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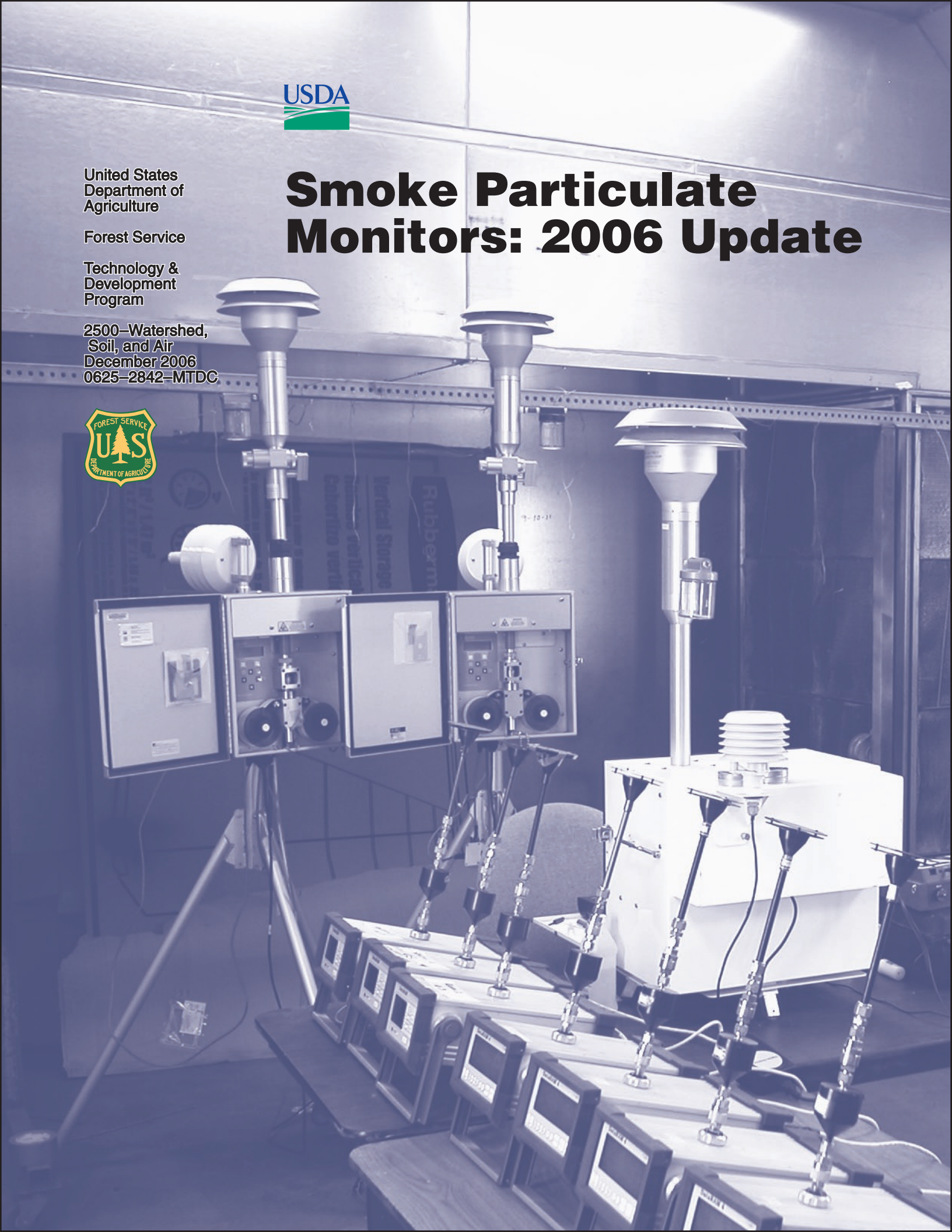
Smoke Particulate Monitors: 2006 Update



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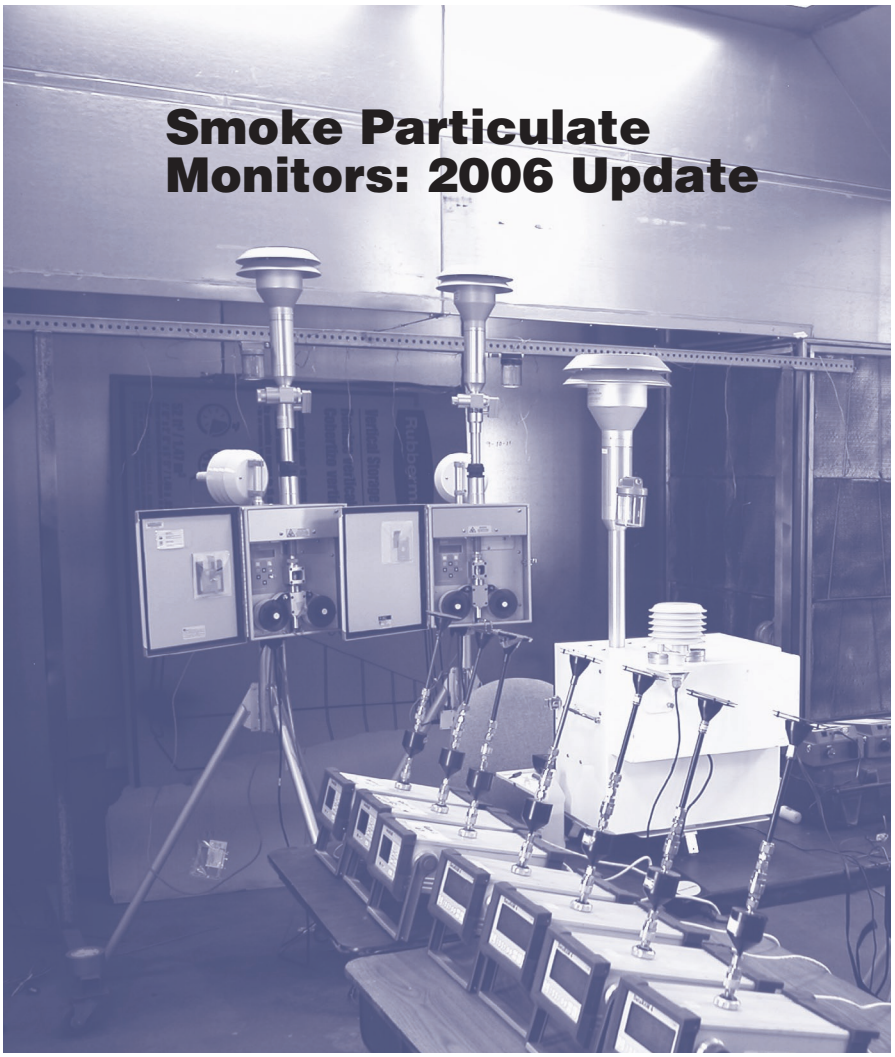

