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A Balloon System for Profiling Smoke Plumes from Forest Fires

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A BALLOON SYSTEM FOR PROFILING SMOKE PLUMES FROM FOREST FIRES

by

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Abstract

This paper is directed to those interested in techniques for measuring emission rates and emission factors for forest fires and other open combustion sources. A source-sampling procedure that involved the use of a vertical array of lightweight, battery-operated instruments suspended from a helium-filled aerodynamic balloon is described. In this procedure, plume profiles from ground level to 600 m can be determined for particulate matter, several combustion gases, windspeed, and temperature. Information on the logistics of the operation and potential application are presented. The advantages and disadvantages of this system, as compared to other ground and airborne sampling systems, are presented. The operational feasibility of the system was demonstrated in a series of 1978 experiments, confirming that this is a viable method of sampling emissions from forest fires.

A BALLOON SYSTEM FOR PROFILING SMOKE PLUMES FROM FOREST FIRES

Introduction

Forestry and air-quality managers currently lack adequate information on emission rates and factors for prescribed forest fires and, therefore, cannot accurately predict smoke concentrations and environmental impacts at locations downwind from a burn. The U. S. Environmental Protection Agency (EPA) currently compiles source emission factors(1) and ranks each set of factors according to the reliability of data upon which it was based. The section on forest fire is ranked D (below average) on a scale of A (excellent) to E (poor). The reason for this low ranking is the limited amount of operational source data available on such fires. Although readers of the EPA document are cautioned about indiscriminate use of questionable emission factors and are encouraged to conduct onsite source tests, many readers use the document as the best available information and proceed to apply these data in their local air-quality plans, operations, and impact studies. Thus, to provide more accurate values in the shortest time, we must rapidly develop operational estimates of emission rates and factors for prescribed forest fire.

The choice of experimental methods for determining emission rates and factors from open burning of forest fuels is limited. In the past, both field(2),(3),(4) and laboratory(5),(6),(7) methods have been employed. For low-intensity fires in complex fuels (i.e., live understory brush mixed with litter and logging debris) and medium- to high-intensity fires, field methods are usually the only approach available. Ground-based and airborne sampling systems have been used, the choice depending on the fuel type and fire behavior to be studied and, to a lesser extent, on topographic factors. In the laboratory, sampling systems of greater precision have been used, but only with low-intensity fires in litter-type fuels (e.g., pine needles).

In a field study, Ward et al.(2) successfully used 12.2-m (40-ft) portable towers to measure total suspended particulate matter (TSP) emission rates from low-intensity prescribed fires backing against the wind. This technique is successful when winds are steady and the angle of plume rise is low enough so that all particulate matter as well as air flow can be sampled. The method loses validity when the smoke rises above the towers.

For medium- to high-intensity fires, aircraft sampling has been used with limited effectiveness. The most serious limitation in documenting smoke plumes from aircraft has been the lack of quantitative information on the rate of fuel consumption. Additionally, practical methods of measuring TSP mass from aircraft have been limited to indirect methods (e.g., nephelometer, particle spectrometer). Ward et al.(3) have shown that problems associated with relative humidity and changing particle size can be the source of major errors with indirect methods. Other problems are caused by inadequate navigational procedures and by backscatter from gases.

An aircraft can sample the convective-lift (CL) phase of fires when flaming combustion generates enough heat energy to entrain emissions into a well-defined plume rising several hundred to several thousand meters.

It cannot sample the no-convective-lift (NCL) phase where smoldering combustion produces high concentrations of smoke near the ground.

The objective of this study was to develop and evaluate a source sampling system that has the capability of collecting emissions data from both well-defined smoke plumes up to 600 m in height and from smoke drifting near the ground.

General Concepts

Figure 1A illustrates sampling in a plume formed during the CL phase of a heading fire (i.e., one moving with the wind) in a pine forest. The convective force generated by the rapidly moving fire front produces a plume that rises vertically until the force of the wind field takes over and bends the plume in the direction of the transport winds. Figure 1B shows the NCL phase of the same fire. In this phase, flaming combustion has diminished, but remaining ground fuels (unburned litter, stumps, fallen trees, etc.) continue to smolder for many hours, producing smoke that tends to drift through and slightly above the canopy as it moves downwind. The sampling system is a vertical array of lightweight, battery-operated sampling packages suspended through the plume below a tethered helium-filled balloon. The height of the balloon and the spacing of the packages can be adjusted to accommodate various plume dimensions.

The sampling and analysis technique is an extension of one described in detail by Ward et al.[2] A vertical array of samplers downwind of a moving fire front measures the emissions and air movement past the array. These data can be used to calculate emission rates for the fire, and, coupled with measurements of fuel consumption, emission factors for the fuel. The technique is fundamentally the same as measuring emissions from smoke stacks except that the stack walls are imaginary in open combustion. For this reason, at least one sampler must be kept above and in some cases also below the plume so that measurement of background levels can confirm that the plume was contained within the vertical array. This procedure assumes that the fire (line source) is uniform along the entire fire front and requires that the vertical sampling array be in a central position to avoid edge effects. It is essential that the wind direction be reasonably steady during the sampling period in order to keep the array centered with the plume. An estimate of the horizontal variability can be obtained by measuring rate of fire spread or ground-level smoke at three or more positions.

System Components

The total sampling system consists of the balloon subsystem and the instrumentation subsystem. The balloon subsystem includes the tether and rapid deflation lines, line winch and other line-handling devices, as well as ground-support equipment. The instrumentation subsystem includes the sampling packages, instrumentation line, ground station and the handling equipment.

