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Air Quality Modeling of Emissions From Prescribed Burning

FINAL REPORT:
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By

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EXECUTIVE SUMMARY

Fuel moisture content, woody fuel and duff consumption, fire behavior, and smoke plumes were monitored on four prescribed burns located on the Oakridge Ranger District of the Wiliamette National Forest. The measured fuel moisture, fuel consumption, and fire behavior data were used to validate an Emissions Production Model (EPM) which predicts fuel consumption, heat release rates, and smoke emissions for a smoke dispersion model called Simple Approach Smoke Estimation Model (SASEM). Both EPM and SASEM have been combined together into a single program called Tiered Smoke Air Resource System (TSARS). Several comparisons were made between predicted results from EPM and measured values to help determine the level of accuracy which could be expected for different levels of data input effort.

In-plume sampling procedures using tethered equipment for sampling of particulate matter and gaseous pollutants were designed, developed, and acquired during this study. Because the objective of this study was to evaluate the model under the July 1 to Labor Day burning ban meteorological conditions, sampling was scheduled only for the summer months. For each study year, a meteorological pattern occurred that severely limited sampling. The summers for all three study years in general were extremely dry; prohibiting burning due to fire danger. Therefore, a smaller number of units were burned than that planned.

Using current weather data, the large, woody fuel moisture contents were predicted within 3 percent of the measured values. This is well within the $\pm$ 5 percent error associated with the ADJ-Th which is a meteorologically-based fuel moisture model.

The line intersect procedure was used to obtain the best fuel loading information. This information was input to the fuel consumption models within the EPM. The model predicted the measured woody fuel and duff consumption within an error range of 4-17 percent. This is well within the error associated with the fuel consumption algorithms. This evaluation has shown that the fuel moisture and fuel consumption models are satisfactorily predicting values for the prescribed burning situations which they were developed for.

The Ranger District burn plan fuel loading and fuel moisture were used as input into EPM. The models continued to predict very well although the difference between the measured and predicted were slightly larger (9 to 23 percent).

TSARS was used to predict the plume height, centerline concentrations and ground level concentrations. Comparisons with the measured values were completed on Black Saddle 6 and Black Saddle 5, since those were the only units from which emission samples were successfully collected.

Using measured fuel consumption inputs, the plume height was predicted within 40 percent of measured, while the centerline concentration was estimated at 10 to 15 times higher than measured. The ground level concentration was predicted within 40 percent of the measured.

I. INTRODUCTION

A. Background & Overview

Over the past several years the conflicts between the development of resources and the protection and preservation of natural resources have grown more serious. The need for adequate means to evaluate the effects of land management activities on air resources has become increasingly evident. Federal land managers are responsible not only for developing our natural resources but also for protecting the air resources that may be affected by their management activities. This is particularly true in the use of fire as a management tool.

Smoke management plans have been a first step of the Oregon and Washington efforts to put both the use of fire and the protection of air quality into perspective. Plans have relied on existing weather data and the ability of the meteorologist to predict on a day to day basis the behavior of smoke from prescribed burns in order to maintain adequate air quality and to insure protection of certain designated smoke sensitive areas. The system has worked well for the states. However, it does not permit the land manager to effectively manage a fire program and carry out responsibilities for the protection of air quality related values in the Class I wilderness areas.

The smoke management system has also been built around the reduction of total emissions emitted from prescribed fires. As a result, the USDA Forest Service (FS) has begun to implement measures which reduce the emissions of pollutants from prescribed burns to meet state regulation requirements. These measures include increased biomass utilization and burning under fuel moisture conditions that minimize pollutant emissions. These measures not only reduce the impact on the air resource, but often mitigate other affects on the site such as the productive capacity of the forest soils.

Although reducing emissions from prescribed burning has been an important air resource management strategy, regulatory agencies have placed an increased emphasis on the downwind movement of smoke pollutants and the protection of smoke sensitive areas. The Aviation and Fire Management office of the USDA FS, Region 6, has been committed for several years to the development and testing of a dispersion model called the Smoke Management Screening System (SMSS). The system was to be tested during 1986 but was never operationally available. In addition to the research and development of SMSS, the Pacific Northwest Research Station, in cooperation with Aviation and Fire Management, USDA FS, Region 6, has developed a model which estimates smoke production and heat release rates from operational prescribed fires in west coast logging slash. The program is called the Emissions Production Model (EPM) and was designed to estimate total emissions for tracking emissions reduction and to become a front end to a dispersion model. The model has been combined with a simple dispersion model called the Simple Approach Smoke Estimation Model (SASEM) which was developed by BLM. The combined models (EPM and SASEM) are packaged as the Tiered Smoke Air Resource System (TSARS).

In an effort to prevent visibility degradation in the National Parks and wildernesses (Class I areas), the states of Washington and Oregon have restricted slash burning during the summer months. All burns are prohibited, regardless of their size, emission potential or proximity to the Class I areas. In hopes of identifying meteorological conditions which minimize the impacts of slash burning and predict which units could be burned on restricted days without significantly degrading visibility, the Bonneville Power Administration (BPA) funded a joint effort. The USDA FS, Nero and Associates, Inc. (NAI), and G_2 Environmental Inc. (G2E) were to test the predictive ability of a model to estimate ambient particulate concentrations downwind of prescribed burns, since particulate matter is the slash burning pollutant with the greatest impact on visibility.

The proposed study was to unite source strength data, meteorological information, and air quality monitoring to check the accuracy of a chosen dispersion model. The model chosen for the test was TSARS. This would increase the credibility and hence provide a useful tool for meeting federal air quality requirements.

B. Project Purpose and Scope

The purpose of the project was to determine the accuracy of a simple Gaussian model in predicting in-plume and ground-based particulate concentrations resulting from slash burns located close to Class I areas. The scope was to measure particulate matter resulting from six different units, burned on different days. The monitoring results were to be compared to the modeled concentrations to provide an initial evaluation of model performance, its strengths and weaknesses, and information that would serve as the basis of further study, if needed. It was hoped that such an analysis would identify meteorological conditions which minimize the impacts of slash burning and predict which units could be burned on restricted days without significantly degrading visibility.

II. MODEL DESCRIPTION

A. Literature Review

Designing an effective model for use in rough terrain is costly. The Environmental Protection Agency (EPA) has expended considerable resources to develop a model for industrial sources located in rough terrain areas. However, EPA has not developed models which are appropriate for mountainous area sources such as slash burning. To improve this situation, the USDA Forest Service (FS) has been developing two models, Topographic Air Pollution Analysis System (TAPAS) and Tiered Smoke Air resource System (TSARS).

