MEASUREMENT OF FIREBRAND PRODUCTION AND HEAT RELEASE RATE (HRR) FROM BURNING KOREAN PINE TREES

S.L. Manzello, A. Maranghides, J.R. Shields and W.E. Mell
Building and Fire Research Laboratory (BFRL)
National Institute of Standards and Technology (NIST), Gaithersburg, MD 20899-8662, USA

Y. Hayashi and D. Nii
Department of Fire Engineering, Building Research Institute (BRI), Tsukuba, Ibaraki 305-0802, Japan

ABSTRACT

A series of real scale fire experiments were performed to determine the mass and size distribution of firebrands generated from Korean Pine (*pinus koraiensis*) trees. The experiments were performed at the Building Research Institute (BRI) in Tsukuba, Japan. The tree height was fixed and tree moisture content was varied to examine the influence that this parameter has on the mass and size distribution of the firebrands that are produced, under ambient wind conditions. The firebrands were collected using an array of water filled pans. This ensured that firebrands would be quenched as soon as they made contact with the pans. The Korean Pine trees were also mounted on load cells during burning to determine the temporally resolved mass loss profiles. The mass loss data were used to calculate the mass loss rate and infer peak heat release rate (HRR). Results of this study are presented and compared to firebrand distribution and HRR of burning Douglas-Fir trees, a conifer tree species indigenous to the USA.

KEYWORDS: Firebrands, Wildland/Urban interface fires, Heat release rate (HRR)

INTRODUCTION

A major complication for fire spread in communities is the generation of firebrands[1,2]. Firebrands are generated as structures and vegetation burn in wildland urban interface (WUI) fires. Firebrands that are produced are entrained in the atmosphere and may be carried by winds over long distances (up to several kilometers in some cases). Ultimately, hot firebrands with significantly long burn-out time land on fuel sources far removed from the initial fire, resulting in fire spread. This process is commonly referred to as spotting. Firebrand ignition has been an outstanding problem that has plagued both the USA and Japan.

Unfortunately, a very limited number of experimental studies have been performed to investigate the mass and size distribution of firebrands produced from burning vegetation and structures[1,2]. The firebrand problem can de divided into three main processes: the generation of firebrands from burning vegetation and structures, their subsequent transport through the atmosphere, and the ultimate ignitability of materials due to their impact[3]. Of these, firebrand transport has been studied most extensively[4-12]. Models have been developed to perform firebrand transport calculations; such models have assumed firebrand sizes to perform these calculations since little quantitative data exists with regard to firebrand size or firebrand mass produced from vegetation and structures. Experimentally determined regime maps that relate firebrand size and firebrand mass distribution generated from common vegetation species are required. Naturally, such regime maps are also a function of vegetation moisture content, vegetation geometry (*i.e.* size and shape), the particular vegetative species, as well as ambient wind conditions. Firebrand generation regime maps are also required to study ignition of fuel beds by firebrands[13,14]. In addition to firebrand production, the heat release rate (HRR) of trees is another factor than can contribute to fire spread in WUI fires. Little data exists in the open literature regarding the HRR of different tree species.

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To this end, a collaborative effort is underway between the National Institute of Standards and Technology (NIST) in the USA and the Building Research Institute (BRI) in Japan to study firebrand production and determine HRR from burning vegetation. The present paper reports on a series of real scale fire experiments that were performed to determine the mass and size distribution of firebrands generated from Korean Pine (*pinus koraiensis*). The height of trees used for the experiments was fixed at 4.0 m (3.6 m crown height) and the tree moisture content were varied from 10 % to 80 % (determined on a dry basis). Firebrands were collected using water filled pans to ensure that the firebrands would be quenched as soon as they made contact with the pans. The firebrands were subsequently dried, the sizes were measured using calipers, and the dry mass was determined using a precision balance. The Korean Pine trees were also mounted on load cells during burning to determine the temporally resolved mass loss profiles. The mass loss data were used to calculate the mass loss rate and infer heat release rate (HRR). Results of this study are compared to the firebrand distribution and HRR of burning Douglas-Fir (*pseudotsuga menziesii*) trees, a conifer tree species indigenous to the USA.

MATERIALS AND METHODS

Fig. 1 is a photograph of one of the Korean Pine (*pinus koraiensis)* trees used for the experiments. Korean Pine was selected as the tree species for these experiments since it is a common conifer species indigenous to China, Japan, and Korea. The height of the Korean Pine trees used was fixed at 4.0 m (3.6 m crown height). This was the largest sized tree that could safely be burned using BRI facilities. The maximum girth dimension was 1.5 m wide. The trees were size selected from a local nursery, cut, and delivered to BRI in Japan. Subsequently, the trees were mounted on custom stands and the trees were allowed to dry. During the experiments, no wind was imposed on the trees.