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6E62F46—Collocation Study of New Smoke Monitors

December 2006

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Contents

Introduction 1

New Laboratory Evaluation 3

Real-Time Instruments 4

Goals and Methods 8

Results and Discussion 9

Conclusions 14

Introduction

The Missoula Technology and Development Center Air Quality Program has been evaluating real-time smoke particulate monitors since 1999. Air quality specialists and fire managers use these commercial monitors to estimate smoke particulate concentrations from prescribed and wildland fires. The center's evaluations include determining the accuracy of the real-time monitors by comparing their results to a gravimetric standard and evaluating the instrument's overall usability and functionality. Usually, evaluations are conducted when new, promising commercial monitors are introduced or when Forest Service personnel are considering using monitors that have not been evaluated.

Since the last evaluation in 2003, several developments in smoke monitoring have prompted a new evaluation. Met One Instruments Inc. has a new external ac electrical pump for their E-BAM particulate monitor. This ac pump can be used as a replacement for the short-lived internal dc electrical pump. Additionally, new firmware updates have been developed for the E-BAM to alleviate some technical issues. Also, some Forest Service personnel were using a monitor manufactured by TSI Inc. called the DUSTTRAK. The DUSTTRAK had not been evaluated by MTDC.

MTDC completed four evaluations of commercial real-time smoke particulate monitors from 1999 to 2003 (figure 1). Most of the evaluation tests were conducted in controlled laboratory

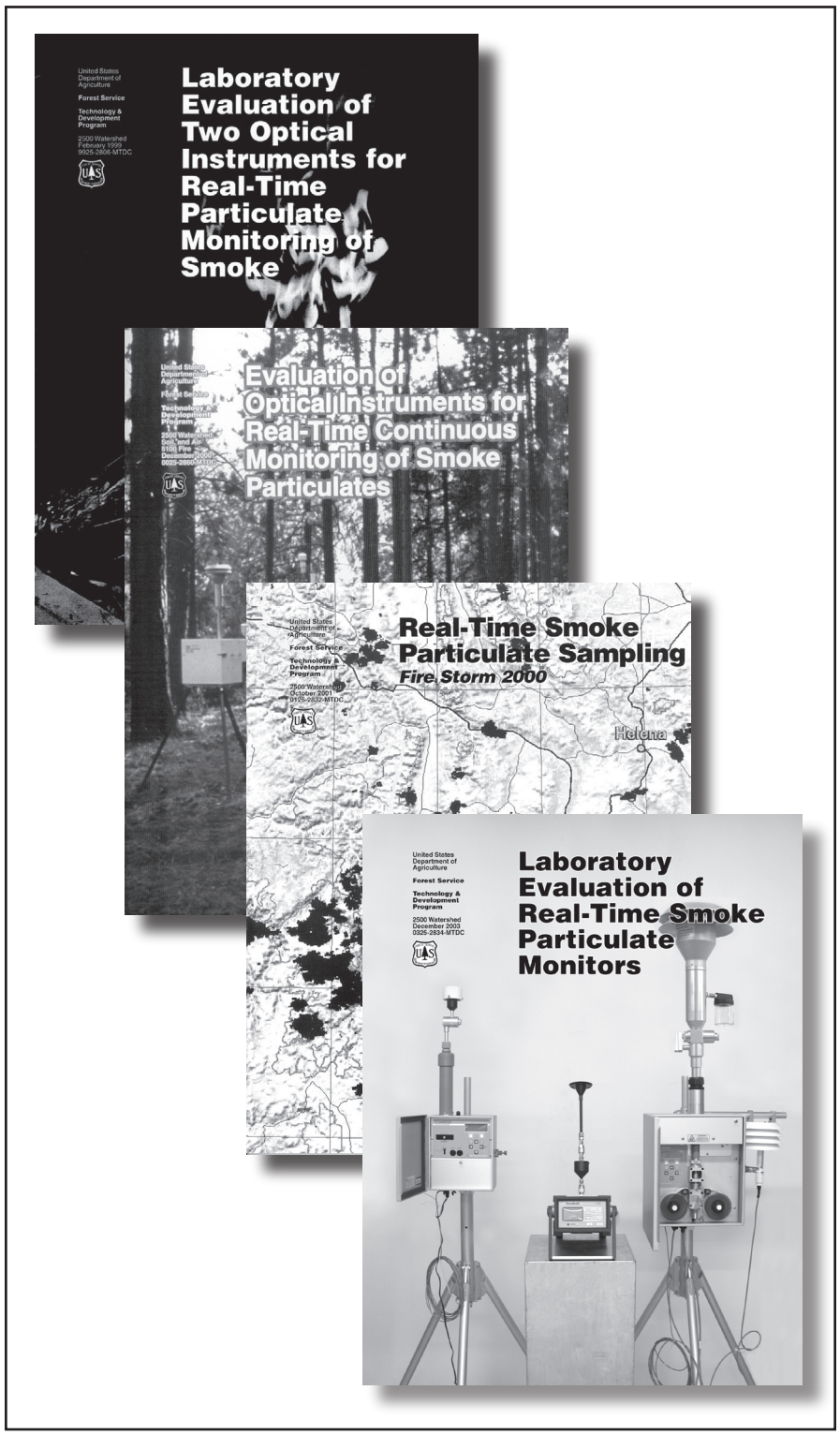

Figure 1—Four reports (9925–2806–MTDC, 0025–2860–MTDC, 0125–2832–MTDC, and 0325–2834–MTDC) detail the evaluations of several real-time smoke particulate monitors in laboratory and field environments.

