Cone Calorimeter Testing of Vegetation: An Update

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Abstract

As part of efforts to address fire problems in the wildland–urban interface, the cone calorimeter is being used to measure the relative flammability of different plant species. In the first two studies, we tested plants used to landscape homes in California and an assortment of plants found in Colorado. Using the effective heat of combustion and the peak heat release rate, we found significant differences between some plants. Current efforts include a study of the relative flammability of native and invasive plants of the northeastern United States. We need to continue our evaluation of the benefits and limitations of using the cone calorimeter to measure the relative flammability of different plant species.

Introduction

Once again in 2002, as in many years past, the safety of homes during forest fires is a major issue. As of June 25 of this year, 618 residences, 760 outbuildings, and 26 commercial structures have been destroyed by wildland fires. While not noted for loss of life, fires in the wildland–urban interface (WUI) are responsible for extremely large property losses. Approaches to the WUI problem include improving the management of forests to reduce fuel loadings, the fire service response, community design, and home designs. Unlike a normal house fire, the forest fire represents an exterior fire exposure. As such, the components of a home that can be immediately affected by exposure to the flames and burning debris of a forest fire include landscape plants near the home, wood decking, exterior siding, and the roof. Homeowners are often given advice to minimize or eliminate the use of highly flammable vegetation when landscaping their property.

We have been evaluating the cone calorimeter (ASTM 1999) as a method to test for flammability of vegetation. The cone calorimeter measures the heat release rate of a burning material using the oxygen consumption technique. It is widely used in research and development of materials and to provide input data for fire models applicable to building fires.

In the initial study, the Forest Products Laboratory (FPL) in Madison, Wisconsin, and the Riverside Forest Fire Laboratory (RFFL) in Riverside, California, cooperated with a Menifee Valley, California, nursery to investigate the flammability of native and ornamental plants for

WI homes in California. The objective was to improve the information on the relative flammability of plants for home landscaping. Initial results were presented at the 21st International Conference on Fire Safety (White and others 1996). The final report on this initial study is in preparation. Results beyond those reported in the 1996 paper are presented in the paper presented here. We also used the cone calorimeter to examine the flammability of Christmas trees; the results were presented at the 24th International Conference on Fire Safety (White and others 1997).

In a subsequent study, the Forest Service cooperated with Colorado State University in tests of a single sampling of 15 plant species prevalent in the WUI in Colorado. In the latest study, FPL is cooperating with the Northeastern Research Station of the Forest Service in testing plants representing native and similar invasive plants from the U.S. Northeast. The objective of this study is to investigate the impact of invasive plant species on fire hazard and related issues.

Cone Calorimeter Test

The ASTM E 1354 cone calorimeter measures the heat release rate of a burning material using the oxygen consumption technique. The sample is exposed to a fixed heat flux. We generally tested three replicates of green or dried samples at 25 kW/m^2; some green samples were tested at 50 kW/m^2. A spark igniter is placed over the 100- by 100-mm specimen. Over the duration of the test, the heat release rate and mass loss rate are measured. Results that are generally reported include peak heat release rate (PHRR), average heat release rate for a period of 60 s after ignition of the specimen is observed, total heat release, time for sustained ignition, and average effective heat of combustion (EHOC). Results for PHRR and EHOC are reported in this paper.

The standard results for heat release rate are reported as kilowatts per square meter of surface area. The surface area of the specimen is somewhat dubious given the nature of the vegetation specimens. Each sample is a layer of foliage; the foliage normally does not cover the entire exposed surface area of the sample holder. The sample holder includes the retainer frame and wire grid specified in the standard. For the purpose of these tests, the surface area is the area of the sample holder. EHOC is reported in terms of mass, so it is not affected by the problem of undefined Surface area. EHOC is the summation of heat release from time zero to end of test, divided by total mass loss, in megajoules per kilogram (MJ/kg).

