CHARACTERIZING FIREBRAND EXPOSURE DURING WILDLAND-URBAN INTERFACE FIRES

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ABSTRACT

This study examines the size distribution and other characteristics of firebrand exposure during the 2007 Angora Fire, a severe Wildland-Urban Interface (WUI) fire in California. Of the 401 houses that received direct interface fire exposure 61% were destroyed and 30% did not burn at all. The ignition of buildings by wind-blown embers, known as firebrands, and the starting of "spot fires" in unburned vegetation ahead of wildfires has been observed for centuries and studied extensively for decades. However, it is not yet possible to empirically quantify the exposure severity or describe how many firebrands of what size and over what duration and distance are causing ignition problems of concern. A seemingly rare opportunity to gather empirical firebrand data from an actual interface fire evolved in the days immediately following the Angora Fire. Firebrand size distributions are reported and compared to firebrand size distributions from experimental firebrand generation in both recent laboratory building ignition studies conducted by National Institute of Standards and Technology (NIST) and from historical firebrand field studies. Such data is needed to form the basis of effective and appropriate interface fire hazard mitigation measures as well as modeling fire spread. Comparisons are made to current wildfire protection building construction regulations and test standards. The most salient results of this study are the documentation of the consistently small size of firebrands and the close correlation of these results with the sizes of experimentally generated firebrands.

INTRODUCTION AND BACKGROUND

The quantitative results of this study are brief and narrowly focused on the sizes of firebrands (embers) lofted from burning vegetation and/or burning buildings, transported ahead of the propagating fire, and deposited on unburned fuel with some potential for igniting a new fire. This firebrand and spot fire phenomenon has been studied extensively and identified as an important fire spread mechanism for a number of "fire problems."[1,2] One reason for conducting this investigation is similarly brief, it was identified as a specific work item in a Governor's Blue Ribbon Fire Commission Task Force Report on disastrous interface fires in California.[3] There is, however, a broader context to the quantitative results that warrants a broader discussion. While the topic of firebrand ignition mechanisms in general, and the phenomenology of interface fire spread in particular, has been extensively studied, the problem of disastrous interface fire losses is widely perceived to be getting increasingly worse.

To the extent that reduced interface fire loss is a desirable end product of fire investigations, studies should be clearly linked to the context and solution of a well identified fire problem. Firebrands have been observed in a wide range of fire problems. Firebrand ignition of "fire proof" buildings has been reported after the 1906 San Francisco earthquake[4] and following the nuclear attack on Hiroshima.[5] The problem of wildfire spreading to readily ignitable buildings has been specifically described for over a hundred years with thousands of buildings destroyed. Building loss on wildfires is a fire problem that has historically received a plethora of labels leading to confusion about the nature of the problem.[6] This problem has more recently been consistently and widely referred to as the "Wildland-Urban Interface." However, the term "Wildland-Urban Interface" has a wide range of definitions including geographical descriptions of areas having a close proximity of vegetation to buildings with no history of large interface fires (nor any clearly identified risk of conflagrations).[7]

The Wildland-Urban Interface can be defined simply in terms of fire spread mechanisms that provide clear paths to hazard mitigation solutions. Butler (1974) coined the "fire interface" terminology in publishing the first comprehensive description of wildfire related disastrous building loss as specific fire problem.[8] From a fire-loss reduction context, the interface fire problem can be most effectively defined as a sequence of factors; 1) exterior vegetation fire exposure during extreme weather conditions with, 2) rapid fire spread to many readily ignitable buildings, 3) overwhelming fire protection resource, 4) resulting in disastrous losses of buildings. For the characterization of firebrand exposure to meaningfully contribute to reduced interface fire losses, it must be directly related to the context and dominant ignition mechanisms of interface fire spread, as Cohen (2000) did for crown fire exposure.[9] For example, studies of very large firebrands or firebrand ignition of lumber at standard fuel moisture content (e.g. 12%) may contribute very little to fire loss reductions if the majority of buildings are ignited by very small firebrands under extreme weather conditions with very low fuel moisture. Conversely, identifying and expending limited hazard mitigation resources on specific building ignition mechanisms, even those involving very small firebrands under extreme conditions, may not be effective in reducing disastrous losses if the specified ignition mechanism is very rare or is overshadowed by other factors.