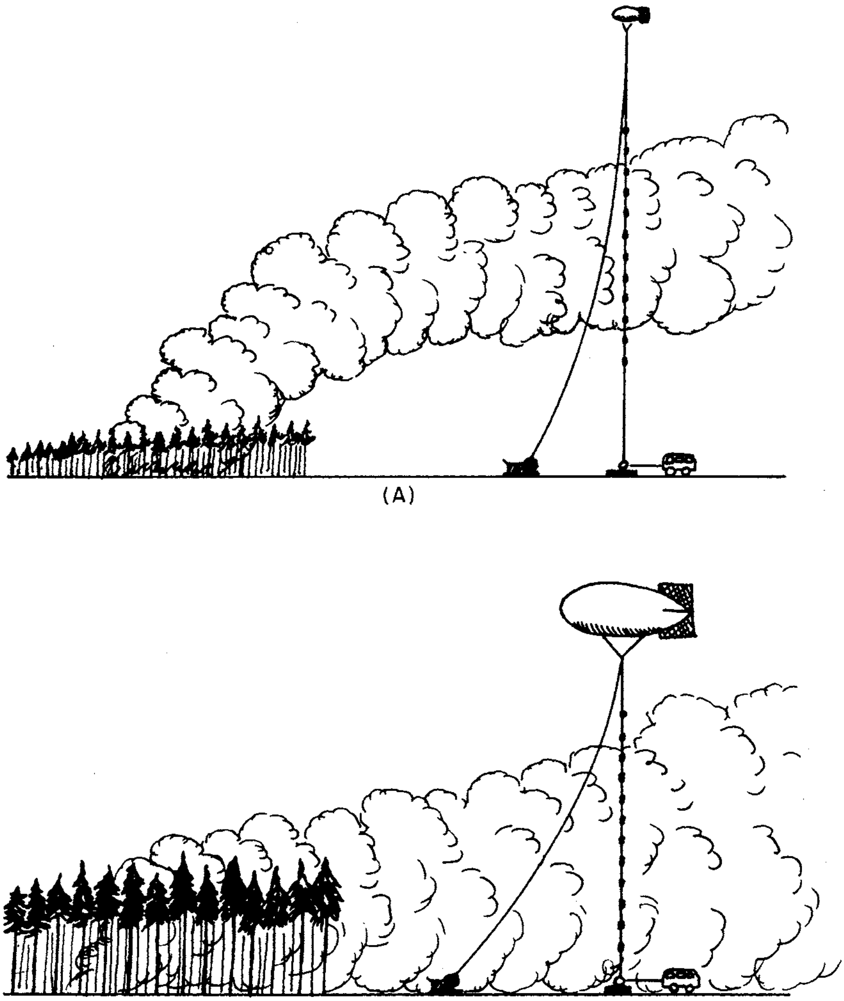


FIGURE I. A CONCEPTUAL REPRESENTATION OF A BALLOON SYSTEM POSITIONED TO SAMPLE (A) THE PLUME FORMED DURING THE CONVECTIVE-LIFT PHASE OF A FIRE AND (B) THE DRIFT SMOKE PRODUCED DURING THE NO-CONVECTIVE-LIFT PHASE.

Balloon Subsystem

Balloon. A search for a tethered balloon for this subsystem led quickly to the Class C, aerodynamically shaped balloon. Other designs available for tethering operations are the vee, barrage, and natural shape. However, the vee balloon has not progressed beyond the experimental stage, and the more streamlined hull and stabilizer design of the Class C gives it a better lift-to-drag ratio than the barrage design.[8] Balloons of natural shape design are limited to operations where large sizes are needed to give a high lift-to-drag ratio for resisting wind blow-down (e.g., in logging operations).

Class C balloons are available in sizes from about 17 m^3 to 7080 m^3. Although none are off-the-shelf items, there are a number of standard models up to 99 m^3 (3500 ft^3) that can be obtained in a reasonably short time. Our payload and elevation requirements made it clear that the largest standard model available would be needed for this task. The Raven Industries, Inc.'s[1/] Model TRFD 3500, (tethered, ridged fin, single dilation panel) 99-m^3 balloon, shown in Figure 2, was selected for its lift as well as delivery and cost considerations. This balloon is 12 m (40 ft) long and has a maximum diameter of 4 m (14 ft). The dilation panel with bungee cord on the bottom provides the expansion needed as the balloon is raised. The TRFD 3500 is a larger version of the 70-m^3 model used successfully by the National Oceanic and Atmospheric Administration (NOAA) during the Atlantic Tropical Experiment of the Global Atmospheric Research Program (GARP).

The gross lift capacity of the TRFD 3500 at sea level is 106 kg. The balloon weighs 43 kg and 600 m of control line weighs 11 kg. Therefore, maximum net lift available for instrumentation and an adequate stability factor is 45 kg. When using the system at higher elevations, gross lift is reduced as shown in Table I.

Tether and Rapid Deflation Lines. Balloon tethers are available in a wide variety of materials, construction, and sizes. In recent years Nylon, Nolaro, and Mylar ropes have been used in various balloon operations. Kevlar, a new lightweight fiber from DuPont, shows promise as tether material. It has both a good strength-to-weight ratio and minimum elongation properties. We used Phillystran, a polyurethane-impregnated Kevlar cable from Philadelphia Resins Corp. for both the tether and rapid deflation lines.

Federal Aviation Administration (FAA) regulations require a balloon tether line to be marked at 15-m intervals above 45 m. For high visibility, we used 0.6 m x 0.9 m strips of orange forestry flagging to mark the line. To prevent the flags from wrapping around the tether as it twists during balloon ascent, L-shaped pieces of wire were secured to the flagging. These wires also made the flags stand out for higher visibility during periods of low windspeed. In addition to tether markings, the FAA requires a safety device that will rapidly deflate the balloon if the main tether line should part. For this purpose, a wire inside the balloon is attached to a rapid deflation line. If the tether parts, tension on this line causes the wire to rip open the balloon.

1/ Mention of commercial firms and products throughout this paper does not constitute endorsement by the U. S. Department of Agriculture.

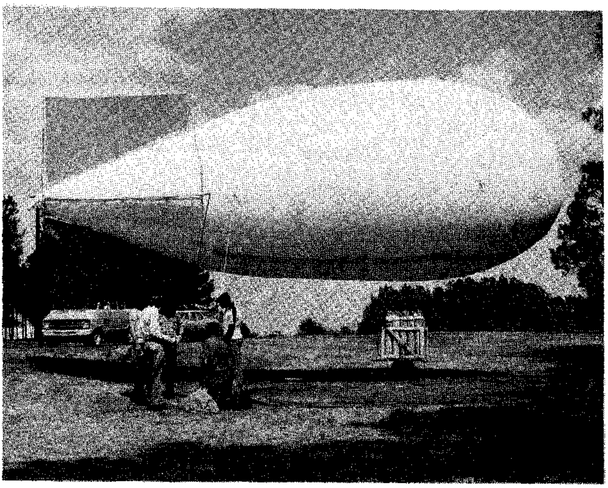


FIGURE 2. The TRFD-3500 balloon provides 106kg of gross lifting capacity at sea level.