California Study

In this initial study, 10 different plants were tested at 4 different times over a 1-year period. At each time, we tested three replicates of the samples with external exposure of 25 kW/m^2 and one replicate at 50 kW/m^2. Plants were supplied by Susan Frommer of “Plants 4 Dry Places” (Menifee Valley, California). Specimens were collected and shipped to the FPL for cone calorimeter testing. Samples were tested “green” and after being ovendried at 95°C. Dry specimens were dried by RFFL prior to shipment to FPL. Green vegetation samples were placed in Ziplock-style plastic bags and shipped in a cooler with commercial presealed icepacks. Green specimens were stored in a refrigerator at FPL until testing. The following plants were tested:

Plants for California Study	**Designation**
Chamise (*Adenostoma fasciculatum* H. & A.)	CHAM
Aloe (*Aloe* sp.)	ALOE
Saltbush (*Atriplex halimus* L.)	ATRI
Wild lilac (*Ceanothus* Joyce Coulter)	CEAN
Crimson-spot rockrose (*Cistus ladanifer* L.)	CILA
Sageleaf rockrose (*Cistus salviifolius* L.)	CISA
Toyon (*Heteromeles arbutifolia* M. Roem.)	TOYO
Prostrate myoporum (*Myoporum parvifolium* Putah Creek)	MYOP
Olive (*Olea europaea* L.)	OLIV
Rhagodia spinescens (no common name available)	RHAG

Seasonal results for dry samples (EHOC and PHRR) and green samples (moisture content and PHRR) are listed in Tables 1 and 2, respectively. For the purpose of comparing different species, the data collected at the four times of the year were combined for analysis. Bonferroni-adjusted multicomparison mean *t*-tests were conducted on EHOC and PHRR data to determine whether there were distinct differences in the results for different species (Table 3). In Table 3, means with the same letter (Bon groupings) are not significantly different at the 95% confidence level. Chamise and olive had distinctly higher EHOC values for dry specimens and higher PHRR values for green specimens. Conversely, aloe had distinctly lower EHOC values for dry specimens and lower PHRR values for green specimens. In future analysis, we will examine the seasonal differences and interactions between species and seasons more closely. One plant—wild lilac (CEAN)—lost moisture and died during the course of the study.

Table 1—Seasonal results for ovendried California samples tested at 25 kW/m²

Species	EHOC[a] (MJ/kg)				PHRR[a] (kW/m²)			
	Aug.	Nov.	March	May	Aug.	Nov.	March	May
OLIV	21.6	21.4	20.7	20.5	258	285	279	238
CHAM	20.6	22.2	19.5	18.1	246	254	253	189
TOYO	19.2	21.8	17.7	15.9	111	167	163	108
MYOP	20.2	20.0	17.0	16.2	148	149	118	99
CILA	18.2	19.4	18.4	14.9	151	158	197	118
CEAN	16.7	17.6	—[b]	—[b]	138	149	—[b]	—[b]
RHAG	16.6	18.3	17.0	16.0	87	181	187	142
ATRI	15.8	18.2	16.4	15.0	93	208	194	132
CISA	15.8	17.7	15.6	13.7	99	166	165	118
ALOE	14.5	13.9	9.3	11.4	92	92	91	94

[a] Mean of three tests of plant material.
[b] Plant died.

Table 2—Seasonal results for moisture content and PHRR for green California samples tested at 25 kW/m²

Species	Moisture content (%)				PHRR[a] (KW/m²)			
	Aug.	Nov.	March	May	Aug.	Nov.	March	May
OLIV	58	88	98	99	127	165	126	115
CHAM	69	65	128	98	102	118	150	91
TOYO	121	102	117	185	45	62	79	34
MYOP	324	465	451	774	35	37	64	17
CILA	109	88	145	163	37	60	45	36
CEAN	121	38	—[b]	—[b]	41	82	—[b]	—[b]
RHAG	250	205	276	341	24	73	59	25
ATRI	182	125	220	306	28	61	89	43
CISA	150	196	199	244	47	32	56	38
ALOE	1800	1100	2400	1900	6	4	3	1

[a]Mean of peak heat release rate data from three tests of plant material.
[b]Plant died.

Table 3—Bonferroni-adjusted multicomparison mean *t*-test results for PHRR of green California samples and EHOC of ovendried California samples tested with heat flux of 25 kW/m²

Species	Value[a]	Bon grouping[b]					
	PHRR of green samples (kW/m²)						
OLIV	133.1	A					
CHAM	115.3	A					
CEAN[3]	61.5		B				
TOYO	55.1		B				
ATRI	54.6		B				
RHAG	45.2		B				
CILA	44.5		B				
CISA	43.0		B				
MYOP	38.1		B				
ALOE	2.8			C			
	EHOC of ovendried samples (MJ/kg)						
OLIV	21.1	A					
CHAM	20.1	A	B				
TOYO	18.6		B	C			
MYOP	18.4		B	C	D		
CILA	17.7			C	D		
CEAN[c]	17.2			C	D	E	
RHAG	17.0			C	D	E	
ATRI	16.4				D	E	
CISA	15.7					E	
ALOE	12.3						F

[a] Values are averages of 12 tests, 3 replicate tests at four different times during the year.
[b] Means With the same letter are not significantly different at the 95% confidence level.
[c] Plant died during the study. Value based on August and November data; mean value was compared to both mean of August and November data of other species and mean of August, November, March, and May data of other species via linear contrast in SAS proc GLM (V.8) using the mean effect model: $y_{ijk} = \mu_{ij} + e_{ijk}$, where i is species, j time of year index, and k replicate index.

