

[17] Department of Forestry & Fire Protection; Office of the State Fire Marshal; Phase II - Emergency Express Terms for the WUI-2001 CBC-Chapter 7A; August 2005

[18] Grijalva, Ruben; 2005; Open Letter to the California Fire Service, "Wildland Urban Interface Building Standards Approved": California Office of the State Fire Marshal; September 22, 2005; http://osfm.fire.ca.gov/pdf/firemarshal/wuibldgstdsapproved.pdf

[19] Ramona Municipal Water District Cedar Fire Hearings, January 2004; http://www.musseygraderoad.org/CedarFire/CedarIndex.htm; also available in original audio format from the Ramona Municipal Water District, 105 Earlham Rd., P.O. Box 1829, Ramona, CA 92065

as not to complicate firefighting activities.

The third method – automated spray systems – is not currently supported by most fire agencies. However, new information, and some historical results, argue that this should be re-evaluated.

Water Spray Systems

Using water a spray system as part of a wildland fire defense strategy is not a new idea. There are numerous patents for various types of water spray systems, and a small industry that sells external structural spray systems. However, to date this method is not widely accepted by fire agencies. A number of arguments are generally used against approval of such systems[20,21]:

1. Sprayers are often arrayed on rooftops, which is pointless for non-flammable roofs.
2. Large volumes of water are necessary, particularly if "fire-flow" levels of thermal protection are required.
3. Spray will be dispersed in the high winds associated with destructive fire events, and leave the most vulnerable fascia exposed in the direction of brand arrival.
4. Municipal water and electric supplies are not dependable during a fire event.
5. Area sprayers decrease in effectiveness as $1/R^2$, with R being the throw range.

Water application methods that minimize these effects are under study in Australia[22]. The most recent studies suggest that a water-drip method is the most effective at protecting the structure with minimal water loss due to wind.

As discussed in the cited previous work by one of the authors, the counter-arguments are applicable for thermal protection of a structure from radiant heat or flame impingement, but much less so if only firebrand protection is required. There are three ways in which sprayer systems can protect from firebrands:

- If the density of spray is high enough, the brands will be extinguished directly.
- Water will accumulate in pools on all flat surfaces on or adjacent to the structure. Embers falling or rolling into these areas will be extinguished.
- Spray and vapor will hydrate light fuels, making them resistant to ignition.

Water Spray Results from the Paint Fire

As noted previously, the Foote thesis demonstrated significant correlations of structure survival with non-flammable roofs and brush clearance. It also reified Australian claims of a very strong correlation between defensive actions taken by structure occupants and structure survival. A result was also obtained for the effect of water spray systems on structure survival. The study was not specific enough to distinguish among various fire protection systems nor between designed fire protection systems and landscape sprinklers turnedon for protection[23]. However, the results still clearly demonstrate that in addition to non-flammable roofing and vegetation clearance, sprinkler system use was also strongly correlated with increased building survival. It is also worth noting that use of a water spray system was subsumed under the superset of 'civilian water application', which showed one of the strongest statistical correlations with structure survival.

The reason that the sprinkler result was less dramatic or significant than the other results is that the cut-off for significance in Foote's study was 95% confidence level. Due to the small number of structures equipped with spray systems, it was not possible to achieve this level of certainty (the results *would* have been deemed significant at the 90% confidence level). The results for sprayers running before, during, and

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20 International Code Council, Inc. 2003 International Urban-Wildland Interface Code; ISBN 1-892395-70-3 (soft); ISBN 1-892395-88-6 (e-document); 2003 (ICC 2003)

21 Fire Protection Association of Australia; Field Study: External Water Spray Systems to Aid Building Protection from Wildfire; Ref: 100-0346; 10 June 2000

22 Ibid.

23 Foote, p. 128

after the fire front are shown in Table 3.