The Topographic Air Pollution Analysis System (TAPAS) is a user-friendly computer system developed by the U.S. Forest Service that contains terrain modules, dispersion models, and graphic display procedures designed to provide quantification tools for air resource managers (Fox et al., 1987). TAPAS is a large system and requires mini-mainframe capacities to house and run. The system is to large and difficult to use for implementation at a local level. The system is also very data hungry and requires more data than most managers will have available to them. At the present time, the system does not have a front end emissions production model for predicting smoke production and heat release rates from prescribed fires.

The Tiered Smoke Estimation System (TSARS) has been selected for in depth evaluation because of its ease of use, and because it was designed specifically for daily use by the land manager. It employs a simple Gaussian model using Briggs (1969) plume rise. It is designed to estimate adverse impacts at the boundaries of specific smoke sensitive areas such as population centers and Class I wildernesses.

The dispersion model portion of TSARS is the Simple Approach Smoke Estimation Model (SASEM) which has been developed by the Bureau of Land Management for use by land managers (Sestak and Riebau, 1987). SASEM was developed with three objectives in mind: 1) minimal data requirements; 2) limited computer resource requirements; and 3) easy application by fire management personnel. Information needed to run the model includes wind speed, wind direction, mixing height, dispersion day, and distance specific receptors are from the prescribed burn. It was designed as a simple screening tool to be used as a first cut at a regulatory decision. It contains simplifying assumptions that tend toward conservative results; i.e, it is more likely to over- than under-predict.

The model estimates maximum ground-level concentration of particulate, the distance at which this concentration would occur from the prescribed burn, and the range of distances from the fire over which specified ambient air quality standards would be exceeded. The minimum visual range at the distance of a specified sensitive receptor site for a variety of meteorological conditions is also estimated by the model.

SASEM was developed for range and pile burning for the state of Wyoming but has been adapted for testing in the Pacific Northwest. An Emissions Production Model (EPM) (Sandberg and Peterson, 1984) was developed by the Pacific Northwest Research

Station's Fire and Air Resource Management Program. The model uses twenty-two input parameters to predict fuel consumption, heat release rates, and particulate matter production rates from prescribed burns in short-needled conifer cover types.

EPM first uses Ottmar's (1983) and Sandberg and Ottmar's (1983) predictive algorithms and heuristic (placing bounds on predicted values) to compute biomass, or fuel consumption (tons per acre) for each fuel-bed component. Then the proportion burned in the two combustion stages is computed for each fuel-bed component and multiplied by predicted fuel consumption. The mass of fuel burned in all components is summed to estimate total fuel consumption in the flaming and smoldering stage.

The model has been added to the front end of SASEM to better characterize smoke dispersion for the Pacific Northwest. The combined models (EPM and SASEM) are packaged as the Tiered Smoke Air Resource System (TSARS) and has been made user-friendly for use by forest managers.

Other models which have been used with partial success are box models that incorporate terrain features. However, these models are cumbersome, requiring extensive coding for each area that is to be modeled and do not have a pollutant production model built in which can predict pollutant rates from open burning. Much of the detail of the box models is unnecessary for a slash burn situation because the impacts are distant from the source. Box models are most appropriately used where the pollutant impacts are close to the source and can be identified in the boxes adjacent to the source.

The best use of the resources for this project would be to provide a tool which can be used on a daily basis by land managers. Of the models available, TSARS would clearly be the best choice. It is already developed and operational on the Willamette and Siuslaw National Forests. Therefore, no resources would be wasted instituting a new system. Also, the input to TSARS is easily obtained on a daily basis, unlike the extensive information needed to run a model like TAPAS.

The ambient aerosol composition data, in association with composition data for airshed emission sources, can be used to back-calculate the impact of specific sources, or source classes, at the receptor. This approach differs from dispersion modeling in that the latter attempts to determine source impacts at a receptor given data on source emission rates, stack parameters, source activity, and meteorology. This methodology is called receptor modeling, and the methodology is covered by Watson (1979) and in EPA's technical series documents (EPA 1981a, 1981b, 1983a and 1983b).

Receptor modeling methods can be applied in particulate source apportionment scenarios in which dispersion models can not be easily used, such as the analysis of source impacts during actual air pollution episodes; in complex terrain and the identification and quantification of sources which heretofore had not been adequately considered in emission inventories.

B. Dispersion Model Selection

The model originally chosen for testing during the summer was the Smoke Management Screening System (SMSS), a model specifically designed by the USDA FS to predict the impacts of slash burning. The SMSS model was part of a larger fire danger rating system being developed by the FS. During the fall of 1986, funding was discontinued for the entire system, making SMSS unavailable for future use.

Several replacement models were considered, including:

- TSARS, developed by the Bureau of Land Management (BLM) for use with slash burns in Wyoming (Riebau et al., 1986)
- TAPAS, a model developed for rough terrain by the USDA FS (Fox et al., 1987)
- All of the EPA-approved dispersion models.

EPA and the USDA FS were asked to review these models and comment on their appropriateness for use in this study. The field was narrowed to SASEM and TAPAS, since one was developed specifically for slash burning and the other could be adapted to slash burning and would account for rough terrain.

On February 3, 1987, the USDA FS and Nero and Associates, Inc. (NAI)/G_2 Environmental, Inc. (G2E) met to perform the final model selection. It was agreed upon that TAPAS was too complex, and would require too much input data and computer time to be a useful screening tool for forest managers. SASEM was chosen as a "first step" in defining the conditions that control adverse slash burning emissions impacts. SASEM is based on EPA-approved models (PTMAX and PTDISD). It can predict both in-plume and ground-based concentrations of particulate matter and visibility impacts for an observer located at the point of impact.

The model had three important limitations:

- Inadequate fuel consumption and emission production module;
- Inadequate plume rise algorithm; and
- Inadequate consideration of the effects of rough terrain.

To remedy the first two of these deficiencies, the USDA FS incorporated the EPM model developed by the Pacific Northwest Research Station as well as a better plume rise equation. The third limitation was avoided by choosing units located so that there was no significantly elevated terrain between the burn units and the sampling sites, thus approximating the flat terrain for which the model was developed.

C. Description of SASEM

The Wyoming Department of Environmental Quality, Air Quality Division requires that each controlled burn be submitted for separate consideration for permitting under the State air quality regulations. SASEM was designed by BLM (Sestak and Riebau, 1987) to demonstrate that range and grassland controlled burns would not cause ambient air pollution standards to be exceeded downwind of the burns.

The model is a simple screening tool for use by land managers. It has minimal data requirements, limited computer resource requirements, and easy application by fire management field personnel.

SASEM includes a simple estimation of particulate emissions from burning of range fuels and screening level estimation of dispersion of these emissions. The model calculates emissions from fire line intensity, average fuel loading, and the type of fuel which is burned. Plume rise is calculated from the fuel type burned, wind speed and stability. Particulate concentrations are obtained from the emission rate, plume rise, wind speed, and stability using the Gaussian dispersion formula for a line source or point source depending on whether the fire was a range burn or pile burn. The model determines the maximum concentration and the distance over which applicable standards will be violated. Since the model was originally developed to meet requirements imposed by ambient air quality standards, the results are expressed in terms of 24-hour averaged ground level concentrations.

