DEVELOPING RAPID RESPONSE INSTRUMENTATION PACKAGES TO QUANTIFY STRUCTURE IGNITION MECHANISMS IN WILDLAND-URBAN INTERFACE (WUI) FIRES

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ABSTRACT

Rapidly deployable instrumentation packages are being developed to be used during actual WUI fires to quantify structure ignition mechanisms. The packages are being designed to be placed near a given structure in the WUI and will provide video imaging of a structure at different vantage points as well as quantitative data on heat flux, wind speed, and relative humidity. Prior to attempting to use these instrumentation packages in real WUI fires, a series of proof-of-concept tests were conducted under prescribed fires. In these tests, a shed was used as a surrogate for a typical structure that would be found in the WUI. This presentation will focus on instrumentation package development and results from a recent deployment in a prescribed fire at Stafford Forge Wildlife Management Area in the State of New Jersey.

INTRODUCTION

Fire spread in the Wildland-Urban Interface (WUI) is an international problem with major WUI fires reported in Australia, Greece, Portugal, Spain, and the USA. In the USA, there have been two significant WUI fires within the past five years in California. The 2003 Cedar fire resulted in $2B in insured losses and destroyed more than three thousand homes. WUI fires can also result in mass evacuations. The most recent destructive WUI fire that occurred in Southern California in 2007 displaced nearly 300,000 homes and destroyed over a thousand structures.

For WUI communities, fire risk is reduced by either reducing wildland fuel loading or by following a series of risk reduction practices. Unfortunately, the fuel treatment methods in practice are predicated on very limited scientific investigations. It is not all clear how effective these methods are with regard to preventing structure ignition. The risk reduction practices follow rule-based and empirically determined checklists and are not the result of a scientifically based effort. Quantitative data on how structures ignite during full scale field experiments is highly desirable.

Not surprisingly, very few full scale field studies have been performed to understand structure ignition mechanisms[1]. Cohen[1] provided some insights into structure ignition mechanisms as part of the International Crown Fire Experiments conducted Canada. In these experiments, Cohen[1] placed various target walls 10 m, 20 m, and 30 m from an approaching crown fire. The test walls were instrumented with water cooled heat flux gages to measure the temporal evolution of heat flux experienced at the target wall as the crown fire approached; data was obtained for seven different crown fires. While these experiments provided some useful insights, Cohen[1] pointed out that the data was collected under a limited set of

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experimental conditions, such as fuel load, wind speed, and terrain. More importantly, fire spread in the WUI is not simply governed only by vegetative fuels to structural fuels but also structural fuels to structural fuels. The role of firebrands during WUI fire spread is not clearly understood as well. Therefore, the capability to collect *in-situ* information on the physical mechanisms related to structure ignition during actual WUI fires is highly desirable.

To this end, rapidly deployable instrumentation packages are being developed to be used during actual WUI fires to quantify structure ignition mechanisms. The packages are being designed to be placed near a given structure in the WUI and will provide video imaging of a structure at different vantage points as well as quantitative data on heat flux, wind speed, and relative humidity. Prior to attempting to use these instrumentation packages in real WUI fires, a series of proof-of-concept tests are being conducted under prescribed fires. In these tests, a shed is being used as a surrogate for a typical structure that would be found in the WUI. This paper is focused on instrumentation package development and results from a recent deployment in a prescribed fire at Stafford Forge Wildlife Management Area in the State of New Jersey.

EXPERIMENTAL DESCRIPTION

Rapid response instrumentation packages that enable *in situ*, temporally resolved measurement of heat flux, wind speed and direction, relative humidity, and ambient temperature as well as full field video imaging were designed. NIST was invited to test the rapid response instrumentation packages by the New Jersey Forest Fire Service as part of their yearly prescribed burns intended to reduce the risk of fire spread by reducing wildland fuel loads in the New Jersey Pine Barrens. These prescribed burns were conducted at the Stafford Forge Wildlife Management Area, Warren Grove, NJ; this is land owned by the state of New Jersey. The New Jersey Forest Fire Service was in charge of the prescribed burns which included coordination, ignition, and suppression efforts.

Figure 1 displays a map of the site where the prescribed fire experiments were conducted. To visualize the ignition of the structure as the crown fire approached, a shed with a dimension of (1.8 m × 2.4 m × 2.0 m) was used as a surrogate for a typical structure that would be found in the WUI. The shed was constructed of OSB with an asphalt tile roof and vinyl siding; figure 2 displays an image of the shed prior to the fire. The fire was ignited using a helicopter equipped with a heli-torch. A crown fire developed and approached the shed. A picture of the crown fire that developed is shown in figure 3.

