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Radionuclide Emission Factors from Prescribed Burns in Northern New Mexico

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Cover photo: Air sampling system at the La Madera burn on 10/10/02.

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by

Tim Reinhardt, Chris Wrobel, and Craig Eberhart

ABSTRACT

Measurements are reported of emission factors for naturally occurring radionuclides from two operational-scale prescribed burns and from burning two loads of forest biomass by an air curtain destructor-type incinerator in northern New Mexico. Emission factors (amount of emission produced per kilogram of fuel burned) are presented for carbon monoxide, carbon dioxide, methane, nonmethane hydrocarbons, total suspended particulate (TSP), and thoracic particulate, which is defined as that fraction of TSP that is sampled through a large particle-excluding inlet with a 50% efficiency at a mass median aerodynamic diameter of 10 micrometers (PM_{10}). Emission factors are also presented for gross alpha, gross beta, polonium-210, lead-210, uranium-234, uranium-235, and uranium-238.

The gross alpha and gross beta emissions were due primarily to polonium-210 and bismuth-210, respectively, which are radon-222 decay products incorporated by or deposited on the vegetation. Emission factors for gross alpha ranged from 0.8 to 5.1 nanocuries per kilogram (nCi/kg) of fuel burned at prescribed burns and from below detection limits to 3 nCi/kg for air curtain destructors. Polonium-210 emission factors ranged from 1.4 to 10.3 nCi/kg at prescribed burns, and from below detection limits to 7.7 nCi/kg from air curtain destructors. Gross beta emission factors ranged from below detection limits to 1.4 nCi/kg at prescribed burns and from below detection limits to 7.9 nCi/kg from air curtain destructors.

Our results for the non-radioactive emissions agreed well with values reported by other researchers. Carbon monoxide emission factors ranged from 29 to 84 grams per kilogram (g/kg) at prescribed burns and from 10 to 70 g/kg from air curtain destructors. Emission factors for carbon dioxide ranged from 1491 to 1697 g/kg at prescribed burns, and from 1712 to 1809 g/kg from air curtain destructors. Emission factors for methane ranged from 1.9 to 11.9 g/kg at prescribed burns and from 0.2 to 0.4 g/kg from air curtain destructors. Emission factors for nonmethane hydrocarbons ranged from below detection limits to 19 g/kg at prescribed burns, and from 0.9 to 1.9 g/kg from air curtain destructors. Emission factors for TSP ranged form 35 to 47 g/kg at prescribed burns, while PM_{10} emission factors ranged from 12.6 to 43.8 g/kg. Emission factors for TSP from air curtain destructors ranged from 1.4 to 2.4 g/kg, while PM_{10} emission factors ranged from 0.3 to 3.2 g/kg.

The particulate and gas-phase non-radioactive emission factors should have wide applicability to similar fuels in the Southwest and prove useful for smoke management purposes. Our radionuclide emission factors allow the calculation of total flux to the atmosphere based on amount of forest biomass burned in northern New Mexico.

1.0 Introduction

This report presents the results of a study conducted by the Los Alamos National Laboratory (LANL) Risk Reduction and Environmental Stewardship Division, Meteorology and Air Quality Group (RRES-MAQ) to develop a preliminary characterization of radionuclides emitted from prescribed burning of wildland fuels. URS Corporation (URS) assisted LANL in this effort, which we believe is the first study to directly quantify emissions of radionuclides from fires in natural wildland fuels.

1.1 Background

At LANL, RRES-MAQ had evaluated radionuclide levels in particulate samples collected during the Cerro Grande wildfire that burned through Los Alamos in 2000.[1] That work assessed the airborne radioactivity contributions from naturally occurring radionuclides in the radon decay chain and from potential LANL-derived radionuclides such as plutonium, uranium, and americium. No increase in plutonium and americium levels were found, and the samples of uranium isotopes collected in areas of public access indicated that only natural uranium was present in the air. The ambient levels attributable to natural radon products (lead, polonium, and bismuth), however, were somewhat elevated. The normal ambient receptor dose calculations performed by RRES-MAQ did not include subtraction of background, normal radon products because no data were available on pre-fire air concentrations for these radionuclides. The calculated potential doses from lead, polonium, and bismuth were quite small, barely above those that would have been experienced had the Cerro Grande fire never happened, and were due to the slight increases in airborne natural radioactive elements. LANL concluded that the potential doses from these sources were insignificant and that no health effects would occur as a result of radiological doses during the Cerro Grande fire.[2]

1.2 Objectives

The study objective was to gather additional data to help determine whether the elevated levels of radionuclides detected during the Cerro Grande fire were due to naturally occurring radioactive materials (NORM) or release of contaminants originating from past activities at the Laboratory. We sought to assess whether measurable levels of radionuclides were emitted from wildland fires in fuels typical of the western U.S. by conducting several test burns in areas where the only known sources of radionuclides were natural geologic sources or normal atmospheric fallout. If comparable levels of gross alpha and gross beta activity were found in the particulate matter emissions from the burns, it would provide additional evidence that the radioactivity measured in the Cerro Grande fire emissions were NORM.

2.0 Methods

2.1 Sampling Overview

Emission factors for wildland fires are expressed in terms of mass of pollutant per mass of fuel consumed. In the carbon mass balance (CMB) approach to developing emission factors, the mass of carbon in a smoke sample is determined and related to the fuel consumed in the fire by simple equations. The amount of each pollutant in the smoke sample is also measured, and the emission factors for each are then calculated based on the mass of fuel represented in each smoke sample.[3, 4]

URS collected samples for total suspended particulate (TSP), thoracic particulate (PM_{10}), carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4) and total nonmethane hydrocarbons (NMHC). Sample collection was coordinated to concurrently sample the gases and particulate matter over a flaming phase and smoldering phase of each burn. The flaming phase is defined as when most of the smoke from the burning forest biomass was from flaming combustion. Similarly, most of the smoke during the smoldering phase is from smoldering combustion (few flames are visible). Samples of the gaseous components were measured continuously (logged as 1-minute averages) before and during each burn using an instrument rack containing ambient-level analyzers for CO, CO_2, CH_4, and NMHC. The TSP and PM_{10} filter samples were also analyzed for gross alpha and gross beta activity as well as specific isotopes of key radionuclides.

2.2 Measurement Methods

2.2.1 Sampling Apparatus

At the prescribed burns, a safe location was established for the gas analyzers, controls and data logging system. A wire rope static line was connected between two support trees 70 to 120 feet apart at approximately 40 feet above ground level via a ratcheting winch shackled to slings around the tree boles. The sampling package was suspended midway across this static line. It was hung from a wire rope cable running vertically to a sheave fixed to the static line, then out to a hand winch fixed to a tree approximately 250 feet away. The winch allowed the sampling package elevation to be adjusted during the fire in response to flame heights and smoke plume trajectory.

The sampling package consisted of a 2-foot by 4-foot box frame of aluminum tubing with sheet metal horizontal decking at the top and bottom. This decking supported two MiniVols at either end of the decking for sampling PM_{10}, and two General Metal Works HiVol sampler bodies mounted side-by-side in the middle of the decking to sample TSP. The sampler housings were wrapped in fiberglass and refractory aluminum foil tape (Nashua Corporation) to prevent heat damage. All filter faces were oriented horizontally above the top decking. At the first burn (Petaca-Las Tablas), the HiVol filter faces were uncovered; at the subsequent sampling events, we reduced deposition of large embers by covering both HiVol filter faces under a single HiVol shed roof mounted several centimeters above the plane of the filter housings (Figure 1).

Figure 1. Sampling system at La Madera burn (10/10/02)

To sample gas-phase emissions from the fire at the sample package, an inline 47-mm filter housing was mounted to the sample package frame, then plumbed with Swagelok® connectors through 250 feet of 3/8-inch teflon tubing to the gas analysis system at ground level. The tubing was wrapped in fiberglass and refractory aluminum tape along with power supply leads to form an umbilical from the sampling package to the gas analyzers. The gas was pulled through the filtered umbilical tubing by a medium-volume air sampling pump.

During the burns, a portable meteorological system was used to determine wind speed, wind direction, ambient temperature, and barometric pressure. For the second and subsequent burns, a K-type thermocouple was added to the sampling package. The sampling package could be quickly raised and lowered as needed to ensure the samplers remained in the smoke plume but were not exposed to excessive heat.

Sampling began when the flaming-phase emissions were observed to reach the samplers. Power was applied to one of the TSP samplers and one of the MiniVols during the flaming phase of the burn. At the end of the flaming phase, the flaming particulate matter samplers were shut down, and power was provided to the smoldering-phase particulate matter samplers.

2.2.2 Carbon Dioxide and Carbon Monoxide

The CO_2 and CO concentrations were analyzed using a gas filter correlation non-dispersive infrared (NDIR) spectrophotometer (Model #ZRH, California Analytical Instruments, Inc.). A small air sampling pump pulled the gas sample through a tee-connection from the filtered sample air drawn through the umbilical tubing. The sample gases were cooled by a sample gas conditioner set at 0 ºC to remove water vapor (Alfa Laval Model #MAK 6-2, Clean Air Express, Inc.) prior to introduction to the NDIR analyzer.

The NDIR analyzer was calibrated by zero adjustment before sampling with ultra high purity nitrogen, and span adjustment with a certified National Institute of standards and Technology (NIST)-traceable standard of 4480 parts per million (ppm) CO_2 in air and 890 ppm CO in air (Scott-Marin Specialty Gases, Inc.) Certified NIST-traceable calibration check gases at a concentration of 455 ppm CO_2 in air and 44.9 ppm CO in air were used to verify calibration accuracy before and after sampling.

2.2.3 Methane/Nonmethane Hydrocarbons

The CH_4 and total NMHC concentrations were measured using a Byron gas chromatograph (GC)-based flame ionization detector (FID) hydrocarbon analyzer. An internal air sampling pump in the hydrocarbon analyzer pulled the gas sample through a tee-connection from the sample package umbilical tubing. This unconditioned gas stream was analyzed for CH_4 and NMHC by using a back-flush chromatography technique. On a timed cycle of approximately one minute, a gas valve injects a sample of the gas via a helium carrier through a packed GC column that retards the larger hydrocarbons but allows the CH_4 to pass unobstructed. The CH_4 peak passes through the FID, then the column is back-flushed and the larger hydrocarbons are routed to the FID for quantification. The NMHC are quantified as propane equivalents.