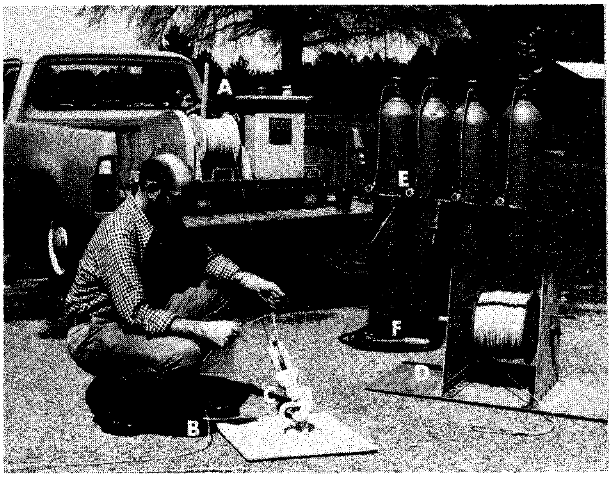


FIGURE 3. Major pieces of balloon inflation and control equipment (a) tether line winch, (b) anchor plate, (c) fairlead, (d) rapid deflation line reel, (e) helium manifold, and (f) inflation hose.

Table I. Affect of altitude on lift of the TRFD 3500 balloon.[a]

Elevation Above Sea Level (m)	Standard Temperature t_s(°C)	Air Temperature t_a(°C)	Density Ratio	Gross Lift C_L(kg)
0	15.0	10	1.000	106
600	11.1	10	0.944	99
1200	7.2	10	0.890	92
1800	3.3	10	0.838	86
2400	-0.6	10	0.789	79
3000	-4.5	10	0.742	74

a/ Adapted from Myers.[(9)]

Tether Line Winch. The most common balloon winches are large and expensive machines that can be mounted on the back of a big truck or on a permanent ground platform. They feature double capstans, level winds, fairleads, and infinitely variable speed control. More suitable for our requirements was a winch that could fit the bed of a pickup truck. The double capstan, needed to take up the stretch in the tether, could be omitted with our minimal elongation tether. The level wind, which spreads the tether over the full width of the drum, can be compensated for by locating the fairlead a sufficient distance from the winch drum. Since the drum receives the full load of the tether, the fleet angle (i.e., the angle at the fairlead, subtended by half the width of the drum) must be kept at no greater than 1.5°[(9)] to minimize wearing of the tether. An infinitely variable, high-speed winch is required for optimum use of the balloon. Line speed must be slow at times when sampling packages are released from the ground; the speed must be high when rapid adjustments are made in the sampling array; change in speeds must be smooth to prevent stresses on the sampling packages that could damage components.

Because none of the available small winches had a variable speed, it was necessary to have one built to our specifications, which were:

(A) Drum capacity--662 m (2500 ft) of 0.318-cm (1/8 in) diameter, dacron-jacketed Phillystran.

(B) Speed--infinitely variable from 0 to 53 m/min (0 to 175 ft/min).

(C) Dynamic pull--181 kg (400 lb).

(D) Static pull--272 kg (600 lb).

(E) Braking--failsafe type that locks drum when control lever is in neutral or motor is turned off.

The winch we purchased is shown in the back of a pickup truck in Figure 3. Designed and constructed by Otis Engineering Corporation, it weighs 356 kg (785 lb) and is approximately 1 m x 1 m x 1 m. A hydraulic pump, powered by a 3-phase, 3-hp, 220 VAC electric motor provides the smoothly variable speed drive. This winch is now an off-the-shelf item available with electric, diesel, or gasoline motors.

Ground Support. Several pieces of equipment are needed to inflate and control the balloon as well as to give it general support. Shown in Figure 3 are:

(A) Tether line winch--a device to take in and pay out the main tether line.

(B) Anchor plate--a square steel plate with U-brackets used to anchor the fairlead to the ground. Where ground is too hard for stakes, a 1.5-m x 1.5-m platform with a slit in the center can be placed over the anchor plate and then loaded with weights (e.g., sandbags).

(C) Fairlead--a 15-cm snatch-block used at the selected anchor point to translate horizontal tether-line motion to vertical motion.

(D) Rapid deflation line reel--a manually operated device to handle the safety line. During flights, it is anchored to the ground and its reel locking bar is in place.

(E) Helium manifold--a device to permit uninterrupted flow of helium to the balloon during filling. A normal balloon filling at sea level requires 17 cylinders of helium.

(F) Inflation hose--attached to the manifold, it can be used separately with a single cylinder.

Not shown in Figure 3, but also required are:

18,000-lb GVW truck to carry helium, balloon, and all equipment.

12-kw 3-phase generator to supply power to the winch, ground station, and support activities.

50-lb sacks of sand for bedding down the balloon and anchoring the fairlead.

Large box with tools,clevices, snap swivels, and miscellaneous items.

Box with tether flags.

Tarpaulin to cover 6-m x 12-m balloon inflation area.

Box with radios.

Instrumentation Subsystem

In the process of developing an instrumentation subsystem for source sampling, several questions had to be answered and several choices had to be made:

(A) What environmental parameters would be measured? What emissions would be sampled?

(B) How would these be measured and sampled? Would off-the-shelf instruments suffice or would new items require development?

(C) How would the packages and sensors be controlled (local or remote; synchronous or asynchronous)? How much would they weigh?

(D) How would the data be transmitted (radio telemetry or hard-wire); timed (continuous or multiplexed); recorded (visual, hard copy or computer compatible)?

It was known that some physical samples (e.g., filter and gas grab samples) would have to be collected continuously and that some data (e.g., windspeed and temperature) could be multiplexed. These requirements, along with power, weight, and cost restrictions, led to the development of a hard-wire, data-multiplexing system with all control and recording functions taking place in ground modules. Provisions were to be made to sample or monitor for particulate matter, combustion gases, windspeed, and temperature. With an estimated weight of 2.3 kg per package, the net lift of the balloon could usually accommodate 12 packages.

The method for attaching packages on the instrument line would have to be such that spacing between them could be varied to accommodate different plume shapes. To accomplish this, an instrumentation line was prepared with attachment points every 3 m. Arrangement of sampling packages would then be completely flexible, limited only by the total line length and the 3-m minimum between package spacing. Within these limitations, any sampling configuration could be established in the field just prior to the experiment. Also, if the plume underwent a major change in dimension, it would be relatively easy to lower the balloon, shift the packages to new spacing, and resume sampling.

Figure 4 is a simplified block diagram of the prototype instrumentation system that was developed. It contains two major components: (1) the ground station and (2) the sampling packages which are connected by a signal and control cable (instrumentation line).

Ground Station. The ground station, shown in Figure 5, contains a basic control section that has the timing, switching, and tone-generating circuits to control package functions, interrogate individual sensors, and synchronize data recording. Audio tones are used for system control functions. Standard touch-tone low-range frequencies of 697, 770, 852, and 940 Hz and high-range frequencies of 1209, 1336, and 1477 Hz were selected because of the ready availability of encoding integrated circuits (IC's).