Plume rise is determined from a modification of the EPA standard formulas (Briggs, 1969). The modifications to the standard plume rise equations are intended to take into account that the fire is generally an irregular line source, and not a point source for which the equations were derived. SASEM also uses the Gaussian plume concentration and an alternately determined result to calculate the minimum visual range at any given distance from the fire.

SASEM also reports calculated minimum visual ranges from up to 10 preselected receptors to assess public nuisance impacts. The reduction in visual range is obtained from a simple scattering coefficient determined by assuming a uniform concentration across the plume.

D. Description of the Emission Production Model

EPM was developed to combine what is known about the factors that control biomass consumption and combustion efficiency during broadcast burns in western Oregon and western Washington (Sandberg and Peterson, 1984). Particulate matter and carbon monoxide emission rates and fuel consumption rates are predicted from a set of 22 or more input parameters. Default values or inference techniques are available for most inputs.

The model first uses Sandberg and Ottmar (1983) and Ottmar and Sandberg (1985) predictive algorithms and heuristic to compute fuel consumption for each fuel-bed component. Then the proportion burned in the two combustion stages is computed for each fuel-bed component and multiplied by predicted fuel consumption. The mass of fuel burned in all components is summed to estimate total fuel consumption, flaming stage consumption, and smoldering stage consumption. Those values are multiplied by fire size, and the appropriate emission factor to compute emission yield from each stage of the burn.

A rate equation (proportion of fuel consumed per minute) is derived for each stage. The average rate proportion for each 10 minutes is multiplied by emission yield to predict flaming and smoldering emissions. The emissions strengths are then summed to estimate total emissions.

The model is written in a user-friendly format, provided the user is familiar with prescribed burning technology and terminology. A minimum of 22 variables (such as ignition period, fuel moisture, preburn fuel loading, etc.) have been shown to influence emissions and are used in the model to predict fuel consumption, select emission factors, or solve rate equations. Default values that represent regional averages, or the most frequent values, or in some cases, a best guess, can be substituted for any of the inputs.

The fuel consumption models within EPM were developed from operational prescribed burns and have been validated. However, a comparison has never been completed to provide error bounds associated with various levels of preburn and post burn fuel inventory and weather data collection efforts.

E. Tiered Air Resource System (TSARS)

TSARS is a modular computer program which has integrated EPM with SASEM. Prior to the integration, SASEM did not have the capability to estimate fuel consumption, heat release rates, particulate matter production rates, or carbon monoxide production rates from the burning of conifer forest fuels of the west coast.

A scientific version of TSARS was developed to produce outputs compatible with data collected downwind of the prescribed burns. The scientific version of the model was specifically developed for this study and has not been made user friendly or distributed to forest managers. The scientific version calculates a plume height and plume centerline concentration at various distances down wind for each 20 minute period during a prescribed burn. The calculations from this version of TSARS was used to compare the model results with values measured downwind of the prescribed burn.

III. FIELD STUDY

A. Unit Selection

The study area was the forested lands of the Oakridge and Sweet Home Ranger Districts on the Willamette National Forest. Six units were chosen each year during 1986-1988 and inventoried for fuel consumption by the Fire and Air Resource Management Project of the Pacific Northwest Research Station. The units for the study were selected on the basis of operability, likelihood to be burned on schedule or during a burning restriction period when emission contaminates from other prescribed fires is less likely, a uniform fuel-bed with fuel loadings to sustain a steady burn rate, geographically suitable for measuring downwind emissions, downwind elevated terrain which could divert the plume, and the willingness of the land manager to cooperate in the research effort.

Two methods were considered for choosing the units. The first method would burn units with uniform fuel characteristics in one geographic location under one set of meteorological conditions and calibrate the model on this data set. This method was attractive because it provides a fairly large data set with potentially small variation. However, only one set of conditions would be tested. In reality, slash burning occurs under many different fuel and meteorological conditions on units in many geographic areas. Evaluating model performance under only one set of conditions would say nothing about its performance under other conditions. If the model did not work well under the limited conditions chosen, an erroneous decision might be made to discontinue use of a model that may work well under conditions other than those tested. Also, it would be extremely difficult to locate enough units with nearly identical geographic and source strength characteristics and burn them under identical meteorological conditions in the course of one summer.

The second method would test the accuracy of the model over the wider range of conditions in which burning typically occurs. This approach would generally define the conditions where the model works well, where it does not, and suggest refinements to make the model an effective tool for routine use. However, greater variability would be expected in the resulting data, with small data sets representing each set of conditions. After discussing the two methods with Bonneville Power Administration (BPA) and USDA Forest Service (FS) personnel, the second method was unanimously chosen as the more desirable of the two for use in this study.

To thoroughly test the sensitivity of the model, we located units to test the following:

> Effects of Geographic Location: To test how the model reacts under different geographic conditions, all units were located in two drainages: one in the Sweet Home Ranger District and one in the Oakridge Ranger District. During the three years, 13 units were inventoried for fuel consumption to increase the chances of being able to monitor the burn and test the Tiered Smoke Air Resource System (TSARS) model.

Effects of Meteorology: To test the sensitivity of the model to meteorology alone, paired units in the same location with similar fuels were scheduled to burn on days that had different forecasted meteorology.

Effects of Downwind Distance: Units were chosen that had good monitoring sites located at varying distances downwind along the expected plum trajectory to test the ability of the model to predict concentrations over long distances (1-5 miles).

Active Plume vs. Smoldering Impacts: Emissions from slash burning occur both during the active phase, where a Gaussian type plume develops, and during the smoldering phase when an elevated plume does not form. To test the relative importance of both phases in impacting wildernesses and the accuracy with which the model predicts these impacts, one unit was chosen that was close to a wilderness and had monitoring sites available from which both the active plume and smoldering phase could be measured.

Clearcut vs. Partial Cut Impacts: A significant number of partial cut units are burned close to wildernesses. Since the fire characteristics for partial cut units are significantly different than those in clearcut units during the active burning phase, one partial cut unit and one clearcut unit were sought which were in the same location and could be monitored to compare the success of the model in predicting their impacts.

B. Emission Production

The Fire and Air Resource Management Project, USDA FS, Pacific Northwest Research Station, has provided fuel moisture, fuel consumption, and emission estimates for the four study burns accomplished during the study period. Emissions were not measured directly, but calculated using the existing emission production model (EPM) of the USDA FS.