The CH_4 and NMHC analyzer response was calibrated to zero using ultra high purity air and calibration gas concentrations of 40 ppm and 30.6 ppm (as hexane), respectively. A plot of analyte concentration versus instrument response was prepared. The slope and intercept of the resulting linear regressions were used to adjust the instrument responses during the subsequent sampling periods. Calibration checks were performed prior to data collection using CH_4 and NMHC concentrations of 3.94 and 3.13 ppm, respectively. Zero, span, and mid-range calibration gases were introduced into the instrument at the end of the final sampling period to verify that the instrument's response did not change significantly.

2.2.4 Particulate Matter (TSP and PM_{10})

Two types of particulate samplers were operated (see Section 2.2.1). The TSP samples used a standard HiVol sampler with volumetric flow control. The TSP samplers sampled air at a nominal 39 cubic feet per minute (CFM) through 8-inch by 10-inch preweighed quartz filters. The volumetric flow rate through the samplers was determined using an NIST-traceable transfer standard (variable orifice). Each calibrated orifice included a linear regression plot of $(\Delta H \cdot (P_a/760) \cdot (298/T_a))^{1/2}$ versus Q_{std}, where

ΔH = differential pressure at orifice (inches H_2O),
P_a = current barometric pressure (mm Hg),
T_a = current temperature (K), and
Q_{std} = flow rate at U.S. Environmental Protection Agency (EPA)-specified standard conditions (298 K, 760 mm Hg).

The variable orifice was fitted over the inlet of the sampling unit and the motor was turned on. The orifice pressure measured in the field at several flow restrictions of the orifice (using a manometer), barometric pressure, temperature, and the slope and intercept that were provided on the original calibration certificate were used to calculate Q_{std} via the following equations:

$y = mx + b;$
$y = (\Delta H \cdot (P_a/760) \cdot (298/T_a))^{1/2}$; and
$x = (y - b)/m.$

A plot of Q_{std} versus the static pressure measured within the body of the sampling unit was then prepared in order to relate the transfer orifice pressure to the sampling unit static pressure. The orifice was removed prior to sample collection. The average of the pre- and post-event pressures along with the slope and intercept from the linear regression plot of Q_{std} versus the sampler pressure measured during calibration were used to calculate Q_{std}.

The PM_{10} concentrations were measured using Airmetrics MiniVol™ battery-operated particulate matter samplers. These samplers were rewired to a 12-volt power supply at ground level to allow remote activation. The inlets had a standard PM_{10} cutpoint, and the pumps drew air through a 47-mm preweighed quartz filter at a nominal flow rate of 4 liters per minute (L/min). During the Petaca-Las Tablas burn the airflow of each unit was calibrated using a NIST-traceable transfer standard (orifice). Each calibrated orifice included a linear regression plot of Q_{act} versus $(\Delta H \cdot (T_a/P_a))^{1/2}$, where

ΔH = differential pressure at orifice (inches of H_2O),
P_a = current barometric pressure (mm of Hg),
T_a = current temperature (K), and
Q_{act} = flow rate at EPA-specified standard conditions (298 K, 760 mm Hg).

The orifice was fitted to the inlet of the sampling unit and the motor was turned on. The orifice pressure measured in the field (using a Magnehelic® gauge), barometric pressure, temperature, and the slope and intercept that were provided on the original calibration certificate were used to calculate Q_{act} using

$$Q_{act} = m \cdot (\Delta H \cdot (T_a/P_a))^{1/2} + b.$$

Q_{std} was then calculated using

$$Q_{std} = Q_{act} \cdot ((298/T_a) \cdot (P_a/760))^{1/2}.$$

A plot of Q_{std} versus the internal MiniVol rotameter setting was then prepared. The orifice was removed prior to sample collection. The rotameter position at the beginning and at the end of each sampling run was recorded and the average of these values was used to calculate Q_{std} using the slope and intercept from the linear regression plot of Q_{std} versus rotameter setting determined during calibration. Calibration curves for the Petaca – Las Tablas sampling event are provided in Appendix A.

The sampling flow rate was determined differently at the La Madera and air curtain destructor events. For these burns, a BIOS Drycal® DC-1 primary flow meter was available, and the MiniVol flow was measured directly, pre- and post-event. The pre- and post-event flows were averaged to obtain Q_{act}. Q_{std} was then calculated using

$$Q_{std} = Q_{act} \cdot (P_a/760) \cdot (298/T_a).$$

All filter mass loadings were determined by gravimetric methods at the Air and Heavy Metals Laboratory of the New Mexico Department of Health, Scientific Laboratory Division in Albuquerque, NM.

2.2.5 Radionuclides

Radionuclides were analyzed by performing measurements on the TSP and PM_{10} quartz filters (8-inch by 10-inch and 47-mm, respectively). Gross alpha and gross beta activity analyses were conducted by gas proportional counting of six separate aliquots (47-mm diameter circles cut from the 8- by10-inch filters). These were the only analyses expected to be above method detection limits. However, radionuclide analyses were also performed for americium-241, lead-210, polonium-210, plutonium isotopes, and uranium isotopes. All analyses were done by Wastren Analytical Laboratory of Grand Junction, CO.

2.2.6 Meteorological Parameters

A portable meteorological (met) station was set up near each burn. The sensors were mounted on a 14-foot tripod and placed in an open area to minimize obstructions, such as large trees, that altered the air-flow. The station sensors continuously measured wind speed, wind direction, and ambient temperature. These data were collected as 1-minute and 1-hour averages using a Campbell CRX-10 datalogger.

2.2.7 Fuels

The forest fuels were characterized by the U.S. Forest Service in their prescribed burn plans. At prescribed burns, fuels were characterized as to average loading by size class over the burn unit, including duff depth. Only preburn fuel moisture was assessed by the Forest Service and determined to average approximately 11% at each prescribed burn. At the air curtain destructor burns, the fuel loaded was roughly estimated by the field team leader as no other measurements were available.

2.3 Calculations

The CMB technique is successful because of the relatively consistent carbon content of forest vegetative biomass, which is approximately 50 ± 5% carbon by weight. In the CMB technique, the carbon content of the emissions are derived from the measured above-background concentrations of the emitted species CO, CO_2, CH_4, and NMHC, and the carbon content of the particulate matter emitted by the fire. The following equations are used to calculate the total fuel consumed for each sample set. Equation 1 provides the total fuel consumed:

$$W_v = \frac{\sum C_n}{R} \quad (1)$$

where

W_v = fuel consumed (grams per cubic meter [g/m^3]),
C_n = the carbon fraction of the emission n (g/m^3),
n = the excess (above background) concentrations of the analytes CO, CO_2, CH_4, NMHC, and particulate matter, and
R = the carbon fraction of the unburned forest fuel (assumed to be 50% by dry weight).

The emission factors for each pollutant are calculated by Equation 2:

$$EF_n = \frac{E_n}{W_v} \quad (2)$$

where

EF_n = the emission factor for pollutant n (g emission/kg fuel), and
E_n = the concentration of the emission n (mg/m^3).

Combustion efficiency, defined as the percentage of fuel carbon oxidized to CO_2, is a key parameter in combustion evaluation.[5] It is simply the actual EF CO_2 divided by the theoretical EF CO_2 of 1835 g CO_2/kg fuel.

3.0 Results

Measurements were made at four fires, each fire consisting of samples separately integrated over the two main phases of combustion: flaming and smoldering. These results allow calculation of emission factors for each pollutant measured at each burn, including gross alpha and gross beta activity. Fire emissions sampling occurred at two operational prescribed burns conducted by the Forest Service, El Rito Ranger District of the Carson National Forest. The first burn (Petaca-Las Tablas) was intended to be a "shakedown" of the sampling system, but because most all of the systems worked, the data obtained were sufficiently representative that these data are included in the reported results. The second burn was expected to be the first of three with complete data acquisition. Because weather and fuel conditions were unfavorable for more prescribed burning during the available weeks for sampling, the remaining two sampling events were of forest fuels burned in an air curtain destructor (a refractory-lined box with forced-air ventilation used for open burning). This equipment was operated by LANL Facility and Waste Operations Division to safely burn large volumes of woody debris accumulated from wildfire mitigation and hazard reduction efforts at LANL. Sampling events are summarized below in Table 1.

Table 1. Emissions Sampling Events

Burn Event	Date	Sampling Location	Fuels
Petaca-Las Tablas Prescribed Burn	9/25/01	El Rito Ranger District, NE quarter, Section 35, T27N, R8E, New Mexico Principal Meridian.	Ponderosa pine overstory with partial cut slash
La Madera Prescribed Burn	10/10/02	El Rito Ranger District, SE quarter Section 28,T25N, R6E, New Mexico Principal Meridian.	Mixed conifer overstory with partial cut slash
Air Curtain Destructor Burn #1 "Xena"	11/13/02	Air Curtain Destructor labeled "Xena;" LANL, Technical Area (TA) 16	Ponderosa pine logs 0.5 to 2 feet in diameter
Air Curtain Destructor Burn #2 "Green Pondo"	11/13/02	Air Curtain Destructor labeled "Xena;" LANL, TA-16	Ponderosa pine green needles/small woody debris <0.5 feet in diameter

The prescribed burns were underburns, a typically low-intensity fire intended to simulate naturally occurring small wildfires. They were ignited as a series of discrete strips sequentially lit across the unit topography that then burned together slowly, consuming ground fuels and small live woody fuels that have accumulated over time. Fuels were a mixture of ponderosa pine (*Pinus ponderosa* Dougl.ex Laws.) and mixed conifers (ponderosa pine, white fir [*Abies concolor* (Gord & Glend.) Lindl. Ex Hildebr.], douglas fir [*Pseudotsuga menziesii* (Mirb.) Franco], and piñon pine [*Pinus edulis*]). The fuel moisture of the small woody fuels (10-hour timelag fuels 1/4 to 1 inch in diameter) was estimated by the Forest Service to be approximately

10% at the time of ignition. Figure 2 shows the sampling system during the flaming phase at La Madera.

