STEM MORTALITY IN SURFACE FIRES. PART II, EXPERIMENTAL METHODS FOR CHARACTERIZING THE THERMAL RESPONSE OF TREE STEMS TO HEATING BY FIRES.

D.M. Jimenez, B.W. Butler*, and J. Reardon
USDA Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory,
Missoula Montana 59807

1. INTRODUCTION

Current methods for predicting fire-induced plant mortality in shrubs and trees are largely empirical. These methods are not readily linked to duff burning, soil heating, and surface fire behavior models. In response to the need for a physics based model of this process, a detailed model for predicting the temperature distribution through a tree stem as a function of time when subjected to a time varying heat pulse has been developed (Jones et al, 2003).

Tree mortality in fires can be caused by three different mechanisms: crown scorch, root heating, and stem heating. These three mechanisms can work individually or in combination to cause tree mortality (Dickinson and Johnson 2001). During low-intensity ground fires (a common scenario for prescribed burns), it is possible for the roots and the crowns of the trees to escape injury (Peterson and Ryan 1986). However, these same low-intensity fires can cause girdling of the plant stem due to stem heating from the burning process.

Stem heating models for fire applications that have been published previous to this study require specification of the stem surface temperature variation with time. Currently used fire behavior models do not directly predict tree surface temperature. Fire models do predict fire intensity, size, and rate of spread, all of which can be combined to generate the heat flux incident on tree stems as a function of time.

In his model Jones (2003) makes use of moisture and temperature dependent thermal properties for bark and wood. Also, the thermal aspects of the processes of bark swelling, desiccation, and devolatilization are treated in an approximate fashion. This model uses a flux-time profile for its boundary condition; making it possible to eventually couple it to fire behavior models.

---

* *Corresponding author address*: B.W. Butler, Fire Sciences Laboratory, P.O. Box 8089, Missoula, MT 59807; e-mail: bwbutler@fs.fed.us

Extensive effort has focused on the development of methods for experimentally validating this model. Typically published numerical stem heating models have only included two or three experiments to validate the model. Herein we outline the experimental procedure conducted for more than 59 separate experiments on four different tree species, including two softwoods common in western US forests: Ponderosa Pine (*Pinus ponderosa*) and Douglas Fir *(Pseudotsuga menziesii),* and two hardwoods common in central US forests: Red Maple (*Acer rubrum*) and Chestnut Oak (*Quercus prinus*). In this paper, we present an overview of the experimental methods and summarize the results.

2. METHODS

The combined stem heating and cell mortality model was evaluated by comparison with experimental data designed to illustrate the extent of thermal damage on stems. Two types of stem heating experiments were performed based on whether the experiment occurred in the laboratory or in the field. Laboratory experiments were conducted on stem sections of each of the four species. Field burns were conducted during research prescribed burns in Montana and Arizona. Only Ponderosa Pine, Douglas Fir, and Lodgepole Pine were evaluated in the field burns.

2.1 Laboratory Experiments

Douglas fir and ponderosa pine sections were collected at the University of Montana's Lubrecht Experimental Forest near Missoula, Montana (elevation 1500 m; N 46:53.503, W 113: 27.012), while red maple and chestnut oak trunk sections were collected from the USDA Forest Services' Vinton Furnace Experimental Forest in southeastern Ohio, USA (elevation 275 m; N 39:11.956, W 82:23.776). Trunk sections were transported in coolers with ice packs to the Forestry Sciences Laboratory in Missoula, MT, and were either tested immediately or stored in an environmental chamber for no more than 3 days post-harvest before being tested. Sections of freshly cut tree samples from each of the four species were instrumented with heat flux sensors