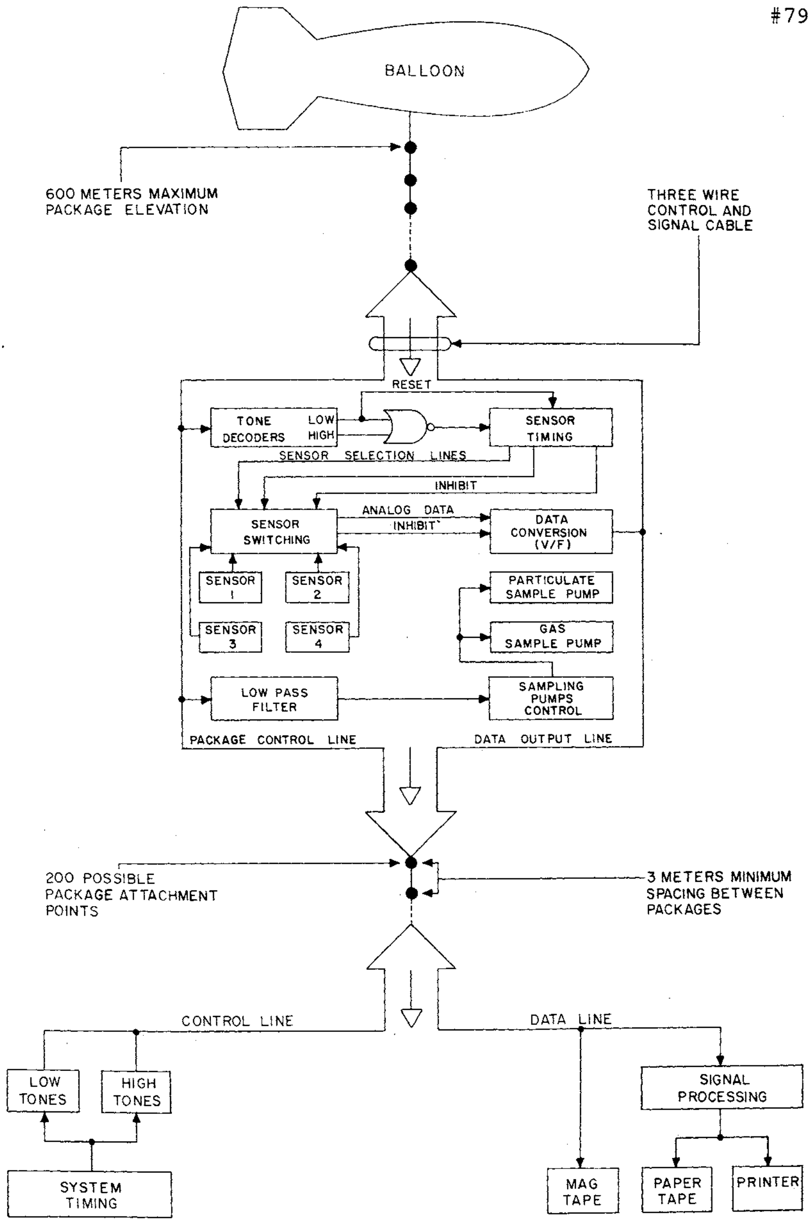


FIGURE 4. PROTOTYPE BLOCK DIAGRAM

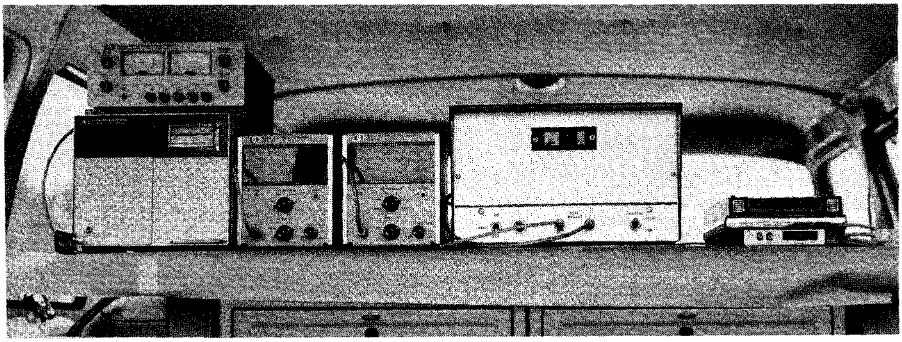
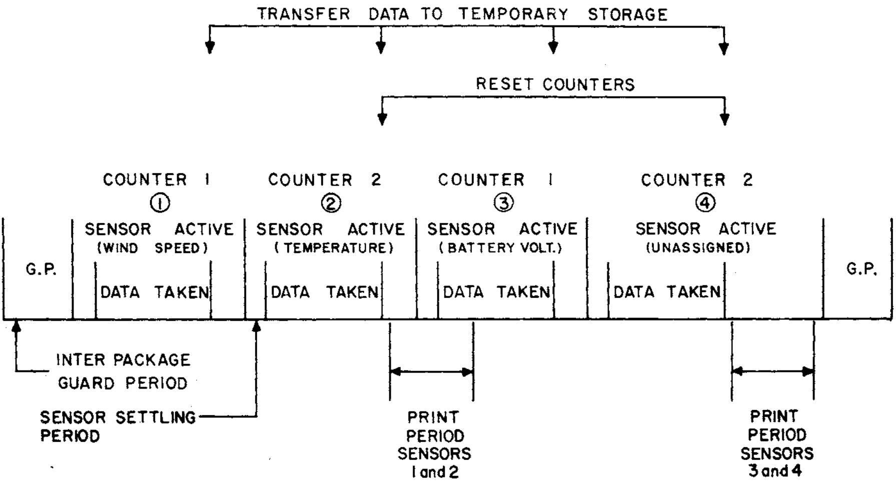


FIGURE 5. The ground station fits in the back of a van for easy transportation and operator access.



PACKAGE ACTIVE	3000 ms
INTER PACKAGE GUARD PERIOD	300 ms
SENSORS ACTIVE	600 ms
SENSOR SETTLING PERIOD	50 ms
SENSOR DATA TAKEN	400 ms
PRINTER CYCLE TIME	325 ms
BASIC SYSTEM CLOCK	100 ms

FIGURE 6. INTERNAL TIMING SEQUENCES WITHIN THE SYSTEM FEATURE GUARD PEROIDS TO ELIMINATE BETWEEN-PACKAGE OR BETWEEN-SENSOR INTERFERENCE.