Figure 2. Flaming phase sampling at La Madera burn (10/10/02)

The air curtain destructor burns both occurred in an operational air curtain destructor—a refractory-lined open metal box (approximately 8 feet by 8 feet by 20 feet) set in the ground, into which air is forced via slots transversely oriented to direct the air across the top of the box along the length of one side. This "air curtain" imparts a horizontal rotation to the air in the box, recirculating it to enhance combustion efficiency, thereby reducing particulate emissions and products of incomplete combustion. The box is filled in batches by a track hoe. Our sampling began after a load of wood debris was placed into the box (blazing coals from the previous load were still present, providing the ignition source), and continued until it was thought that sufficient particulate matter was obtained to exceed method detection limits.

3.1 Gas Measurement Calibration Response

Summaries of CO, CO_2, CH_4, and NMHC pre- and post-sampling calibration check and span checks for each event are provided in Tables 2, 3, and 4. The accuracy of the calibrations is measured by the percent of theoretical recovery, while the coefficient of variability (CV—the standard deviation of the responses divided by the average) is a measurement of precision. Replicate measurements of instrument response to calibration check gases were only obtained for

CO and CO_2 at the Petaca-Las Tablas burn; however, by the last two burns (Xena and Green Pondo), we obtained replicate measurements for all calibration gases, enabling us to calculate CV results for each.

Table 2. Calibration Check Results for Petaca-Las Tablas Prescribed Burn

Analyte	Calibration Gas Concentration (ppm)	Mean Instrument Response (ppm)	Percent of Theoretical (%)	CV[a] (%)
CO	44.9	44.3	98.6	9.4
	890	939	105.5	NA[b]
CO_2	455	451	99.2	3.5
	4480	4230	94.4	NA
CH_4	3.94	2.98	75.5	NA
	40.0	41.0	102.6	NA
NMHC	3.13	3.27	104.4	NA
	30.6	32.3	105.5	NA

[a] Coefficient of Variation
[b] Not Available (no replicate measurements obtained for this calibration gas)

Table 3. Calibration Check Results for La Madera Prescribed Burn

Analyte	Calibration Gas Concentration (ppm)	Mean Instrument Response (ppm)	Percent of Theoretical (%)	CV[a] (%)
CO	44.9	45.4	101.2	8.6
	890	879	98.8	NA[b]
CO_2	455	446	98.0	4.0
	4480	4230	94.4	NA
CH_4	3.94	3.46	87.9	0.7
	40.0	43.0	107.6	NA
NMHC	3.13	2.34	74.9	7.2
	30.6	29.4	96.0	NA

[a] Coefficient of Variation
[b] Not Available (no replicate measurements obtained for this calibration gas)

Table 4. Calibration Check Results for Air Curtain Destructor Burns

Analyte	Calibration Gas Concentration (ppm)	Instrument Response (ppm)	Percent of Theoretical (%)	CV[a] (%)
CO	44.9	46.8	104.1	9.0
	890	949	106.6	4.4
CO_2	455	410	90.1	18.9
	4480	4465	99.7	0.5
CH_4	3.94	3.20	81.1	0.2
	40.0	39.6	99.0	0.4
NMHC	3.13	2.93	93.6	3.7
	30.6	32.7	106.7	0.2

[a] Coefficient of Variation

The results show generally good accuracy for all gases except the methane and nonmethane hydrocarbons. Precision was good for all gases except the low-level CO_2 at the air curtain destructor burns. In particular, these quality control data indicate that

- low-level CH_4 was apparently biased low at Petaca-Las Tablas;
- low-level CH_4 accuracy was better but still biased low at La Madera;
- low-level NMHC were apparently biased low at La Madera, but the high-level measurement retained good accuracy; and
- low-level CH_4 accuracy was biased low at the two air curtain destructor burns.

The data were not corrected for apparent low bias, but these quality control indicators assist in interpreting the results.

3.2 Measured Gas and Particulate Matter Concentrations

The measured concentrations of CO, CO_2, CH_4, NMHC, TSP, and PM_{10} for the three sampling events are summarized in Table 5.

Table 5. Summary of Measured Gas and Particulate Concentrations

Burn Name, Date	Fire Phase	Sample Duration	Phase-Average Sample Concentrations					
			CO (ppm)	CO_2 (ppm)	CH_4 (ppm)	NMHC (ppm)	TSP (mg/m^3)	PM_{10} (mg/m^3)
Petaca-Las Tablas	Flaming	25 minutes (14:01–14:26)	66.7	2718	30.7	19.7	15.1[a]	24.3
9/25/2001	Smoldering	109 minutes (14:26–16:15)	140	1987	36.8	22.1	14.8[a]	19.3
	Background	42 minutes (13:07–13:49)	1.9	330	2.5	2.1	NA[b]	NA
La Madera	Flaming	26 minutes (12:42–13:08)	32.3	769	1.4	0.0	13.7	10.3
10/10/2002	Smoldering	116 minutes (13:10–15:06)	24.7	530	1.6	0.0	8.8	8.3
	Background	100 minutes[c] (10:22–12:00 +15:29–15:30)	-3.6	334	0.1	-0.2	NA	NA
Air Curtain Destructor "Xena"	Flaming	20 minutes (13:20–13:40)	18.1	1938	1.7	2.0	2.4	0.3[d]
11/13/2002	Smoldering	34 minutes (13:40–14:14)	91.7	3308	0.8	1.5	3.1	2.7
Air Curtain Destructor "Green Pondo"	Flaming	20 minutes (15:03–15:23)	243	4030	2.8	4.2	5.9	8.2
11/13/2002	Smoldering	40 minutes (15:23–16:03)	165	3684	3.2	4.3	6.1	8.1
	Background	33 minutes (12:06–12:39)	4.2	330	1.1	0.6	NA	NA

[a] Post-sampling flowrate calibration check indicated a probable quantitation error for these samples.
[b] Not Available—No background measurement obtained.
[c] CO and CO_2 background obtained from 12:17–12:41 after preburn calibration adjustments
[d] Laboratory gravimetric results were unusually low for an exposed sample; no explanation is available.

3.3 Gas Measurement Results

Instrument readings were recorded by the data logger in one-minute intervals. The data corresponding to each phase of a burn was identified and the averages of all the one-minute average gas concentrations were calculated for each gas during that period. Concentrations of CO and CO_2 measured during flaming and smoldering phases were comparable to reference values for broadcast prescribed burns in long-needled pines (such as *Pinus ponderosa*) and mixed conifers.[6] The $CH_4$and NMHC results were elevated as would be expected considering the relatively concentrated gas samples as indicated by the CO and CO_2 results. Figure 3 shows the CO and CO_2 concentrations during the Petaca-Las Tablas burn. To facilitate showing detail in these data, the CO concentrations are plotted versus the right-hand Y-axis, while the CO_2 concentrations are plotted versus the left-hand Y-axis. Figure 4 shows the corresponding hydrocarbon data, also plotted on different axes to enhance visualizing the data details.

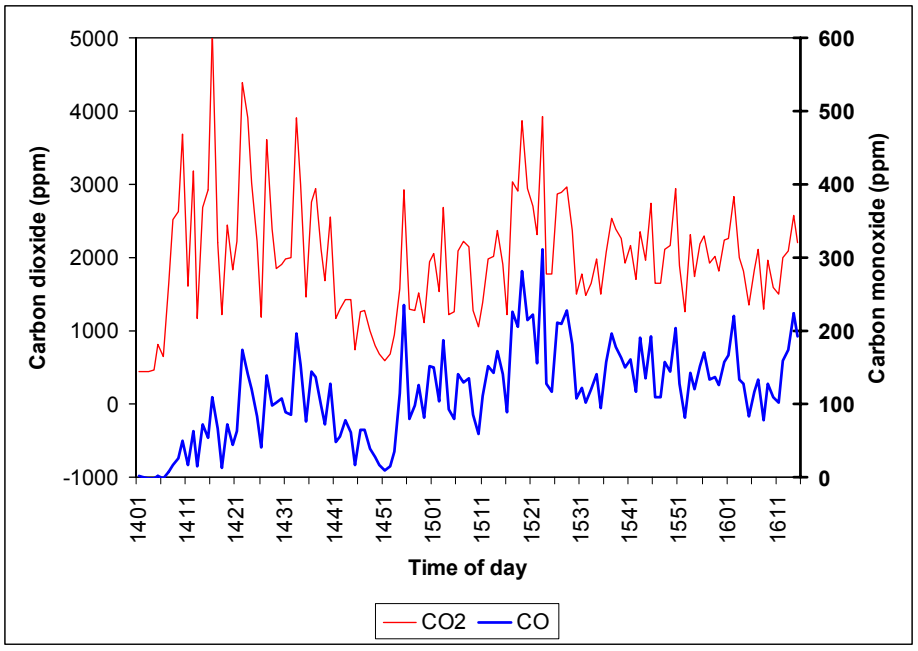


Figure 3. Petaca-Las Tablas CO and CO_2 concentrations

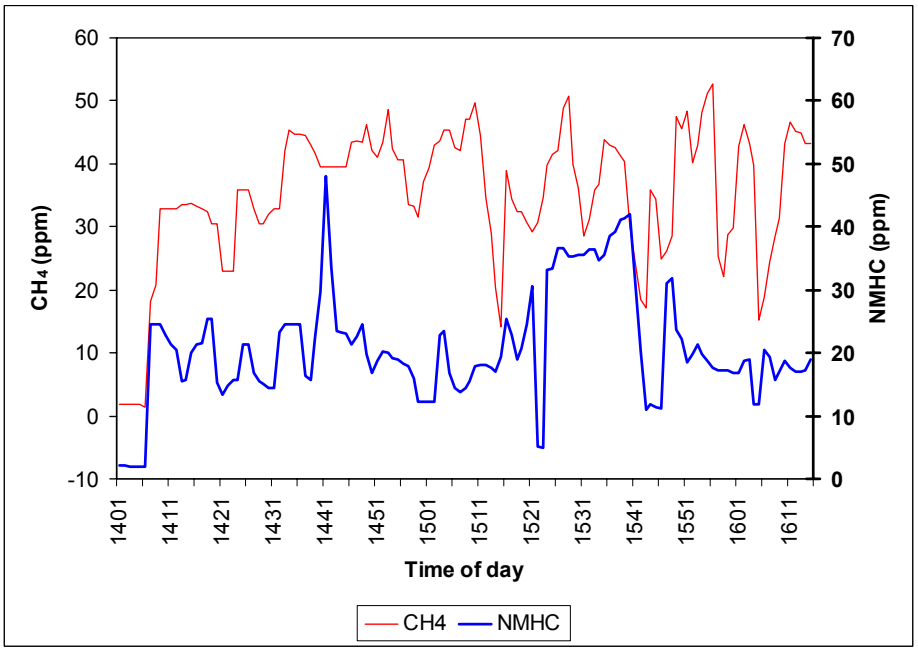


Figure 4. Petaca-Las Tablas hydrocarbon concentrations

The hydrocarbon instrument sample/backflush cycle, in concert with the one-minute averaging time of the datalogger, dampens and averages the recorded variations in hydrocarbon levels (Figure 4) when compared to the CO and CO_2 data in Figure 3. Figures 5 and 6 show the same parameters at La Madera.

