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Mass and size distribution of firebrands generated from burning Korean pine (*Pinus koraiensis*) trees

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SUMMARY

The present study 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*), a common conifer species indigenous to China, Japan, and Korea. The experiments were performed at the Building Research Institute in Tsukuba, Japan. The total tree height was fixed at 4.0 m 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 pans. The pans used for firebrand collection were filled with water. This ensured that firebrands would be quenched as soon as they made contact with the pans. The firebrands were subsequently dried and the mass and size of more than 500 firebrands were measured. 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 compare the total amount of mass collected as firebrands with the total amount of mass burned. Results of this study are presented and compared with the mass and size distribution of firebrands collected from burning Douglas-fir trees, a conifer tree species indigenous to the U.S.A. Copyright © 2008 John Wiley & Sons, Ltd.

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INTRODUCTION

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.

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Understanding how these hot firebrands are formed and the mechanisms by which they can ignite surrounding fuel beds is an important consideration in mitigating fire spread in communities. Firebrand ignition has been an outstanding problem that has plagued both the U.S.A. and Japan.

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. Waterman [1] burned full-scale segments of different roof assemblies; the firebrands collected were generally disk shaped. Waterman [1] did not perform any experiments concerning firebrand generation from vegetation.

An advance in WUI fire research would be the development of a model to predict: 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 [2]. Of these, firebrand transport has been studied most extensively [3–12]. These models have generally assumed firebrand sizes to perform transport calculations, since little quantitative data exist 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 (MC), 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 [13–15].

To this end, an international collaboration has been established between the National Institute of Standards and Technology (NIST) in the U.S.A. and the Building Research Institute (BRI) in Japan to study firebrand production from burning vegetation and structures. 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*), a common conifer species indigenous to China, Japan, and Korea. The height of trees used for the experiments was fixed at 4.0 m and the tree MC was 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 compare the total amount of mass collected as firebrands with the total mass burned. Results of this study are compared with the mass and size distribution of firebrands collected from burning Douglas-fir (*Pseudotsuga menziesii*) trees, a conifer tree species indigenous to the U.S.A.

EXPERIMENTAL DESCRIPTION

Figure 1(a) is a photograph of one of the Korean pine (*P. koraiensis)* trees used for the firebrand collection 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 for the firebrand collection experiments was fixed at 4.0 m. 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.

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(a)


Figure 1. (a) A photograph of Korean pine (*Pinus koraiensis)* tree used for the firebrand collection experiments, MC = 13% and (b) a drawing of the hexagonal burner used to ignite the Korean pine and Douglas-fir trees.

The MC of the tree samples was measured using a Computrac‡ moisture meter. 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 a bi-weekly basis. The MC, determined on a dry basis, is given as

$$\textit{Moisture content} = \frac{M_{\text{wet}} - M_{\text{dry}}}{M_{\text{dry}}} \times 100 \tag{1}$$

where M_{wet} and M_{dry} are the mass of the tree samples before and after oven drying, respectively. At ignition, the tree MC 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 MC levels of 30% or below. 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 the ambience. The justification for the moisture ranges used in this study is provided below.

A total of six Korean pine trees were burned to collect firebrands, all 4.0 m in height. The trees were ignited using a custom burner assembly specifically designed for these experiments. The

‡Certain commercial equipments are identified to accurately describe the methods used; this in no way implies endorsement from NIST.