Figure 1 Satellite map where the prescribed fires occurred in the New Pine Barrens; the prescribed burning area was 0.1 km^2.

Figure 2 Image of the shed exposed to the prescribed fire.

Figure 4 displays a schematic of the field deployable rapid response instrumentation packages as well as the setup configuration used in these tests. As shown in the figure, the instrumentation packages consisted of a main station that was 19.5 m away from the shed and two remote stations that were placed adjacent to the shed. The main station included a laptop with custom software for data logging, two wireless cameras, a wireless radio modem, and a wireless router. Each remote station that faced the East and North, respectively, was equipped with single board computer (SBC) for data acquisition, a wireless radio modem, a total heat flux gage, an anemometer, directional flame thermometer (DFT), and a thermistor-humidity sensor. All physical signals (in volts) measured from each device in the remote station were collected through the SBC located in a thermally insulated enclosure and simultaneously transmitted to the laptop at 9600 bytes per second (bps) through a pair of wireless radio modems.

Figure 3 Image of the prescribed fire.

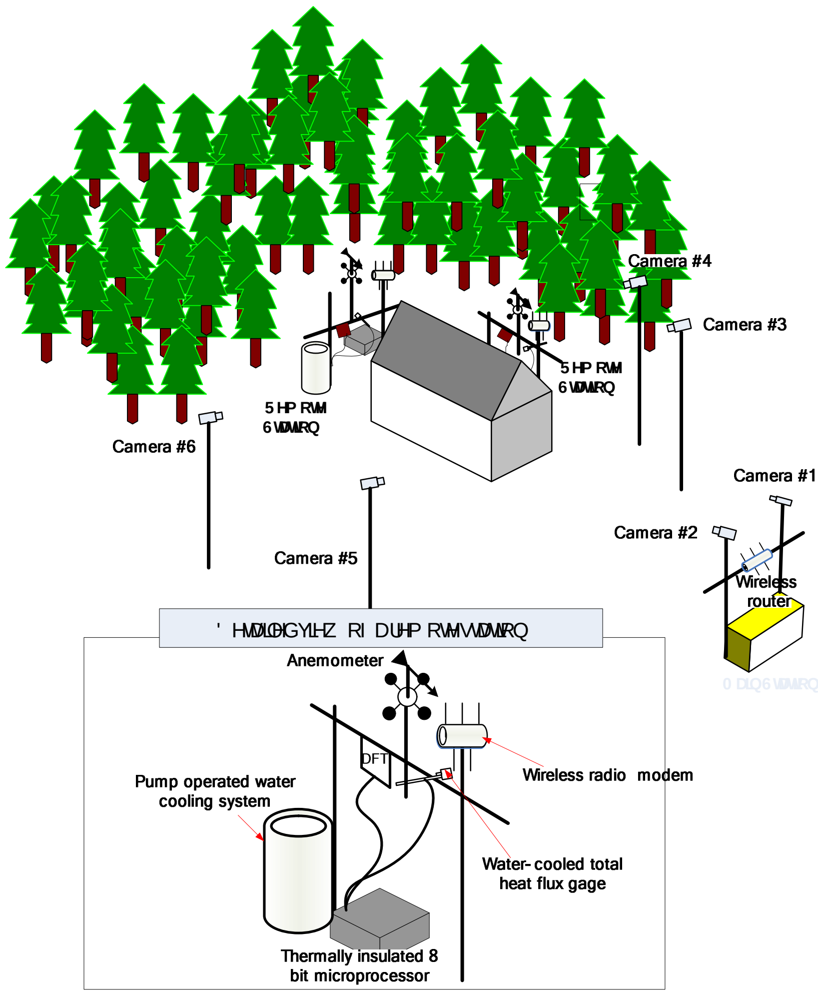


Figure 4 Schematic of the field deployable rapid response instrumentation packages and configuration.