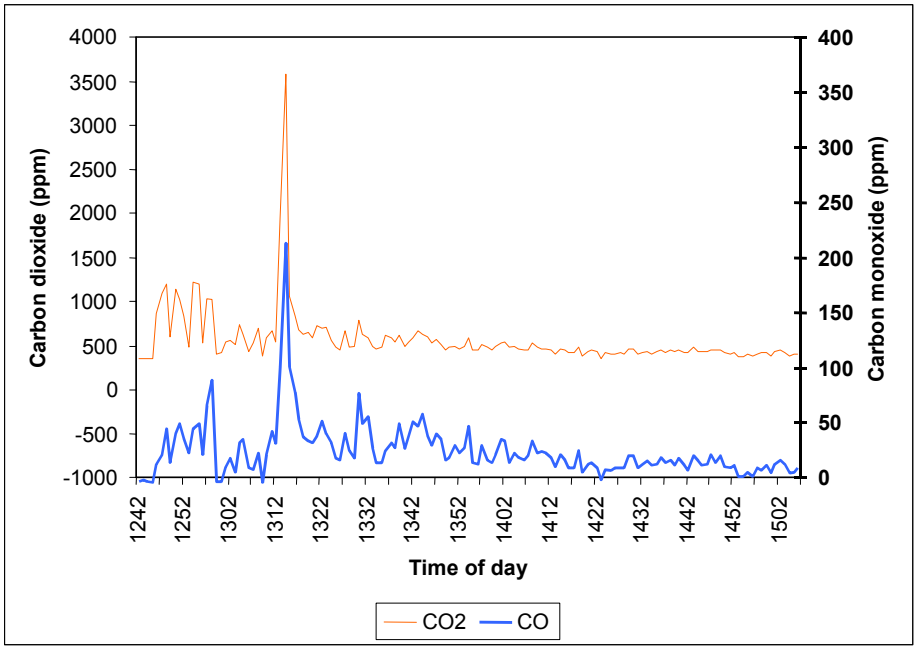


Figure 5. La Madera CO and CO_2 concentrations

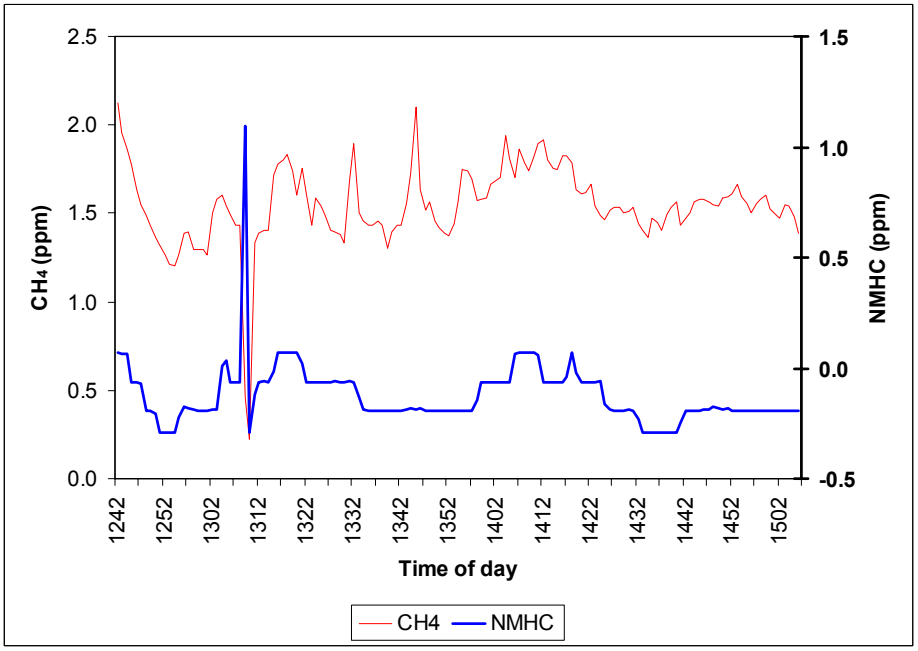


Figure 6. La Madera Hydrocarbon concentrations

Smoke concentrations were much lower at La Madera, especially during the well-defined smoldering phase. Ambient winds created much more active combustion during the smoldering phase at Petaca-Las Tablas. Figure 7 shows the sampler during the smoldering phase at La Madera.

Figure 7. Sampling the smoldering-phase emissions at La Madera burn (10/10/02)

The background CO concentration at La Madera was below measurable levels (-3.6 ppm), despite a good response to the low-level calibration gas (101%). Difficulties were encountered during the preburn calibrations of the instrumental response to CO_2, but this should not have affected the CO response. The low response may have been simply due to ambient temperature-related drift in the instrumental response.

The background CO concentration at the air curtain destructor burns (Xena and Green Pondo) was slightly elevated (4.2 ppm) but this may have been due to the several diesel-powered trucks and track hoe in operation within a few hundred yards of the sampling location. Figures 8 and 9 show the CO/CO_2 and hydrocarbon data, respectively, from the Xena burn.

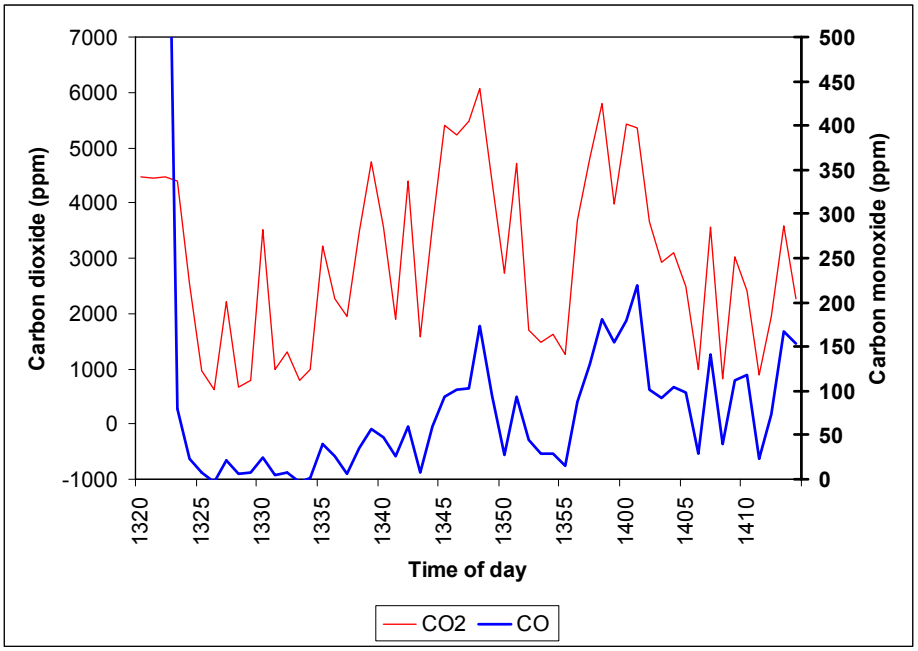


Figure 8. CO and CO_2 concentrations at Xena

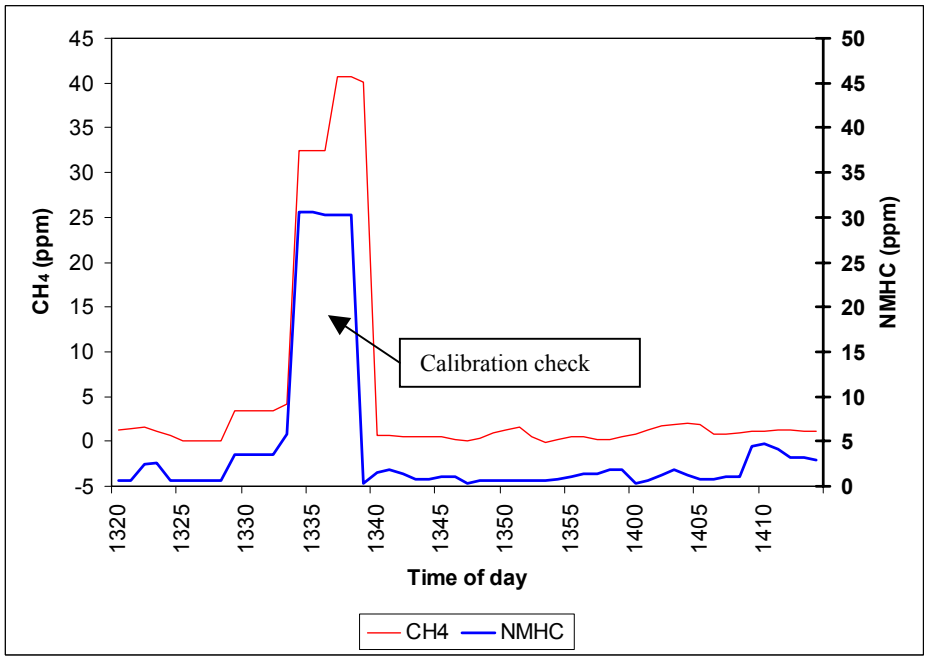


Figure 9. Hydrocarbon results from Xena

Note the check of calibration response that occurred at the Xena burn; hydrocarbon emissions were very low from the air curtain destructor. Some measurement-related inadequacies are apparent in the lower-concentration hydrocarbon data, although this is a relatively minor issue because the CO and CO_2 are the key measurements needed to calculate emission factors (they comprise the bulk of the carbon emissions). For example, NMHC

emissions at La Madera were below measurable levels, possibly a consistent instrumental problem as indicated by the low response (75%) to the low-level calibration check gas. Background measurements for CH_4 and NMHC at all other burns were higher than would have been expected in nonurban environments (see Table 5); this result may have also been due to instrumental drift. The Byron instrument may not be the best tool when low-concentration hydrocarbon measurements are necessary.

