# A Portable System for Characterizing Wildland Fire Behavior

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**Abstract**

A field deployable system for quantifying energy and mass transport in wildland fires is described. The system consists of two enclosures: The first is a sensor/data logger combination package that allows characterization of convective/radiant energy transport in fires. This package contains batteries, a programmable data logger, sensors, and other electronics. The standard sensors consist of radiometers that measure total and radiant energy fluxes, a small-gauge thermocouple that senses flame and air temperature, and probes that sense the magnitude and direction of airflow before, during, and after the fire passes. The second is a fire proof enclosure housing a video camera. The boxes have a double lens configuration with the exterior lens consisting of high temperature glass and the interior lens consisting of coated glass that reflects infrared radiation (heat), while allowing visible light to pass through. The cameras can either be turned on manually or can be set to trigger and record through a wireless link to the data loggers. The system has been used extensively in full scale wildland fires. Analysis of the visual video images provides an objective method for measuring flame height, flame length, flame depth, flame angle and fire rate of spread. Typically each sensor package is coupled with a video package for simultaneous recording of video and in-situ measurements allowing researchers to better evaluate fire behavior measurements relative to flame size and local spread rate. The camera images can provide estimates of flame height, depth, angle and fire rate of spread.

**Keywords:** Fire Behavior, Fire Intensity

## 1. Introduction

Fire behavior models that are used for day-to-day fire management for the most part have been largely empirical with perhaps some analytical foundation (Rothermel, 1972); examples include BEHAVE (Andrews, 1986), Farsite (Finney, 1998), and FireStem (Jones, et al. 2004). A parallel focus has been to use experiments to develop new understanding of the physical and chemical processes driving fire ignition and spread. Such measurements benefit wildland fire behavior research and modeling by providing data against which models can be checked and providing information to inform fire research. Typically, data have largely consisted of measurements from experiments burned under controlled conditions (Anderson, et al. 2010; Butler 1993; Catchpole, et al. 1998; Viegas, 2002; Weise and Biging, 1996); however, more recently efforts have been directed at actual wildland fires (Alexander 1990; Hiers, et al. 2009; Stocks, et al. 2004).

Despite the realization of the need for additional measurements and data, generally speaking, quantitative measurements of energy and mass transport in wildland fire have been relatively sparse. The reasons for the paucity of data, especially from full-scale fires are likely related to the risks and hazards to humans and equipment associated with wildland fires as well as the high degree of uncertainty in the weather. Additionally, only in the past 15 years has the technology become readily available at a cost that allows deployment of such instrumentation.

Building on the experience gained from the International Crown Fire Experiment (Butler, et al. 2004; Putman and Butler, 2004; Stocks, et al. 2004) and subsequent field experiments (Butler and Putnam, 2001) a field deployable, fire resistant, programmable sensor array mounted in a fire resistant enclosure and coupled with a video imaging system has been developed. This system reduces the safety risks to research team members and improves utility and reliability of the instruments. The development of this technology was not trivial and required a constant level of effort over a significant amount of time to develop, construct, and test various sensors and designs. A digital video system has also been developed that can be coupled with the fire sensor system based on the premise that interpretation of the fire behavior data is enhanced when digital video footage of the specific fire behavior at the sensor location is provided. Recent improvements in the video system include a programmable trigger that allows the system to automatically initiate data and video recording when a fire is sensed (Jimenez, et al. 2007).

The following describes the system in detail and presents a sample of the data that is can be collected with this system.

## 2. System Design

The system consists of two enclosures: The sensor/data logger package is termed the Fire Behavior Flux Package (FBP). It measures 27 cm by 15 cm by 18 cm and in its current configuration weighs approximately 5.3 kg (fig. 1). Various enclosure materials have been used from mild steel, stainless steel and aluminum, the latest design consists of 3.7mm thick aluminum welded at the seams. A 12 volt 2.2Ah sealed lead acid battery or 8 AA dry cells provide power to the logger. A separate 8 AA dry cell battery array provides power for the flow sensors. Wiring and circuit diagrams can be found at www.firelab.org