There is substantial fire research to support the widely held observation that firebrand exposure has a significant role in the spread of disastrous interface fires[10]. Every multivariate retrospective study of interface fire building survival indicates firebrand exposure as a problem and those involving wood roofing have found a statistical correlation between wood roofing and increased building loss.[11,12,13,14] The most recent of these studies (1990 Santa Barbara Paint fire) found that for buildings without evidence of fire suppression, there was an 82% increase in the proportion of buildings surviving the fire where houses had: 1) a non-flammable roof and; 2) at least 10 m (30 ft) of brush clearance. The statistical analysis revealed that these two factors were mutually and independently associated with building survival and accounted for 59% of the variability in building survival on that fire.[15] It has been widely reported that firebrand exposure is a dominate fire spread mechanism in wood roof conflagrations which implies empirical support that firebrand exposure exists to some extent during interface fires with or without the wood roof factor being present.

Recent building ignition modeling, full-scale crown fire exposure experiments, and case studies indicate that radiant heat transfer from forest fires is significantly less important as an interface fire building-ignition mechanism than previously assumed. There is limited but growing experimental evidence for firebrand exposure as an ignition mechanism of buildings not involving wood roofing.[16] Observational studies have long identified a building ignition mechanism where very small firebrands penetrate under non-combustible tile roof covering to ignite the building.[17,18] Recent full-scale firebrand exposure investigations of building ignition provided experimental confirmation of this ignition mechanism.[19] This work utilized an experimental apparatus recently developed by Manzello *et al.* known as the NIST Firebrand Generator (NIST Dragon) used to investigate ignition vulnerabilities of structures to firebrand exposure. The NIST Dragon is able to generate a controlled and repeatable size and mass distribution of glowing firebrands. The experimental results generated from the marriage of the NIST Dragon to the Building Research Institute's (BRI) Fire Research Wind Tunnel Facility (FRWTF) have uncovered the vulnerabilities that structures possess to firebrand showers for the first time.[20,21,22] These detailed experimental findings are being considered as a basis for performance-based building standards with the intent of making structures more resistant to firebrand attack. The substantial public interest in this issue was illustrated during the recent triennial amendments to the International Building Code by the California Building Standards Commission. The issue of firebrand size and related building ignition mechanisms on interface fires received more public comments and Office of the State Fire Marshal agency response than any other issue during final consideration of the fire and life safety provisions for adoption of the 2010 California Building Code.[23] The firebrand size distributions developed from the Angora Fire are believed to be the first such data from an interface fire. These results together with the experimental work from NIST provide additional steps toward characterizing interface firebrand exposure.

Angora Fire Study Area, Weather, Fuels and Interface Fire Exposure

The Angora Fire started in a stand of dense unmanaged conifer forest located at the south end of Lake Tahoe approximately 240 km (150 mi) east-northeast of San Francisco California near the Nevada state boundary. The fire burned 1,243 ha (3,072 ac) and approximately 353 buildings of all types. Within the fire perimeter there were 401 houses with direct fire exposure, and of the 282 houses that burned, 87% were completely destroyed. The area around the unburned houses and the 13% of damaged houses were the source of the firebrand data collection portion of this study.

The probability that firebrands will potentially ignite buildings or "spot fires" in vegetation requires that firebrands will be produced, lofted, transported, deposited on a receptive target fuel bed. This firebrand propagation phenomenon is dominated by weather conditions, the configuration and condition of both the source and target fuel beds, and the fire intensity. These factors were documented to the extent possible on the Angora Fire during the course of routine fire incident management and post-fire damage assessment.[24] The general weather over the Angora Fire area was dominated by a cold front moving through the Lake Tahoe Basin. Weather conditions during the period when all the houses were destroyed were reported to be 10% relative humidity at 27 ºC (80 ºF) with eye level winds at 4.5 m/s to 6.7 m/s (10 m/h to 15 m/h), gusting to 13 m/s (30 m/h). Fuel moistures were extremely low for the area and time of season. The oven-dried fuel moisture content (FMC) was 9% for large dead vegetative fuels ("10-hour") and near a record low of 37% for live woody vegetative fuels. Most firebrand data was collected from "exposed" locations where the fine dead vegetative ("1-hour") FMC was calculated[25] to be 2% with a corresponding PIG[26] (probability of firebrand ignition) of 100%.