Figure 10 shows the temperature at the sampling point above the fire for the Xena burn. The temperature data are useful to interpret how diluted the plume was by the time it reaches the sampler.

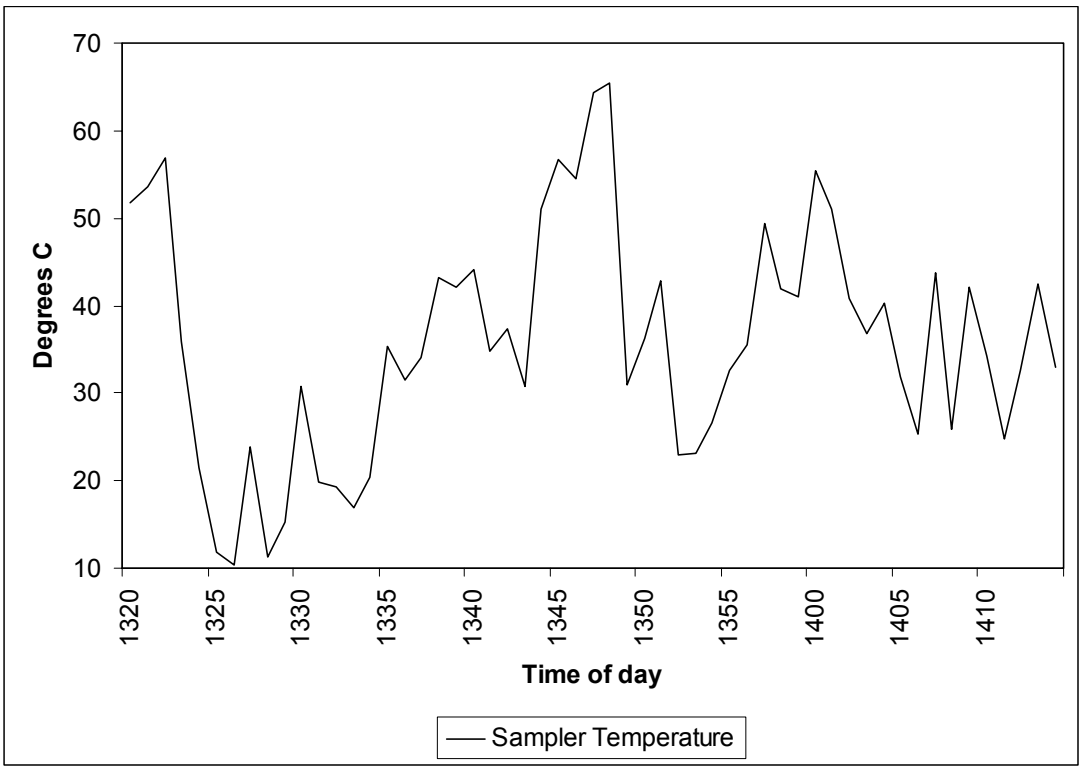


Figure 10. Sampling point temperature at Xena burn

Figures 11 and 12 show the CO/CO_2 data and hydrocarbon data, respectively, for the Green Pondo burn.

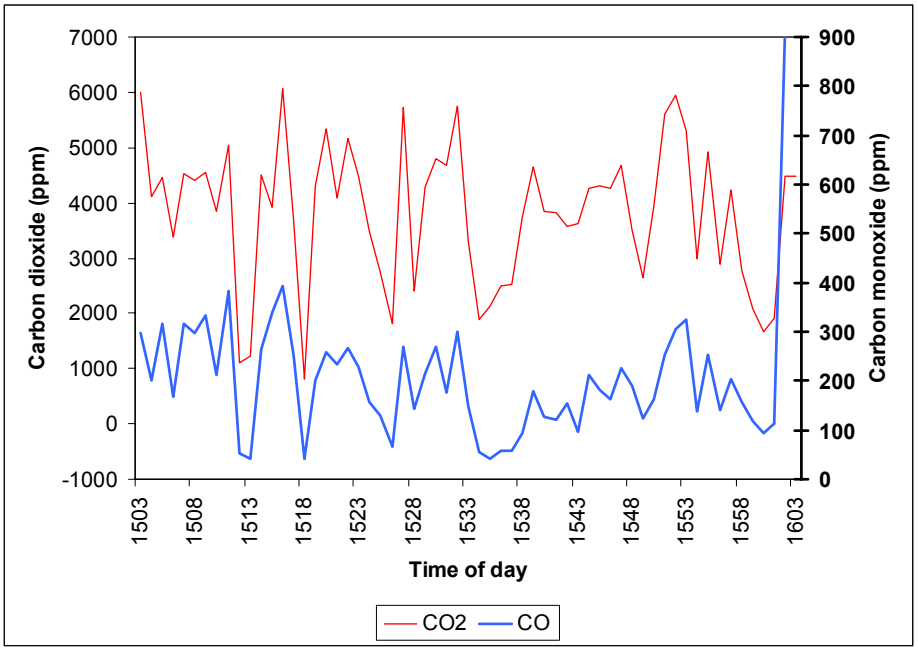


Figure 11. CO and CO_2 concentrations for Green Pondo burn

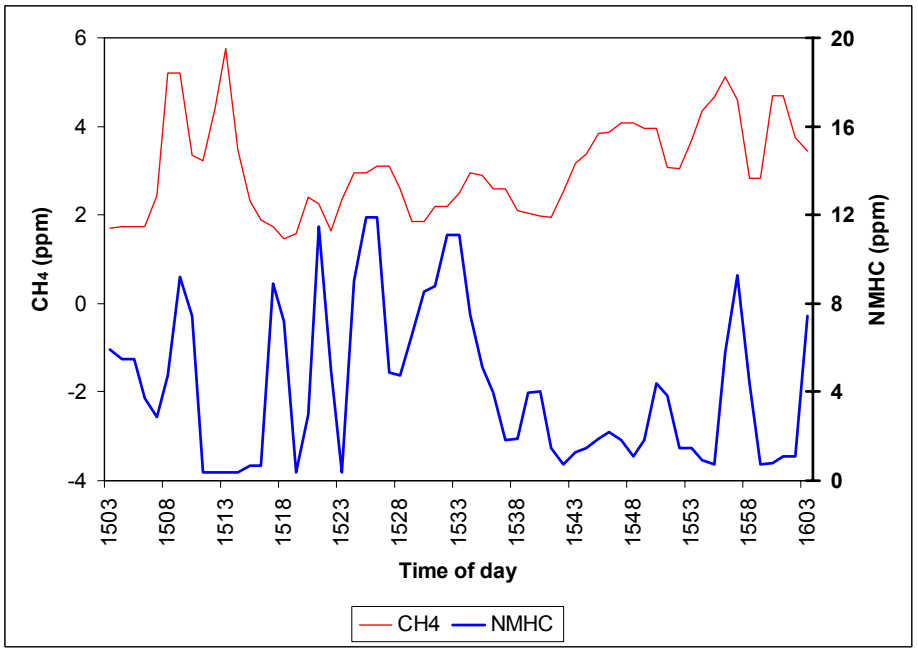


Figure 12. Hydrocarbon concentrations for Green Pondo Burn

Figure 13 provides the sampling point temperature results for the Green Pondo burn. The sampler was more consistently located in the plume for this burn than for the Xena burn.

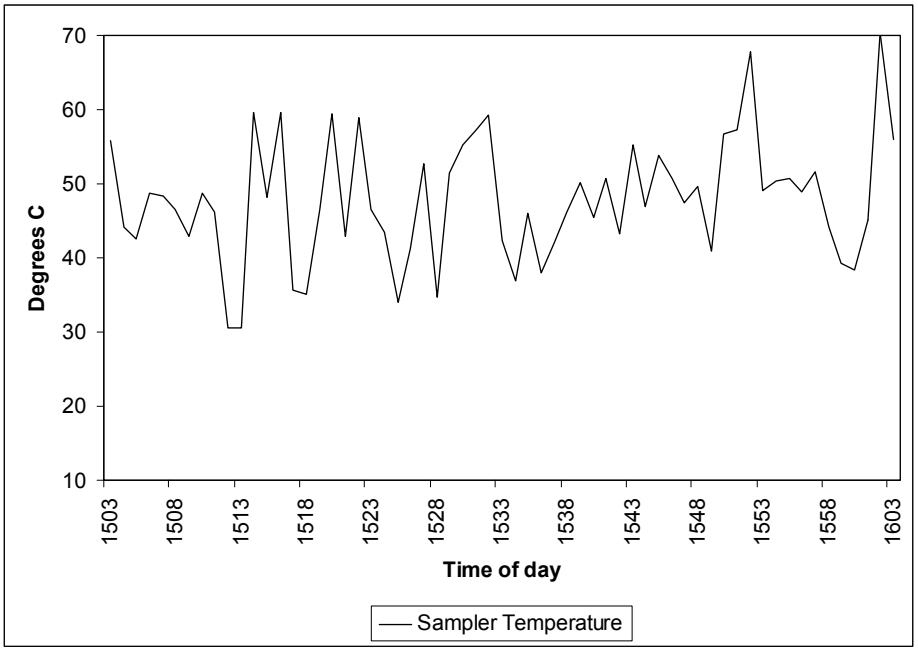


Figure 13. Sampling point temperature at Green Pondo burn

3.4 Particulate Measurement Results

The TSP and PM_{10} concentrations measured at these burns were comparable to those measured at prescribed burns in similar fuels.[6] Problems were evident in some specific measurements, however. The TSP concentrations measured during the first burn (Petaca-Las Tablas) were lower than the PM_{10} concentrations. This was likely caused by two separate problems. During the smoldering phase, the heat shielding used to protect the equipment, shifted position and caused an exhaust flow restriction in the unit. In addition, it was determined that both HiVol units had worn gaskets. These leaking connections caused much less air to be sampled during the event, which resulted in an underestimate of the TSP concentrations.

The PM_{10} concentration for the flaming phase of the Xena burn was unusually low (showing a negative weight change consistent with the blank filters for this set). No laboratory or field notes can explain this result, which appears to be the result of an indeterminate error affecting only this sample.