Colorado Study

In a subsequent study, we tested a single sampling of 15 Colorado plant species. We tested three replicates of the samples exposed to 25 kW/m^2 heat flux and one replicate of green samples exposed to 50 kW/m^2 heat flux. The following plants were tested:

Plants for Colorado Study	Designation
Rocky Mountain juniper (*Juniperus scopulorum*)	RMJU
Utah juniper (*Juniperus monosperma*)	UJUN
Lodgepole pine (*Pinus contorta*)	LPIN
Douglas-fir (*Pseudotsuga menziesii*)	DFIR
White fir (Abies concolor)	WFIR
Bitterbrush (*Purshia tridentata*)	BITB
Sage (*Artemesia* sp.)	SAGE
Colorado pinyon (*Pinus edulis*)	CPIN
Ponderosa pine (*Pinus ponderosa*)	PPIN
Serviceberry (*Amelanchier alnifolia*)	SERB
Engelmann spruce (*Picea engelmannii*)	ESPR
Mountain mahogany (*Cercocarpus montanus*)	MAHO
Snowberry (*Symphoricarpos albus*)	SNOB
Gambel oak (*Quercus gambelii*)	GOAK
Chokecherry (*Prunus virginiana*)	CBER

Bon groupings are provided for the peak heat release of green samples and average effective heat of combustion of dry samples (Table 4). There are few significant differences between most species, as indicated by the bon groupings. Tests of dry samples indicated that the two junipers, lodgepole pine, and Douglas-fir had significantly higher EHOC values than did gambel oak, chokecherry, snowberry, and mountain mahogany. For green samples, the two junipers and Douglas-fir had the highest PHRR values, but mountain mahogany also had a relatively high PHRR value. This result for mountain mahogany likely reflects its relatively low moisture content (Table 4). Moisture content was measured at Colorado State University using ovendried samples.

Table 4—Bonferroni-adjusted multicomparison mean *t*-test results for PHRR of green Colorado samples and EHOC of ovendried Colorado samples tested with heat flux of 25 kW/m²

Species	Moisture content[a]	Value[b]	Bon grouping[c]					
PHRR of green samples (kW/m^2)								
UJUN	76	228	A					
DFFIR	128	188	A	B				
RMJU	108	186	A	B				
MAHO	41	141		B	C			
WFIR	113	140		B	C			
BITB	73	139		B	C			
ESPR	90	130		B	C			
CPIN	159	117		B	C	D		
LPIN	115	110		B	C	D	E	
PPIN	85	89			C	D	E	
SERB	143	80			C	D	E	
SAGE	114	77			C	D	E	
CBER	172	55				D	E	
SNOB	154	52				D	E	
GOAK	107	41					E	
EHOC of ovendried samples (MJ/kg)								
RMJU		20.2	A					
UJUN		18.7	A	B				
LPIN		18.1	A	B	C			
DFFIR		17.9	A	B	C			
WFIR		17.8		B	C	D		
BITB		17.1		B	C	D		
SAGE		16.8		B	C	D		
CPIN		16.7		B	C	D		
PPIN		16.5		B	C	D	E	
SERB		16.3			C	D	E	
ESPR		16.3			C	D	E	
MAHO		15.8			C	D	E	F
SNOB		15.6				D	E	F
GOAK		14.2					E	F
CBER		13.8						F

[a] Moisture content (%) of green samples.
[b]Values listed are averages of 3 tests of plant materials.
[c]Means with the same letter are not significantly different at 95% confidence level.