conditions at the Rocky Mountain Research Station's (RMRS) Fire Sciences Laboratory in Missoula, MT. Other evaluations were conducted by monitoring prescribed and wildfire smoke. The previous reports include:

- Laboratory Evaluation of Two Optical Instruments for Real-Time Particulate Monitoring of Smoke (*http://www.fs.fed.us/t-d/pubs/htmlpubs/htm99252806/*)
- Evaluation of Optical Instruments for Real-Time Continuous Monitoring of Smoke Particulates (*http://www.fs.fed.us/t-d/pubs/htmlpubs/htm00252860/*)
- Real-Time Smoke Particulate Sampling—Fire Storm 2000 (*http://www.fs.fed.us/t-d/pubs/htmlpubs/htm01252832/*)
- Laboratory Evaluation of Real-Time Smoke Particulate Monitors (*http://www.fs.fed.us/t-d/pubs/htmlpubs/htm03252834/*)

This Web site (*http://www.fs.fed.us/t-d/*) requires a username (t-d) and password (t-d).

New Laboratory Evaluation

This evaluation included two Met One Instruments Inc. E-BAM monitors (one with a dc pump, and the other with an ac pump), two Met One Instruments Inc. E-Samplers, three TSI Inc. DUSTTRAK monitors, four Thermo Electron Corp. DataRAM 4 monitors, and three Thermo Electron Corp. DataRAM 2000 monitors.

The U.S. Environmental Protection Agency's Federal Reference Method (FRM) gravimetric sampler, a BGI Inc. PQ–200, was used as the standard. The FRM gravimetric filters were weighed by the RMRS Fire Sciences Laboratory in Missoula, MT.

Previous laboratory evaluations were conducted at the RMRS laboratory. Because the laboratory was not available for this evaluation, it was conducted in a large enclosed room at MTDC. The room is an industrial paint booth 14 feet wide, 9 feet tall, and 30 feet long. The ends of the booth were blocked off using a large plastic tarp and cardboard to keep the smoke in the room.

Monitors were set up side by side inside the chamber (figure 2). Smoke was made by burning small amounts of pine needles on a piece of thick aluminum foil on the floor of the paint booth. A fan mixed the smoke in the room.

The accuracy of the real-time monitors was determined by comparing the real-time results to the results from an approved FRM gravimetric sampler. The FRM sampler uses a pump to draw air across a filter that captures the smoke particulate. The filter is weighed before and after the tests to determine the total amount (mass) of particulate that was captured. The sampler calculates the volume of air that is drawn across the filter during the test. The average smoke concentration, represented in micrograms per cubic meter, can be calculated by dividing the mass by the total volume. The average real-time particulate concentration is calculated for the time the FRM sampler was operating.

Figure 2—The real-time smoke particulate monitors and the Federal Reference Method sampler shown inside the smoke chamber during testing.

Real-Time Instruments

E-BAM—The E-BAM (the E stands for environmentally protected) monitor (figure 3) uses a three-part process to estimate the mass concentration of particulate. First, beta particles from a naturally occurring radioactive isotope are emitted through a clean filter tape and counted. Second, sampled air is passed through the exposed filter tape and particles are deposited. Finally, beta particles are passed through the tape again and recounted. The second count will be lower than the first, because beta particles will have been absorbed by the deposited particulate. The instrument uses an empirically derived algorithm to estimate the total mass of the deposited particulate. The estimated mass is divided by the volume of sampled air to calculate the average concentration in mass per unit volume. The exposed filter tape will advance automatically and begin a new collection after a user-specified time period or when the tape becomes clogged.

Figure 3—The E-BAM ambient particulate monitor. This instrument collects particulate on a filter tape and uses beta ray attenuation to estimate particulate concentrations.

The E-BAM is a portable instrument that can operate using line (110 volts ac), battery, or solar power in the harsh environments typically found near a wildland fire without the need for an additional enclosure. It can be configured with EPA-approved PM_{10} and $PM_{2.5}$ particle size separators (cutoff inlets) to remove particulate larger than 10 micrometers (PM_{10}) or 2.5 micrometers ($PM_{2.5}$,) mean diameter, respectively. It uses pressure and ambient temperature sensors to recalculate flow at standard atmospheric conditions.

The E-BAM can be mounted on a tripod and configured to accept a variety of meteorological sensors for monitoring ambient windspeed and direction, relative humidity, and temperature. A six-channel data logger stores all the information. The range of measured concentration is 0 to 100 milligrams per cubic meter. The data logger can be programmed to report as often as every minute. Data can be downloaded at any time using an RS–232 serial port. A laptop computer or a modem can be configured to transmit the data using telephone lines, cell phone connections, or satellite telemetry.

The E-BAM is 16 inches high by 13½ inches wide by 8 inches deep. It weighs about 28 pounds without the PM_{10} or $PM_{2.5}$ cutoff inlet. The cutoff inlets combined weigh an additional 7.5 pounds and add 30 inches to the total instrument height. The power supply for 110-volt ac line power weighs 14 pounds. The ac pump (figure 4) is 10 by 16 by 18 inches and weighs 30 pounds. For more information, visit the Met One Instruments Inc. Web site at *http://www.metone.com* or call 541–471–7111.

Figure 4—The E-BAM monitor can be used with an external ac electrical pump rather than the internal dc pump, which is more likely to fail after extended use.