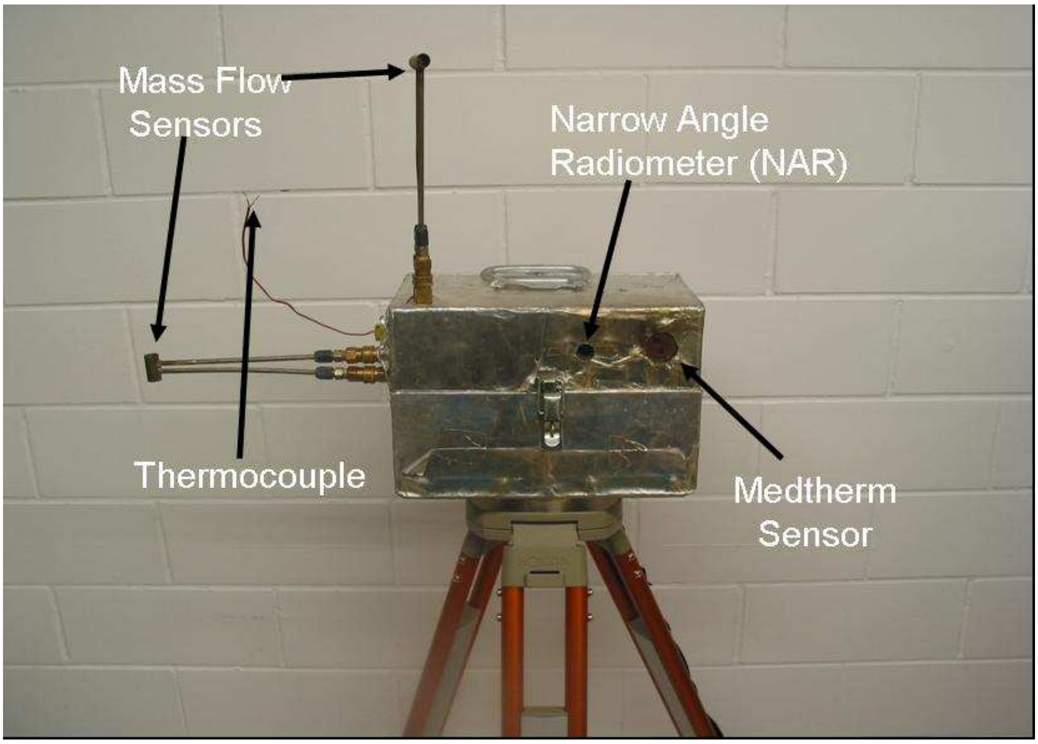


**Figure 1 Photograph of Fire Behavior Package.**

The dataloggers used are Campbell Scientific® model CR1000. The dataloggers are capable of logging over one million samples, providing 20 hours of continuous data logging. This logger is user-programmable and accepts a wide range of analog and digital inputs and digital output. It is thermally stable and has been relatively insensitive to damage incurred in shipping and handling. Alternative and lower cost dataloggers are available but generally do not have all of the features found in the aforementioned. The standard sensors consist of a Medtherm® Dual Sensor Heat Flux sensor (Model 64-20T). These sensors provide incident total and radiant energy flux, a type K fine wire thermocouple (nominally 0.13 mm diameter wire), a custom designed narrow angle radiometer (Butler, 1993), and two pressure based flow sensors (McCaffrey and Heskestad, 1976). Table 1 provides details about individual sensors and their engineering specifications.

Table 1. ***Insitu* Fire Behavior Package (FBP) Specifications**

| **Narrow Angle Radiometer** | |
|---|---|
| Sensor | 20-40 element thermopile |
| Spectral Band of Sensor | 0.15 – 7.0 μm with sapphire window |
| Field of View | ~4.5º controlled by aperture in sensor housing |
| Transient Response | Time constant of sensor nominally 30msec |
| Units of Measurement | Calibrated to provide emissive power of volume in FOV in $kW\text{-}m^{-2}$ |
| **Total Energy Sensor** | Medtherm Corp® Model 64-20T Dual total Heat Flux Sensor/Radiometer |
| Sensor | Schmidt-Boelter Thermopile |
| Spectral Band of Sensor | All incident thermal energy |