Northeast Study

In the latest study, we tested plants representing native and similar invasive plants in the northeast portion of the United States. One premise is that invasive plants might alter the natural fire regime by either increasing the fire return interval or making the stands less prone to fire. We are also seeking to modify BEHAVE fuel models (Andrews 1986, Andrews and Chase 1989, Burgan and Rothermel 1984) to more accurately reflect the vegetation in the northeast region. We are proposing to use the cone data for the heat content input for BEHAVE in addition to surface area/volume ratio and other visual characteristics. This raises the question as to the added value of the cone calorimeter compared with the oxygen bomb calorimeter. A second set of objectives is concerned with the problem of invasive plants. The flammability of these plants is to a great extent unknown, but they are replacing native plant communities in the wildland–urban interface in the northeast.

Native Plants for Northeast Study	**Designation**
Red maple (*Acer rubrum*)	ACRU
Speckled alder (*Alnus incana* spp. rubra)	ALIN
Canada shadbush (*Amelanchier* cf. *canadensis*)	AMCA
Virginia cutleaf (*Leersia virginica*)	LEVI
Interrupted fern (*Osmunda claytoniana*)	OSCL
Trembling aspen (*Populus tremuloides*)	POTR
Chokecherry (*Prunus virginiana*)	PRVI
Rose (*Rosa* sp.)	ROSP
Goldenrod (*Solidago rugosa*)	SOCA
Highbush blueberry (*Vaccinium corymbosum*)	VACO
Maple-leaved viburnum (*Viburnum acerifolium*)	VIAC
Arrowwood (*Viburnum dentatum*)	VIDE
Grape (*Vitis* sp.)	VITIS

Invasive Plants for Northeast Study	**Designation**
Norway maple (*Acer platanoides*)	ACPL
Common barberry (*Berberis vulgaris*)	BEVU
Asian bittersweet (*Celastrus orbiculatus*)	CEOR
Russian olive (*Elaeagnus angustifolia*)	ELAG
Japanese knotweed (*Fallopia japonica*)	FAJA
Alder-leaved buckthorn (*Frangula alnus*)	FRAL
Asian honeysuckle (bush) (*Lonicera* sp.)	LOJA
Purple loosestrife (*Lythrum salicaria*)	LYSA
Apple (*Malus* sp.)	MALUS
Japanese stiltgrass (*Microstegium vimineum*)	MIVI
Eastern ninebark (*Physocarpus orbiculatus*)	PHOR
Black locust (*Robinia pseudoacacia*)	ROPS
Multiflora rose (*Rosa multiflora*)	ROMU
Deadly nightshade (*Solanum dulcamara*)	SODU

Specimens were collected from several locations in the northeastern United States. Specimens were dried to constant weight in a drying room (60°C) at the University of Maine. This drying procedure was followed to minimize water content while minimizing any volatization of secondary compounds that may affect the results. Samples were stored in a 27°C, 30% relative humidity room at FPL prior to testing. This study is continuing with the collection of additional samples. Some overall results are shown in the figures.

Combined Database

Flammability is obviously affected to a great extent by the moisture content of the plant material. Peak heat release rates for ovendried specimens were much higher than those for green specimens (Figure 1). Effects of moisture content were also indicated in the relative results for individual species. Further statistical analysis of the data is needed to more clearly define the relationship of moisture content and species to flammability. As mentioned previously, the high PHRR value for mountain mahogany likely reflects its low moisture content. Overall comparison of PHRR with moisture content is shown in Figure 2. Aloe, a species with extremely high moisture content, was not included in the data shown in Figure 2.