E-Sampler—The E-Sampler (figure 5) is a forward-scattering nephelometer that uses light-scattering principles to estimate mass concentrations of airborne particulate. An internal visible laser diode is directed through the sample of air. Particulate in the sample scatters a portion of the light. The scattered light is collected at a forward angle and focused on a

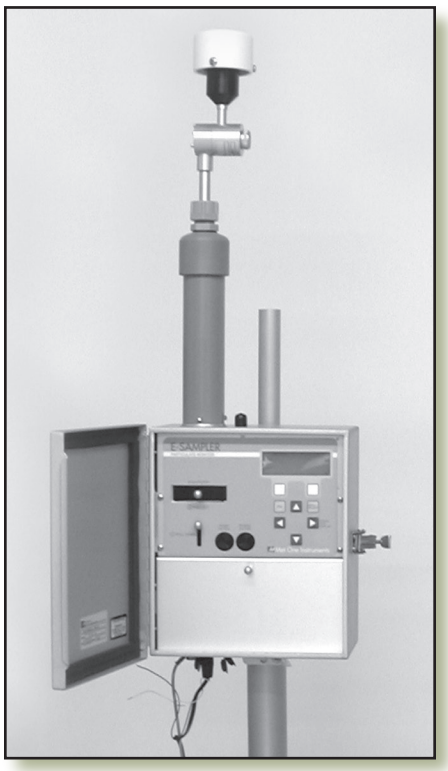

Figure 5—The E-Sampler uses light scattering to estimate particulate concentrations.

photodiode that converts the light to an electrical signal. The resulting signal strength is proportional to the amount of scattered light. An empirically derived algorithm converts the electrical signal to an estimated mass concentration.

The E-Sampler is a small, lightweight instrument housed in an environmentally protected enclosure. It can estimate particulate concentrations as high as 100 milligrams per cubic meter. It can be configured with a cutoff inlet to measure total suspended particulate (TSP), PM_{10}, $PM_{2.5}$, or PM_1. The E-Sampler can be mounted on a tripod and operated using line, solar, or battery power. A six-channel data logger accommodates other meteorological sensors that measure windspeed and direction, relative humidity, and ambient temperature. The sampler also has an inlet heater that can be programmed to operate when the inlet airflow's relative humidity reaches a particular level. Humidity can cause the instrument to overestimate particulate concentrations. The heater removes moisture from the air before it is sampled. However, the heater also may remove certain hygroscopic aerosols or convert them to a gas, reducing the estimated particulate concentration.

The E-Sampler is considered a dual technology instrument. Besides the real-time optical scattering measurement, the E-Sampler also incorporates a gravimetric filter system using the same 47-millimeter filters as the FRM sampler. While the gravimetric device does not provide results in real time, it can be used to develop correction algorithms to improve the accuracy of the real-time estimations.

The E-Sampler is compact—just 10 inches wide by 12 inches high by 5 inches deep. It weighs 13 pounds with the $PM_{2.5}$ cutoff inlet, heater, and power supply.

For more information, visit the Met One Instruments Inc. Web site at *http://www.metone.com* or call 541–471–7111.

DUSTTRAK—The DUSTTRAK (figure 6) is a portable, battery-operated laser photometer that gives a real-time digital readout with a built-in data logger. The DUSTTRAK provides a real-time measurement based on 90-degree light scattering. A pump draws

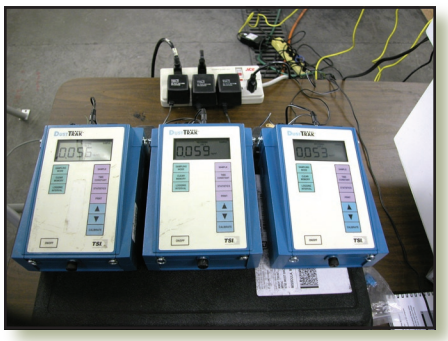

Figure 6—The DUSTTRAK is a lightweight portable aerosol monitor.

the sample air through an optics chamber where it is measured. The DUSTTRAK uses a system to provide a sheath of clean air that isolates the aerosol in the chamber, keeping the optics clean for improved reliability and reduced maintenance.

The DUSTTRAK has a measurement range of 0.001 to 100 milligrams per cubic meter with a particle size range of 0.1 to 10 micrometers. Flow rate can be adjusted from 1.4 to 2.4 liters per minute. The monitor can be configured to measure TSP, PM_{10}, $PM_{2.5}$, or PM_1. The internal data logger can store 31,000 data points (about 21 days of logging at one data point per minute). The DUSTTRAK can run on ac power or batteries. Four C-size alkaline batteries allow it to operate for 16 hours.

The DUSTTRAK measures 8.7 by 5.9 by 3.4 inches and weighs 3.3 pounds with batteries. An environmental enclosure is available to protect the unit when it is used outdoors.

For more information on the DUSTTRAK, visit the TSI Inc. Web site at *http://www.tsi.com* or call 800–874–2811.

DataRAM 2000—The DataRAM 2000 (figure 7) is a compact, self-contained monitor that estimates mass concentration internally from the measured scattering of light. The monitor can measure particulate concentrations from 0.1 to 400,000 micrograms per cubic meter. The monitor continuously displays the current and time-weighted average mass concentration while logging up to 10,000 data points. Data can be downloaded from the monitor through an RS–232 serial data port. The DataRAM can be configured with either a $PM_{2.5}$ or PM_{10} impactor head to prevent particles larger than 2.5 or 10 micrometers, respectively, from entering the optical chamber. For custom calibrations, or to analyze chemical composition, particulates can be collected on a 37-millimeter filter in the instrument's base.

An inline heater also may be installed for monitoring in humid conditions (the manufacturer suggests using the heater when the relative humidity is higher than 70 percent). The monitor's tubular heater is designed to heat the sampled air stream to evaporate liquid water from airborne particles or to eliminate fog droplets. The DataRAM is powered by an internal rechargeable battery or by an external dc or ac power source. The DataRAM has a built-in, internal calibration device. Thermo Electron Corp. no longer manufactures the DataRAM 2000.