Thirteen cable-yarded units which fit the criteria were selected for the study. Douglas fir (Pseudotsuga menziesii [Mirb.] Franco) and western hemlock (Tsuga heterophylla [Raf.] Sarg) comprised most of the woody residues on the sites. Although all thirteen sites were ground-inventoried for fuel consumption, only four units were burned and post-burn information collected.

1. Preburn fuel loading

Loadings of the large, woody fuels for each unit were estimated from a planar intersect inventory (Brown, 1974). The sampling density consisted of 50-foot line transects located at 80 semi-permanent points on a systematic grid. The small fuels were measured along the 50-transect lines established at each of the 18 permanent plots.

Duff depths (fermentation and humus forest floor layer) were determined from a destructive sampling technique after the burn. Sixteen metal and ceramic spikes called duff pins were inserted flush with the duff layer around each permanent plot. During the post burn inventory, each duff pin was located and a measurement was taken from the top of the pin to mineral soil. An average duff depth from determined for the unit.

2. Biomass consumption

The consumption of the large fuels were measured as diameter reduction (which was converted to volume reduction) from 40 randomly chosen logs 3 to 9 inches in diameter. The logs intersected fuel-inventory transect lines established at each of 18 permanent plots. Wires attached to numbered tags for log identification were tightly wrapped around the logs before the burning and cinched up after burning. The exposed wire lengths were measured to determine diameter reduction.

Twenty of the logs were raised 16 inches above the ground and placed on steel stands to determine the amount of diameter reduction which occurred during the flaming stage only. The steel stands would not allow the large, woody material to collapse with the surrounding fuel bed as it was consumed. Consequently, the diameter reduction measured from these logs would represent that which occurred during the flaming stage.

Duff consumption was measured as duff-depth reduction according to procedures adapted from Beaufait et al. (1977). Duff pins, which included eleven metal spikes and five ceramic strips were inserted flush with the duff layer around each permanent plot. A measurement was taken of the amount of duff removed by the fire from each of the duff pins. An average duff reduction was calculated for each unit.

The ceramic pins were coated with a temperature-sensitive paint which melts at the average temperature at which the flaming combustion period changes to smoldering. These special ceramic pins were used to measure how much of the duff was consumed during the flaming stage.

3. Independent variables

Several independent variables were measured for comparison of fuel moisture and fuel consumption models within EPM. Two fuel-moisture samples were obtained from the large and small ends of each log immediately before the burn. Average fuel moisture content for the small fuels was determined from 20 samples randomly collected from each unit. Average duff moisture content for each unit was calculated from 18 samples. The samples were collected from around each duff-consumption plot. If a distinct dry layer on top of a wet layer was found in the duff profile, a sample from each layer was collected and the dry layer depth was recorded. All samples were oven dried at 162° F for 96 hours.

Throughout this report, there is a mixture of English and metric units. This mixture is intentional. Foresters commonly use English units, but dispersion models commonly require metric inputs. Air resource managers use a mixture of units, which we attempt to duplicate here. The nearest representative weather station was used to monitor environmental conditions before burning each unit. Ignition of the four units occurred when the small fuels were dry enough to allow nearly complete combustion of the fine fuels and when wind direction and wind speeds were optional for downwind emissions evaluation. The daily weather was also used to predict large, woody fuel moisture content using a moisture algorithm called the ADJ-TH (Ottmar and Sandberg, 1985).

4. Fire behavior

Ocular estimation of percent area of the unit in the flaming and smoldering stage during each prescribed burn was made. Each unit was surveyed and a grid-scale map produced with noted reference markers for the ocular estimation. A trained observer recorded the ignition and die-down time of each fire strip ignited during the burns. The flaming stage was assumed to terminate when the flames were less than 1.5 feet high, and isolated pockets of slash continue to burn with no continuous flames. Strip widths were estimated and position sketched on the grid-map.

5. Emission Production Model Runs

The EPM was run separately from TSARS for testing. The model was run with four levels of data collection efforts and compared with measured values collected from the research plots. The data levels include:

1) Ranger District burn plan inputs. The burn plan would include an estimated, preburn fuel loading for the unit and fuel moisture and weather criteria under which the burn would occur to meet silviculture and site preparation objectives. The burn plans are usually developed during the winter season after consultation with other forest disciplines. Various techniques are used to determine preburn loading estimates which include office estimates, photo series cruises, or line intersect inventories.

2) Ranger District burn plan preburn loading estimates, predicted fuel moisture content from the nearest weather station operating on the district, and weather information on the day of the burn.

3) Preburn fuel loading values determined from a 4000 foot, line intersect inventory, measured fuel moisture content from an on site weather station, and weather information on the day of the burn.

4) Post burn fuel moisture and fuel consumption information and ocular estimation of burn area in the flaming and smoldering phase over time.

A comparison was made to provide error bounds associated with various levels of preburn and post burn fuel inventory and weather data collection efforts.

6. Tiered Smoke Air Resource System runs

The scientific version of TSARS was run with four levels of input data used to test the plume rise and centerline concentration calculations of SASEM. The model was first run with fuel loadings estimated by Oakridge Ranger District personnel and the weather and fuel moisture conditions prescribed in the burn plan. The second run included fuel loading estimates determined by the line intersect method (Brown, 1974), and weather and fuel moisture data on the day of the burn. The third run used measured fuel moisture values, measured preburn fuel loadings, and on-site weather information from the day of the burn. The final run included post burn fuel consumption information and on site weather data on the day of the burn.

C. Site Selection and Ambient Monitoring

Test sites downwind from the burn unit (normally three, Figure III-1) were selected with several factors in mind:

1) In line with, or bracketing, the anticipated path of the plume at a distance of 1 to 5 miles from the unit;

2) Easy accessibility for equipment and personnel;

3) Sufficient clearing to safely deploy the test balloons; and

4) Away from roads or other local conditions which could affect sampling.

To measure particulate and gaseous concentrations in the plume itself, the most cost-effective method was a helium-filled tethered balloon to which lightweight particle samplers were attached. The balloons, obtained from Atmospheric Instrumentation Research, Inc. (AIR), Boulder, Colorado, had the capability of carrying a 10 lb. payload up to 1 km above ground level.

Two of the three balloons were located in the plume to ensure an adequate number of samples. The position of the samplers within the plume was documented since the concentrations predicted by the model are for the center of the plume. This was done by operators on either side of the plume path using cameras, theodolites, and VCRs.