The wildland fuels in the area consisted of a continuous White Fir - Jeffrey Pine forest with heavy understory surface fuel loadings. Most of the area burned was unmanaged forest in the USFS Lake Tahoe Basin Management Unit. Several areas of forested land directly adjacent the exposed residential development had been subjected to fuel reduction treatments creating "shaded fuel breaks.". The vegetation fuels in the areas of residential development were discontinuous and varied widely from green grass lawns to ornamental landscaping and stands of conifer trees. Many of the building lots were undeveloped with managed vegetation. Pine needles and forest litter were common on, and around, surviving houses and in the surrounding unburned neighborhoods.

The density of building fuels was low with respect to urban fire spread. Building lots were approximately 0.04 ha to 0.20 ha (0.1-0.5 ac) in size, and 40% to 50% of the lots were undeveloped leaving houses separated by 10 m to 100 m. Paved roads 6 m to 9 m wide, clear of crown canopy cover, divided the area of residential development preventing surface fire spread between blocks. The common building construction of the surviving houses, which were observed to be representative of the destroyed houses, consisted of wood siding, wooden decks, and 80%-90% ignition resistant roofing.

The wind-driven fire transitioned to an active crown fire within 100 m – 200 m of the origin and spread at 0.34 m/s (0.75 m/h) for the first 3-4 hours in the wildland fuels with a maximum spotting distance estimated to be 402 m (0.25 mi). The burning index was reported to be 49 with an energy release component in the 90th percentile, a record high value for that date. The crown fire was observed to drop in intensity with 1.2 m (4 ft) flame length under the shaded fuel breaks adjacent to the residential development. An empirical study of fuel treatment effectiveness on the Angora Fire generalized that 50m of specific treatments is sufficient to reduce a crown fire to a surface fire.[27] The fire behavior changed dramatically in the places where the fire spread from the shaded fuel breaks into areas of residential development. These areas showed a mosaic of unburned landscape vegetation, surface fire under surviving conifer forest, total destruction of buildings, and patches of conifer forest completely consumed.

METHODS

The field data consisting of firebrands and firebrand burn patterns was obtained in conjunction with an existing post-fire damage assessment effort. Digital analysis of the burn patterns was conducted to determine the number and size distribution of the burn patterns. Current and historical research was reviewed for comparable findings and observations as well as wildfire protection building construction regulations and standards.

A rare combination of circumstances and resources on the Angora Fire provide the opportunity to expand the routine incident damage assessment to record observations on all unburned houses that received direct wildfire exposure. These were defined as a house located within 30 m (100 ft) of anything that burned including small vegetation spot fires and firebrand burn patterns on building materials. The approximate size of assumed firebrand burn patterns, consisting of scorch marks, shallow char marks, and holes melted through plastic-type materials, were measured when observed. These burn patterns were assumed to indicate the presence of flaming or glowing firebrands with some potential for ignition of the target fuel. It was assumed that deposited firebrands would rest flat on the target fuel surface resulting in a two-dimensional burn pattern area with the maximum dimension representing the approximate length of the firebrand and the smaller burn pattern dimension representing either the diameter or width of the firebrand (for cylindrical or flat shaped firebrands respectively). It is probable that some burn patterns were larger in area than the firebrand due to progressive combustion or melting, but it was assumed that the overall size distributions of burn pattern areas were representative of actual firebrand sizes. Burn patterns with evidence of sustained or progressive combustion from firebrand ignition, such as a combustion spreading to an adjacent piece of building construction lumber, were not included as an indicator of firebrand size. A backyard trampoline provided two separate sets of firebrand size distribution data in addition to the fire area wide burn pattern data collected.