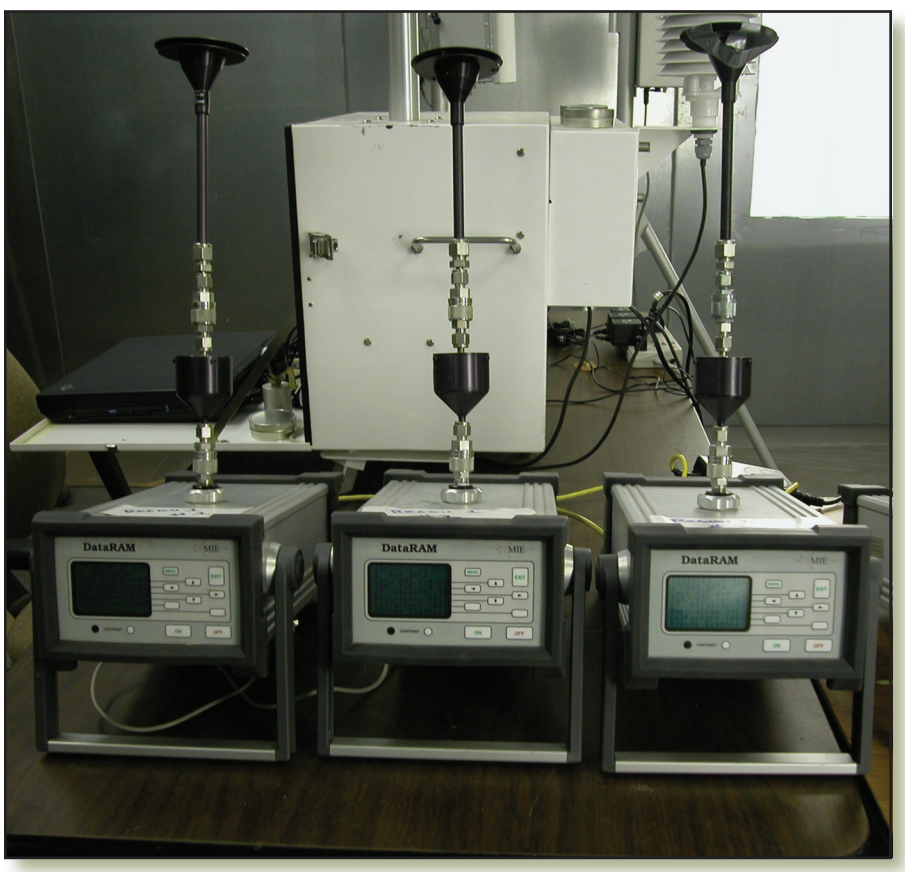

Figure 7—The DataRAM 2000 is a single-wavelength, light-scattering monitor. Several of these monitors are being used by Forest Service air quality specialists, although they are no longer commercially available.

DataRAM 4—The DataRAM 4 (figure 8) is an upgraded version of the DataRAM 2000. The DataRAM 4 uses light-scattering principles to estimate mass concentrations. The DataRAM 4 uses two light sources with different wavelengths (600 and 880 nanometers). In theory, this dual wavelength allows the DataRAM 4 to better estimate mass concentrations using an algorithm that incorporates scattering from each light source. The algorithm uses the mean particle diameter size computed from the light scattering to correct the mass concentration.

Some of the new features of the DataRAM 4 include internal temperature and relative humidity sensors, the ability to autocorrect concentrations when measuring air that has high relative humidity, and the ability to measure mean particle diameter size. The monitor can measure particulate concentrations up to 400 milligrams per cubic meter and has a built-in data logger that can store as many as 50,000 data points. Like the E-Sampler, the DataRAM 4 has a built-in gravimetric filter system for custom calibrations, although its 37-millimeter membrane filter is smaller than the 47-millimeter filter used in the FRM sampler.

The DataRAM 4 monitor is 5.3 inches high by 7.3 inches wide by 13.6 inches long and weighs 11.7 pounds.

For information on the DataRAM 4, visit the Thermo Electron Corp. Web site at *http://www.thermo.com* or call 1–800–241–6898.

Figure 8—The DataRAM 4 is a dual-wavelength, light-scattering monitor that estimates particulate concentrations.

Goals and Methods

The main goal of this evaluation was to determine the accuracy of the real-time instruments when estimating smoke particulate concentrations. This was accomplished by comparing the real-time results to results from an FRM gravimetric sampler. A correction algorithm can then be established for each type of instrument that allows for better estimation of smoke particulate concentrations in the field. We were also interested in any difference in the results from the E-BAM with the ac pump compared to the dc pump. We tested at least two instruments of each model so we could begin to understand the consistency in performance between identical instruments.

All the instruments except the DUSTTRAK were configured with their respective $PM_{2.5}$ particle size cutoff device installed. We used the PM_{10} cutoff inlet with the DUSTTRAK because Forest Service personnel who use the instrument for smoke monitoring requested that we test the monitor in this configuration. We conducted one test with a DUSTTRAK configured with the $PM_{2.5}$ cutoff inlet to determine its effectiveness. We calibrated all the instruments before the tests. Instrument sample airflows were checked. All the real-time instruments were set for an average time of 1 minute and were run continuously throughout the tests.

Before testing each day, a self test was conducted on the E-BAM monitors to ensure that they were functioning properly. The E-Sampler, DUSTTRAK, and DataRAM monitors were calibrated and zeroed using procedures recommended by the manufacturer. The DataRAM 4s were programmed with the particle size correction feature set to "enable, " which allows the monitor to correct the estimated mass concentration based on the mean particle diameter.

The FRM sampler was programmed to run for different lengths of time, depending on the smoke particulate concentrations. For these tests, the FRM was programmed to run between 20 and 120 minutes. After the filters were weighed, the mass of the collected particulate was divided by the total volume of air drawn through the filter for the particular time period to obtain the average mass concentration. That value was compared to the average mass concentration estimated by the real-time instruments during the same period.

Results and Discussion

A total of 38 tests were conducted. The average particulate concentrations ranged from 21 to 1,706 micrograms per cubic meter as measured by the FRM sampler. Statistical results were based on least squares-linear regression equations and correlation coefficients (R^2). Table 1 shows the results for all the instruments. Figures 9 to 15 show the results for each instrument when compared to the FRM sampler. Each figure shows the appropriate data points, the slope equation, and the correlation coefficient for the best-fit line. A line representing a 1:1 relationship also is shown. Figure 10 shows the comparison between the ac pump and dc pump versions of the E-BAM. Figure 13 shows the comparison between a DUSTTRAK with the $PM_{2.5}$ cutoff inlet installed and two DUSTTRAKs with PM_{10} cutoff inlets installed.