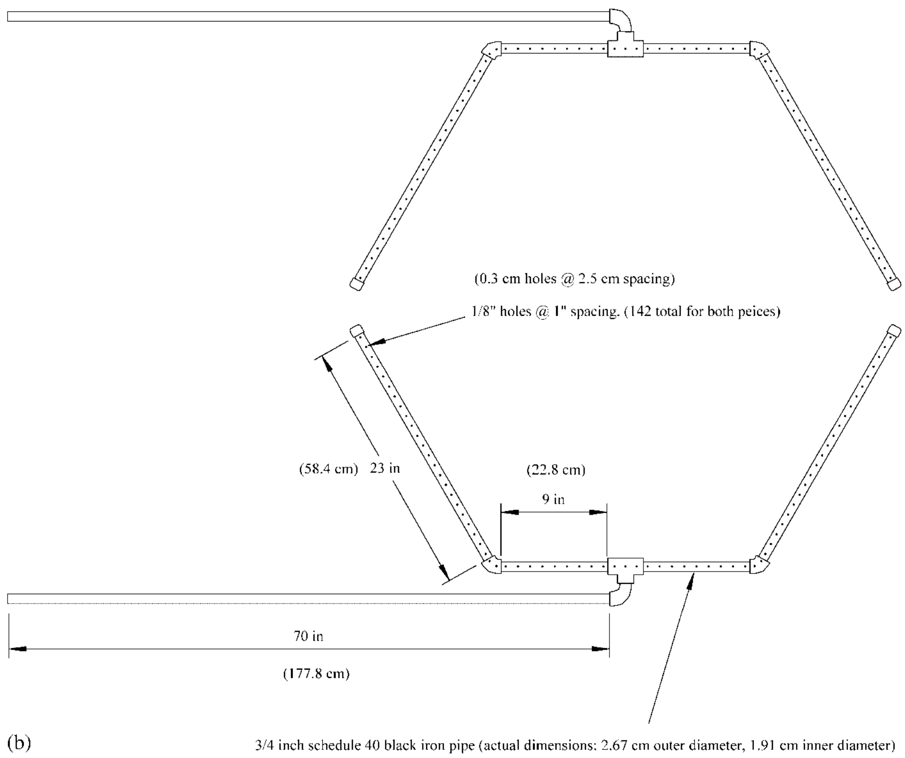

Figure 1. *Continued.*

burner was hexagonal in shape and surrounded the tree at its base, and was fueled with propane (see Figure 1(b)). 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 2 displays a schematic of the firebrand collection pan assembly. A total of 68 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 maintained at 104°C for 8 h. 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

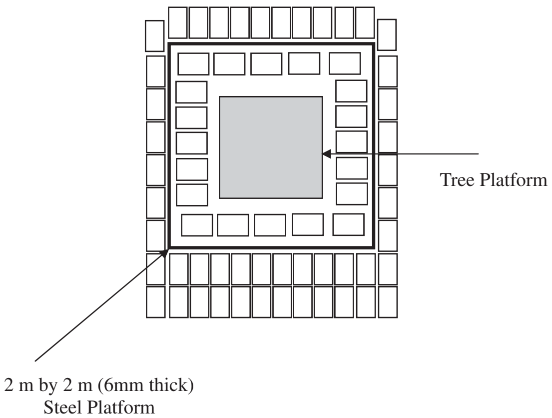

Figure 2. Schematic of firebrand collection pan assembly.

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.

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 [16, 17]. It has been reported that for Douglas-fir trees with MC (determined on a dry basis) greater than 70%, it was not possible to sustain burning after ignition. Within MC limits of 30–70%, a regime occurs where Douglas-fir trees will only partially burn after an ignition source is applied. Below 30% MC, the Douglas-fir trees were observed to burn intensely; typically the entire tree was engulfed in flame within 20 s after ignition [16, 17].

Therefore, the firebrand collection experiments were performed in the following manner. Korean pine trees of 4.0 m were ignited at a MC of 50%. It was observed that the Korean pine trees would only partially burn. Furthermore, at the 50% MC level, a significant number of firebrands were not produced. From these results, experiments were then performed using lower MCs. 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 MC was maintained below 35%, with no wind applied.

Figure 3 displays a digital photograph of the firebrands collected from the Korean pine tree burns. 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 Korean pine trees (11% average MC) were 5.0 mm in diameter and 34 mm in length.