In situ, time-resolved images of the fire are the most important features of the instrumentation packages. Six expendable wireless internet protocol (IP) cameras were installed at different view angles around the shed as well as the main station and were used to image the spreading fire front. The images were captured at 3 frames per second (fps) and simultaneously transmitted to a laptop inside the main station through a wireless router. Transmitted images were then saved in MPEG (Moving Picture Experts Group) format. The total heat flux gages (Schmidt-Boelter type; 5/8" diameter sensor) and DFT's were used to measure the total incident heat flux from the fire front. Each was installed at the same height (from the ground; 1.4 m) and view angle. The total heat flux gages were water-cooled during the test and calibrated using a black body source before the test. Ambient temperature and relative humidity were measured using a thermistor-humidity sensor. Local wind velocity and direction were measured using a cup and vane anemometer only at the remote stations.

It is important to point out the unique features of instrumentation developed as part of this effort. This included sending all data signal to a hardened location (NIST WUI Black Box or Main Station) wirelessly in order to allow the use of relatively inexpensive cameras that do not need to be hardened to survive the fire; this greatly reduced cost and distinguished our instrumentation packages from others used in wildfire experiments[1-2]. It was also desired to quantify heat flux without the use of water cooled heat flux sensors. Thus, the DFTs were used and as part of this proof of concept exercise and water cooled total heat flux sensors were used for a direct comparison of the heat flux obtained from the DFT's. DFT's do not require water cooling and this is highly desirable since the ultimate goal of this effort is to deploy this instrumentation during actual WUI fires. Accordingly, deploying water cooled heat flux sensors is not desired.

RESULTS AND DISCUSSION

In prior wildfire studies, the spread of the fire front was monitored or visualized through thermocouple measurements[3-4] and a series of thermally insulated CCD cameras[1-2,4] and infrared imaging devices[5]. However, high quality temporally resolved images of the spreading fire front spread were not available in those studies.

Figure 5 displays *in-situ* images of the fire approaching the structure with respect to time. The data loggers were started some four hours before the fire was ignited. The instrumentation was setup within 20 minutes but due to weather conditions, the fires were not ignited until more than four hours after setup. Distinct fires were first observed at 4h 5m 28s and propagated toward the shed along the wind. As shown in the figure, ignition on the shed was not observed before the fire front passed by the structure. In the view of camera #5, only shrinkages of vinyl side on the back of the shed were observed at 4h 6m 20s before the passage of fire front. Upon the arrival of fire front the shed was partially engulfed in the fire at 4h 6m 26s.

In addition to *in-situ* time resolved images of fire front, the measured ambient temperature, relative humidity, and local wind speed and direction were determined with respect to time and are shown in Figures 6 and 7, respectively. All results were interpreted based on data obtained from the remote station #2 (that is approximately 0.4 m away from the shed). It is also important to note that all measurements were halted (at 4h 6 m 23s) just before the passage of fire front over the remote station because wireless communications between main and remote stations were lost. The inverse relationship between ambient temperature and relative humidity was observed. Note that the influences of radiative heat losses on the thermistor sensor were not taken into account in ambient temperature measurements. An accurate measurement of the ambient and fire temperature was complicated due to the influence of radiation as the fire front was approaching. However, it was previously shown that the measured ambient temperature in wildland fire studies[3-4] remained constant before the arrival, similar to the present study. Therefore, it appears that the temperature corrections in the present study are necessary around the point (i.e. approximately at 4h 6m 10s) when the variations in the temperature become predominant as the fire front spreads toward the structure. Detailed discussion on the temperature correction method in the fire is described elsewhere[4,6].

As shown in Figure 7, the local wind speed gradually decreased as the fire front approached; the average wind speed for the period examined was 3.0 m/s. The wind came mainly from the East (270°) and the South (0°), oscillating in two different directions as shown in the figure.

To elucidate the ignition mechanism in WUI fires requires the temporal evolution of heat flux. The total heat flux gage and DFT used in the test measured the combined effects of radiation and convection:

$$q_{total} = a q_{inc,r} - e s T_s^4 + q_{conv} \tag{1}$$

where q_{total} is the total heat flux absorbed through the plate, a is the surface absorptivity $q_{inc,r}$ is the incident radiative heat flux, e is the surface emissivity, T_s is the surface temperature, q_{conv} is the convective heat flux. In the present study, the heat fluxes measured from both the total heat flux gage and DFT were compared to each other in order to investigate the performance of these devices. The heat flux measurement principle of the DFT is quite similar to that of a plate thermometer[7]. The DFT included two 3 mm inconel plates which have an oxidized surface to minimize variations in the surface emissivity. On the other side of each plate (facing the insulation side), K type thermocouples are welded to the center of plate and covered with 25 mm thick insulation material.