The moisture content of the tree samples was measured using a Computrac moisture meter (certain commercial equipment are identified to accurately describe the methods used; this in no way implies endorsement from NIST). Needle samples as well as small branch samples (three heights, four radial locations at each height) were collected for the moisture measurements. The measurements were taken on bi-weekly basis. The moisture content (MC), determined on a dry basis, is given as:

$$Moisture\,Content = \frac{M_{wet} - M_{dry}}{M_{dry}} * 100 \qquad [1]$$

where M_{wet} and M_{dry} are the mass of the tree samples before and after oven drying, respectively. At ignition, the tree moisture content was varied from 10 % to 80 %. The uncertainty in these measurements is estimated to be ± 15 %. More than 40 days of drying time was required to reach moisture content levels at or below 30 %. In order to dry the trees in a controlled manner, a custom drying room was constructed at BRI and it housed two dehumidifiers. The moisture removed from the room by the dehumidifiers was discharged to ambient. The justification for the moisture ranges used in this study is provided below.

A total of 6 Korean Pine trees were burned for data collection. The trees were ignited using a custom burner assembly specifically designed for these experiments. The burner was hexagonal in shape and surrounded the tree at its base, and was fueled with propane. The propane flow rate was measured using a dry test meter and this flow information was used to calculate the heat release rate (HRR) of the hexagonal burner assembly, 130 kW. The total ignition time was 60 s. Both digital still photography and standard color video (standard 30 frames per second) were used to record the ignition and burning process of the Korean Pine trees.

FIGURE 1. A photograph of one of the Korean Pine (*Pinus Koraiensis)* trees used for the experiments, MC = 13 %, 4.0 m height (3.6 m crown height)

Fig. 2 displays a schematic of the firebrand collection pan assembly. A total of 40 rectangular pans (water filled) were used to collect firebrands. Each pan was 49.5 cm long by 29.5 cm wide. The arrangement of the pans was not random; rather it was based on scoping experiments to determine the locations where the firebrands were most likely to land. After the experiments were completed, the pans were collected and the firebrands were filtered from the water using a series of fine mesh filters. The firebrands were subsequently dried in an oven held at 104 °C for eight hours. The firebrand sizes were then measured using precision calipers (1/100 mm resolution). Following size determination, the firebrands were then weighed using a precision balance (0.001 g resolution). For each tree burned, more than 150 firebrands were dried and measured. In all, more than 500 collected firebrands were sized and weighed.

The trees were mounted on a 2 m (width) by 2 m (length) by 6 mm (thickness) steel platform. The platform had a total weight of 200 kg. Four load cells (200 kg maximum load each, total 800 kg, with 20 g resolution) were mounted under the steel platform to obtain the temporally resolved mass loss profiles during burning. The load cells were calibrated using a series of standard weights (both below the tree weight and above the tree weight). The voltage from the load cells was recorded using custom data processing software as the trees burned with a temporal resolution of 100 ms. The load cell calibration, specifically mass as a function of voltage, was used to deduce the mass from the temporally resolved voltage plots.