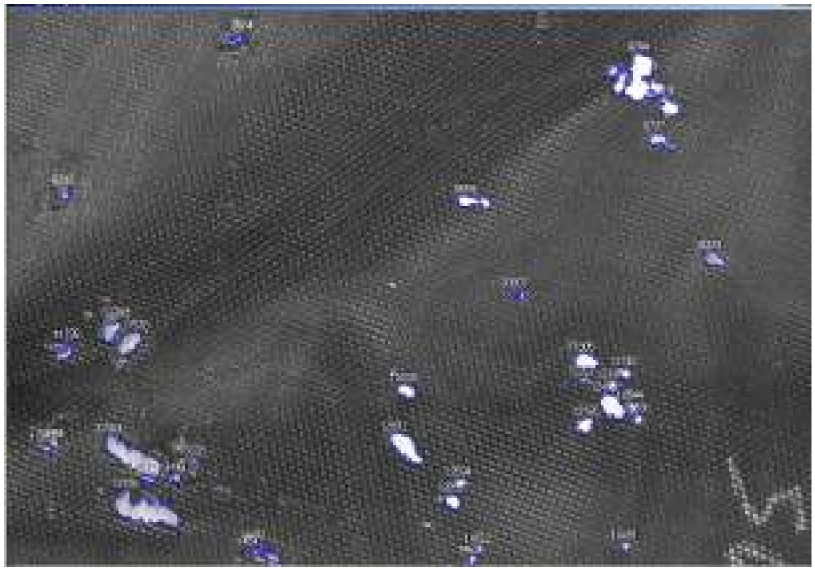
The trampoline was located on a green grass lawn approximately 6.1 m (20 ft) from a wood-sided house that survived with superficial burn damage. The trampoline has a 3.7 m (12 ft) diameter base supported by a metal frame and springs approximately 0.9 m (3 ft) off the ground. Foam covered metal poles supported a vertical wall extending approximately 1.5 m (5 ft) above the base completely around the trampoline perimeter. The house was located less than a mile downwind from the area of wildland crown fire and 9.8 m (32 ft) (perpendicular to the wind direction) from a house that burned to the ground. The burning of the latter house appeared to have caused extensive scorching to the exterior wood wall covering on one side. A large grove of 6 to 12 conifer trees burned with extreme intensity approximately 6.1 m to 15.2 m (20-50 ft) upwind of the trampoline, as did numerous other trees and more than a dozen houses within several hundred meters upwind of the trampoline.

The trampoline was shipped to NIST for analysis. The trampoline base was–divided into a series of quadrants. Digital images were taken of each quadrant for subsequent image analysis. To spatially resolve the holes for image analysis required dividing the trampoline into 133 quadrants (see Figure 1). To better identify the burn holes produced by firebrands, white paper sheets were laid under each quadrant prior to taking digital images.

Figure 1. Image of trampoline base divided into 133 quadrants

Figure 2 displays a digitized image of one of the quadrants of the trampoline. This image has been converted to an 8 bit grayscale image. Image analysis software was then used to determine the area of burn holes (see outline in image). The area of the burn pattern was subsequently calculated by converting the pixel area using an appropriate scale factor.

Figure 2. Digitized image of a given quadrant.



Babrauskas (2003) and Koo *et al*. (2010) provide a comprehensive review of existing research on firebrands, spot fires, firebrand exposure, and firebrand ignitions[28,29] Empirical and experimental research on firebrand size distributions is very limited. Since the burn patterns collected on the Angora Fire is the only known data on firebrand size from an actual interface fire, previous research was reviewed for data or observations that could be compared to the Angora Fire findings.

The NIST Dragon was designed to be able to produce a controlled and repeatable flux of firebrand exposure characteristic in size and weight to firebrands produced from burning trees. Manzello *et al.* conducted a series of experiments quantifying firebrand production from burning trees.[30] In that work, an array of pans filled with water was used to collect the firebrands that were generated from the burning trees. The firebrands were subsequently dried and the sizes were measured using calipers, and the dry mass was determined using a precision balance. Based on the results of two different tree species of varying crown height and moisture content (Douglas-Fir Trees and Korean Pine Trees) burning singly under no wind, cylindrical firebrands were observed to be produced. The size distribution of firebrands generated using the NIST Dragon is presented in the results for comparison with the Angora Fire data.