Table 1—Evaluation results for each instrument evaluated. The abbreviation for serial number is S/N.

Real-time Particulate Monitor	Regression Slope	Correlation Coefficient
E-BAM (S/N C5193—ac pump)	1.01	0.96
E-BAM (S/N E4052—dc pump)	1.01	0.97
E-Sampler (S/N 4886)	1.08	0.96
E-Sampler (S/N 5126)	1.18	0.94
DUSTTRAK (S/N 22347)	3.25	0.96
DUSTTRAK (S/N 22349)	3.18	0.96
DUSTTRAK (S/N 85200005)	3.09	0.96
DataRAM 2000 (S/N 2574)	1.25	0.97
DataRAM 2000 (S/N 2575)	1.30	0.97
DataRAM 2000 (S/N 2576)	0.89	0.97
DataRAM 4 (S/N D041)	2.61	0.95
DataRAM 4 (S/N D042)	2.19	0.96
DataRAM 4 (S/N D043)	2.58	0.95
DataRAM 4 (S/N D044)	2.37	0.96

E-BAM—Comparisons between the E-BAM monitors and the FRM sampler are shown in figure 9. Results were essentially identical. Both of the E-BAMs overestimated the smoke particulate concentrations by 1 percent. Correlation coefficients were 0.96 and 0.97. Figure 10 shows the comparison between the ac pump version of the E-BAM and the dc pump version. Results of the two E-BAMs were almost identical.

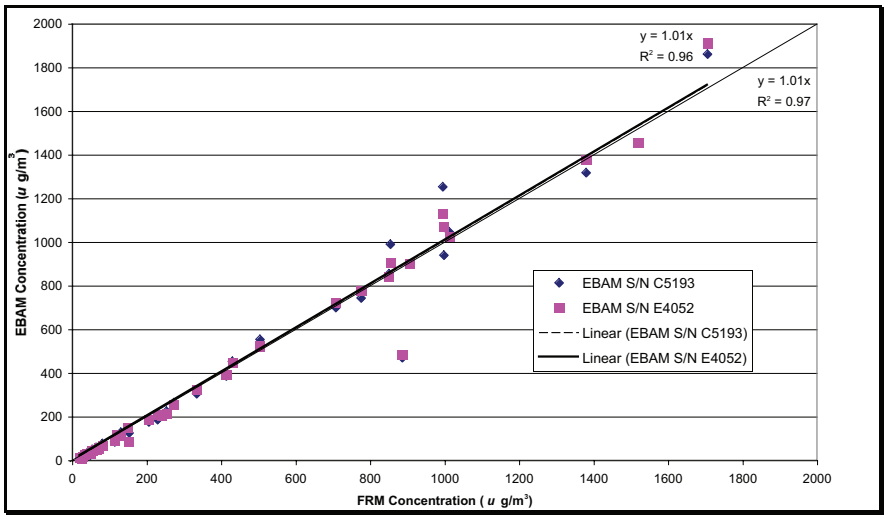

Figure 9—Results for the two E-BAM monitors compared to the BGI PQ-200 Federal Reference Method sampler.

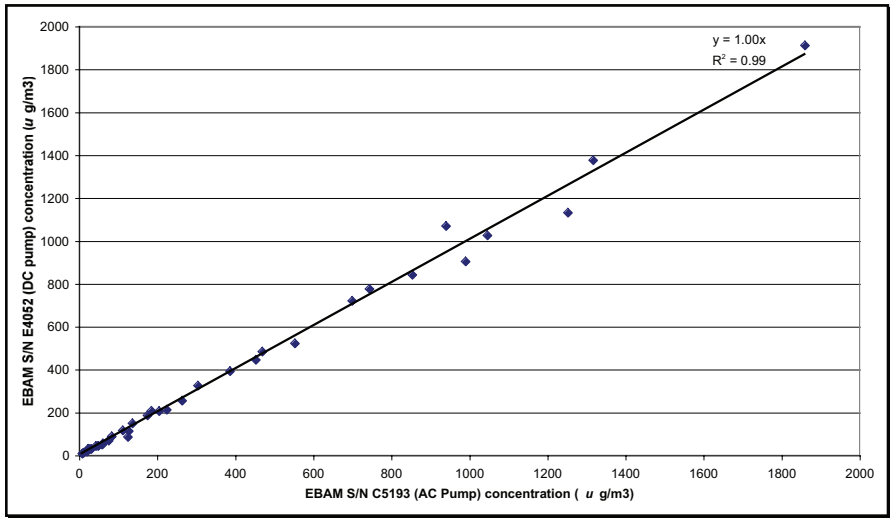

Figure 10—Results comparing an external ac electrical pump to an internal dc pump on an E-BAM monitor.

E-Sampler—Figure 11 shows the comparison of the E-Samplers and the FRM sampler. On average, the E-Samplers overestimated the concentration by 13 percent. E-Sampler serial number 4886 overestimated the concentration by 8 percent while E-Sampler serial number 5126 overestimated the concentration by 18 percent. Correlation coefficients for both results were higher than 0.94.

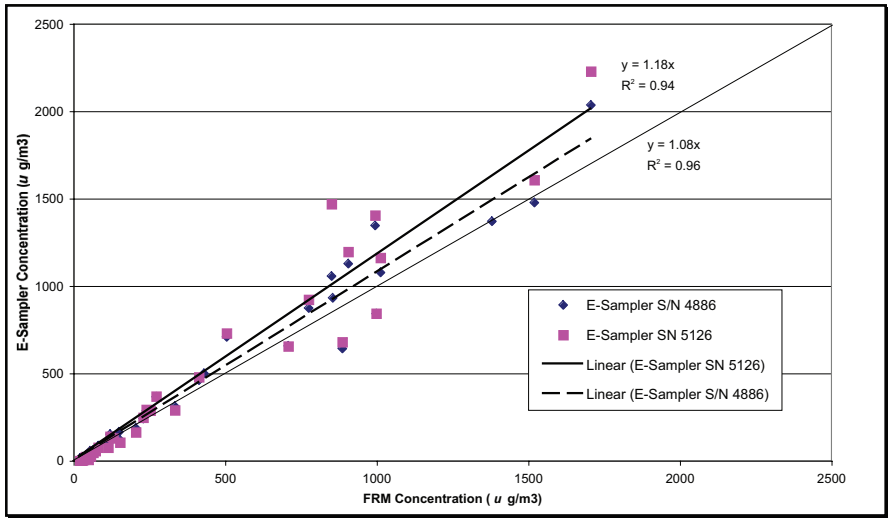

Figure 11—Results for the two E-Samplers compared to the BGI PQ-200 Federal Reference Method sampler.