| | |
|---|---|
| Field of View | ~130º controlled by aperture in sensor housing |
| Transient Response | < 290msec |
| Units of Measurement | Total heat flux incident on sensor face in kW-m$^{-2}$ |
| **Hemispherical Radiometer** | Medtherm Corp® Model 64-20T Dual total Heat Flux Sensor/Radiometer |
| Sensor | Schmidt-Boelter Thermopile (Medtherm Inc) |
| Spectral Band of Sensor | 0.15 – 7.0 µm with sapphire window |
| Field of View | ~130º controlled by window aperture |
| Transient Response | < 290msec |
| Units of Measurement | Radiant energy incident on sensor face in kW-m$^{-2}$ |
| **Air Temperature** | |
| Sensor | Type K bare wire butt welded thermocouple, new, shiny, connected to 27ga lead wire |
| Wire Diameter | 0.13mm |
| Bead Diameter | ~0.16-0.20mm |
| Units of Measurement | Degrees Celsius |
| **Air Mass Flow** | |
| Sensor | SDXL005D4 temperature compensated differential pressure sensor |
| Pressure Range | 0-5 in $H_2O$ |
| Sensor Design | Pressure sensor is coupled to custom designed bidirectional probe with ±60º directional sensitivity. |
| Units of Measurement | Calibrated to convert dynamic pressure to velocity in m-s$^{-1}$ assuming incompressible flow |
| **Sensor Housing Dimensions** | 150× 180 × 270 (mm) |
| **Housing Weight** | 7.7 kg |
| **Insulation Material** | Cotronics Corp® 2.5cm thick ceramic blanket |
| **Tripod Mount** | ½ inch female NCT fitting permantly mounted to base of enclosure. |
| **Power Requirements** | 12V DC |
| **Power Supply** | Rechargeable Internal Battery |
| **Data Logging** | Campbell Scientific Model CR1000 |
| **Sampling Frequency** | Variable but generally set at 1 Hz |
| **File Format** | ASCII |

The second part of the system is a fire proof enclosure housing a video camera and is termed the In-situ Video Camera (IVC). The IVC measures 10 cm by 18 cm by 19 cm and is constructed of 1.6 mm aluminum for a weight of approximately 1.8 kg (fig. 2). The front of the IVC has a two circular windows nominally 45 and 20 mm in diameter. A double lens configuration of high temperature pyrex glass and a second lens of hot mirror coated glass (Edmund Optics) is mounted in the ports. This multi-layer dielectric coating reflects harmful infrared radiation (heat), while allowing visible light to pass through. The cameras can either be turned on manually or can be set to trigger and record through a wireless link to the FBP data loggers (Jimenez, et al. 2007). The wireless trigger is based on the SONY proprietary LANC technology, thus only SONY cameras are compatible with the automatic trigger system. The preferred model is the SONY PC-1000 HandyCam digital video camera; however other models can be substituted. These cameras were chosen for their relatively high quality construction, image quality, and reliability. The system allows users to trigger the recording mechanism of the camcorder remotely by using its own unique internal computer source code. Radio frequency was chosen over Infra Red (IR) technology due primarily to line-of-sight and interfering reflectance issues. Once the FBP and IVC boxes are deployed the trigger system is armed from readily accessible switches in the respective enclosures.


**Figure 2 Insitu Video Camera package.**

The enclosures are designed to be mounted on low cost tripods. Thin wall galvanized 2.5 cm diameter mild steel pipe presents an optimum design in terms of weight to thermal resistance. The tripods typically have one extendable leg to facilitate deployment on slopes. Once mounted on the tripods the FBP and IVC are powered up, and a single layer of 2.5 cm thick ceramic blanket is wrapped around the box. The ceramic blanket is enclosed in a single layer of fiberglass reinforced aluminum foil.

The FBP enclosures can be constructed for approximately $500 USD per box plus cost of data loggers, and sensors. The IVC enclosures can be constructed for $700 USD per box plus cost of cameras.

The system has been used extensively in full scale wildland fires. Analysis of the visual video images provides an objective method for measuring flame height, flame length, flame depth, flame angle and fire rate of spread. Typically each FBP is coupled with an IVC for simultaneous recording of video and in-situ measurements allowing researchers to better evaluate fire behavior measurements relative to flame size and local spread rate. Provided that a calibration object is in the camera field-of-view estimates of flame height, depth, angle and fire rate of spread can be acquired for the video record. The result is a system that is not only robust, but also easy to operate, simple to deploy, fire proof, and light weight.