Particulate concentration was also monitored near the ground (5 ft.) to determine the impact from the smoldering phase of the fire. These samplers were located at sites D_1 downwind of the burn and U_1 upwind of the burn. Carbonaceous material analysis was

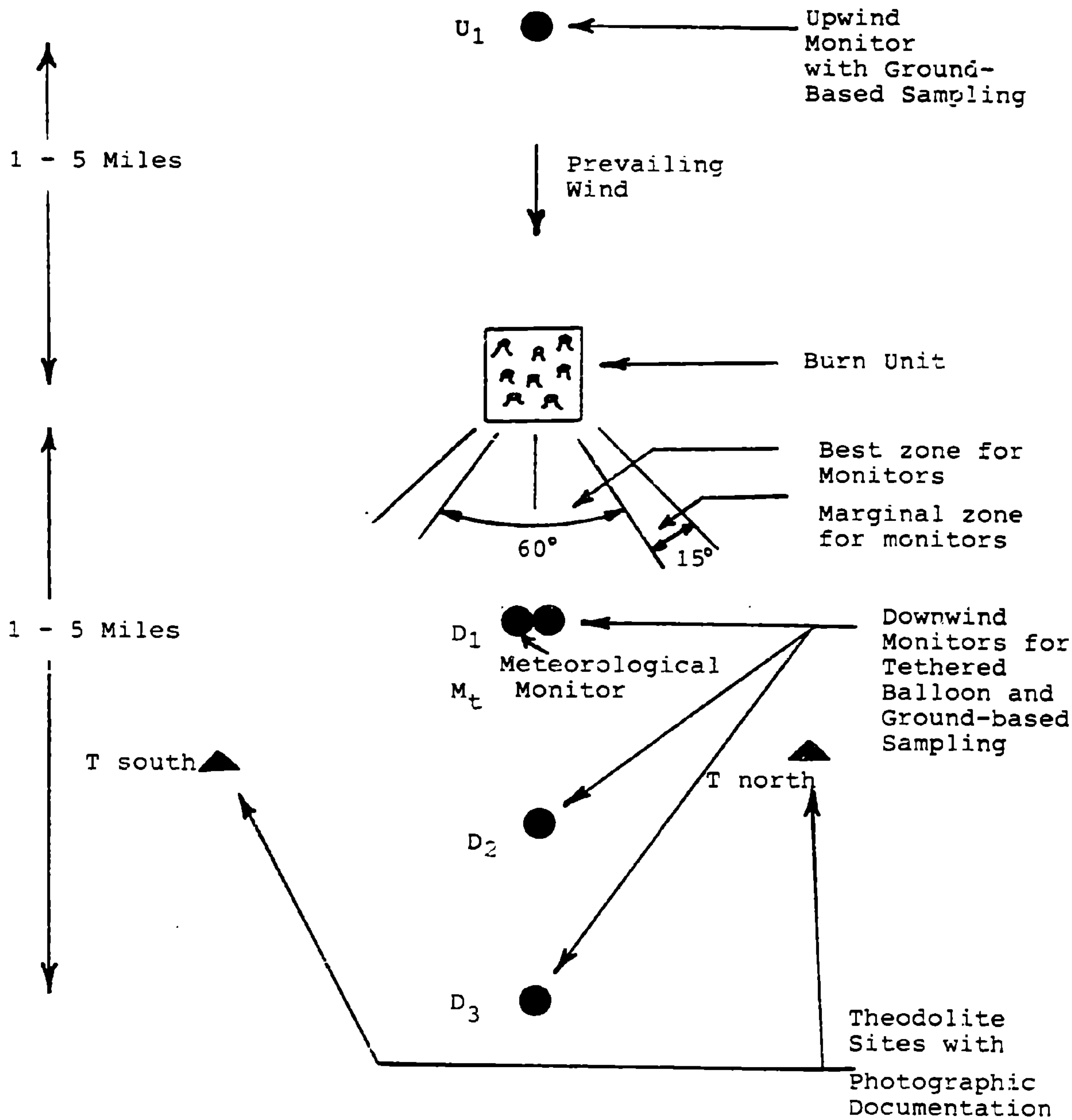


Figure III-1. General Configuration of Sites and Monitors performed on quartz fiber filters. Samples collected were stored at -10° C, to avoid loss of organics between sample collection and analysis. Representative samples were chemically analyzed. All other samples were archived for future reference and possible analysis. Gaseous samples were also taken, for methyl chloride analysis, at these plume- and ground-based sites. Methyl chloride is easy and relatively inexpensive to measure and may provide a tracer to help separate slash and field burning impacts.

Dispersion of pollutants is dependent not only on source characteristics, but also upon meteorological conditions of the atmosphere into which the pollutants are emitted. Factors such as wind speed and direction and atmospheric stability must be input to an air quality model before concentrations can be predicted. To use a model as a screening tool to determine whether or not a slash burn is likely to cause adverse impacts, routinely collected meteorological data would have to be used. This generally consists of the information available from the National Weather Service (NWS) and the USDA FS. However, the nearest NWS soundings were taken in Salem, Medford, and Seattle. For a model evaluation study such as this, site-specific information was needed to allocate the modeling errors and to determine if NWS data are adequate or if it must be extrapolated to mountainous areas.

Therefore, a tethered balloon equipped with a Tethersonde meteorological monitoring package was used as part of this study to determine atmospheric conditions affecting each plume. The Tethersonde and its accompanying Atmospheric Data Acquisition Systems (ADAS) were also obtained from AIR. While suspended below the balloon, the Tethersonde measured on wind speed and direction, wet and dry bulb temperature, and pressure as the balloon was deployed at various elevations.

The effect of slash burning on visibility is complex. Slash plumes may interfere with long range visibility either as plume blight or haze. The states of Washington and Oregon measure long range visibility from elevated sites but particulate matter is measured at ground-based sites. As a result, a plume may be observed to impact long-range visibility, but may not be measured at the lower elevations at which the particle samplers are located. Or a low-level plume may impact the particle sampler but not measured visibility. This may be one of the major causes of the poor correlation observed between visibility and particulate matter. This project provided the first opportunity in the Northwest to simultaneously measure particle concentrations in an elevated plume and the resultant visibility degradation from that concentration. A direct correlation between particle concentrations and plume blight can be developed for slash burning. This may be very important in determining whether individual burns should be restricted based on visibility considerations.

A summary of test sites follows (Table III-1):

> <u>RAWS Site M1</u>: A portable meteorological station measuring wind speed and direction along with temperature was located at an upwind ridge site. This meteorological data was transmitted via satellite and accessed with a computer.

Table III-1

SUMMARY OF MEASUREMENTS AND EQUIPMENT BY SITE

Measurements and/or Equipment	Upwind	Downwind				Theodolite	
	U_1	M_t	D_1	D_2	D_3	T_n	T_s
Particulates PM2.5							
Plume			X	X	X		
Ground	X		X				
Methylchloride							
Plume			X	X	X		
Ground	X		X				
Meteorological Information							
Plume		X					
Ground							
Camera and Theodolite						X	X
VCR							X
Cassette Tape Recorder						X	
Balloon & Winch							
$7m^3$			X	X	X		
$3.25m^3$		X					
Generator	X	X	X	X	X		
Nephelometer			X				
He Tanks		X	XX	XX	XX		
Gas Tanks	X	X	X	X	X		
Radio	X	X	X	X	X	X	
Technician 1	X	X	X	X	X	X	
Technician 2		X	X	X	X		
Op. Manager			X				

Upwind Site U1 (Figure III-1): The upwind site contained the ground-based monitors for particulate and methyl chloride. The ground-based units operated for 2 to 24 hours depending on burn conditions. A gasoline-powered generator powered the monitors.