DUSTTRAK—Results for the three DUSTTRAK monitors evaluated and the FRM sampler are shown in figure 12. On average, the DUSTTRAK overestimated the smoke particulate concentration by 217 percent (3.17 times). The difference of the results among the instruments was +/-2.5 percent.

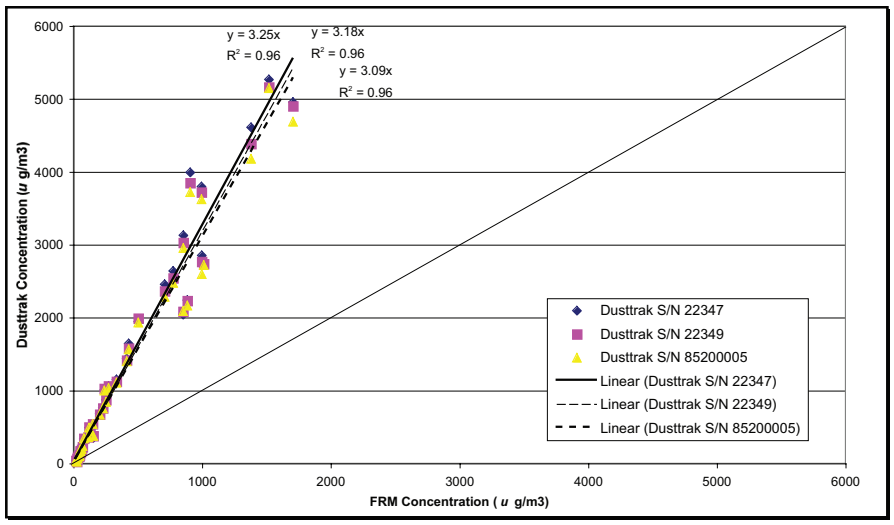

Figure 12—Results for the three DUSTTRAK monitors compared to the BGI PQ-200 Federal Reference Method sampler.

Figure 13 shows the comparison between the DUSTTRAK equipped with the $PM_{2.5}$ cutoff inlet installed and the DUSTTRAKs with the PM_{10} cutoff inlet installed. Results (5-minute averages) were essentially identical. Most smoke particles are smaller than 2.5 microns, so neither cutoff inlet would be expected to have much effect.

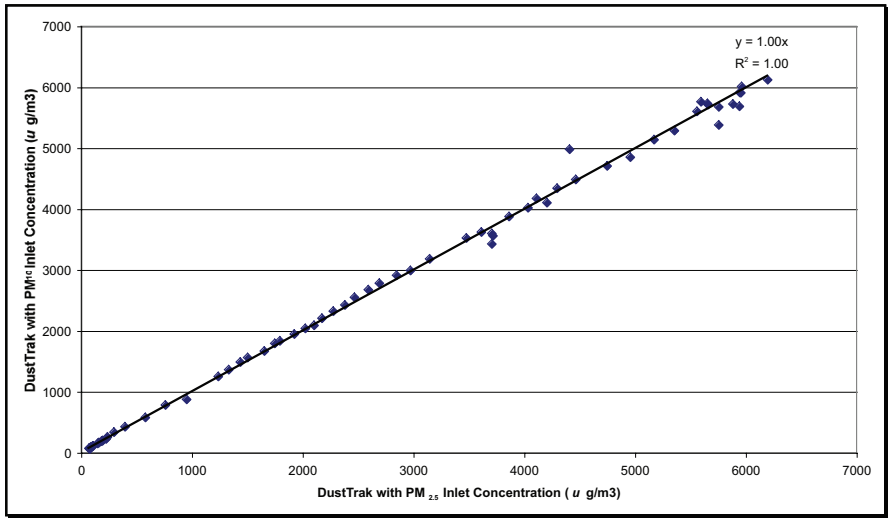

Figure 13—Results showing DUSTTRAK monitors configured with a $PM_{2.5}$ or a PM_{10} cutoff inlet.

DataRAM 2000—Three DataRAM 2000s were operated during the tests. Figure 14 shows the results from the DataRAM 2000 monitor compared to the FRM sampler. On average, the DataRAM 2000s overestimated particulate concentrations by 15 percent. DataRAM serial number 2575 overestimated the particulate concentrations by 30 percent while DataRAM serial number 2576 underestimated the concentrations by 11 percent. Correlation coefficients were 0.97.

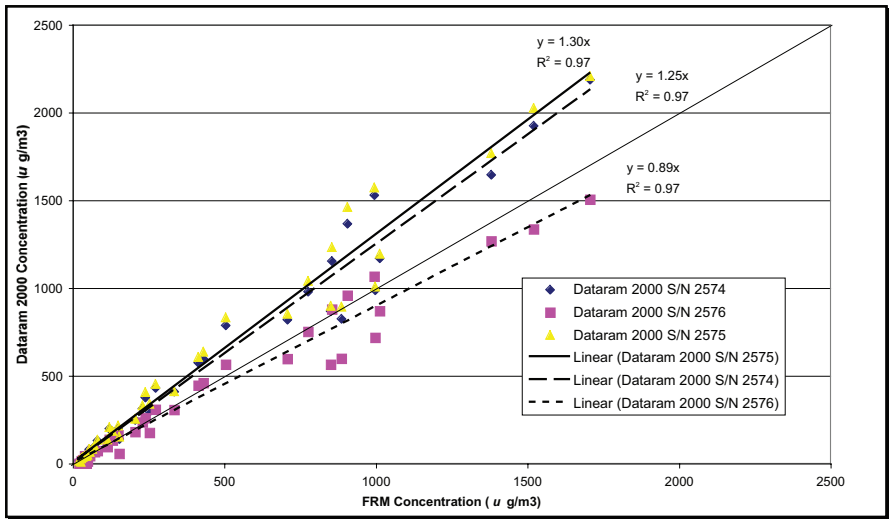

Figure 14—Results for the three DataRAM 2000 monitors compared to the BGI PQ-200 Federal Reference Method sampler.