The packages are typically deployed so that the sensors are directed towards the oncoming fire front and arranged so that most often an FBP and IVC are deployed in pairs. The FBP is oriented to "look" at the expected fire approach direction, while the IVC is positioned to image both the FBP and approaching fire front (fig. 3-4). The FBP and IVC's are mounted on tripods, the are powered up, and they are positioned. The FBP's have LED's to indicate that the logger is indeed running, the IVC's also have an LED to indicate that they are running and have entered "sleep" mode if they are used with the remote automatic trigger system.

**Figure 3 Insitu Video Camera mounted on tripod.**

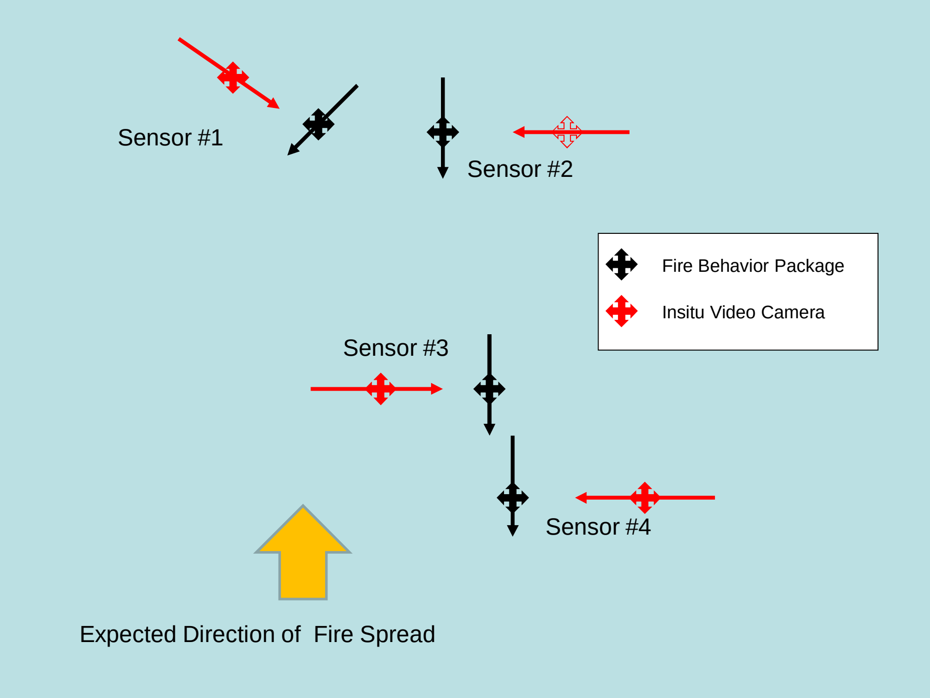


**Figure 4 Typical sensor arrangement.**

After the enclosures are mounted, positioned and "turned on" a GPS position is recorded for each, including reference orientation (compass direction), height above the ground, and any other local vegetation, or environment information deemed relevant. The insulation is then installed.

Due to the automatic trigger system the sensors can be deployed hours or days ahead of the expected arrival of the fire. However, if the system is exposed to precipitation or signifcant moisture there is the possibility that moisture could affect the transmission properties of the radiometer window and pressure ports on the flow sensors.

At the completion of a burn, the research team carefully records evidence of burning around the sensors, the condition and consumption of fuels, and any other pertinent information. The sensors are then turned off and transported to a secure location. At that point the data is downloaded from the loggers and they can be reset for a subsequent deployment.

## 3. Data Analysis

Figures 5-7 present a typical set of measurements from the system. The temperature measurements (fig. 5) are typically collected using a type K fine wire thermocouple. Error associated with this measurement can be considerable. The use of new (shiny therefore low emissivity), small diameter (reduces radiant energy absorption), thermocouples can decrease measurement uncertainty (Ballantyne and Moss, 1977; Satymurthy, et al. 1979; Shaddix, 1998). It is estimated that the measurements collected insitu using the 0.13mm diameter thermocouples specified above are subject to a measurement uncertainty of nominally ±50K but measurement uncertainty can be much larger depending on the temperature of the gas, the surroundings and the radiative properties of the local environment. It reasoned that as the thickness of the flames increases the error decreases. For small or thin flames the uncretainty can be hundreds of degrees depending on the condition and size of the thermocouple (Pitts, et al. 1999).