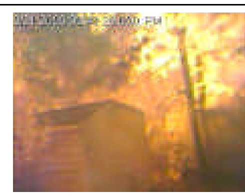
Time	Camera #2	Camera #3	Camera #5
4h 5m 28s			
4h 5m 41s			
4h 5m 54s			
4h 6m 07s			
4h 6m 20s			
4h 6m 23s			
4h 6m 26s			

Figure 5 *In-situ* temporally resolved images of fire front spread; the data loggers and cameras were started approximately four hours before the fire was ignited.

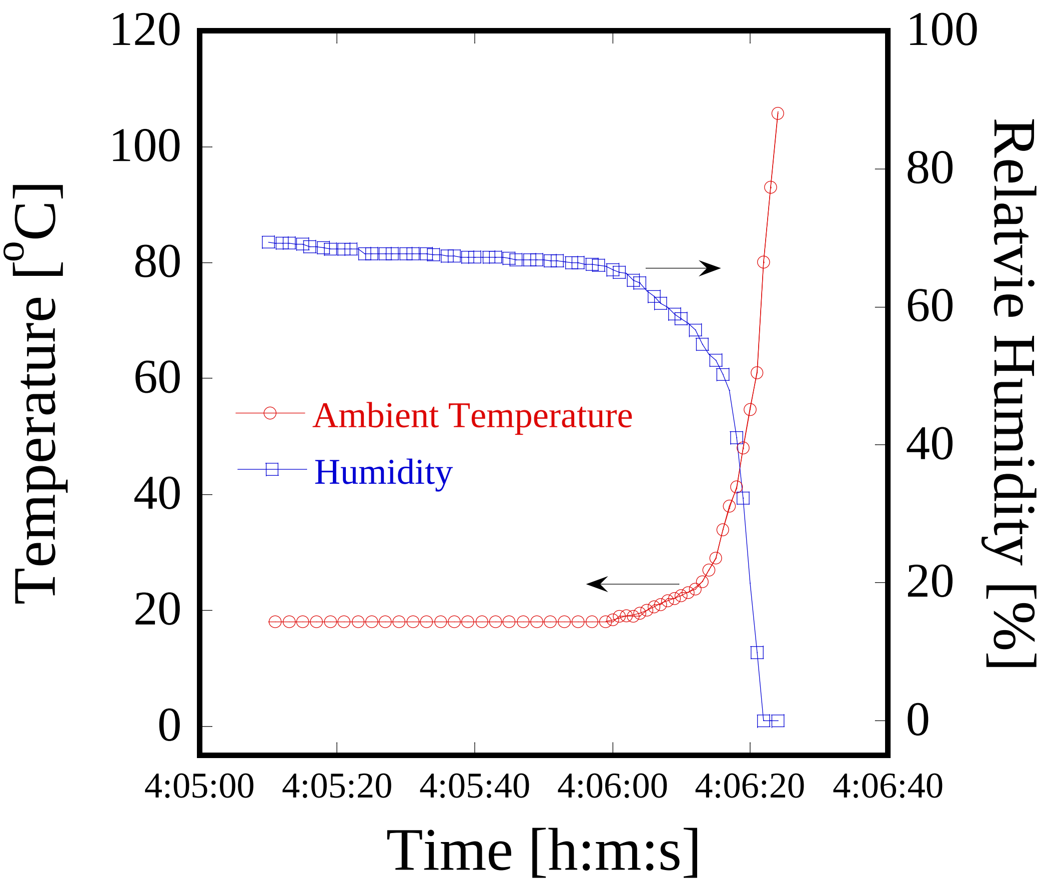


Figure 6 Measured ambient temperature and relative humidity profiles versus time.

The DFT plate surface (facing the fire) is subject to an unknown heat flux via radiative and convective heat transfer from the fire while the temperature at $x=L$ was measured using the thermocouple with respect to time. Under these conditions, the governing one-dimensional transient heat conduction is given as:

$$\frac{\partial^2 T}{\partial x^2} = \frac{r c_p}{k}\frac{\partial T}{\partial t} \qquad (2)$$

$$\left.\frac{\partial T}{\partial x}\right|_{x=L} = 0 \qquad (3)$$

$$q(t)_{total} = -k\left.\frac{\partial T}{\partial x}\right|_{x=0} \qquad (4)$$

$$T(x,0) = T_i \qquad (5)$$

where T is the temperature, t is the time, ? is the density, c_p is the specific heat, and k is the thermal conductivity.