Downwind Site D1 and Mt: This joint downwind site had numerous monitors. It was also the field command post. All communication from the test sites was directed to the operations manager at this site via two-way radio. The site had ground-based monitors for particulate and methyl chloride. It also had plume particulate and methyl chloride samplers. A nephelometer was operated at this site. The Tethersonde package monitored meteorology from the adjacent Mt site. Atmospheric conditions were to be measured from an hour before the burn to the time when there was only apparent smoldering.

All monitors were operated for 2 to 24 hours. The sampling time varied because of variability in plume height and duration of each phase of the burn.

Downwind Sites D2 and D3: These sites each contained an airborne particulate and methyl chloride sampler.

Theodolite Sites Tn and Ts: Each site had a theodolite and a camera and were operated for the duration of the visible plume or as determined by the operation manager at site D_1. One site had a VCR to help document visibility conditions. These sites were also used to advise balloon operators on positioning the balloons in the plume.

Slash Units: The slash units selected for the study are described in Table III-1.

D. Equipment Used for Ambient Monitoring

1. The helium-filled balloons (Figure III-2) were developed specifically by AIR to serve as a vehicle for air-borne instrumentation. The balloon skin is 1.5 mil urethane plastic and International Orange in color for easy observation. The 7.0 m^3 volume (21.6 feet long by 5.9 feet diameter) provided sufficient lift to support the approximate 10 lb payload of the instruments.

2. The electric powered winch used to raise and lower the balloon weighed 65 lbs and had a remote control which provided variable speeds for raising and lowering the balloon. Each winch was loaded with 1 km of line. Electric power to the winch was provided by a portable gasoline generator located downwind from the test site.

Helium Filled Balloon Characteristics:

Size: $7m^3$

Lift: 5 kg to 1 km in height

Color: Orange/Red

Payload: 4.5 kg or 10 lb. to 100m in winds < 6 m/s

Manufacturer: AIR Inc., Boulder, Colorado

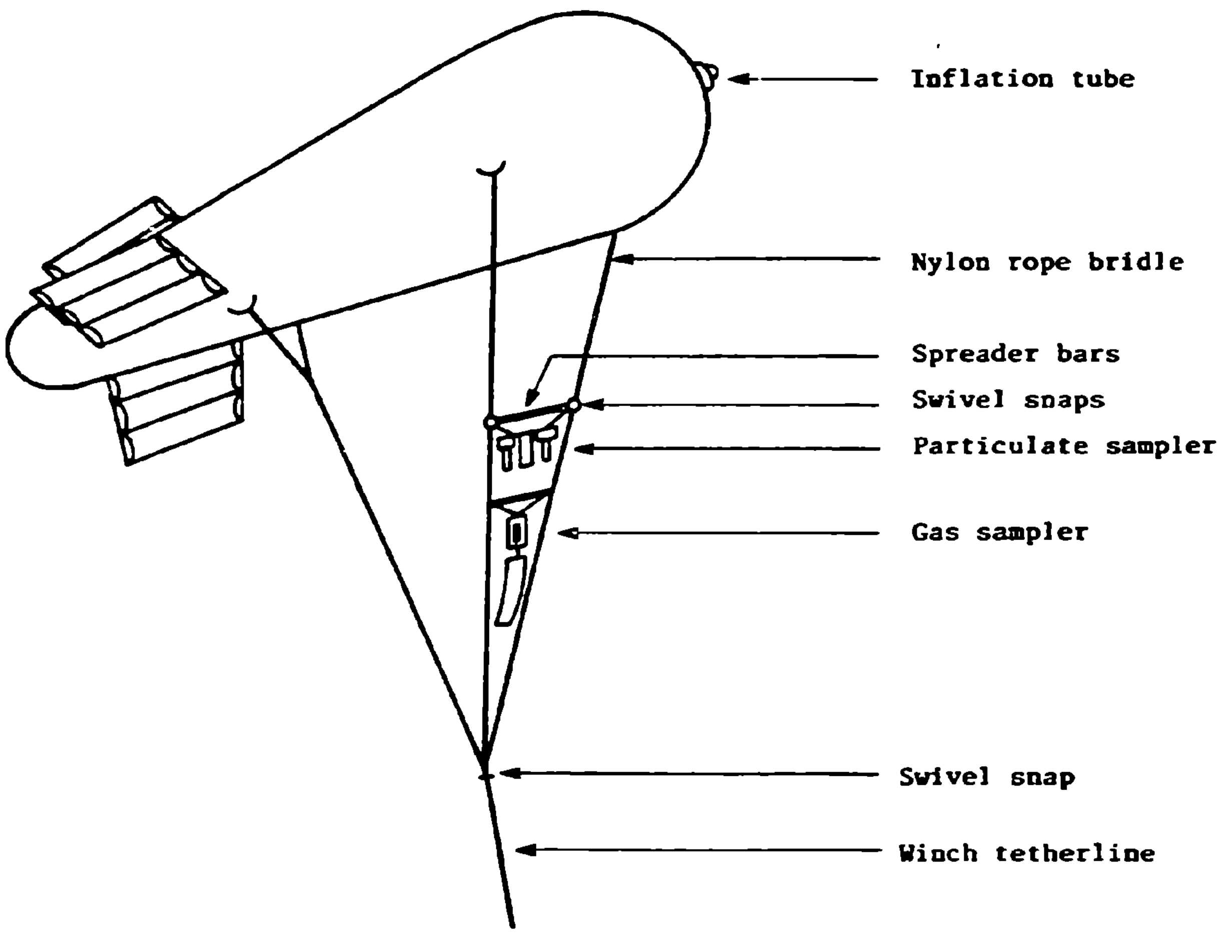


Figure III-2. Tethered Balloon Characteristics

3. Particulate samplers were designed in two styles: one to be air-borne by the balloon and another to be ground-based. There were three air-borne samplers, one for each of the downwind test sites. A ground based sampler was located at D1 and U1. All five samplers were powered by rechargeable batteries (Figure III-3).

The function of the sampler was to draw air through a stilling chamber at the top and direct the airflow at an impact plate covered with a thin film of grease. Particles larger than 2.5 μm were caught on the treated plate while the smaller particles were directed down a column and caught on a porous filter. The remaining air was exhausted. The volume of airflow was controlled by a small rotameter. Schematic of the particulate sampler is shown in Figure III-3.