DataRAM 4—Four DataRAM 4s were evaluated. Figure 15 shows the results of DataRAM 4 monitor compared to the results from the FRM sampler. On average, the DataRAM 4s overestimated the smoke particulate concentration by 144 percent. DataRAM 4 serial number D041 overestimated concentrations the most (161 percent), while DataRAM 4 serial number D042 overestimated concentrations the least (119 percent). Correlation coefficients were all high, at least 0.95.

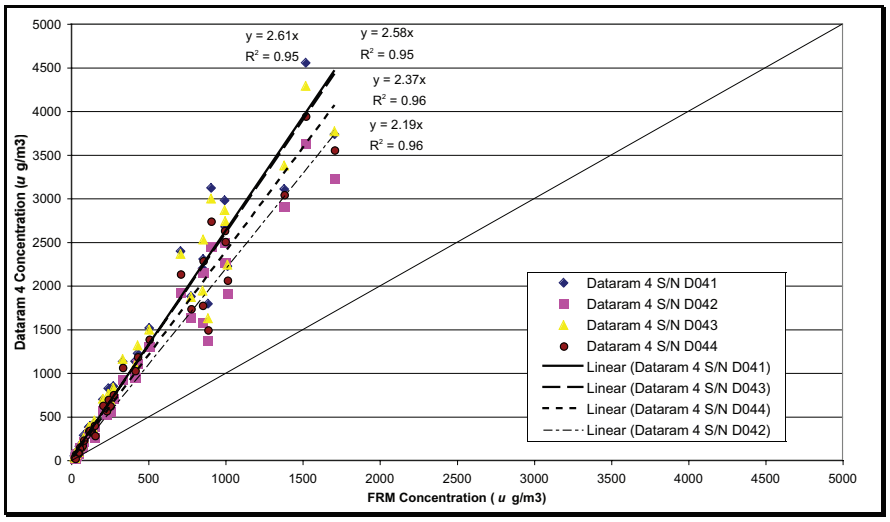

Figure 15—Results for the four DataRAM 4 monitors compared to the BGI PQ-200 Federal Reference Method sampler.

Conclusions

Of the five instruments we evaluated, the Met One Instrument E-BAM was the monitor that most closely estimated smoke particulate concentrations when compared to the FRM sampler. It overestimated the smoke particulate concentration by 1 percent. The tests also showed that the ac and dc pump versions of the E-BAM produced similar results. The E-BAM loses some of its portability when the bulky ac pump is used. For some users this loss in portability may be a small inconvenience compared to having to replace the dc pump periodically.

The E-Sampler was also fairly accurate when estimating smoke particulate concentrations. The two E-Samplers overestimated concentrations on average by 13 percent with a difference of just +/- 4 percent between results of the two instruments and the FRM average. Users should consider correcting the estimates from the E-Sampler by 13 percent (multiply the values by 0.89) when measuring smoke particulate.

The DUSTTRAK monitors overestimated the concentration by 217 percent. The difference between results of the three instruments was just +/-2.5 percent. This consistency is the best we have seen in all of our evaluations of these types of instruments. A correction algorithm of 0.32 (multiply the estimated concentration by 0.32) is recommended for those using the DUSTTRAK. The use of the $PM_{2.5}$ or PM_{10} cutoff inlet does not make much difference when estimating smoke particulate concentrations with the DUSTTRAK.

The DataRAM 4 monitors overestimated the smoke particulate concentrations by a large amount, although this was not unexpected based on previous evaluations. On average, the four instruments overestimated concentrations by 144 percent. Previous tests have showed that the DataRAM 4 with the size-correction feature "enabled" overestimated concentrations even more. Previous recommendations suggested a correction factor of 0.37. Based on these new results, we recommend a slightly higher correction factor of 0.39.

On average, the DataRAM 2000 monitors overestimated the mass concentration by 15 percent. This is somewhat of a surprise because previous tests indicated that the DataRAM 2000 normally overestimates the concentration by more than 100 percent. The monitors used in these tests had not been evaluated previously. Based on these results, it may be prudent to develop individual correction algorithms for the DataRAM 2000s.

These tests were conducted using smoke generated by burning dry pine needles. Results may differ if the vegetation type or moisture content is significantly different. Smoke from burning buildings or other sources with different fuels may yield dramatically different comparisons between smoke particulate monitors and the FRM sampler.

About the Author

Andy Trent is a project engineer at the Missoula Technology and Development Center. He received a bachelor's degree in mechanical engineering from Montana State University in 1989. Before coming to MTDC in 1996, Andy worked as a civilian engineer for the U.S. Navy. He works on projects in the nurseries and reforestation, forest health protection, and watershed, soil, and air programs.

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Trent, Andy. 2006. Smoke particulate monitors: 2006 update. Tech. Rep. 0625–2842–MTDC. Missoula, MT: U.S. Department of Agriculture Forest Service, Missoula Technology and Development Center. 14 p.

This evaluation updates earlier evaluations of real-time monitors. These monitors can be used to evaluate air quality in areas affected by smoke from wildland fires. The evaluation was conducted in a laboratory setting and compared each monitor to at least one more identical monitor, to the other monitors evaluated, and to a Federal Reference Method sampler that was used as the standard. The DUSTTRAK monitor manufactured by TSI Inc. had not been evaluated before, nor had the external ac pump available for the E-BAM monitor manufactured by Met One Instruments Inc.

Keywords: air quality, DataRAM, DUSTTRAK, E-BAM, E-Sampler, Federal Reference Method, nephelometers, prescribed fires, real time, wildland fires