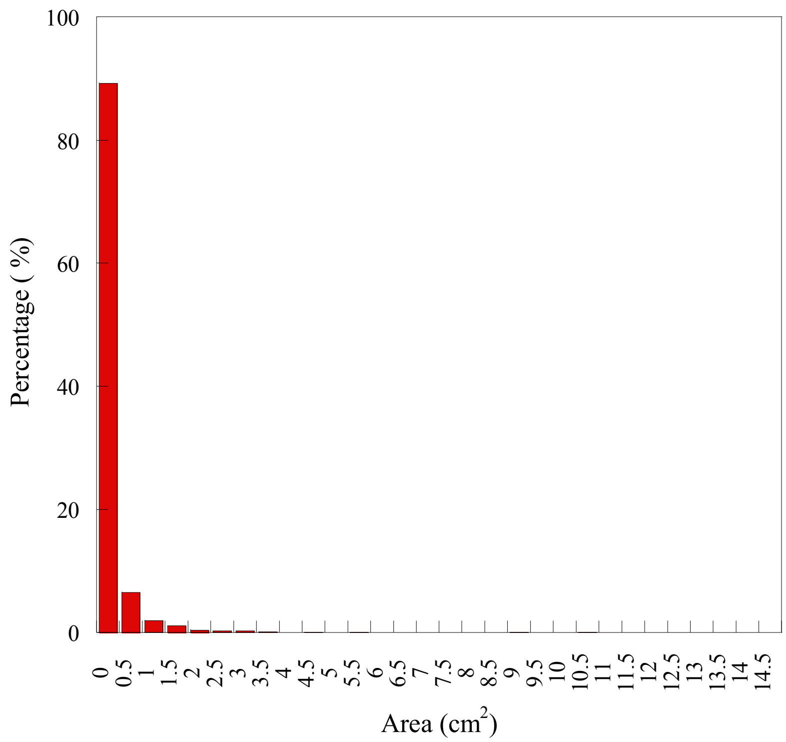
A firebrand size distribution from experimental building fires is also presented for comparison. Vodvarka (1969) measured firebrand deposition by laying out 3 m x 3 m (10 ft x 10 ft) sheets of polyurethane plastic downwind from five separate residential buildings burned in full-scale fire experiments.[31] These firebrand field studies were part of research programs sponsored through the U.S. Naval Radiological Defence Laboratory which also sponsored studies into mass fire and firewhirls. Very large firebrands are occasionally documented such as an eyewitness account by Richard Rothermel from a full-scale mass fire experiment in the Nevada desert where he saw two very large firebrands, one measuring 1.8 m (6 ft) long by 3.18 cm (1.25 in) diameter, and a second firebrand measuring 0.9 m (3 ft) long by 6.36 cm (2.5 in) diameter.[32]

Wilson and Ferguson (1986) hypothesized that tall vegetation between a building and an approaching fire may serve to protect the structure by heat flux shielding and by filtering out firebrands. Alternatively, a wind profile over vegetation with leeward-side eddies, similar to agricultural windbreaks, may increase the threat to structures by causing areas of high density firebrand deposition.[33]

RESULTS

The round 10.5 m² (113 ft²) trampoline base had 1,800 melted holes measured by digital image analysis, with an average density of 16 holes per square foot. Figure 3 displays the distribution of hole size frequency calculated from image analysis software. The single largest hole in the trampoline base measured 10.25 cm² in total area. More than 85% of the holes were less than 0.5 cm² in size.

Figure 3 Distribution of burn patterns (area burned) for trampoline collected from the Angora fire.