One interesting observation is that there was no notable correlation with structure survival when the sprayers were operated only before the fire. This is in accordance with eyewitness observations that most ignitions occur after, rather than during or before, the arrival of the fire front[24].

Table 3. Sprinkler Data from the Paint Fire (from Foote[25])

	Destroyed	Survived	Total	Probability	Yule Q
Structures without sprinklers	32	148	180		
Sprinklers before fire	4	17	21	0.89	-0.04
Sprinklers during fire	1	37	38	0.01	0.78
Sprinklers after fire	1	33	34	0.01	0.75

Another interesting conclusion can be obtained from Foote's multivariate analysis of the data[26]. It does not seem that the improvement of the survival odds due to sprinklers was correlated with whether or not the structures had a flammable roof. Hence, a suggestion that the sprinklers enhanced survival only for structures with flammable external fascia such as roofing would not be supported. The improvement of survival odds was approximately a factor of 6-8. However, statistical variations commensurate with a 95% confidence level allow this range to vary from 54 down to (slightly) less than 1.0. Because 1.0 (null result) fell within this range, the result was not deemed significant at the 95% confidence level. This is, however, an inevitable result when only a small number of systems are in service.

Wind-Enabled Ember Dousing (WEEDS)

In a previous paper[27], one of the authors proposed a wind-resilient spray system specifically designed to reduce the threat of ember ignition during wind-driven wildland fires. The basic principle is quite simple, and has been placed into public domain: If the spray is directed outwards from the structure, the wind will blow it back onto the structure. Furthermore, spray will tend to accumulate in the same areas that embers will tend to fall, pre-wetting flammable materials and creating pools of standing water.

The key features of this system that circumvent the shortcomings of previous water-spray systems include:

- Wind resilience is achieved by outward direction of the spray.
- An operational lifetime of three to four hours has been achieved with a 5000 gallon (19,000 liter) reservoir, which is a commercial size in common use in the US.
- Agricultural/landscaping irrigation spray heads reduce water consumption (as compared to sprinklers specifically designed for fire suppression).
- A coarse spray is used, which allows better penetration into a headwind.
- A backup system to provide electrical power automatically in the event of power loss was included.

A photo of the system in operation is shown in Figure 2.

The support systems required to supply water under realistic wildland fire conditions are shown in Figure 3.

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[24] RMWD hearings.

[25] Foote; p. 262

[26] Foote; pp. 129-131

[27] Joseph W. Mitchell, 2006

Figure 2. WEEDS in operation

Photo of the WEEDS sprinkler system in operation. 32 nozzles delivering about 4 liters per minute each are directed away from the structure. Photo by Nanette Martin (www.nanettemartin.com).

Figure 3. WEEDS support systems

Supply and backup systems for WEEDS include from left to right a 12 kW generator, a 5000 gallon (21 k liter) storage tank, a pump, pressure tank, and propane supply.

This system was constructed in 2002, and all backup systems were installed by October 24, 2003. On October 26, 2003, the Cedar fire overran the property. The system was activated prior to evacuation, and all systems performed well. The structure survived the fire, whereas all adjacent properties lost structures. The structure is in a corridor that was deemed hazardous to fire personnel, and no professional fire support was made available until the day after the fire front had passed through. This area suffered a 60% structure loss rate, despite the absence of flammable roofing as a contributing factor.

A post-hoc analysis of the spray system was performed to determine whether the spray densities it generated are sufficient to douse embers. Reviews of experiments that collected data on water spray extinguishment of cribs were done by Novozhilov et al[28]. and by Grant et al.[29]. These indicate that the water spray density required to extinguish a burning crib is in the range of 1.5 to 5 gm/m^2-sec. To determine whether the WEEDS installation was able to produce spray densities in this range, a simple modelling was performed.