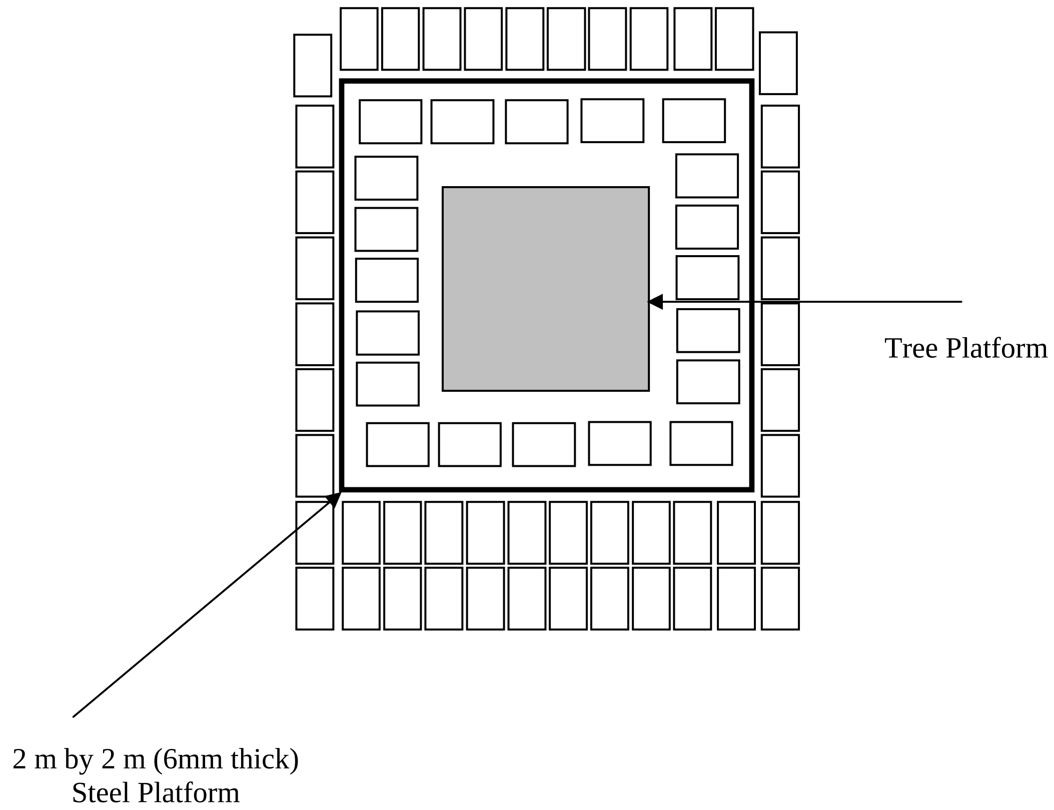

FIGURE 2. Schematic of firebrand collection pan assembly and platform supported by load cells

RESULTS AND DISCUSSION

To the authors' knowledge, experimental measurements to characterize the burning regimes of Korean Pine trees are not available in the open literature. Consequently, prior investigations using Douglas-Fir trees were used to guide the present experiments for Korean Pine trees[15,16]. It has been reported that for Douglas-Fir trees with moisture content (determined on a dry basis) greater than 70%, it was not possible to sustain burning after ignition. Within moisture content limits of 30 % to 70%, a regime occurs where Douglas-Fir trees will only partially burn after an ignition source is applied. Below 30 % moisture content, the Douglas-Fir trees were observed to burn intensely; typically the entire tree was engulfed in flame within 20 seconds after ignition[15,16].

Therefore, the firebrand collection experiments were performed in the following manner. Korean Pine trees of 4.0 m were ignited at a moisture content of 50 %. It was observed that the Korean Pine trees would only partially burn. Furthermore, at the 50 % moisture content level, a significant number of firebrands were not produced. From these results, experiments were then performed using lower moisture contents. Under these conditions, the Korean Pine trees were observed to burn more intensely and copious amounts of firebrands were produced. In summary, Korean Pine trees generated firebrands only if the moisture content was maintained below 35 %, with no wind applied.

For all experiments performed, the firebrands were cylindrical in shape. The average firebrand size measured (based on three similar experiments; 550 firebrands measured) for the 4.0 m (3.6 m crown height) Korean-Pine trees (11 % moisture content, average based on three trees) were 5.0 mm in diameter, 34 mm in length. Fig. 3 displays the distribution of the diameter and length of all firebrands collected for the Korean Pine tree experiments. A large percentage of the firebrands collected and weighed were less than 0.3 g. The largest mass class of firebrands measured for the Korean Pine trees were in the range of 3.7 g to 3.9 g.

The temporal variation of the mass loss rate (determined from measured load cell data) during burning is shown in Fig. 4 for a representative Korean Pine tree experiment (4.0 m in height, 3.6 crown height, 10 % moisture content). The peak mass loss rate was 0.2 kg/s.

Douglas-Fir tree burns have been performed at the Large Fire Laboratory (LFL) at NIST. Douglas-Fir was selected as the tree species for the experiments in the USA since it is abundant in the Western United States of America and it is this part of the USA where WUI fires are most prevalent[1,6]. The height of the Douglas-Fir trees used for the firebrand collection experiments was varied from 2.6 m (2.4 crown height) to 5.2 m (4.5 m crown height). The maximum girth dimension was 1.5 m wide and 3.0 m wide, for the 2.4 m and 5.2 m crown heights, respectively. Results will only be presented here, as further experimental details regarding the Douglas-Fir tree burns used for firebrand collection are described in detail elsewhere[17].