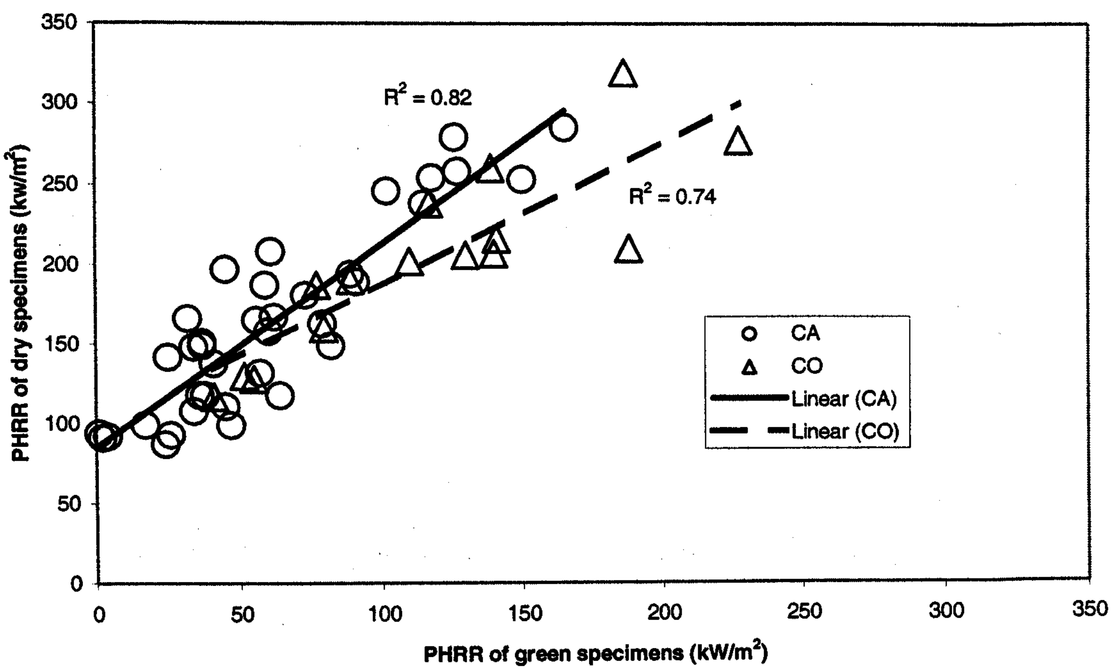

Figure 1—Comparison of PHRR for green versus dry specimens tested with heat flux of 25 kW/m² in California (CA) and Colorado (CO) studies.

In this paper, the results include PHRR of green specimens and EHOC of dry specimens. The data suggest that some results obtained from cone calorimeter testing can be sensitive to the initial mass of the specimen. This appears to be particularly the case for the times for sustained ignition. Because EHOC is heat produced on a per mass basis, it is not directly affected by the problem of defining the surface area of the specimen. In the analysis to date, the data have not indicated a confounding effect of initial specimen mass on EHOC. For green specimens, EHOC would need to be corrected for mass loss resulting from moisture loss. Given the relatively small specimen mass and the lack of precision in the moisture content data, this correction would likely lead to increased variability. For green specimens, the alternative is PHRR. Because the peak value is measured at discrete intervals, there is some inherent variability in the PHRR data. Also, the initial specimen mass may have a confounding effect on PHRR. The R^2 values for the correlation between PHRR and EHOC of dry samples were 51% for CA data, 62% for CO data, and 29% for northeast United States (NE) data (Figure 3).

The heat of combustion reported for the cone calorimeter is called the “effective” heat of combustion. This is in contrast to the heat of combustion (HOC) normally reported, which is for the oxygen bomb calorimeter. In both cases, HOC is heat release divided by mass loss. The “effective” HOC with our vegetation testing would be less than what could be expected from the oxygen bomb calorimeter because some combustible material is likely to remain at the end of the cone test. The samples in the bomb calorimeter are first ground and then made into pellets and combusted in an oxygen environment. Although the bomb calorimeter has obvious limitations, it was the standard test used in BEHAVE. To better utilize the cone data, comparative data should be gathered to establish the link between the two measurements of HOC and to determine the benefits of the cone calorimeter compared to the bomb calorimeter.