The mass distribution obtained for the 4.0 m Korean pine trees is displayed in Figure 4(a). A large percentage of the firebrands collected and weighed were less than 0.3 g. The largest mass class

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Figure 3. Digital photographs showing samples of the firebrands collected as a function of moisture content. Experimental conditions: tree height 4.0 m and moisture content 13%.

of firebrands measured for the Korean pine trees were in the range of 3.7–3.9 g. The surface area distribution was also calculated assuming cylindrical geometry and plotted *versus* the measured mass for the collected firebrands. These data are shown in Figure 5, along with data for Douglas-fir trees, which is discussed below. The surface area of the firebrands scaled with firebrand mass.

The temporal variation of the mass loss during burning is shown in Figure 6(a) for three similar experiments of Korean pine burns (4.0 m in height, $\approx$11% average MC). The initial mass was set to zero upon ignition in order to more clearly track the evolution of mass loss. The average mass loss after approximately 2 min of burning was 1.58 kg (varied from 1.25 to 1.91 kg, see Figure 6(a)). It is worthwhile to compare the average mass collected as firebrands at the pan locations with the average mass loss during burning. For three Korean pine tree burns, the average mass collected as firebrands was 33 ± 15 g. Therefore, of the 1.58 kg mass that was lost during burning, 2% was measured as firebrands at the pan locations, provided no wind was applied and the trees were maintained at 11% average MC.

Comparison to Douglas-fir (P. menziesii) trees

Douglas-fir tree burns have been performed at the Large Fire Laboratory (LFL) at NIST. It is useful to compare some results from these experiments with data obtained from Korean pine, a different species, under similar MC. Douglas-fir was selected as the tree species for the experiments in the U.S.A. since it is abundant in the Western United States of America and it is this part of the U.S.A. where WUI fires are most prevalent [5, 18]. The total height of the Douglas-fir trees used for the firebrand collection experiments varied from 2.6 to 5.2 m. The maximum girth dimension was 1.5 m wide and 3.0 m wide, for the 2.6 and 5.2 m tree heights, respectively. Results will only be presented here; further experimental details regarding the Douglas-fir tree burns used for firebrand collection are described in detail elsewhere [19].

Douglas-fir trees do not produce significant numbers of firebrands if the MC is larger than 30% (no wind applied) [19]. 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

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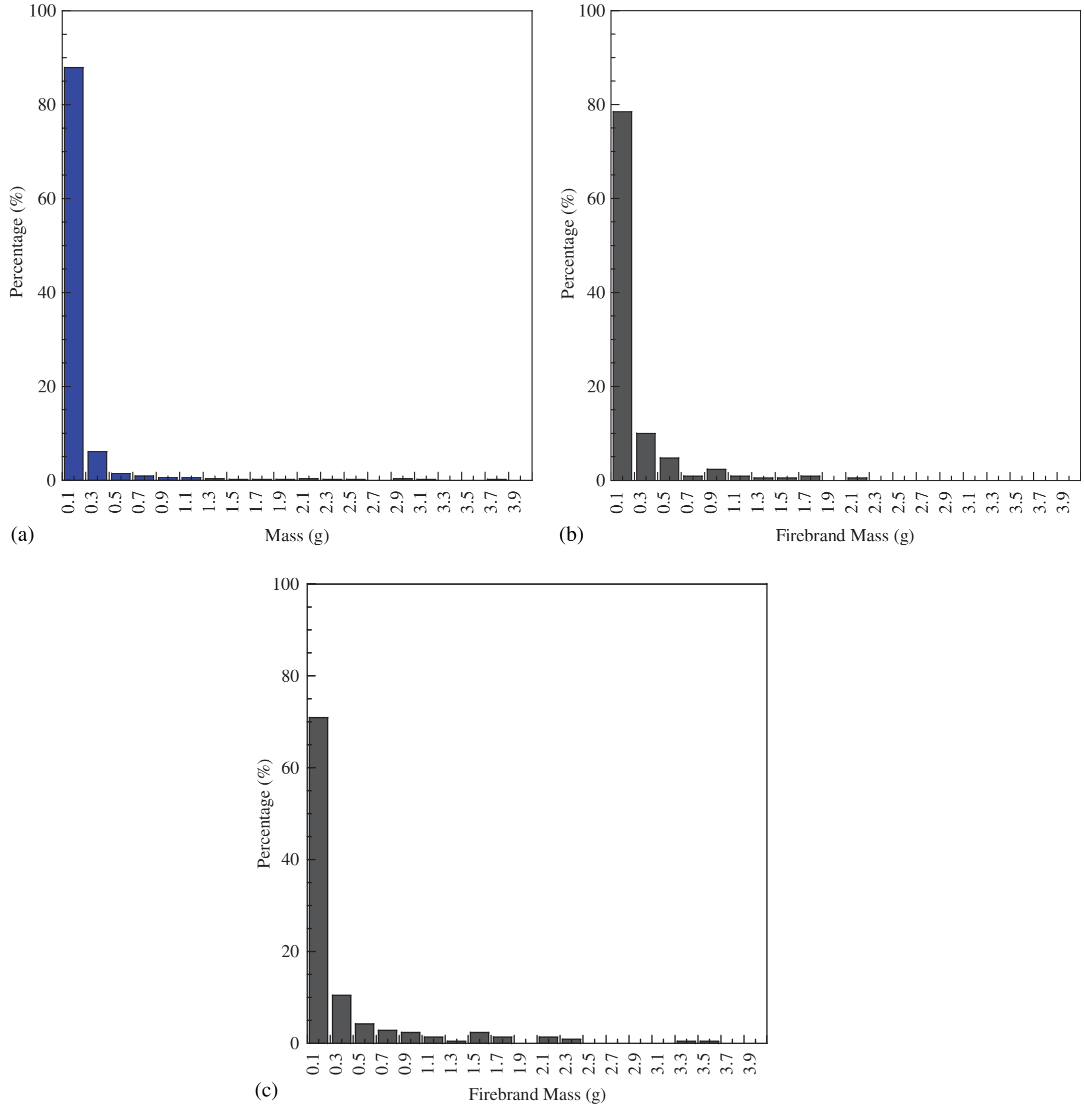