The equation of motion for a spherical droplet in a headwind is given by[30]:

$$\frac{\partial}{\partial t}\left(m_d \vec{u}_d\right) = m_d \vec{g} - \rho C_d A_d \left(\vec{u}_d - \vec{u}_w^{\,e}\right)\left|\vec{u}_d - \vec{u}_w^{\,e}\right| \qquad [2]$$

Where

C_d : The drag coefficient

m_d : The mass of the droplet

A_d : The cross-sectional area of the droplet

$\vec{g}$: The gravitational constant

ρ : Density of the water droplet (1000 kg/m^3)

$\vec{u}_d$: Droplet velocity

$\vec{u}_w^{\,e}$: Effective wind velocity near structure

The drag coefficient is obtained from the relation[31]

$$C_d = \frac{4gd(\rho - \rho_{air})}{3\rho_{air} u_t^{\,2}} \quad (u_t \text{ is terminal velocity}) \qquad [3]$$

A simple computer model was used to propagate water droplets using a conical annular spray pattern and assuming a droplet size distribution similar to other agricultural spray heads[32]. This model demonstrated that the spray densities achievable given the water usage of the constructed WEEDS system are sufficient to extinguish firebrands. They also indicated that the system will be wind-resilient (i.e. no gaps between spray patterns) at least to a wind speed of 50-60 km/hr. This is a conservative estimate, however, since no attempt was made to model the aerodynamic drag around the structure, which reduces the effective velocity in its immediate vicinity. The modelled spray pattern on the wall of a structure for a wind speed of 20 km/hr is shown in Figure 4.

DISCUSSION

Examination of the historical record of wildland fires reveals that firebrands play a key role in the ignition of structures. Restricting firebrand entry, removing ignition points, and extinguishing embers are methods that can be used to significantly reduce structure loss rates on the WUI.

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[28] Novozhilov, V., et al.; Solid fire extinguishment by a water spray; Fire Safety Journal 32; (1999) 119–135

[29] Grant, G., J. Brenton, and D. Drysdale; 2000; Fire suppression by water sprays; Progress in Energy and Combustion Science; 26: 79-130

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[31] Clift, R., Grace, J.R. and Weber, M.E.; Bubbles, Drops and Particles; Academic Press, New York; Figure 5.14; 1978

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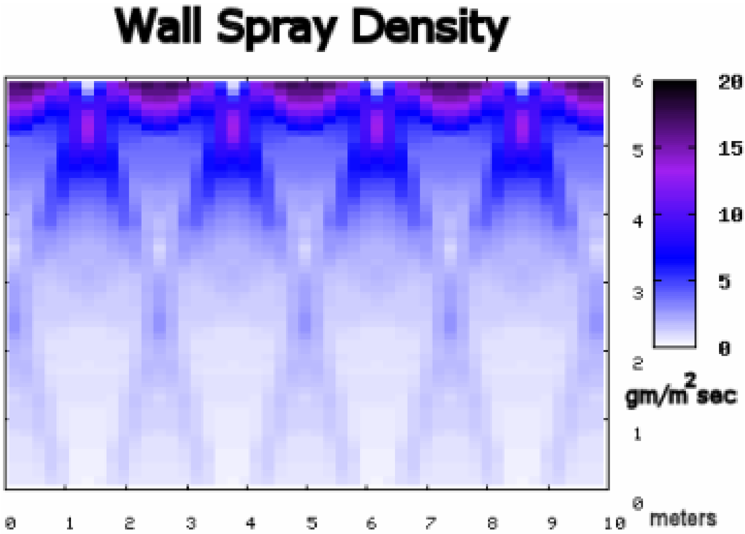
Figure 4.



Calculated spray density on the wall of a structure for an effective wind speed of 20 km/hr.

It is important to differentiate situations where radiant heat and flame impingement contribute more heavily to structure ignition:

- Structures in suburban or urban neighborhoods, where homes are within 10 meters of each other. House-to-house ignition is common under these conditions.
- Structures surrounded by vegetation
- Structures in forests where crown fires may occur.