PM_{10} concentrations during the Green Pondo burn were also higher than the corresponding TSP concentrations. There were no obvious problems with the sampling equipment during this event and the cause of these low TSP concentrations is unknown.

3.5 Radionuclide Measurement Results

The measurements of gross alpha, gross beta, and individual radioisotopes are summarized in Table 6. Many of the measurements were below the practical quantitation limits, likely due to insufficient sample volume. These results are less than their corresponding net 2-

sigma uncertainty concentrations in air, shown in parentheses. The PM volume data for the first burn (Petaca-Las Tablas) were indicated to be in error, thus the radionuclide data were not calculated.

3.6 Emission Factor Results

Calculated combustion efficiency and the emission factors for the main pollutants from each fire are presented in Table 7. Combustion efficiencies and emission factors are comparable to those previously reported for similar fuel types.[7] The lowest emission factors for CO and PM_{10} are associated with the highest combustion efficiencies, at the Xena and Green Pondo air curtain destructor burns. The PM_{10} emission factor for the flaming phase of the Xena burn is likely to be artificially low due to the suspect gravimetric result for the 47-mm filter exposed during this phase. The flaming phase gross alpha, gross beta, and lead-210 values obtained from this filter (refer to Table 6) were among the higher concentrations reported in the study. These measurable levels indicate that air was drawn through the filter and radioactive particulate was trapped on its surface and support our suspicion that the filter gravimetric result was spuriously low. The HiVol-derived TSP emission factors from the Green Pondo burn are slightly lower than the concurrent MiniVol-derived PM_{10} emission factors. The majority of particles in forest fire smoke are of small diameter, but the TSP mass should always be higher than PM_{10}. Thus, the measurements of net mass change for the HiVol filters from this burn may be biased slightly low, or the net PM_{10} mass change measurements may be biased slightly high—it cannot be determined from the available data. In either case, the emission factors for TSP and PM_{10} are reasonably close to each other, and adequate for estimating emissions.

Emission factors for radionuclides are summarized in Table 8. Values that are unlikely to be significant because the measured concentrations were below the corresponding 2-sigma uncertainty concentrations (refer to Table 6) are printed against a gray background.

Table 6. Summary of Measured Radionuclide Concentrations

Burn Name, Date	Fire Phase and Particulate fraction	Sample volume (m^3)	Phase-Average Sample Concentrations (with net 2-sigma sample uncertainties in parentheses)[a]									
			Gross Alpha (fCi/m^3)[b]	Gross Beta (fCi/m^3)	Pb-210 (fCi/m^3)	Po-210 (fCi/m^3)	Am-241 (fCi/m^3)	Pu-238 (fCi/m^3)	Pu-239 (fCi/m^3)	U-234 (fCi/m^3)	U-235 (fCi/m^3)	U-238 (fCi/m^3)
Petaca-Las Tablas	Flaming TSP	NA[c]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Flaming PM_{10}	0.116	6631 (3083)	-1472 (4101)	3982 (4515)	9059 (1238)	104 (178)	-27.3 (48.8)	13.2 (89.9)	-114 (141)	-88.6 (105)	-105 (162)
9/25/2001	Smoldering TSP	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Smoldering PM_{10}	0.504	1183 (648)	278 (977)	377 (1035)	1911 (273)	-1.99 (33.2)	6.25 (18.1)	-4.32 (15.3)	-5.89 (63.5)	-7.21 (49.5)	4.63 (50.2)
La Madera	Flaming TSP	21.25	1391 (338)	526 (526)	361 (56)	1937 (142)	-0.21 (1.08)	-0.19 (0.46)	0.92 (0.95)	4.09 (8.23)	0.47 (2.12)	-0.70 (7.66)
	Flaming PM_{10}	0.106	1961 (2378)	255 (4417)	-376 (4895)	3976 (656)	-66.8 (82.1)	-19.4 (56.4)	0.56 (69.9)	53.5 (329)	119 (268)	-20.1 (204)
10/10/2002	Smoldering TSP	101	369 (78)	113 (112)	121 (13)	843 (53)	-0.06 (0.2)	0.03 (0.15)	0.15 (0.18)	0.29 (1.74)	0.03 (0.46)	0.90 (1.72)
	Smoldering PM_{10}	0.470	635 (575)	505 (1036)	447 (1127)	1548 (178)	4.68 (22.7)	0.51 (14.4)	-2.43 (11.7)	-18.8 (43.2)	-0.21 (43.9)	17.8 (39.8)
Air Curtain Destructor "Xena"	Flaming TSP	31	28 (150)	259 (403)	47 (32)	76 (9)	0.45 (1.09)	0.26 (0.35)	0.09 (0.35)	6.49 (3.99)	1.11 (1.12)	4.48 (3.82)
	Flaming PM_{10}	0.075	3657 (3557)	9619 (6916)	9378 (13684)	86 (1142)	-96.5 (325)	-22.0 (69.9)	85.2 (208)	-35.7 (563)	-85.2 (353)	-103 (638)
11/13/2002	Smoldering TSP	48	8.1 (94.4)	403 (276)	49 (21)	70 (8)	-0.14 (0.64)	-0.03 (0.12)	-0.08 (0.09)	2.70 (2.46)	0.92 (0.76)	3.17 (2.48)
	Smoldering PM_{10}	0.128	1074 (1612)	2241 (3658)	-1090 (7803)	-137 (584)	-157 (168)	-3.42 (36.6)	26.1 (103)	-142 (266)	-102 (222)	-122 (337)
Air Curtain Destructor "Green Pondo"	Flaming TSP	29	13 (154)	484 (439)	206 (36)	101 (13)	-0.08 (1.09)	0.41 (0.51)	0.07 (0.24)	5.10 (3.40)	-0.25 (0.80)	3.75 (3.34)
	Flaming PM_{10}	0.067	-1078 (2106)	4761 (7039)	-2096 (15293)	1710 (1528)	8.98 (397)	-6.59 (68.7)	83.2 (245)	361 (652)	-209 (376)	19.0 (696)
11/13/2002	Smoldering TSP	57	14 (79)	511 (239)	65 (17)	42 (5)	-0.06 (0.51)	0.03 (0.15)	0.09 (0.17)	1.16 (1.89)	0.56 (0.59)	2.58 (2.01)
	Smoldering PM_{10}	0.143	126 (1182)	2297 (3292)	-420 (7652)	-148 (442)	51.8 (198)	50.1 (67.1)	-4.48 (72.7)	216 (323)	-117 (260)	-369 (313)

[a] Values in parenthesis are the net 2-sigma uncertainty concentrations in air.
[b] fCi/m^3 = femtocuries per cubic meter.
[c] Not Available—Volume measurement was in error.

Table 7. Summary of Emission Factors by Fire

Burn Name, Date	Fire Phase	Combustion Efficiency (percent)	Phase-Average Emission Factors					
			EF CO (g/kg)[a]	EF CO_2 (g/kg)	EF CH_4 (g/kg)	EF NMHC (g/kg)	EF PM (g/kg)	EF PM_{10} (g/kg)
Petaca-Las Tablas	Flaming[b]	92.5	29.3	1697	7.3	12.5	NA[c]	12.6
9/25/2001	Smoldering[b]	85.9	83.7	1577	11.9	19.0	NA[c]	13.7
La Madera	Flaming	87.6	84.3	1607	1.9	-0.6	35.3	26.5
10/10/2002	Smoldering	81.3	136	1491	4.3	-1.0	46.5	43.8
Air Curtain Destructor "Xena"	Flaming	98.6	10.0	1809	0.2	1.6	1.9	0.3
11/13/2002	Smoldering	96.8	33.2	1776	0.2	0.9	1.4	1.2
Air Curtain Destructor "Green Pondo"	Flaming	93.3	70.5	1712	0.3	1.7	2.1	2. 9
11/13/2002	Smoldering	94.7	53.1	1738	0.4	1.9	2.4	3.2

[a] Emission factors are in grams of pollutant per kilogram of fuel burned.
[b] Emission factors based on PM_{10}, rather than particulate matter due to air flow calibration problem at this burn.
[c] Not Available—No accurate measurement obtained.

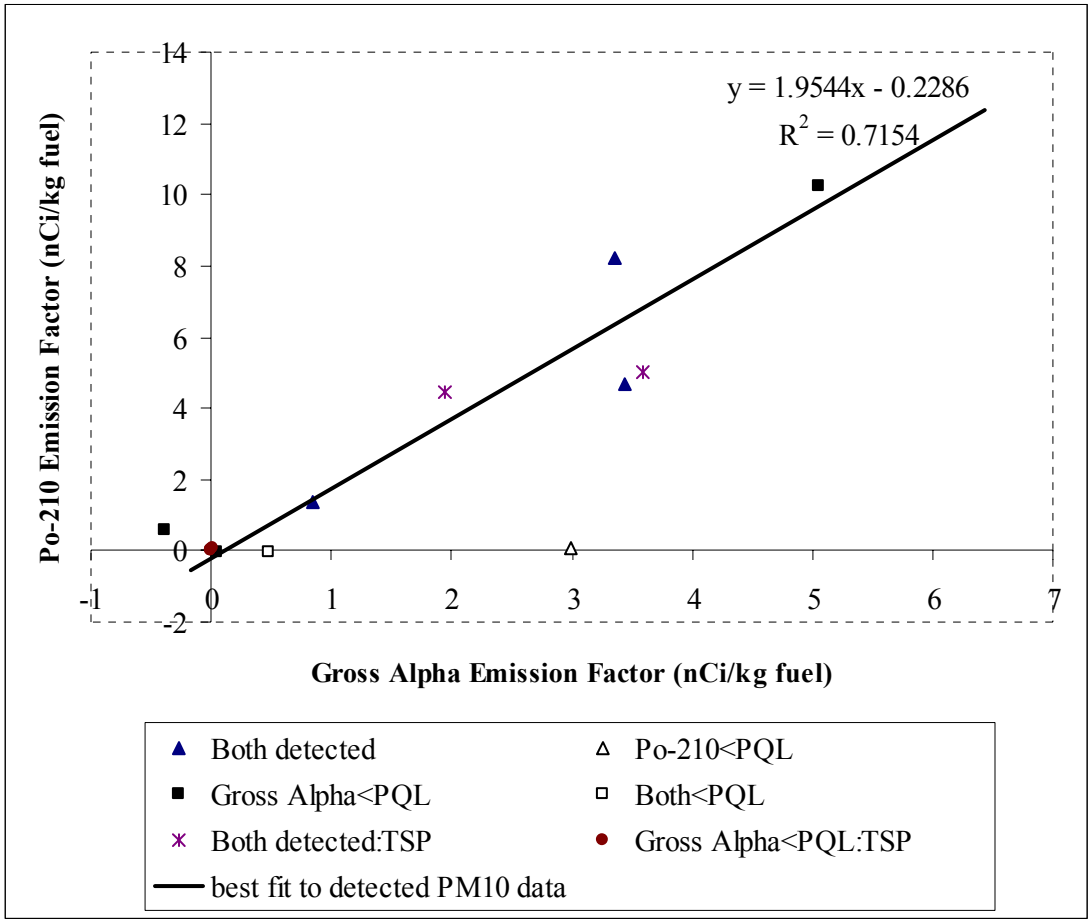
Table 8. Summary of Radionuclide Emission Factors