at the surface and thermocouples under the bark. Figure 1 illustrates schematically the arrangement of the instrumentation. In order to place the thermocouples as near the cambium as possible, 0.20 cm diameter holes were drilled roughly 15 cm deep along the interface between the bark and wood, parallel to the stem axis. The Type K thermocouples (nominally 1.0 mm bead diameter) were inserted into the drilled holes. Where possible, these thermocouple locations were positioned under the thick plates in the bark. More precise thermocouple placement location was
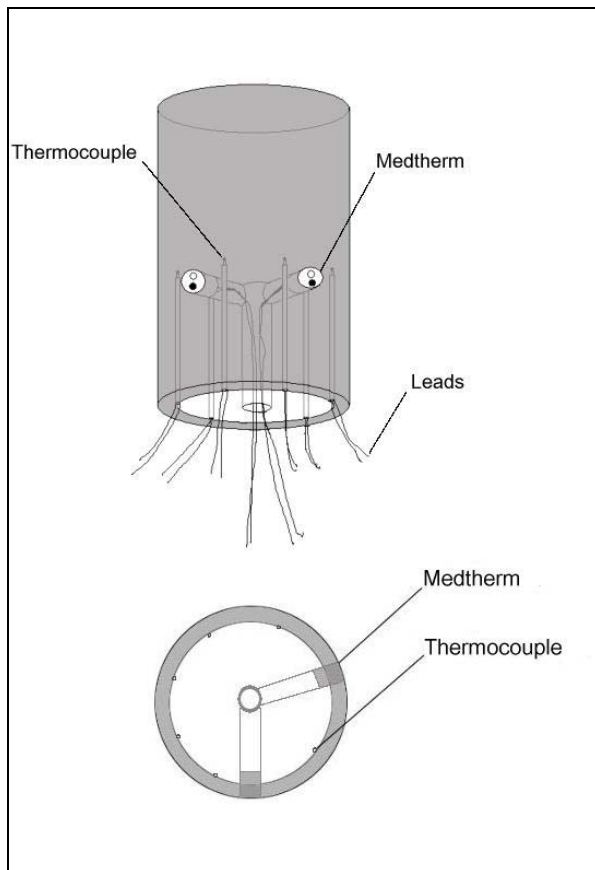

Figure 1. Oblique view and bottom view showing how the instruments were inserted through the bottom surface of a section of a tree stem during the laboratory experiment.

determined by dissecting the bark after the burn was conducted. The number of thermocouples used for each experiment varied from 3 to 6 and was dependent on the stem diameter. Subsurface temperature measurements in the bark were intended to quantify temperatures at the vascular cambium. Not surprisingly, measurements from the multiple thermocouples revealed considerable variation in temperature. These measurements

were averaged for comparison with the model predictions. The variation in peak cambial temperatures among the several thermocouples was quantified by presenting the maximum spread in individual temperature measurements.

Schmidt-Boelter type heat flux sensors were used to measure heat flux at the surface of the test specimens. Either one or two, depending on sample diameter, holes 2.5 cm diameter were drilled normal to the bark surface for mounting the heat flux sensors (see Figure 1). When mounted, these faced outward so as to measure the total (radiative and convective) heat flux incident on the gage. The heat flux gages and the thermocouples were placed nominally at the same height above the stem section base (15 cm). Figure 2 shows a temperature profile and corresponding heat flux trace associated with a typical laboratory experiment.

The bark thickness and moisture are critical parameters in the model. This is because desiccation proves to be a very effective energy absorption mechanism that protects the vital tissues from elevated temperatures. The moisture content was determined for the stem samples by sectioning the bark into inner and outer regions, and making careful weight measurements on the inner bark before and after drying. The outer and inner bark moistures were determined on a dry mass basis, calculating the ratio of the difference in wet and dry bark weights to the dry bark weight.

A kerosene-soaked cotton rope was wrapped around the perimeter of the stem at the bottom of the sample, wired into place at the base of the stem, and ignited to simulate a surface fire, in a manner similar to the experimental procedure of Russell and Dawson (1994). The method resulted in heating around the entire sample. The duration of the burn was controlled by the diameter of the rope used. Experiments done in this manner yielded heat flux magnitudes and burn durations that were similar to measurements obtained in actual surface fires (Hengst and Dawson 1994).

Heat flux measurements ranged from 15 to 40 kW-m^{-2} and burning duration ranged from 5 to 10 minutes, after which the flames subsided.