Douglas-Fir trees do not produce significant numbers of firebrands if the moisture content is larger than 30 %, no wind applied[17]. For all of the Douglas-Fir experiments performed, the firebrands were cylindrical in shape. In fact, the geometry of the collected firebrands was similar for both species. The average firebrand size measured (based on three similar experiments; 210 firebrands measured in total for each height) from the 2.4 m crown height Douglas-Fir trees (11 % moisture content, average based on three trees) were 3 mm in diameter, 40 mm in length. The average firebrand size measured (based on three similar experiments) for the 4.5 m crown height Douglas-Fir trees (18 % moisture content, average based on three trees) was 4 mm in diameter with a length of 53 mm. Fig. 3 displays the distribution of the diameter and length of all firebrands collected for the Douglas-Fir tree experiments.

The mass distribution of firebrands produced from the two different tree species under similar tree moisture levels and size ranges were similar for mass classes less than 0.3 g. A noticeable difference occurred in the larger mass classes. Firebrands with masses up to 3.5 g to 3.7 g were observed for the 4.0 m Korean Pine and 5.2 m Douglas-Fir trees, but not for the 2.6 m Douglas-Fir trees.

The temporal variation of the mass loss rate during burning is shown in Fig. 4 for a representative Douglas-Fir tree experiment. For a 2.4 m crown height Douglas-Fir tree experiment performed at 10 % moisture content, the peak mass loss rate during was 0.4 kg/s. For the 4.5 m crown height Douglas-Fir tree experiment (see Fig. 4) performed at 23 % moisture content, the peak mass loss rate during burning was 1.4 kg/s; three and half times more than the smaller Douglas-Fir trees used.

It is important to note that the LFL at NIST is equipped with a 9 m by 12 m hood assembly which can be used to measure the HRR of burning objects using oxygen consumption calorimetry. If the hood system was operated, the firebrands generated would be drawn into the hood; thus no firebrand collection was possible. Therefore, for the experiments described in this work, it was not possible to measure the HRR in the LFL using oxygen consumption calorimetery; rather only mass loss was recorded. The facilities at BRI were not equipped with oxygen consumption calorimetry.

The HRR was estimated from mass loss rate for the Korean Pine trees and Douglas-Fir trees. The heat of combustion (H_C) of the gaseous fuel used for Douglas-Fir was 17,700 kJ/kg. This result was obtained by averaging the Douglas-Fir wood and foliage measurements[18,19]. To the author's knowledge, data is not available in the open literature for the heat of combustion for Korean Pine volatiles. Consequently, the results used for Douglas-Fir H_c were used to estimate the HRR for the Korean Pine trees. Assuming an efficiency factor of $\chi = 0.6$, the peak HRR was estimated to be 2.1 MW, 4.2 MW, and 16.6 MW for the Korean Pine trees, 2.4 m crown height and 4.5 crown height Dougals-Fir trees, respectively. The peak HRR was considerably lower for 3.6 crown height Korean Pine trees as compared to the smaller 2.4 crown height Douglas-Fir trees.

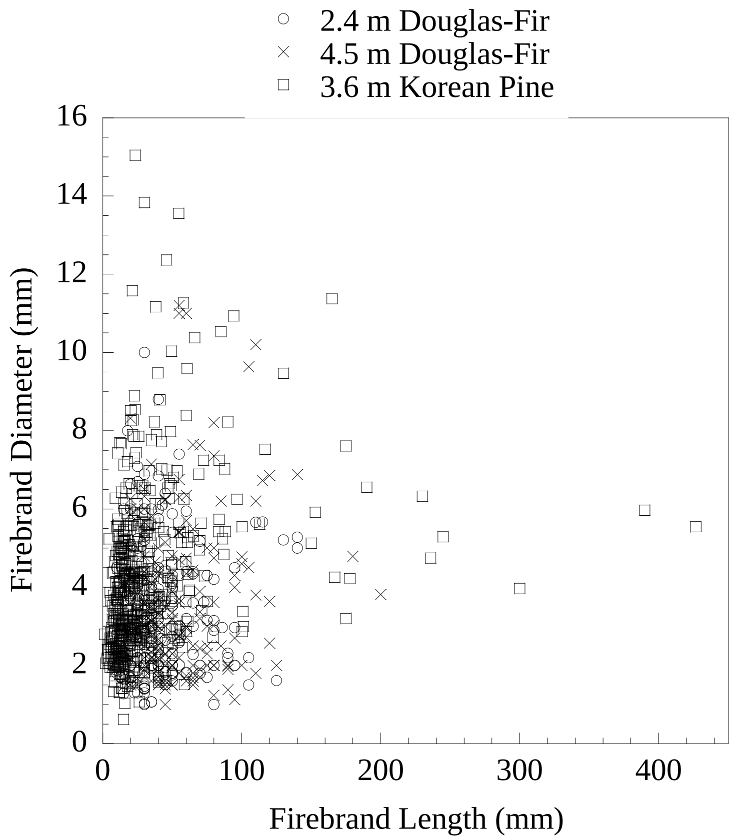

FIGURE 3. Measured firebrand length and diameter for Douglas-Fir and Korean Pine trees