Figure 4. Mass distribution of collected firebrands for (a) 4.0 m Korean pine trees; (b) 2.6 m Douglas-fir trees; and (c) 5.2 m Douglas-fir trees.

in total for each height) from the 2.6 m Douglas-fir trees (10% average MC) were 3 mm in diameter and 40 mm in length. The average firebrand size measured (based on three similar experiments) for the 5.2 m Douglas-fir trees (18% average MC) was 4 mm in diameter with a length of 53 mm.

The mass distribution obtained for the 2.6 m Douglas-fir trees is displayed in Figure 4(b). A large percentage of the firebrands collected and weighed were less than 0.3 g. Manzello *et al.* [15] have found that cylindrical firebrands constructed from Douglas-fir with a mass of 0.3 g are able to cause ignition of fuel beds. The largest mass class of firebrands measured for the 2.6 m Douglas-fir

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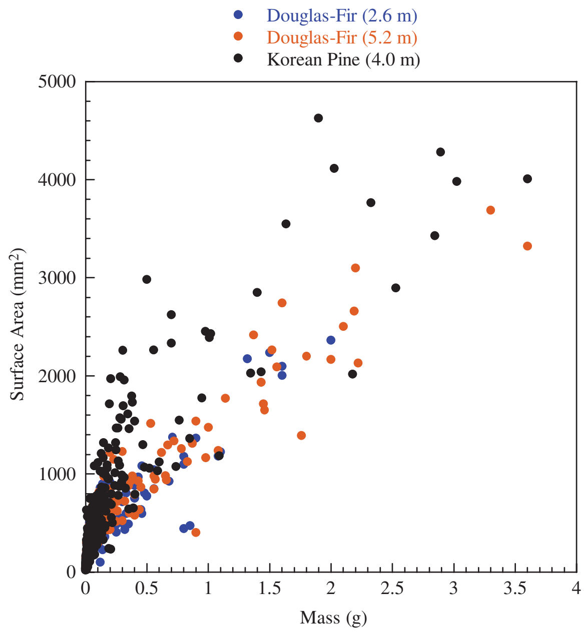

Figure 5. Calculated surface area plotted as a function of the mass of the collected firebrands.