2.2 Field Experiments
Field experiments were conducted in the field under prescribed burning conditions. Three separate sites were selected: the Lubrecht Experimental Forest in western Montana, Tenderfoot Experiment Forest in central Montana,
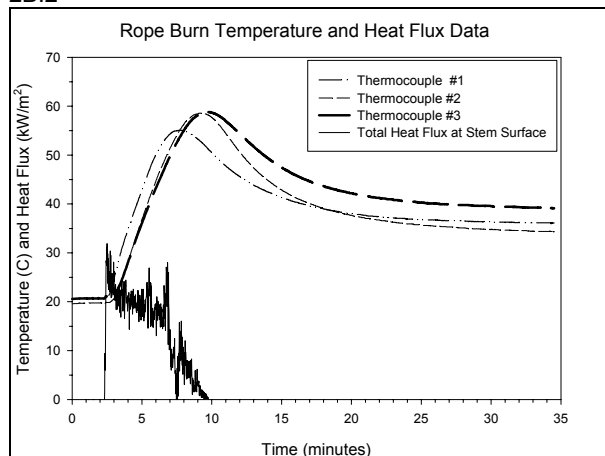
Figure 2: Example of laboratory experiment data.

and the Tonto National Forest in central Arizona. For these burns tree stems were instrumented in a similar fashion to the laboratory experiments while keeping the natural fuels intact. Fuel loads ranged
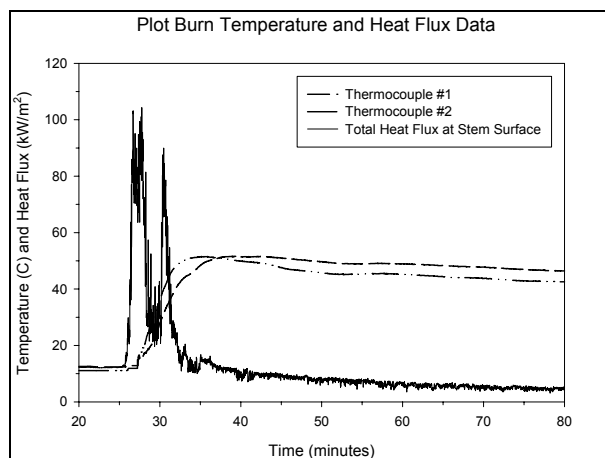

Figure 4: Example of field experiment data.

from light needle cast to heavy downed woody debris. Additional fuels were sometimes built up around sample trees in order to achieve greater fire intensity.

One to two thermocouples were placed under the bark, the tips of the thermocouples, when in place, were never closer than 4 cm to the heat flux instrument. The heat flux sensors were inserted from the back of the stem through a 2.5 cm hole. The wiring and data loggers were heavily insulated prior to ignition. Experiments done in this manner yielded heat flux magnitudes of 15 to 80 kW-m^{-2} and burning duration from 5 to 20 minutes. Figure 4 shows a temperature profile and corresponding heat flux trace associated with a typical plot burn.

3. CONCLUSIONS

Two different techniques were used to gather validation data for the stem heating model. Both methods proved to be dependable and provided excellent results. A total of 45 laboratory and 14 field experiments were conducted.

The methods developed for the laboratory experiments proved to be an effective and reliable technique for collecting large amounts of data with relative ease. Future validation experiments will provide additional data for species yet to be tested. Field experiments provided important information about the intensities and heating levels representative of prescribed burns.

4. REFERENCES

Dickinson, M.B. and Johnson, E.A. 2001. Fire effects on trees. *In* E. A. Johnson and K. Miyanishi (eds) Forest Fires: Behavior and Ecological Effects. Academic Press, New York. pp. 477-525.

Hengst, G.E., and Dawson, J.O. 1994 Bark properties and fire resistance of selected tree species from the central hardwood region of North America. Can. J. For. Res. **24**: 688-696.

Jones, J.L., 2003. Development of a model for prediction of stem mortality under fire conditions. MS Thesis, Brigham Young University, Provo, UT.

Jones, J.L., Webb, B.W., Jimenez, D., Reardon, J., and Butler, B. 2003. Development of an advanced one-dimensional stem heating model for application in surface fires. Can. J. For. Res. (in press).

Peterson, D.L. and Ryan, K.C. 1986. Modeling postfire mortality for long-range planning. Environmental Management. **10**, No. 6: 797-808.

Russell, M.S. and Dawson, J.O. 1994. The effects of artificial burning on cambial tissue of selected tree species of the central hardwood region of North America. *In* 1994 Proceedings of the Midwest Oak Savanna Conferences.