Two types of filters were used in the samplers. One was made of Teflon,while the other was made of quartz fibers. The Teflon filters were carefully weighed at DRI before and after the test to determine the net increase of collected particulate material for a recorded period of time to determine particulate concentrations. These filters were analyzed by x-ray fluorescence to determine the elemental composition of the collected particulate material. An area in the center of the quartz filter was analyzed to determine the organic and elemental carbon composition of the collected particulate matter.

4. Methyl chloride was sampled on the ground and in the plume. The airborne package consisted of a battery-powered pump, batteries, rotameter, and a Teflon bag to contain the sample as shown in Figure III-4. The unit operated in the air for one to two hours before the sample was recovered. Once on the ground, the collected sample was transferred to a metal canister for shipment and analysis.

The 1987 ground-based gas sampler consisted of a trunk containing an air pump powered by a portable generator, a flow regulator, and a metal cylinder to contain the sample. These units were operated for at least 6 hours. The 1988 sampler consisted of a metal cylinder and regulated flow intake valve.

5. The Tethersonde package, designed to measure local atmospheric conditions was flown from a smaller balloon (3.5 m^3). it measured wind speed, wind direction, relative humidity, dry and wet bulb temperature, pressure, and elapsed time. This information was telemetered from the sensor package to the ground unit for processing in an ADAS. Data were processed and printed immediately as well as recorded on cassette tape for later processing.