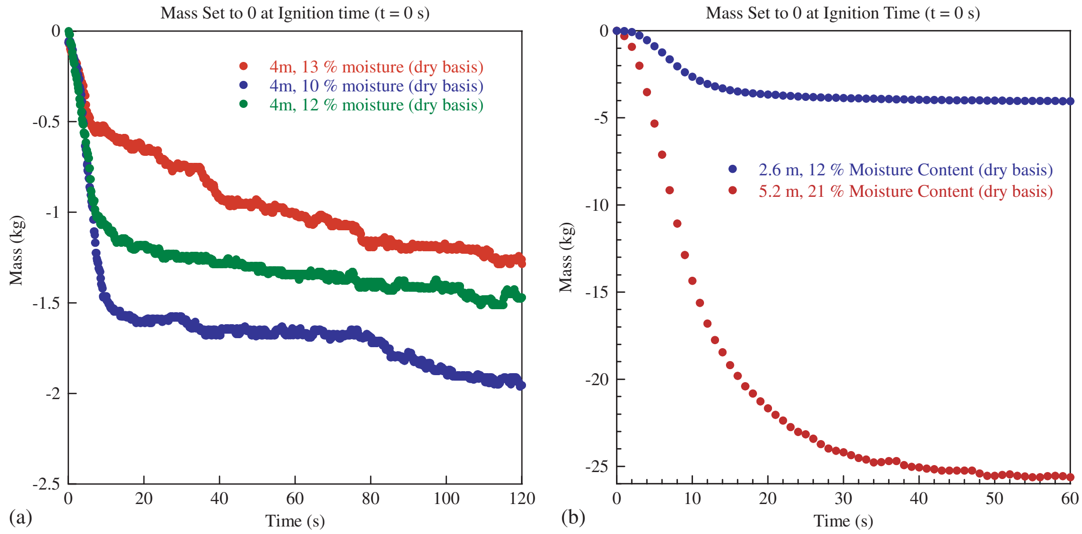

Figure 6. (a) Temporal variation of mass during burning for Korean pine trees (4.0 m), three replicate experiments are shown and (b) temporal variation of mass during burning for Douglas-fir trees (for 2.6 and 5.2 m heights).

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trees were in the range of 2.1–2.3 g. The mass distribution obtained for 5.2 m Douglas-fir trees is displayed in Figure 4(c). 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 3.5–3.7 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 surface area distribution was also calculated assuming cylindrical geometry and plotted *versus* the measured mass for the collected firebrands. These data are shown in Figure 5. Although the surface area of the generated firebrands scaled with firebrand mass for both species, the scaling clearly shows a dependence on tree species.

The temporal variation in the mass loss during burning is shown in Figure 6(b) for Douglas-fir trees (2.6 m in height, 10% average MC). For the 2.6 m Douglas-fir tree experiments performed at 10% MC, the average mass loss during burning was 4 ± 0.1 kg. The average firebrand mass collected in the pans based on three replicate experiments was 18 ± 4 g. Therefore, of the 4 kg of mass that was lost during burning, 0.45% was measured as firebrands at the pan locations.

For the 5.2 m Douglas-fir tree experiments (see Figure 6b) performed at 18% average MC, the average mass lost during burning was 24 ± 1 kg (based on three similar experiments, Figure 6(b) displays the results of only one 2.6 and one 5.2 m tree experiment for clarity), about six times more than the 2.6 m Douglas-fir trees. A mass of 50 ± 5 g was measured as the total mass collected as firebrands in the pans. When comparing the mass collected as firebrands with the mass lost during burning, this ratio decreased from 0.45% for the 2.6 m trees to 0.2% for the 5.2 m trees.

An interesting comparison between the two species tested was that the mass loss during burning was considerably less for 4.0 m Korean pine trees as compared with the Douglas-fir trees (even the smaller 2.6 m Douglas-firs), under similar initial tree MC. As a result, when comparing the ratio of the amount of mass collected as firebrands to the total mass burned, Korean pine trees produced a larger number of firebrands, per mass of fuel burned. A similar result was also observed when comparing the ratio of the amount of mass collected as firebrands with the total initial tree weight. These results are summarized in Table I.