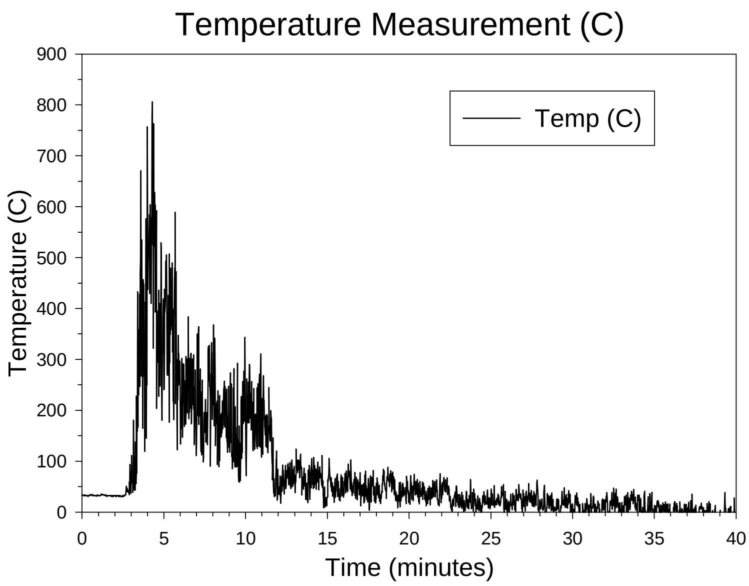


**Figure 5 Temperature data collected from a typical fire.**

Figure 6 presents typical heat flux measurements from the total and radiant sensors. The sensors are calibrated to provide total incident energy flux and total radiant incident flux. In theory the convective heat flux at the sensor face would be the difference between the two sensors. The flux on the sensor face may not necessarily represent that incident on a nearby vegetation component. Surface incident energy flux is highly dependent on the properties of the surface itself. The sensors come from the factory calibrated against a high temperature source that emits the bulk of its energy in the near infrared. This source does not represent the spectral energy source produced by a typical wildland fire. The thermal transmission of the window on the radiometer has specific spectral properties. Thus the energy transmitted to the sensor in the calibration environment is not the same as that transmitted in the fire environment. Without additional calibration using a spectrally broad source all that can be deduced from the radiometer data is that they represent the energy that would be incident on the face of the sensor if the source were similar to the calibration source. The radiometers can be calibrated using a blackbody source over the expected range of energy flux to minimize error due to the spectral differences between the manufacturer calibration and that of a typical wildland fire source. However, ultimately, unless one uses a correction term determined from a known source (Frankman, et al. 2010), uncertainty exists in the radiation measurement.

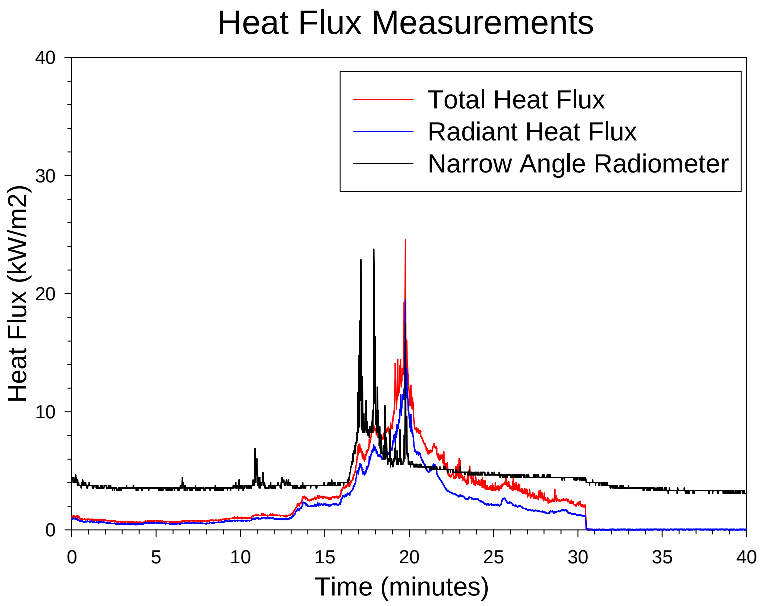


**Figure 7 Typical heat flux data captured from FBP.**

Figure 7 presents typical flow measurements captured using the differential pressure probes (McCaffrey and Heskestad, 1976). These sensors have been used extensively in laboratory experiments to characterize the flow field in and around flames generated by woody fuels