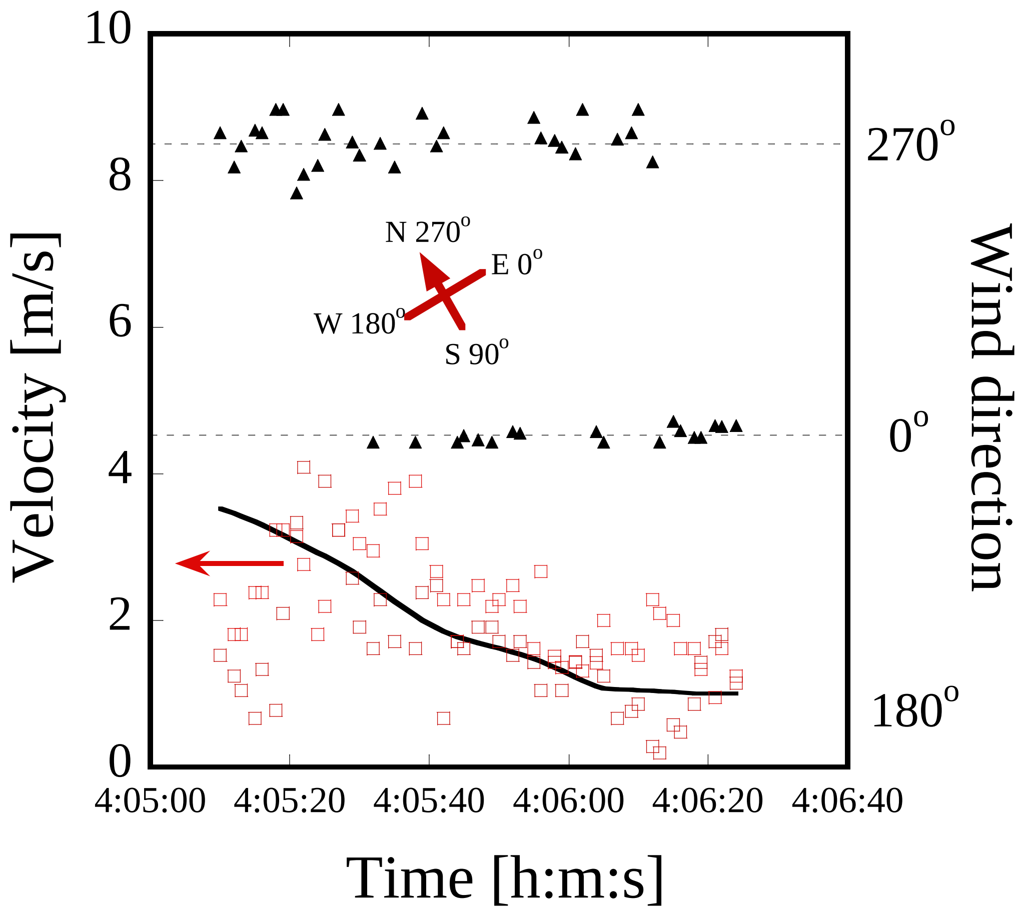


Figure 7 Measured wind velocity and direction profiles versus time.

Since the problem is related to solving the unknown heat flux history on the surface using the given temperature history at $x=L$, it falls into the category of an inverse heat conduction problem (IHCP). In contrast to the direct heat conduction problem for which a wide range of solutions are available, only a few solutions to the IHCP have been proposed[8-9]. In the present study, the problem was solved using an IHCP code; IHCP1D that is based upon a future temperature estimation algorithm[9]. In this algorithm, the surface and interior temperatures are estimated using a guessed heat flux as a function of time and then the estimated temperatures at $x=L$ (that is calculated based on the guessed heat flux) was compared to the measured temperatures at the same time and location. In order to obtain the appropriate surface temperatures, this routine repeats until the least square error between the estimated and measured temperatures at $x=L$ is minimized.