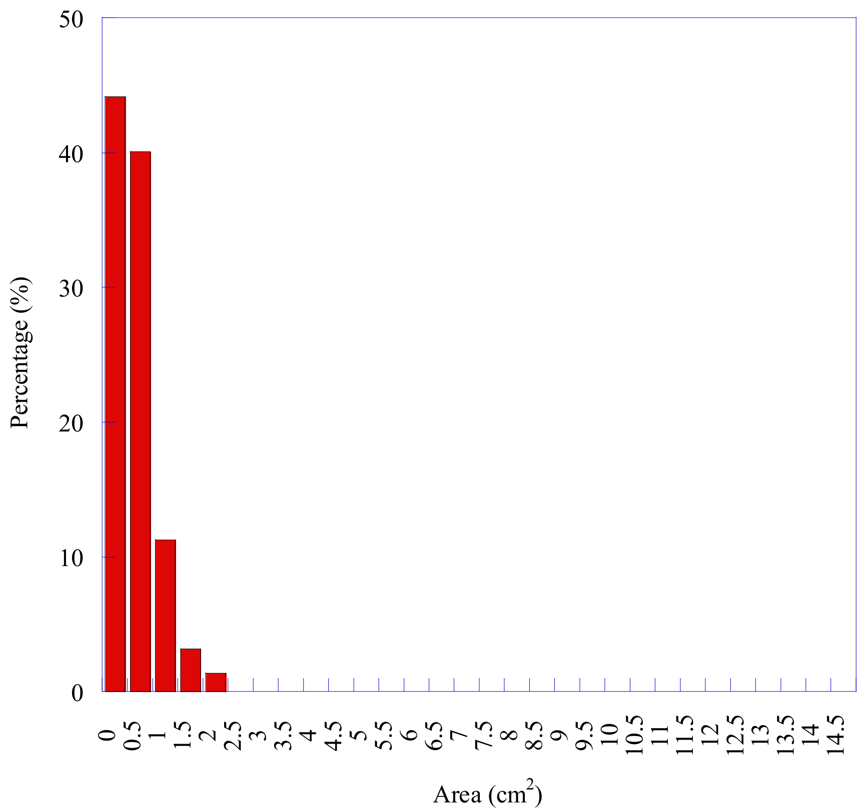


The size distribution of holes in the vertical trampoline safety net wall was observed to be similar to that of the trampoline base. However, the trampoline wall was constructed of a different material than the base which has not lent itself to effective digital image analysis of the burn patterns.

In addition to the trampoline data, burn patterns on building materials and plastic outdoor furniture were observed at 212 individual locations on or near numerous Angora Fire buildings. A large majority of these firebrand indicators were less than 0.40 cm² (.06 in²) with the largest being 2.02 cm² (.31 in²) or 0.64 cm x 3.18 cm (.25 in x 1.25 in). Most of the burn patterns on building materials consisted of shallow scorch or char marks on wooden or composite lumber decks. No actual firebrands were identified in association with these burn patterns. Most of the holes that melted through non-building materials (other than the trampoline) were found on outdoor furniture or hot tub covers. Approximately 10% of these firebrand indicators were found on plastic covered foam outdoor furniture cushions. A piece of charcoal, assumed to be the remains of a firebrand, was found at the bottom of a few of the foam cushions. It was not possible to ascertain what combustion phase the firebrand was in (glowing or flaming), nor what the fuel source of the firebrand was—that is, burning vegetation or building materials.

For comparison to actual fire data (Figure 3), Figure 4 illustrates the size distribution of firebrands produced by the NIST Dragon, which has been used for full-scale building ignition experiments in the BRI FRWTF. Figure 4 shows the results of a previous study with firebrand size measurement scaled to facilitate comparison between the experimentally generated firebrand sizes and firebrand sizes from an actual interface fire (see Figure 3). As can be seen, the NIST Dragon produced firebrands are commensurate to those generated from a real fire.

Figure 4. Area of firebrands generated from NIST Dragon.



The 1969 firebrand field studies measured firebrand size and transport distances of 4,748 firebrands that were collected from five full-scale experimental building fires. Very small firebrands dominated the size distribution with 89% of the firebrands less than 0.23 cm² (0.1875" x 0.1875"). Localized high-density firebrand deposition was observed on two of the experimental fires. On one fire, a single plastic sheet, located just downwind of a large tree, received 97% of the 2,325 firebrands recorded from over 50 plastic sheets used on this experiment.

A review of wildfire protection building construction regulations found that screens intended to protect against firebrand entry ranged in opening size from 0.03 cm² to 0.40 cm² (1/16th in to 1/4th in) [34,35,36,37].

There are no nationally recognized American building construction test standards or design practices for exterior wildfire or interface fire exposure protection. The *Recommended Practice for Protection of Buildings from Exterior Fire Exposures* is only intended to protect against ignition as a result of radiative heat transfer.[38] The three standard fire test methods for roof coverings (UL790, NFPA 256 and ASTM E108) apparently originate from 1903 and are only intended to simulate exposure conditions from an adjacent burning building. Building codes typically require roof coverings to resist fire penetration into the building from firebrand exposure by specifying one of three "fire classifications" based, in part, on relative burning brand test exposure from light (14.44 cm^2 size "Class C" brands) to severe (930.25 cm^2 size "Class A" brands). However, until recently some building codes have exempted non-combustible roof coverings (e.g. clay, ceramic, or concrete tiles) from standard evaluation and considered them as a "Class A" roof coverings without fire testing.