Tones are fed through the system via a hard-wire control line. Various functions in the instrumentation packages are activated in response to selected single or dual tones, i.e., a tone-pair. Any single low tone will activate the sample pumps in all packages. A tone-pair is required to activate the sensors in a given package, each package responding to a unique tone-pair. To select a given sensor, the high tone of the tone-pair is pulsed a number of times, e.g., once for windspeed, twice for temperature.

As design and construction of the system progressed, it seemed desirable to provide room for expanding the number of sensor slots in each package beyond the two used for temperature and windspeed. Accordingly, the system has been wired to accommodate four sensors per package. The switching circuits controlling the low tones have a repetition rate of 3 seconds. During the 3 seconds a given package is active, the high tone for that package is pulsed four times to activate each of the sensors for 600 milliseconds (ms). As shown in Figure 6, data are actually taken for only 400 ms during this period to eliminate the effect of switching transients and to accommodate the relatively slow mechanical printer used as one of the data recorders. Total time to interrogate and receive data from the 48 sensor positions is 36 seconds.

The ground station has three provisions for data recording. As output from each sensor is impressed on the data line, it is converted to base 10 numerical format by the signal processors and frequency counters. These output data are simultaneously printed on paper and punched on paper tape. The printed record is available for immediate inspection to verify system operation and identify response of individual sensors. The paper tape records all the data appearing on the printed record. Its main use, however, is for transferring data to a computer for further reduction and analysis. The magnetic tape is used as a backup record for all system functions. A 2-track cassette is used, one track records the control tones and the second records activity on the data line. With this record we can completely reconstruct all package input and output signals.

Sampling Package. The 2.3-kg sampling package developed for the balloon consists of four major components: (1) temperature monitor, (2) windspeed monitor, (3) particulate-matter sampler, and (4) gas-grab sampler. The first two components were developed from basic electronic parts, while the latter two consist of modified off-the-shelf equipment. Figure 7 shows the entire package connected to the instrumentation line. The tone-decoding required to activate various functions in each package is done by phase-lock loop (PLL) circuits set to respond to the frequencies assigned each package. Tuneable PLL's are employed, enabling rapid reconfiguration to meet changing field conditions. In the absence of a particular frequency, the output from a low-tone decoder is used to reset all functions of the package and prepare it for its next active period. In actual use, multiple reset commands are issued because in a complete system cycle any given low tone is turned on and off three separate times. When the correct combination of low and high tones is sent for the first time after a reset, an electronic switch moves to its first position, thus enabling sensor number one. As mentioned earlier, the high tones are pulsed at 600-ms intervals. As these pulses occur, the switch moves progressively through all sensor positions, enabling each one in turn.

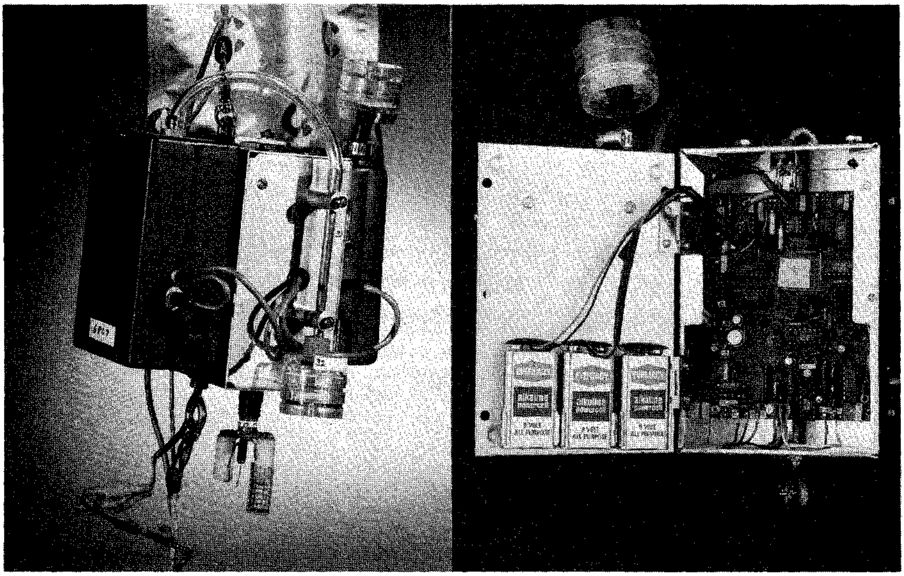


FIGURE 7. (Left) Snap-hooks and quick-disconnect terminals attach a fully configured package to the instrument line, (Right) an open package.

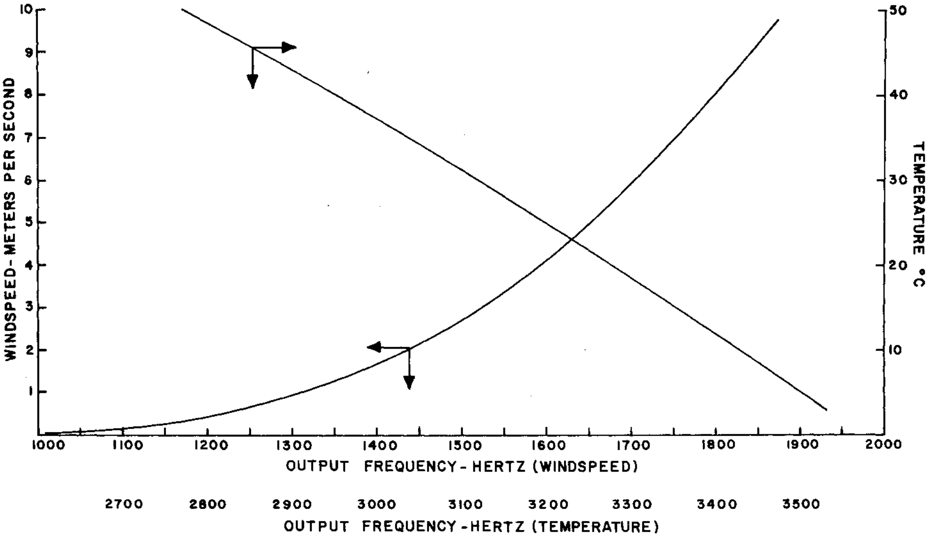


FIGURE 8. TYPICAL FREQUENCY RESPONCE CURVES FOR THE CIRCUITS MEASURING TEMPERATURE AND WINDSPEED.