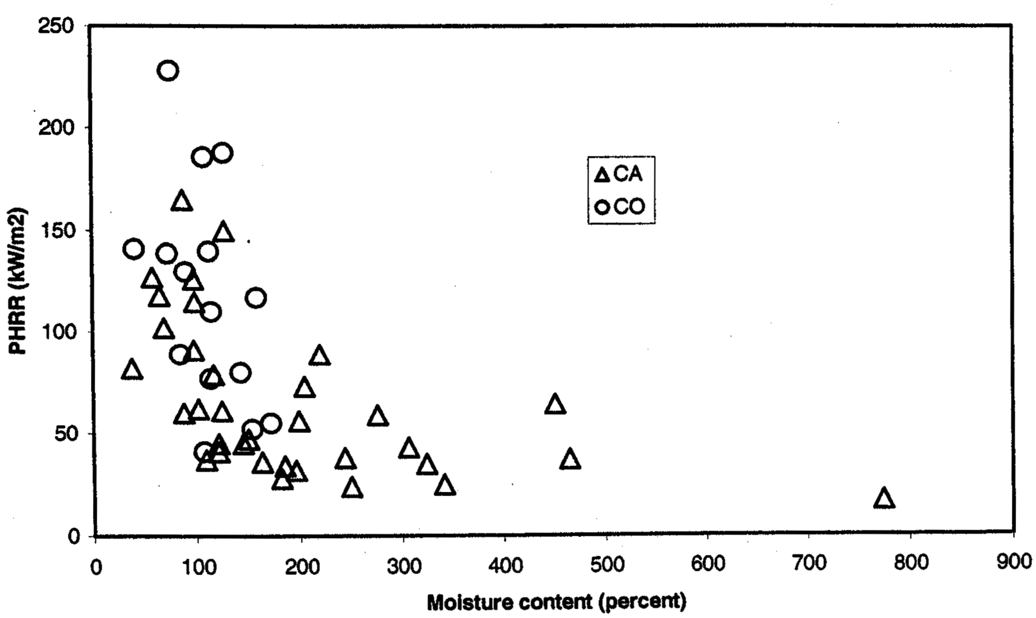

Figure 2—PHRR as a function of sample moisture content. Data are averages presented in Tables 2 and 4.

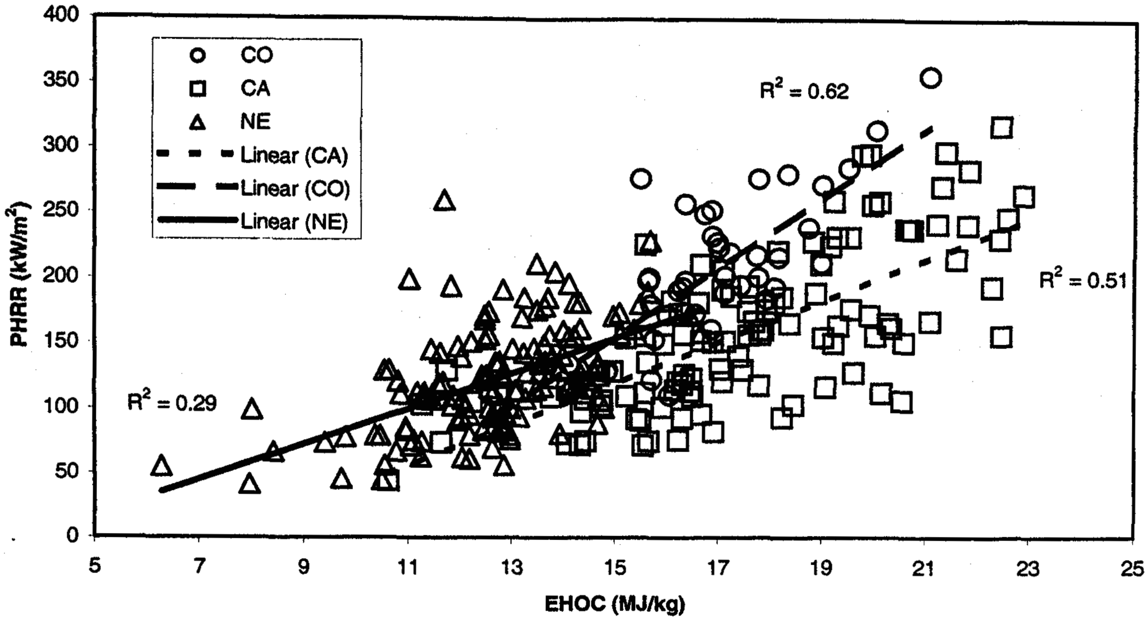

Figure 3—Comparison of PHRR and EHOC of dry specimens in Colorado (CO), California (CA), and northeast U.S. (NE) studies.

This discussion also brings up the issue of green versus dry samples. Production of "dry" samples is always a difficult issue because ideally we remove the moisture but not the volatile gases. For wood, we typically ovendry (i.e., o.d.) samples at 105°C. For the California study, we used 95°C; for the Northeast study, we dried samples at 60°C. For green samples, the issue is change in moisture content from collection to time of testing.

In these studies, we generally tested three replicates using an external heat flux of 25 kW/m^2. Some tests were conducted using a heat flux of 50 kW/m^2, but these were only single replicates. Visual comparison of the results for different external heat fluxes (Figure 4) appears to indicate higher PHRR with the 50-kW/m^2 heat flux but generally consistent rankings.