Burn Name, Date	Source of Radioactive Emission Data	Phase-Average Emission Factors[a]									
		EF Gross Alpha (nCi/kg)[b]	EF Gross Beta (nCi/kg)	EF Pb-210 (nCi/kg)	EF Po-210 (nCi/kg)	EF Am-241 (pCi/kg)[c]	EF Pu-238 (pCi/kg)	EF Pu-239 (pCi/kg)	EF U-234 (pCi/kg)	EF U-235 (pCi/kg)	EF U-238 (pCi/kg)
Petaca-Las Tablas	Flaming TSP	NA[d]	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Flaming PM_{10}	3.44	-0.76	2.07	4.70	53.9	-14.2	6.85	-59.2	-46.0	-54.7
9/25/2001	Smoldering TSP	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Smoldering PM_{10}	0.84	0.20	0.27	1.36	-1.41	4.44	-3.06	-4.18	-5.12	3.29
La Madera	Flaming TSP	3.59	1.36	0.93	4.99	-0.54	-0.48	2.37	10.5	1.21	-1.81
	Flaming PM_{10}	5.05	0.66	-0.97	10.3	-172	-50	1.46	138	306	-51.9
10/10/2002	Smoldering TSP	1.95	0.60	0.64	4.47	-0.34	0.17	0.80	1.54	0.14	4.77
	Smoldering PM_{10}	3.36	2.67	2.37	8.20	24.8	2.71	-12.9	-99.5	-1.13	94.3
Air Curtain Destructor "Xena"	Flaming TSP	0.02	0.21	0.04	0.06	0.37	0.21	0.08	5.30	0.91	3.66
	Flaming PM_{10}	2.98	7.85	7.65	0.07	-78.7	-17.9	69.5	-29.2	-69.5	-84.5
11/13/2002	Smoldering TSP	0.004	0.18	0.02	0.03	-0.06	-0.02	-0.04	1.21	0.41	1.42
	Smoldering PM_{10}	0.48	1.00	-0.49	-0.06	-70.3	-1.53	11.7	-63.5	-45.8	-54.7
Air Curtain Destructor "Green Pondo"	Flaming TSP	0.005	0.17	0.07	0.04	-0.03	0.15	0.03	1.81	-0.09	1.33
	Flaming PM_{10}	-0.38	1.69	-0.74	0.61	3.19	-2.34	29.5	128	-74.1	6.72
11/13/2002	Smoldering TSP	0.005	0.20	0.03	0.02	-0.02	0.01	0.04	0.46	0.22	1.03
	Smoldering PM_{10}	0.05	0.92	-0.17	-0.06	20.7	20.0	-1.79	86.4	-46.8	-147

[a] Values in gray highlighting are estimates below the practical quantification limit.
[b] nCi/kg = nanocuries per kilogram of fuel consumed.
[c] pCi/kg = picocuries per kilogram of fuel consumed.
[d] Not Available—Volume measurement calibration problems.

For those samples with results above practical quantification limits (Table 6), the emission factors for radionuclides in Table 8 do not vary a great deal. For example, the gross alpha ranges from a low of 0.84 nCi/kg during the smoldering phase at Petaca-Las Tablas to a high of 3.59 nCi/kg during the flaming phase at La Madera. In most cases, the radioisotopes measured in the PM_{10} samples yielded a higher estimated emission factor than results based on the TSP samples.

The nature of the radioactive species in forest biomass fires has been previously identified.[8] In our measurements, gross alpha and gross beta emission factors correlated well with emission factors for polonium-210 and lead-210, respectively. Figure 14 shows the relationship between gross alpha and polonium -210. The regression line is based on the three measurable results for the pairs of PM_{10} measurements due to the few TSP results of both gross alpha and polonium-210 above the practical quantification limit. The two measurable results for these analytes in the TSP filters are also shown on the graph.



PQL = practical quantitation limit

Figure 14. Correlation between polonium-210 and gross alpha emission factors

Figure 15 shows the relationship between gross beta and lead-210 emission factors. For these analytes, more pairs of measurable results were found in the TSP data than the PM_{10} data,

and the regression is based on these six data pairs. The lone measurable PM_{10} result is shown as well.

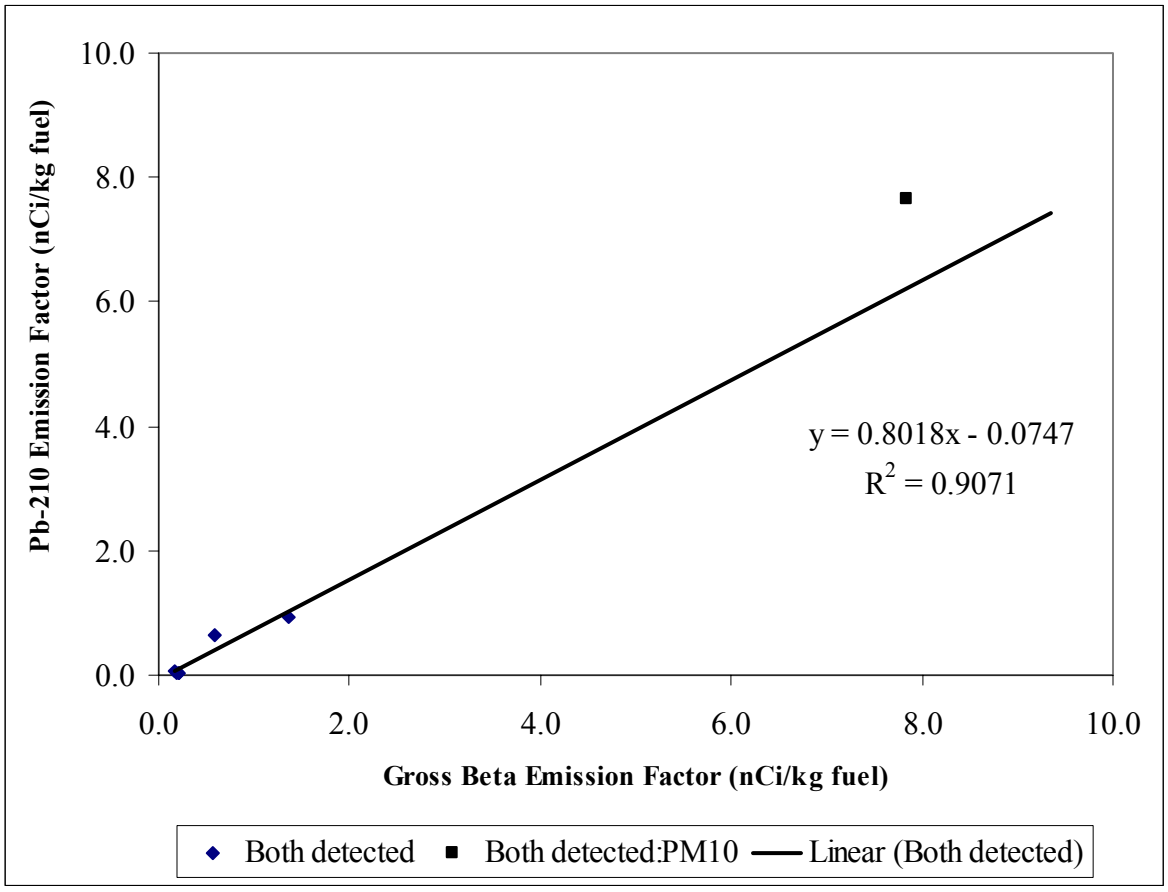


Figure 15. Correlation between lead-210 and gross beta emission factors

From these data, it would seem apparent that lead-210 accounts for most of the gross beta measured in both TSP and PM_{10} emissions. However, because lead-210 beta particles are low in energy, the gross beta measurement is mainly due to bismuth-210, which should be comparable to the amount of lead-210 present because it is a short-lived decay product of lead-210. In contrast, polonium-210 emission factors are about twice the measured gross alpha. As LANL researchers have pointed out in similar measurements during the Cerro Grande fire, the gross alpha concentrations are measured from face counts of alpha activity, which would underestimate actual concentrations due to alpha emitters buried further within the filter matrix.[9]

4.0 Discussion

Emission factors for the dominant pollutants characteristic of forest biomass combustion (CO, CO_2, CH_4, and NMHC) are consistent with measurements reported by others at prescribed burns and wildfires in *Pinus ponderosa* and mixed conifers. The particulate and gas-phase nonradioactive emission factors should have wide applicability to similar fuels in the Southwest and prove useful for smoke management purposes. The emission factors for gross alpha, gross beta, and NORM reported are the first results quantifying emission factors of technologically enhanced NORM from burning forest biomass.

These data show measurable levels of several radioactive isotopes are emitted from burning of natural woody fuels in northern New Mexico. Most of the gross alpha and beta emissions are due to polonium-210 and lead (actually, its decay product, bismuth)-210, respectively; these are relatively long-lived isotopes in the decay chain of natural radon-222. Both polonium-210 and lead-210 have been measured in fire emissions, and measurements have found that plants contain approximately 1 pCi per gram of dry weight.[8, 10, 11] Our emission factors for gross alpha appear likely to underestimate the actual emission factor by about 50% due to the limitations of the measurement technique (face counting).