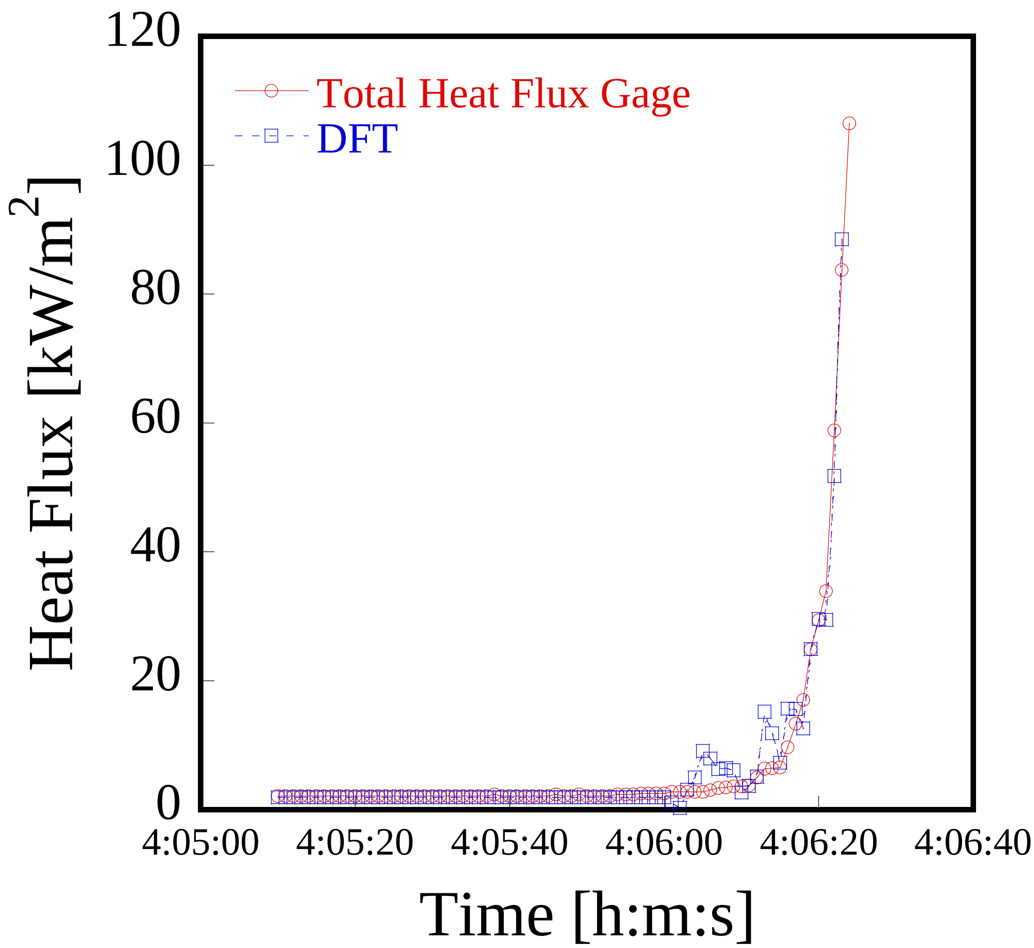


Figure 8 Measured total heat flux with respect to time.

The heat flux measured using the total heat flux gage and determined from the DFT were plotted as a function of time in Figure 8. The expanded uncertainty in estimating the total heat flux from the inverse heat conduction method is ± 11 %. As shown in the figure, the heat flux determined from the DFT measurement is in good agreement with results measured using the total heat flux gage. The shrinkage of vinyl siding that covered the shed was observed at 4 h 6m 20s; the measured heat flux at this time was 25 kW/m^2. The measured heat flux increased to 84 kW/m^2 after three seconds (4 h 6m 23s). In experiments using the LIFT (Lateral Ignition and Flame spread Test) experiments[10], it was found that vinyl siding began to shrink 30 s after an incident heat flux of 33 kW/m^2 was applied. For flaming ignition in the LIFT[10], an incident heat flux greater than 80 kW/m^2 for 10 s was required.

CONCLUSIONS

Rapidly deployable instrumentation packages were developed to be used during actual WUI fires to quantify structure ignition mechanisms. The packages are intended to be placed near a given structure in the WUI and will provide video imaging of a structure at different vantage points as well as quantitative data on heat flux, wind speed, and relative humidity. Prior to attempting to use these instrumentation packages in real WUI fires, a series of proof-of-concept tests were conducted under prescribed fires. In these tests, a shed was used as a surrogate for a typical structure that would be found in the WUI. This proof-of-concept test was successful and has demonstrated that relatively inexpensive instrumentation can be used and that the DFT's are acceptable for use in place of water cooled heat flux gages. Continued work will make use of this type of instrumentation to quantify how effective various fuel treatment strategies are in mitigating ignition as well as placing structures further away from the vegetation to investigate firebrand ignition mechanisms.

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