The sensors or transducers used in this system are analog types, i.e., they produce a continuously variable voltage in direct response to a physical phenomenon. Because of the differing line configurations encountered in field work, it is not practical to work directly with the relatively low voltage levels produced by these sensors. The analog output from each sensor is therefore converted to a frequency signal by a V-to-F circuit, and the desired information is transmitted in this form to the ground station for recording.

Any sensor producing a voltage output may be used in this system. Thus far, we have used thermistors to measure temperature and windspeed and a simple resistance voltage divider to monitor battery levels in the packages. Data from these sensors are multiplexed on the data line as described earlier.

Temperature Sensor. Ambient temperature is measured with a Yellow Springs thermistor (YSI 44202) operated in a non-self-heat condition. This thermistor has a basic accuracy of ± 0.15°C. Typical response from the thermistor, when converted to frequency by a V-to-F circuit, shows a slightly curvilinear response with about 16 Hz decrease in frequency for each degree increase in temperature (Figure 8).

Windspeed Sensor. Windspeed is measured by a Fenwal thermistor (G-126) operated in a self-heat condition. A bridge circuit supplies an amount of power needed to maintain a fixed resistance in the thermistor and produce a fixed amount of heat. Wind moving past the thermistor increases heat dissipation, which shifts thermistor resistance. The bridge circuit senses the unbalanced condition and shifts power supplied to the thermistor to restore balance. The voltage change associated with the shift in power (which includes correction for ambient temperature) is fed to the V-to-F circuit as the measure of windspeed. The response of the windspeed circuit is shown in Figure 8. The response is not linearized and thus gives greater frequency resolution and interpolation accuracy at low speeds--approximately 277 Hz/km (500 Hz/mi) at 1.3 m/s (3mi/h) than at higher speeds--approximately 11 Hz/km (20 Hz/mi) at 7.6 m/s (17 mi/h).

Sampling Pump Control. A low-pass filter with a cut-off at 1 KHz (greater than 48 Db/octave) separates the high and low control tones. All low tones pass through the filter and are used by a pump-control circuit to activate the vacuum pumps used to collect the particulate matter and gas samples. Since a low tone is always present during sampling, the pumps run continuously.

Particulate-Matter Sampler. This sampler is a lightweight, 37-mm, disposable, millipore, plastic, filter holder containing either a preweighed Teflon or glass-fiber filter; it is connected to a battery-operated DuPont P4000A constant-flow pump. Teflon filters have greater mechanical stability than glass-fiber filters, but they are more susceptible to pressure drop upon loading. The P4000A pump has an effective flow range of 500 to 4000 cm^3/min. Constant flow control during the sampling period assures control of the preset flow rate with ± 5% accuracy. Any change in pressure drop of up to 25 cm of water (at 4000 cm^3/min) is automatically compensated for by a feedback signal which speeds up the pump to overcome the higher inlet pressure drops. Without this automatic control, the flow rate would decrease upon loading, causing appreciable errors in the calculation of the sample volume, and consequently, the calculated concentration of particulate matter. Pumps can operate for a minimum of 8 hours with a fully charged battery pack. Filter holders were connected to the pumps by a short (2.5-cm) piece of vacuum tubing, which allows for a rapid reloading with fresh holders as needed. Gravimetric analysis is performed on the filters in the laboratory with a sensitive electrobalance. In order to be able to start and stop the samplers during flight, the manual-start switch was by-passed with a pump control circuit controlled at the ground station.

Gas-Grab Sampler. Combustion gasses are collected in a 5-liter aluminized sampling bag connected to a DuPont P-200 constant-flow pump equipped with a glass fiber pre-filter. The flow range of the P-200 pumps is 50 to 200 cm^3/min with $\pm$ 5% accuracy up to 63 cm of water-pressure drop. Various bag sizes and flow rates can be accommodated. At 50 cm^3/min, the 5-liter bag could sample effectively for approximately 50 minutes before having to be replaced. Various types of bags (Teflon, Saran, Mylar, etc.) can be used. Miniature sorbant tubes containing Tenax GC, XAD resins, etc. can also be incorporated into this sampler so that a complete range of gas and vapor constituents can be collected. Analysis of the bag contents and sorbant traps can take place either onsite or later at the laboratory, depending on the constituents to be analyzed and the methods used for analysis. During this developmental stage, the procedures were focused on the onsite analysis of gas samples for carbon dioxide (CO_2), carbon monoxide (CO), and nitrogen oxides (NO_x) with non-dispersive infrared, electrochemical, and chemiluminescence techniques. Of the three, it was imperative to carry out the NO_x analysis rapidly in order to minimize errors from sample degradation. Thus, a support van containing a Thermo-electron 14D NO_x analyzer was provided, and procedures were developed to analyze for NO_x within 15 minutes after the grab sample was removed from the instrument line. Carbon monoxide and carbon dioxide in the samples do not degrade rapidly and can be analyzed hours or days later.

The reason for CO and NO_x analysis is obvious from their status as Criteria Pollutant. The reason for CO_2 analysis may be less obvious and calls for a brief digression here. Vines et al.(10) and later Goss and Miller(11) reported on an indirect method to determine fuel consumption for open combustion. Ordinarily, forest fuel consumption is determined by tedious, before-and-after sampling on the site according to gravimetric lift and weigh techniques. Vines et al.(10) pointed out that since CO_2 was the predominant (90%) combustion product of carbonaceous fuels, it is possible to approximate the moles of fuel consumed from moles of CO_2 produced if combustion equations and stoichiometric principles are employed. At the present time, scientists at the Southern Forest Fire Laboratory (SFFL) are attempting to refine this technique by using model fires in the laboratory.

In the earlier work by Vines et al.(10), the only carbon product of combustion measured and used in the analysis was CO_2. In the new work (at SFFL) all major carbonaceous products, i.e., CO_2, CO, hydrocarbons, and particulate matter, will be incorporated to reduce the variability and error. This carbon-balance technique is crucial to monitoring wildland fire emissions where lift-and-weigh techniques are not possible. The balloon system provides an opportunity to obtain data for verifying the technique under field conditions.

System Evaluation

Initially, each subsystem was evaluated independently during the developmental stages. As might be expected, several potential problems were identified and corrected during these evaluations.

The balloon winch, for example, was found to have two problems caused by faults in the hydraulic system. First, the spring-loaded reel-brake would not engage. The hydraulic pressure used to hold the spring-release mechanism was not being relieved when the control lever was in its neutral or braking position. Second, the winch would lose power and stall when demands of high winch load and high reel-in speed were combined. These two problems, caused by the same components, were corrected by the manufacturer without much trouble. However, if we had tried to operate with the winch as it was received, there could have been some serious balloon-holding and control problems.