CONCLUSIONS AND DISCUSSION

The Angora Fire trampoline burn pattern size distribution data, while small and limited to a single point on the Angora Fire, is supported by the individual firebrand burn patterns collected over a wide area of the Angora Fire and by the similar firebrand size distributions seen in the historical field studies. But drawing conclusions from a single study of a single fire has inherent limitations. Fortunately, the lines of study, results, and conclusions reported on here can be reasonably used in the interim to support decisions on public policy, fire protection, and future studies until more robust research yields scientific conclusions in the future.[39]

It is possible to consistently generate experimental firebrands of a size that are representative of firebrand exposure from an actual interface fire and from full-scale experimental building fires. This study provides validation the firebrand size distribution generated by the NIST Dragon and the horizontal wind-blown firebrand exposure used in recent NIST building ignition experiments. The trampoline wall burn pattern observations shows that, under the conditions at that time and location on the Angora Fire, firebrand exposure characterization needs to include horizontal transport and deposition well above the ground (1.8 m or 6 ft). Firebrand ignition is the only reasonable fire spread mechanism that can account for propagation across wide streets leaving unburned fuel between destroyed houses.

There is empirical data to support the contention that large numbers of very small ($<0.5cm^2$) firebrands can be a significant part of the interface fire exposure problem. Clearly, this data suggests that the trampoline was bombarded with many wind driven firebrands significantly smaller than firebrand sizes used in current fire test standards. High density firebrand deposition in the vicinity of unburned fuels, especially with 100% "probability of ignition" as seen on the Angora Fire, indicates that there is a significant probabilistic function to the target fuel ignition phase of firebrand related fire spread. The high density of firebrand burn patterns on the trampoline base may be localized, and further evidence of leeward side wind-eddies concentrating firebrand deposition downwind of trees. Or, it may be that the high density of actual firebrand exposure was more widespread and the trampoline was simply more receptive to burn patterns relative to the surrounding unburned fuel surfaces.

Several effective and relatively simple methods of firebrand and burn pattern size data collection are possible with efficient analysis for both real and experimental fires. This work shows that it can be relatively easy to improve upon eyewitness statements, professional judgment, and anecdotal observations as a basis for evaluating firebrand building ignition hazard mitigation measures. The building-ignition oriented experimental studies by NIST over the past four years, with support from empirical, statistical, and observational work on interface fires, have provided evidence-based rationale for improved wildfire protection building construction methods.

The fuel source of firebrands, frequency of large firebrands, and relative significance of these factors to interface fire exposure remains especially elusive. Little empirical evidence was found to help identify what the relative importance is of firebrands generated from buildings versus firebrands generated from burning vegetation. Based on eyewitness statement in a case study of the Angora fire, it was reported that "a large number of houses burned from firebrands generated from other burning houses rather than wildland fuel."[40] There would certainly have been firebrands lofted from burning building materials exposing down-wind fuels to potential firebrand ignition. However, most of the burned houses were also well within spotting distances for an active conifer forest crown fire or for torching trees that were common within the area of residential development on the Angora fire. Large, distinctive looking (see Koo et al. 2010, fig. 8) but not empirically described, pieces of burned wood presumed to be wood roof firebrands were found downwind of several destroyed buildings. But without burn patterns, it is difficult to distinguish between deposition of burning firebrands, windblown fire debris, or extinguished firebrands. There would have been some potential for very-large size firebrand production from the Angora crown fire. But neither evidence of large-size firebrands, nor evidence of firewhirls was found.

Evaluating the risk of large size firebrand exposure and the relative importance of the most common interface fire building ignition mechanisms will be critical for effective and cost-efficient hazard mitigation in the near future. While the traditional conflagrations that ravaged American cities around the turn of the past century[41] are a thing of the past, characterizing firebrand exposure and solving the interface fire problem may be important for reducing losses from the real potential of disastrous post-earthquake fires and intentional conflagrations.

Some solutions are not scientifically elusive. The frequency of wood roof conflagrations that averaged one to three disasters every year in the early twentieth century have been virtually eliminated, other than as a part of an interface fire.[42] The solution advocated by Wilson, the proper use of building materials and the provision of exposure protection rather than massive human effort at the time of the fire, is just as applicable today as it was 45 years ago.[43] The significant contribution of wood roof hazards to increased fire losses may appear axiomatic to some, but in California there was a public policy debate on this issue from the repeal of a Berkeley fire-resistant roofing ordinance in 1923 to calling wood roofs a "scapegoat" for inadequate fire protection in 1990.[44] What was missing then was basic empirical fire loss data.[45] How to cost-effectively retrofit the large stock of existing buildings at risk from interface fires, including many with untreated wood roofs, will be a major challenge in the coming decades. The extent of firebrand exposure and building ignition characterization will have a major impact on future interface fire losses.

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