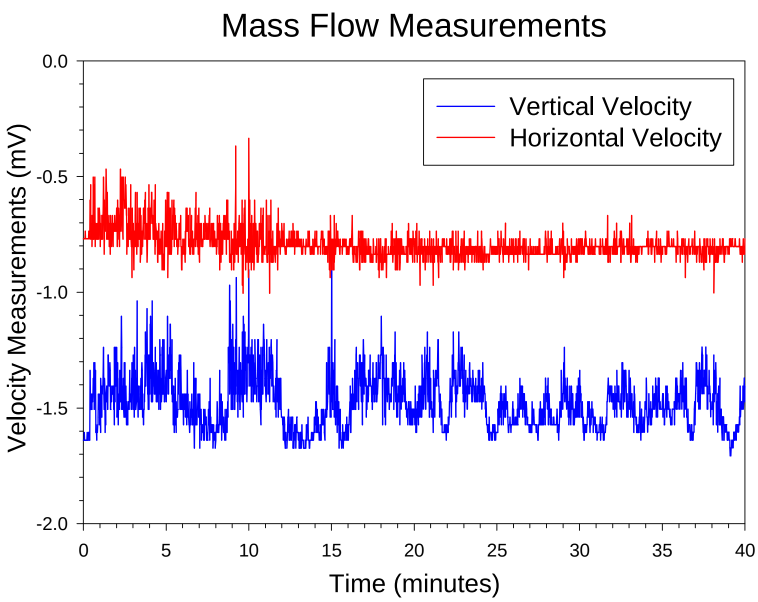


**Figure 6 Typical horizontal and vetical measurements from FBP sensors.**

(Anderson, et al. 2010). They are designed to capture the general horizontal or vertical flow given a nominally ±30 degree acceptance angle. The sensors are calibrated by comparison to a known sensor in a controlled flow. Because these sensors are based on pressure differences between the dynamic and static ports they are sensitive to changes in gas density as would occur due to temperature variations. Therefore the flow measurements require an air temperature measurement for determination of density. Additionally no correction is made for changes in the relative humidity of the air flow. Given the uncertainty associated with the air temperature measurement it is estimated that the flow measurement uncertainty is approximately ±30% and may be larger.

Ideally, these measurement systems would be deployed with careful measurements of pre and post fire vegetation consumption. Other measurements could include energy transport into the soil and emissions. A suite of such measurements provides a comprehensive snapshot of fire that can inform research questions and direction.

One of the challenges associated with characterizing physical processes in fire is the spatial heterogeneity introduced by variations in vegetation, terrain and weather. The sensors described here sense energy and mass transport at a very small scale relative to that of wildland fires. Consequently, another challenge is how to interpret data from these systems over the broad spatial scales charateristic of wildland fire. One approach is to deploy enough sensors to collect a statistically representative distribution. Alternatively, ground based sensors can be used to evaluate and correct remotely sensed data that represent spatial scales. Hardy and Riggan (2003) attempted to address this option.

Measurement success depends on a number of factors, including equipment reliability, and weather. The use of this system with the automatic trigger option has increased the success of research efforts to quantify fire behavior; however, even in ideal conditions a realistic success rate of 50-80% is likely.

## 4. Conclusions

A relatively low cost, light weight, ruggedized, portable, and programmable sensor system has been designed to provide researchers with the capability to measure energy and mass transport in wildland fires. The system has been used to collect quantitative fire information for support of fire spread models, fire-induced plant mortality studies, firefighter safety zone studies, crown fire transition studies, and for comparing ecosystem management methods and techniques on prescribed and natural fires from Alaska to Florida, Europe, and Australia. The designs can be adapted to fit other sensors and data loggers. A remote trigger allows the fire behavior and video packages to stay in “sleep” mode until a measurable rise in heat flux is detected. When a fire is sensed, the fire behavior sensor package begins logging data and sends a wireless signal to activate the video package. This system can be constructed from widely available materials using basic tools and techniques.

The measurement of energy and mass transport in reacting systems is, at best, tenuous. Despite the uncertainty associated with the sensors, the data have been shown to correlate well with measured consumption of vegetation. The development of nonintrusive systems shows promise for reduced measurement uncertainty and increased temporal and spatial resolution in laboratory settings. However, such systems that can operate successfully in a natural fire environment have yet to be developed. It is the opinion of the authors that for the near term, the use of sensors like those described here is the only practical solution to gathering quantitative information about energy and mass transport in wildland fires.

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