In the process of testing and evaluating the winch, another potentially serious problem was discovered with the tether line orginally chosen (3.2-mm-O.D., braided Phillystran with a rated breaking strength of 545 kg). Twisting of such a line under stress weakens it and leads to early failure. After one test in which the braided line parted under a load of only 180 kg, we switched to 7 x 7 stranded Phillystran line and have had no further problems.

Concurrent with the initial evaluations of the balloon subsystems, the electronic circuit designs related to package control, sensor conditioning, and sensor response were evaluated. Potential problems were also uncovered here. For example, a relatively standard method had been tried for measuring windspeed--a pair of matched thermistors were employed in opposite legs of a bridge circuit, one to measure windspeed and one to furnish temperature compensation. With this approach, the thermistor furnishing compensation must be operated and exposed in the same manner as the thermistor measuring windspeed, except that it must be completely shielded from the wind. No adequate shielding mechanism could be fabricated to permit this circuit to operate satisfactorily. Therefore, temperature compensation for a single thermistor wind-sensing bridge circuit was provided by a second thermistor not directly in the main bridge and not required to operate in a self-heated condition.

Field Testing

A series of full-scale field tests was conducted within a 50-km radius of the laboratory. During these tests, it became obvious that a minimum of seven people are required to safely handle the entire system under a full range of operating conditions. Assignments shift within various phases of the operation. After arrival at a given site, one five-person team prepares the balloon. They unpack all equipment, spread the deflated balloon on a tarpaulin, assemble the tail section, establish the anchor points, partially inflate the balloon, attach the tail, and attend to all other preflight details. Meanwhile, the second team is preparing the instrumentation line, packages, and ground station. When all goes smoothly, it takes from 2 1/2 to 3 hours to ready the system. (Our first attempt took well over 4 hours.) The most critical times in balloon handling occur during launching and recovery. At these times, everyone is assigned to help with the balloon.

After the tether, safety, and instrumentation spacer lines are attached, the balloon is raised to a holding elevation so that the instrumentation packages can be attached. During this period, the assigned personnel again function as two coordinated teams (i.e., a balloon team and an instrumentation team) until all packages are in the air and the balloon is at its final elevation.

...We recommend that this system be used with no less than seven persons in the balloon handling crew.

Handling the instrumentation line and packages during balloon ascent was initially quite awkward. The operation has been simplified greatly by using the package "clothesline" shown in Figure 9. Packages are preattached to the instrumentation line at the desired interval and hung on the "clothesline." On ascent, the packages are simply payed out with the line as the balloon rises. This arrangement also facilitates handling the packages during an experiment when package spacing, filters, gas bags, or batteries have to be changed. It takes about 15 to 30 minutes to recover, reconfigure, and relaunch the packages, depending on balloon height.

During one test, we encountered ambient winds so low that the smoke did not move in a single direction and valid samples could not be obtained. The samplers were alternately in smoke and clear air. In this case, the windspeed was below that which is normally recommended for prescribed burning. (In timber stands, windspeeds normally recommended for prescribed burning are from 0.9 to 4.5 m/s; ambient windspeeds are usually divided by a stand density factor of 2 or 4 to obtain in-stand values.) With consistent windspeed and direction, the system can be positioned in relation to the fire front so as to be in a representative portion of the plume with perfect alignment between smoke flow and sampling packages for the duration of the fire.

...We recommend that this sampling system not be used with ambient windspeeds of less than 3.6 m/s.

...We recommend that this sampling system not be used when wind direction is varying more than 45° from either side of the desired azimuth.

In our work, there are many times when the smoke to be sampled will not rise above 75 m. Therefore, we were interested in how stable the packages would be at low elevations. To evaluate stability, we flew the balloon in an open field near our laboratory. When the balloon was tethered at about 100 m, with winds gusting to only about 8 to 11 m/s, it was not stable. Instead, it tended to make figure eights which impart sharp oscillations to the instrumentation line. Under these conditions the packages, especially those closest to the ground, are continually in motion and may swing 15 to 20 m or more on either side of an imaginary centerline.

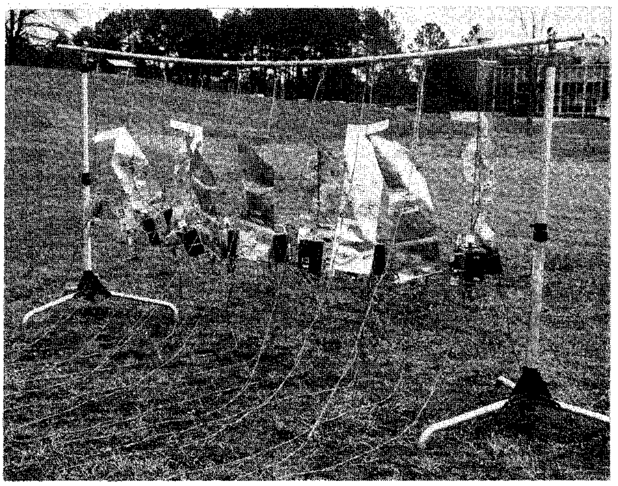


FIGURE 9. Hanging packages on a "clothesline" helps prevent tangles in the instrumentation line and facilitates sending packages aloft.

...*We recommend that when all instrument packages must be close to the ground, a 100- to 300-m spacer be inserted between the balloon and instrumentation line to permit optimum balloon elevation and desired package heights.*

...*We recommend that this system not be used with ambient windspeed or gusts exceeding 18 m/s or with extreme turbulence in the area.*

It must be emphasized that this system requires a certain amount of open space to operate successfully. The amount of clear area around the anchor point depends on windspeed and, more importantly, on the amount of low-level turbulence or gustiness. Normally, burning takes place in forested areas where open spaces are sometimes small. Here, we have to make a choice: not fly, sacrifice trees to enlarge an opening, or chance flying in the natural opening. We have successfully flown in very narrow forested canyons at night when windspeeds were less than about 1 m/s. We have also chanced flying in openings which were less than optimum in size and have had some trouble in recovering the balloon when unexpected gustiness occurred.

...*We recommend that this system be operated in a cleared area with a radius of no less than 35 m.*

During one of our tests, a small, fast-moving thunderstorm became visible in the distance. The storm would not have affected the burn, but while it was in the area, we experienced a failure in the package interrogation circuitry. The failure of two IC's, which blocked the sequencing of all packages, was attributed to the electric fields generated by the storm. Most of our electronic circuits have been built around Complementary-Metal-Oxide-Silicon (CMOS) IC's because they have very low power requirements. Unfortunately, CMOS devices are also susceptible to damage from static electricity. Consequently, we added some further system grounding features, and since have not experienced similar failures. (However, we have not flown the packages in areas with thunderstorm activity again either!)