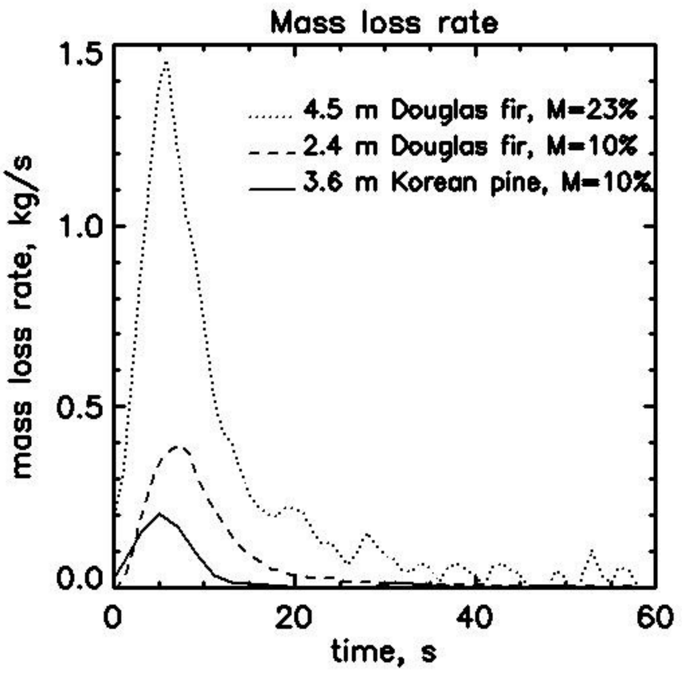

FIGURE 4. Temporal variation of mass loss rate during burning for Korean Pine Trees and Douglas-Fir trees; a representative experiment is displayed for each size tested

Babrauskas[15] developed an empirical correlation for the maximum heat release rate based upon a series of Douglas-Fir trees burns. The correlation is given as:

$$\frac{\dot{q}}{m} = e^{5.84-0.017M} \qquad [2]$$

where $\dot{q}$ is the peak heat release rate in kW, m is the total pre-burn mass of the tree in kg, and M is the needle moisture content in percent dry weight. For the 2.4 m crown height and 4.5 m crown height Douglas-Fir trees, the total pre-burn mass was 9.5 kg and 53 kg, respectively. Using the Babrauskas correlation results in a calculated peak HRR of 2.8 MW and 12.2 MW for the 2.4 m crown height and 4.5 crown height Douglas-Fir trees, respectively. The agreement is reasonable for both the smaller and larger tree sizes tested here; a surprising result for the 4.5 m crown height trees as the correlation was developed using a series of Douglas-Fir trees similar in size to the smaller 2.4 crown height trees.

CONCLUSIONS

Korean Pine trees do not produce significant numbers of firebrands burning singly with no imposed heat flux if the moisture content is larger than 35 % (no wind applied). For all tree experiments performed, the firebrands were cylindrical in shape. In fact, the geometry of the collected firebrands was similar for both species. The average firebrand size measured from the 4.0 m (3.6 m crown height) Korean Pine trees were 5 mm in diameter, 40 mm in length. The peak HRR was considerably lower for 3.6 crown height Korean Pine as compared to the smaller 2.4 crown height Douglas-Fir tree. The data generated from these experiments will be useful for fire models used to predict spotting in WUI fires.

ACKNOWLEDGEMENTS

Mr. S. Nanno and Mr. K. Nakamura (BRI Guest Researchers, under the supervision of Dr. Ichiro Hagiwara of BRI) completed some of the analysis for the firebrand mass and size distributions of Korean Pine tree experiments; their able help is this regard is appreciated. The assistance of Mr. Marco G. Fernandez, Engineering Technician, of BFRL-NIST with the experiments is acknowledged. Dr. William Grosshandler, Fire Research Division Chief, is acknowledged for supporting this research at NIST.

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