The common point of all these situations is that there are flammable materials near enough to the structure to cause significant radiant heating or allow flame impingement. Additional protective measures that deal with the particular threat presented need to be taken in order to reduce the risk of structure loss.

Being able to accurately gauge the effectiveness of any protective measures will require that the collection of data be improved. Examination of structures is currently a forensic activity, which has meant that destroyed structures have dominated statistics. Where “threatened” structures are included, the definition of “threatened” is subjective if included at all. One useful technique in future fires would be to rapidly identify and uniformly investigate neighborhoods that were “triaged-out” by fire services as presenting too high a risk for direct intervention by fire personnel. Inherent fire-resistance and civilian actions will be the sole determinants of structure survival in these areas, making data from them particularly useful. Another change strongly suggested by this paper’s results is that curved tile roofs be broken out into their own category for future analyses. They were strongly correlated with an elevated probability of home loss, and only more data can delineate whether this can be or is usually mitigated by proper construction and maintenance. It is also important when evaluating statistics to realize that correlation does not necessarily imply causation. Measured factors are not independent of each other. For instance, some WUI residents are more “fire wise” than others, and it is to be expected that preventative measures may be performed as a cluster of related activities by such residents. Also, the location, period and style of construction will often inject correlations between structure characteristics.

Water spray systems should also be re-evaluated, at least in cases where a reliable independent water reservoir is available (especially gravity-fed) and where there is likely to be someone available to activate the system. The lack of corroborating data for sprinklers is currently due to the comparative rarity of such systems, rather than any non-performance. One property of water spray systems found by the Paint Fire analysis is that they are most effective when they are operated during or after the fire passes and this illuminates a key weakness of such systems: activation. Ideally, the system should be activated as close to the arrival of the fire as possible in order to get the maximum overlap of the system lifetime and the threat period. This encourages late evacuation. Furthermore, many structures in some areas are unoccupied for a substantial fraction of the year, and these would have no one available to activate a protective system. The possibility of either remote or automatic activation is under study within the commercial sector. Either one comes with problems. Effective remote activation requires that the person initiating activation of the system will have accurate knowledge of a fire's location and movement. This is rarely the case during catastrophic fires given the current state of remote detection technologies. Furthermore, communication grids are often knocked out during catastrophes. Automatic systems must be capable of differentiating legitimate threats from false triggers (such as the neighbor's barbecue grill). Additionally, the system may be under threat from embers well before the main fire front arrives and current systems are not sensitive enough to detect such a threat.

The water-spray activation problem is not an issue, though, for those civilians who decide to shelter within their structure. While strongly recommended by many Australian fire agencies, this is only rarely viewed as an option by American fire services. The data is extraordinarily clear that civilian actions greatly enhance structure survival. What is still necessary is more information on civilian injuries, medical incidents, and casualties during such actions. This needs to be compared to the death and injury rate due to evacuation, especially the last-minute evacuations typical of the American fire scene. In any case, a water spray system would provide added protection to anyone choosing to remain with their homes during a wildland fire.

Finally, it must be remembered that designing for firebrands means designing for high wind. No technique or construction can be considered protective against wildland fire unless it works under high-wind conditions.

CONCLUSION

Obtaining substantial reductions in structure loss rates within the wildland-urban interface requires that the primary causes of structure ignition be discovered and that these be addressed. Historically, flammable roofs and vegetation adjacent to the structure have been demonstrated to be correlated strongly with structure loss. As these have been addressed, the remaining problem of firebrand-induced ignition has become more evident. Addressing this threat requires new techniques and research. Among possibilities, the introduction of wind-resilient water spray defense (where water is available) needs to be re-evaluated, based on historical statistics, case studies, and theoretical analysis of spray patterns and extinguishing capability. These analyses suggest that water spray systems may join vegetation clearance and structural solutions as a valuable tool in WUI structure protection. Regardless of method chosen, however, preventing firebrand-induced ignitions is the next “big win” in the Wildland Urban Interface.

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