...*We recommend, for the safety of both personnel and equipment, that the system not be used when thunderstorms are nearby.*

All the testing near the laboratory was in flat or gently rolling terrain. To learn how the system would work in mountainous areas, we arranged for a series of smoke sampling experiments on the Ft. Apache Indian Reservation at Maverick, Arizona in the fall of 1978. A brief résumé of related experiences from this field work may illustrate some of the reasons for the scarcity of data for fires in many forest fuel types.

The first Arizona flight was made as one part of an all-night experiment designed to show how air drainage in a steep-walled canyon would affect downwind dispersion of residual smoke from a fire burned at the head of the canyon. Late afternoon skies were clear on the day of this experiment; temperatures, at that time, were about 3°C and were predicted to go much lower that night. Even though the instrumentation packages were not designed for below-freezing temperatures, we decided to fly because bad weather was moving in. The electronic system did not perform well that night. Acceptable voltage levels of the batteries were shortened by the cold from an expected 5 to 6 hour life to about 30 minutes of operation. Output temperature and windspeed data became progressively more unreliable as temperatures descended below freezing. Below -3°C, the package interrogation circuitry did not function.

After the weather cleared, we chose to begin our second experiment even though fuel moisture levels were higher than desired and another weather system with predicted snow and sleet was approaching. This experiment required burning three blocks in the same forest type and was to be accomplished in 1-1/2 days with the balloon system essentially in the same location. Our first fire for this experiment was ignited early one afternoon when the temperature was in the mid 60's. Balloon and instrumentation systems functioned very well during the smoke sampling period.

After securing the fire late that evening, we left the balloon inflated and flying at a safe elevation, in anticipation of the next morning's burn. Unfortunately, the weather system arrived during the night and brought excessively high wind levels which prevented the continuation of the experiment. The high, gusty winds also made it extremely difficult to recover the balloon and probably would have destroyed it if it had been moored near the ground. All hopes of conducting further smoke sampling in Arizona during the fall of 1978 were ended by the snow which arrived with this weather system.

System Extension and Applications

Thus far, discussions of the balloon system have centered on the use of a single balloon with multiple packages deployed in a fixed vertical array. Our experience to date has suggested several extensions to this concept which are worth noting because they could be achieved with only minor modifications to the current system. Briefly, they include the following:

(A) Sequencing balloon packages.

(B) Traversing balloon packages.

(C) Ground grid applications.

Sequencing Balloon Packages. Documentation of the emissions from different fire phases could be accomplished with more accuracy and greater control if the ground station could randomly activate the packages. Samplers for TSP and gases on one-half the packages, for example, would be used during one fire phase and the other half during the other phase. Packages 1, 3, 5, 7, 9, and 11 could operate during the CL phase and 2, 4, 6, 8, 10, and 12 during the NCL phase. In this way, there would be no need to lower the balloon and change samplers between phases.

Another modification would be to use a lightweight manifold and switching circuit to collect several filters and grab-bag samples on each package on a time-sequenced basis. The sequencing would be controlled from the ground station.

We have also considered using portable towers with the balloon system to achieve similar results. In this case, the balloon system would carry aloft the packages needed for the CL phase, up to 600 m (2000 ft), while "crank up" towers, up to 37 m (120 ft) could be instrumented for the NCL phase.

Traversing Balloon Packages. Lift problems of the present system at high altitudes can be overcome by reducing the number of packages and then raising and lowering the balloon so that the sampling packages would traverse the plume as it passes through the instrument line. In place of a fixed vertical array of 12 packages, 2 to 4 packages could integrate the concentration gradients that exist within the plume. A plume profile of smoke concentrations would not be obtained with this approach, but the integrated values would still provide the data by which to calculate emission rates and factors.

Ground Grid Applications. During the course of developing the balloon system, it became apparent that the instrumentation subsystem (i.e., packages, line, and ground station) could be applied in a variety of ground grid networks. With little or no modification, this subsystem can be used in any ground application that calls for the collection of samples coordinated in time and space. Some examples are:

---The packages could be deployed along a horizontal vector to quantify the variability along a fire front.

---The packages could be placed along a vector perpendicular to the fire front for quantifying ground concentrations of smoke at different distances from the vicinity of the fire. The current length of the instrument line (610 m) could easily be lengthened to 1000 m or longer. Information from this type of array would help in the development of reliable predictive models for ground concentrations close to line sources.

---The packages could be used in complex terrain (e.g., a "v" shaped array in a canyon) for studies associated with "down slope or down canyon" transport of smoke during nighttime temperature inversions.

Finally, it should be noted that the balloon system also has application and merit in conjunction with emission studies for other open sources besides forest fires. Fugitive dust, refuse dump burning, coal refuse piles, and agricultural burning are all sources that result in plumes which cannot be easily measured by conventional methods.

Costs

Approximate costs for system components described in this paper are as follows:

Balloon		$5,000
Balloon winch		6,500
Tether and Safety line		1,000
Instrument control line		350*
Helium (one inflation)		350
Miscellaneous ground support (manifold, tarpaulin, etc.)		500
Instrumentation Package		
Sensors and electronics	12 ea. @ $ 75	900*
Particulate matter sampler	12 ea. @ $ 700	8,400
Gas-grab sampler	12 ea. @ $ 500	6,000
Ground Station		
Electronic control module		500*
Printer		1,300
Magnetic tape recorder		300
Paper punch		400

*Parts cost only--fabrication costs would be additional.

These costs do not include those of support vehicles, generators, or other general items which are neither unique nor an integral part of the balloon system.

Summary and Conclusions

The capabilities of the balloon system for source monitoring can be summarized as follows:

Provides plume profiles from line sources which cannot be sampled from ground or aircraft-based sampling systems.
Can be repositioned and sequenced to accommodate changes in plume geometry during different phases of a fire.
Can be transported and operated in remote mountainous and forested areas.
Can be readily modified to accept a variety of sampling and sensor devices.
Can be used in various types of atmospheric monitoring in both vertical and horizontal grid arrays.

The feasibility of this balloon system as a viable sampling method for monitoring emissions from forest fires and other line sources has been confirmed. Testing to date has been effective in demonstrating the system's operating characteristics and identifying design modifications which could lead to improved performance. Additional field testing is desirable to improve operating procedures for the balloon system and the instrumentation packages.

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