Plutonium isotopes (Pu-238, Pu-239) were not found above practical quantification limits at any of the burns. Uranium isotopes (U-234, U-235, and U-238) were found at measurable concentrations in many of the samples. These long-lived isotopes are predominantly from naturally occurring uranium in the soil. It should be noted that uranium-238 is the parent isotope of uranium series that also includes uranium-234, radon-222, bismuth-210, and polonium-210.

The measured emission factors may be used as inputs to a modeling system to calculate the production and dispersion of these isotopes from both prescribed burns and air curtain destructors. With measurement or calculation of fuel consumption at a prescribed burn or air curtain destructor (e.g., in terms of kg of woody debris burned per hectare or day), either by direct inventory or estimation from a prescribed burning fuel consumption model such as CONSUME 3.0, these data allow an estimate of the phase-average emissions of the measured isotopes as well as gross alpha and gross beta.[12] The emission factors multiplied by the fuel consumed yield phase-average production of the measured radioactive emissions. With the simplifying assumption that these corresponding emission rates are constant over the course of flaming and smoldering combustion, the emission rates can be used as inputs to a regional-scale dispersion model such as CALPUFF, which can then model the estimated concentrations in the atmosphere at varying directions and distances downwind of the source area. These data thus provide a basis for a quantitative retrospective look at the potential emissions associated with the Cerro Grande fire in the Los Alamos area. Where smoke from the fire impacted ambient air monitors in the Los Alamos vicinity, actual measurements of airborne radioactivity may be compared with levels predicted by our source measurements. Our radionuclide emission factors allow the calculation of total flux to the atmosphere based on amount of forest biomass burned in northern New Mexico; these emission factors may have wider applicability as well, especially for similar fuels from regions with similar ambient radon-222 levels, because the surface area,

growth, and respiration rates and thus uptake of these radionuclides should be similar to the fuels we conducted measurements in.

Acknowledgment

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Appendix: Sample Data

Filter Sample Data for Burn 1 (Petaca-Las Tablas, 9/25/01)

LANL TSP Loadings

Net Radionuclide Results

	Filter Number	Loading (g)	Volume (m^3)	Net PM Conc. (mg/m^3)	Gross alpha (fCi/m^3)	Gross beta (fCi/m^3)	Am-241 (aCi/m^3)	Pb-210 (fCi/m^3)	Po-210 (fCi/m^3)	Pu-238 (aCi/m^3)	Pu-239 (aCi/m^3)	U-234 (aCi/m^3)	U-235 (aCi/m^3)	U-238 (aCi/m^3)
8 x 10 filters														
Field Blank	Q7548268	0.0029	N/A	N/A										
Field Blank	Q7548269	0.0012	N/A	N/A										
Field Blank	Q7548270	0.0042	N/A	N/A										
TSP #2	Q7548271	0.4312	28	15.08	2773	533	282	544	4348	-208	-97	1523	1014	1176
TSP #3	Q7548272	1.7614	119	14.76	281	232	-101	188	1080	-18	308	702	89	139

	Filter Number	Loading (mg)	Volume (m^3)	Net PM Conc. (mg/m^3)	Gross alpha (fCi/m^3)	Gross beta (fCi/m^3)	Am-241 (aCi/m^3)	Pb-210 (fCi/m^3)	Po-210 (fCi/m^3)	Pu-238 (aCi/m^3)	Pu-239 (aCi/m^3)	U-234 (aCi/m^3)	U-235 (aCi/m^3)	U-238 (aCi/m^3)
47-mm filters														
Mini-Vol #1	Q-2001001	2.5480	0.116	24.25	6631	-1472	103881	3982	9059	-27269	13202	-113980	-88587	-105324
Mini-Vol #4	Q-2001002	9.45	0.504	19.26	1183	278	-1985	377	1911	6253	-4317	-5889	-7212	4632
Field Blank	Q-2001003	-0.2260	N/A	N/A										
Field Blank	Q-2001004	-0.1850	N/A	N/A										
Field Blank	Q-2001005	-0.3500	N/A	N/A										

fCi/m^3 = Femtocuries per cubic meter
aCi/m^3 = Attocuries per cubic meter

Filter Sample Data for Burn 2 (La Madera, 10/10/02)

LANL TSP Loadings

Net Radionuclide Results

	Filter Number	Loading (g)	Volume (m^3)	Net PM Conc. (mg/m^3)	Gross alpha (fCi/m^3)	Gross beta (fCi/m^3)	Am-241 (aCi/m^3)	Pb-210 (fCi/m^3)	Po-210 (fCi/m^3)	Pu-238 (aCi/m^3)	Pu-239 (aCi/m^3)	U-234 (aCi/m^3)	U-235 (aCi/m^3)	U-238 (aCi/m^3)
	8 x 10 filters													
Field Blank	Q7548276	0.0062	N/A	N/A										
Field Blank	Q7548277	0.0025	N/A	N/A										
Field Blank	Q7548278	0.0017	N/A	N/A										
TSP #2	Q7548275	0.2943	21.25	13.69	1391	526	-210	361	1937	-187	921	4087	471	-701
TSP #3	Q7548274	0.8901	101	8.78	369	113	-64	121	843	32	150	292	26	901

	Filter Number	Loading (mg)	Volume (m^3)	Net PM Conc. (mg/m^3)	Gross alpha (fCi/m^3)	Gross beta (fCi/m^3)	Am-241 (aCi/m^3)	Pb-210 (fCi/m^3)	Po-210 (fCi/m^3)	Pu-238 (aCi/m^3)	Pu-239 (aCi/m^3)	U-234 (aCi/m^3)	U-235 (aCi/m^3)	U-238 (aCi/m^3)
	47-mm filters													
Mini-Vol #1	Q2001019	1.0060	0.106	10.29	1961	255	-66828	-376	3976	-19390	565	53462	118596	-20142
Mini-Vol #4	Q2001020	3.7990	0.470	8.27	635	505	4684	447	1548	511	-2427	-18777	-213	17798
Field Blank	Q2001007	-0.0780	N/A	N/A										
Field Blank	Q2001008	-0.1030	N/A	N/A										
Field Blank	Q2001009	-0.0820	N/A	N/A										

fCi/m^3 = Femtocuries per cubic meter
aCi/m^3 = Attocuries per cubic meter

Filter Sample Data for Burns 3 and 4 (Xena and Green Pondo, 11/13/02)

	LANL TSP Loadings			Net Radionuclide Results									
	Filter Number	Loading (g)	Volume (m^3)	Net PM Conc. (mg/m^3)	Gross alpha (fCi/m^3)	Gross beta (fCi/m^3)	Am-241 (aCi/m^3)	Pb-210 (fCi/m^3)	Po-210 (fCi/m^3)	Pu-238 (aCi/m^3)	Pu-239 (aCi/m^3)	U-234 (aCi/m^3)	U-235 (aCi/m^3)	U-2 (aC
	8 x 10 filters													
Field Blank	Q7548285	0.0034	N/A	N/A										
TSP #2 (xena)	Q7548281	0.0766	31	2.38	28	259	454	47	76	260	94	6492	1110	44
TSP #3 (xena)	Q7548282	0.1486	48	3.05	8.1	403	-139	49	70	-34	-82	2704	925	31
TSP #2 (green pondo)	Q7548284	0.1757	29	5.90	13	484	-82	206	101	411	72	5105	-247	37
TSP #3 (green pondo)	Q7548283	0.3528	57	6.10	14	511	-56	65	42	28	92	1162	558	25
	Filter Number	Loading (mg)	Volume (m^3)	Net PM Conc. (mg/m^3)	Gross alpha (fCi/m^3)	Gross beta (fCi/m^3)	Am-241 (aCi/m^3)	Pb-210 (fCi/m^3)	Po-210 (fCi/m^3)	Pu-238 (aCi/m^3)	Pu-239 (aCi/m^3)	U-234 (aCi/m^3)	U-235 (aCi/m^3)	U-2 (aC
	47-mm filters													
Mini-Vol #1(xena)	Q2001010	-0.1670	0.075	0.34	3657	9619	-96461	9378	86	-21972	85207	-35726	-85207	-10
Mini-Vol #4(xena)	Q2001011	0.1480	0.128	2.65	1074	2241	-157205	-1090	-137	-3424	26149	-142159	-102416	-12
Mini-Vol #1(green pondo)	Q2001013	0.3520	0.067	8.15	-1078	4761	8984	-2096	1710	-6588	83251	361353	-209026	18
Mini-Vol #4(green pondo)	Q2001012	0.9690	0.143	8.13	126	2297	51819	-420	-148	50138	-4482	216611	-117362	-36
Field Blank	Q2001014	-0.1390	N/A	N/A										
Field Blank	Q2001015	-0.2200	N/A	N/A										
Field Blank	Q2001016	-0.2180	N/A	N/A										

fCi/m^3 = Femtocuries per cubic meter
aCi/m^3 = Attocuries per cubic meter

Gas Sample Concentrations for All Burns

Name, Date of Burn	Sample Period	Pressure	Temp	CO (ppm)	CO_2 (ppm)	CH_4 (ppm)	TNMHC (ppm)
Petaca-Las Tablas 9/25/2001	Flaming	0.750	294	66.7	2718	30.72	19.70
Petaca-Las Tablas 9/25/2001	Smoldering	0.748	299	140.1	1987	36.76	22.06
						Background for Burn	
				CO	**CO_2**	**CH_4**	**TNMHC**
				1.9	330	2.46	2.10
La Madera 10/10/2002	Flaming	0.778	291	32.3	769	1.40	-0.16
La Madera 10/10/2002	Smoldering	0.778	291	24.7	530	1.57	-0.13
						Background for Burn	
				CO	**CO_2**	**CH_4**	**TNMHC**
				-3.6	334	0.14	-0.16
Xena 11/13/2002	Flaming	0.778	302	18.1	1938	1.69	2.01
Xena 11/13/2002	Smoldering	0.778	313	91.7	3308	0.84	1.52
Green Pondo 11/13/2002	Flaming	0.778	320	243.4	4030	2.76	4.19
Green Pondo 11/13/2002	Smoldering	0.778	321	165.2	3684	3.15	4.25
						Background for Burns	
				CO	**CO_2**	**CH_4**	**TNMHC**
				4.2	330	1.13	0.59

Notes:

1: TNMHC concentrations are calculated as propane

2: Pressures are in atmospheres

3: Could not subtract background concentrations from CH_4 during smoldering phase of Xena burn on 11/13/2002

Los Alamos NM 87545