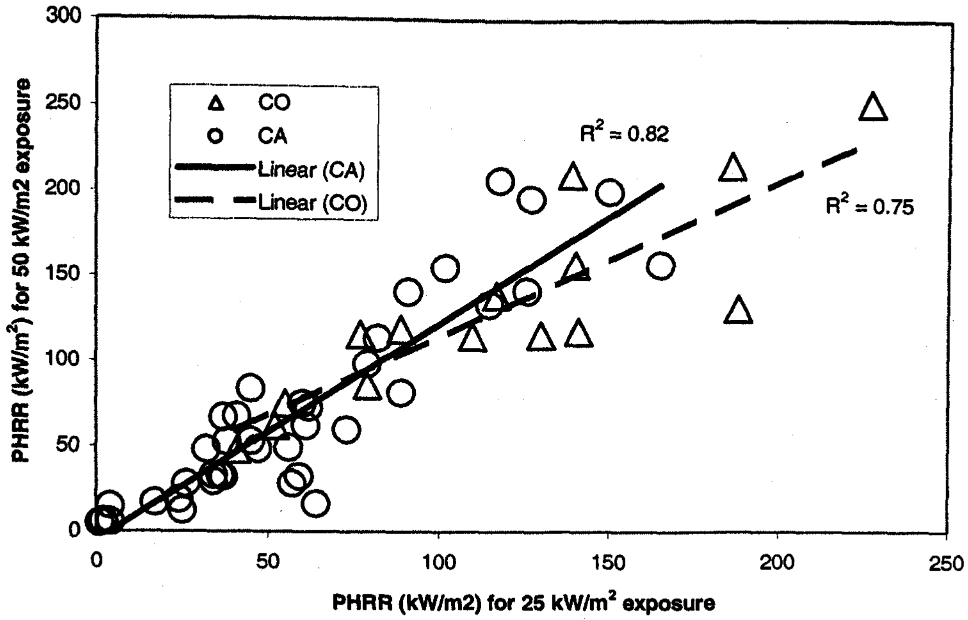

Figure 4—Comparison of average PHRR obtained using 25-kW/m² heat flux with that obtained in a single replicate using 50-kW/m² heat flux. Data are from California (CA) and Colorado (CO) studies.

We are testing relatively small samples in the cone calorimeter to measure the heat release rate. One difficulty is judging the appropriate amount of material to use per holder. Inconsistencies occurred in the coverage of the sample holder with different vegetation samples. We used the criterion of trying to put "one layer" of materials into the sample holder. As a result, there was considerable variation in sample mass. Time for sustained ignition appears to be significantly affected by sample mass. Because we are potentially interested in all aboveground portions of the plants, another question is what to put in the sample holders. Do we put only proportional amounts of each component? Do we test just leaves and just stems? Yet another problem is the absence of defined surface area. One option for sample placement in the cone is grinding the plant material as for the bomb calorimeter and then filling the holder with the ground material. In studies to date, we have had mixed success in obtaining significant differences between different sets of vegetation samples. We need to further examine the question of desired levels of detection of significant differences and the number of replicate tests needed to determine such differences.

Conclusions

The cone calorimeter was used to evaluate the relative flammability of different sets of vegetation samples from three regions in the United States. Although no significant differences occurred between most species, species of inherent low and high flammability have been identified in the studies conducted to date. Species of high relative flammability include olive, chamise, Utah juniper, and Rocky Mountain juniper. Species with low flammability include aloe, chokecherry, gambel oak, and snowberry. As expected, moisture content is a significant factor in the relative flammability of any vegetation.

Acknowledgments

The studies reported here were possible as the result of the efforts of many individuals. We appreciate all the assistance that we have received. As mentioned previously, Susan Frommer of "Plants 4 Dry Places" in Menifee Valley, California, provided the plants for the California study. Ecologist Bonnie Corcoran prepared the samples at Riverside Forest Fire Laboratory (RFFL) and made supplemental measurements of their characteristics prior to shipment to Forest Products Laboratory (FPL). Julie E. Ward, an undergraduate student at Colorado State University, collected the plants for the Colorado study. For all the studies, technician Anne M. Fuller conducted the cone calorimeter tests at FPL and prepared an initial tabulation of the data. Statistician Patricia K. Lebow of FPL provided assistance in data analysis. For the Northeast study, we appreciate the field assistance of Catherine A. Rees of the Northeastern Research Station. Vegetation of the Northeast is under study by Alison Dibble and William A. Patterson, 111, of the University of Massachusetts, Amherst, and funded by the Joint Fire Sciences Program, Boise, Idaho. The focus of the Northeast study is the interaction between fire and invasive plants.

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