The fuels that are observed to burn during the combustion of trees can be divided into three broad mass classes: needles, twigs from 0 to 6 mm diameter, and twigs from 6 to 10 mm diameter. Twigs larger than 10 mm diameter are not observed to burn during tree combustion over the range of MCs considered in the present study. For the 2.6 m Douglas-fir trees, 65% of the burnable mass is needles, 17.5% is twigs from 0 to 6 mm, and 17.5% is twigs from 6 to 10 mm. Similar results have been obtained for larger Douglas-fir trees. For Korean pine trees, it was observed that 58% of the burnable mass is needles, 24% is twigs from 0 to 6 mm, and 18% is twigs from 6 to 10 mm.

Table I. Summary of firebrand masses collected (m_{fb}) and ratio of mass collected as firebrands to mass lost during burning as well as ratio of mass collected as firebrands to total tree mass.

Tree species	Mass of firebrands, m_{fb} (g)	Mass of firebrands/mass lost during burning (%)	Mass of firebrands/total tree mass (%)
Korean pine (4.0 m)	33 ± 15	2	0.28
Douglas-fir (2.6 m)	18 ± 4	0.45	0.15
Douglas-fir (5.2 m)	50 ± 5	0.2	0.08

Notes: Initial moisture content of all trees tested was similar.

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It is interesting to see that for the two species, the breakdown of burnable mass classes are very similar, and in both cases the largest percentage of burnable mass is needles, and needles do not form firebrands. Therefore, the difference in the mass of firebrands produced per mass of fuel cannot be explained in this manner.

A plausible explanation for this behavior may be related to the dynamic burning process of the two different species itself. For Douglas-fir trees, the structure of the tree is fuller than Korean pine trees. As a result, after the ignition source was applied, the Douglas-fir trees were observed to burn intensely; complete burning occurred after 50–60 s after ignition for both sizes tested (see Figure 6(b)). For Korean pine trees, the tree structure was more open, specifically it was possible to actually see through the trees. Accordingly, after the ignition source was applied, the Korean pine trees were observed to burn in a more sporadic process, taking on average over 2 min for burning to cease. Therefore, in the case of Douglas-fir trees, the amount of energy release was greater, as heat release scales with the mass loss rate, which increased dramatically as the Douglas-fir tree size was increased. Recently, Manzello *et al*. [20] estimated the HRR for Douglas-fir trees and Korean pine trees and have quantitatively shown that the HRR is larger for Douglas-fir trees compared with Korean pine trees (of similar size and moisture content). Since the majority of firebrands collected from both species lay in a small mass range, it is postulated that in the case of Douglas-fir trees, most of the firebrands produced are actually consumed since these small mass classes of firebrands are exposed to a more intense fire plume, as compared with Korean pine trees. Manzello *et al.* [13–15] have found that the burnout time for smaller firebrands was indeed less than firebrands with larger initial mass.

SUMMARY

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 (*P. koraiensis*) trees, a common conifer species indigenous to China, Japan, and Korea. The height of trees used for the experiments was fixed at 4.0 m and the tree MCs were varied from 10 to 80% (determined on a dry basis). Results of this study were compared with the mass and size distribution of firebrands collected from burning Douglas-fir (*P. menziesii*) trees, a conifer tree species indigenous to the U.S.A.

Korean pine trees do not produce significant numbers of firebrands if the MC 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 Korean pine trees was 5 mm in diameter and 40 mm in length. Although the surface area of the generated firebrands scaled with firebrand mass for both species, the scaling clearly shows a dependence on species. Korean pine trees produced a larger mass of firebrands, per amount of fuel burned. A plausible explanation for this behavior may be related to the dynamic burning process of the two different species itself. The data generated from these experiments will be useful for fire models used to predict spotting in WUI fires.

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tree experiments; their able help is this regard is appreciated. The assistance of Mr M. 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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