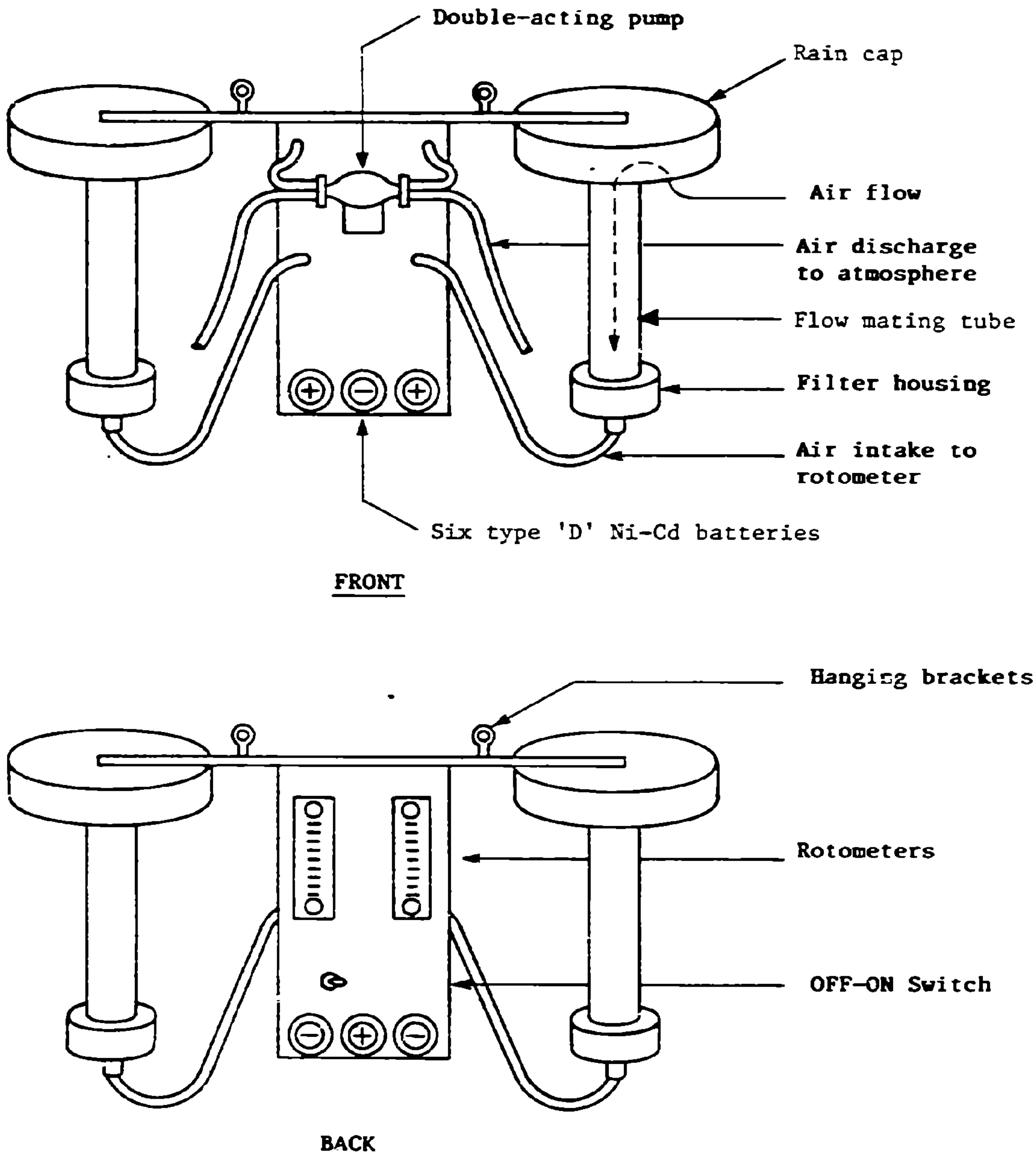


Figure III-3. Particulate Sampler

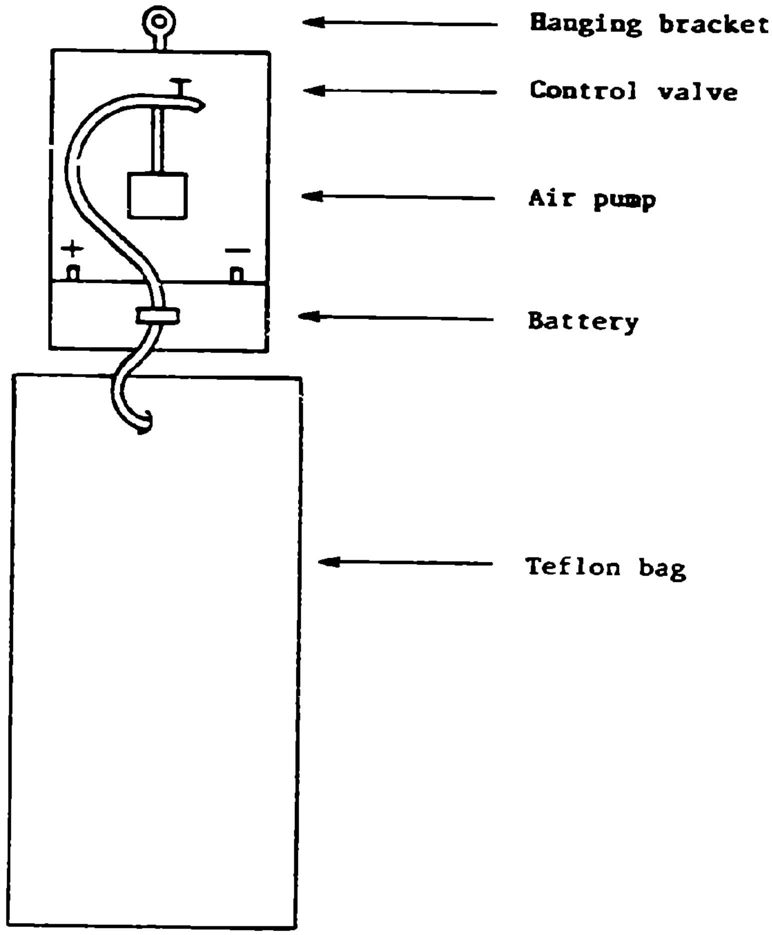


Figure III-4. Gas Sampler

6. A Nephelometer was located at site D1 to detect and estimate the fine particulate (smoke) impact at the ground level. The use of a nephelometer allowed measurement of continuous variations of fine particulate concentrations. The nephelometer output was recorded and stored for potential use.

E. 1986 Field Study

Early in the summer of 1986, six units were chosen for testing and prepared for source strength determination, monitoring equipment was assembled and technicians were trained. The model was run for each of the chosen units using typical summertime meteorology to predict likely plume behavior. This information was used to help choose the sampling sites and periods necessary to capture both the active plume and the smoldering phase emissions. Unfortunately, little time was available between the award of the contract and the burning season, so a specialized plume sampling system could not be designed; instead, ground-based monitors were to be used.

Although the monitoring program was ready, the burns could not take place during August due to extreme fire danger. Nor could the units be burned in September due to the extremely rainy conditions. It was felt that if the model were tested under October weather conditions, the results would not be valid under the summertime meteorological conditions during which burning is restricted by the states' visibility regulations. In October, the decision was made by all concerned parties to delay the monitoring until the summer of 1987.

F. 1987 Field Study

Between the 1986 and 1987 monitoring seasons, several of the units selected in 1986 had to be burned. Thus, of the original 6 units, only 3 remained unburned at the beginning of the 1987 season. Other candidate units were reviewed to determine whether there were adequate fuel loadings to sustain a steady burn rate, whether there were adequate downwind sampling sites, and to ascertain that there was no significant downwind elevated terrain to divert the plume before it could reach the samplers. Additional units were chosen, sampling locations selected, and fuel characteristics determined. Data were collected on two units during 1987, before the dry summer weather conditions caused a halt in all burning for the remainder of the summer. A brief summary of each of the two burns follows:

Burn 1 - Black Saddle No. 6

Burn day for Burn 1 was July 30, 1987. Loading of equipment began at 4:30 a.m. and all teams were on site by 5:30 a.m. A heavy fog filled the valley accompanied by a light mist. The scheduled 6:00 a.m. start time was put on hold until the valley cleared. This delay gave each team extra time to inflate their balloon and get all test equipment set up and ready. At 11:00 a.m., radio contact with the crews notified everyone that the burn had started. A controlled narrow border was burned around each unit before the main burn began. After the border was completed, three to five men walked across the downwind side of the unit with drip-torches lighting a strip. The number of lighters and the speed at which they walked controlled the speed of the burn. A USDA FS supervisor directed this procedure.

At approximately 11:30 a.m., the first sign of smoke appeared over the downwind test sites. No defined plume formed, but smoke started to drift down the valley. Test balloons and instrument packages were air-borne by 12:00 when smoke became dense but still no defined plume was formed. The two theodolite stations kept each balloon site informed as to whether they should raise or lower their balloon to stay in the thickest strata of smoke. Azimuth and vertical angles were recorded periodically for each balloon and photographs were taken to show conditions during the test. By 1:00 p.m., one-half of the unit had been burned and by 4:50 p.m., the entire unit was burned. At 5:00 p.m., all balloons were lowered and the test was complete. The methyl chloride samples were transferred to appropriate metal cylinders and the particulate filters and holders were put back in their protective "baggies" and all test equipment was dismantled. Crews reported back to headquarters and equipment was unloaded. The next day, all equipment was checked, cleaned, filled, or repaired as needed in preparation for the next burn.

Burn 2 - Black Saddle No. 5
Burn day for Burn 2 was August 10, 1987. Loading of equipment began at 3:30 a.m. and all teams were on site by 4:30 a.m. Balloons were inflated and equipment assembled between 6:00 and 7:00 a.m. Ignition of the unit began at 8:40 a.m. and balloons were raised and sampling begun by 10:00 a.m. Theodolite operators again kept the test sites informed as to whether they needed to raise or lower the balloons to keep them in the center of the dense smoke. By 11:00 a.m., the unit was completely ignited and tests were concluded at 12:00. Equipment was disassembled and all teams returned to headquarters to unload.

Further details of the field preparation, testing and results are included in our 1987 Progress Report (NAI, 1987).

G. 1988 Field Study

An additional four sites were selected for the 1988 monitoring season:

a. Squaw Slope 1
b. Squaw Slope 2
c. Dr. Jekyll 8
d. Dr. Jekyll 9

The selected sites were in the general vicinity of those tested in 1987, but required new balloon launch sites and observation points. After reviewing the 4 proposed burn sites, Squaw Slope 2 site was chosen for the first burn. Input from the Forest Rangers familiar with the area helped determine the best possible sampling sites relative to wind direction, distance from the burn, and cleared areas for safe balloon deployment.

On-site investigation of the area downwind from the proposed burn site was made to determine several optional balloon launch sites. The same basic plan of having three balloon launch sites downwind from the burn site was followed. An improved plan of selecting a number of possible launch sites for greater mobility was adopted this year. Theodolites were located on either side of the predicted path of the plume from the burn (Figure III-1), to verify balloon height and location, and to direct launch crews in the deployment of the balloons. One burn was accomplished, Squaw Slope 2, before the dry summer weather conditions prohibited further burning.

Squaw Slope 2

Burn day for Squaw Slope 2 was July 14, 1988. All crews arrived at their respective sites at 6:45 a.m. and prepared their equipment. Low-lying fog delayed ignition until 2:00 p.m. due to lack of visibility.

Smoke from the initial burn (i.e., a band of controlled burning around the borders of the burn unit), indicated the plume was off to one side of where it was originally predicted. The Operations Manager was able, by use of the two-way radios, to shift one balloon team to a more advantageous position. The smoke was high and only two of the three balloons were deployed. Wind velocity at the elevation of the smoke was near the limit for balloon deployment; and they were swept downwind so far that much was lost in elevation.

By 3:30 p.m., the smoke became dense enough to alert the balloon teams, which in turn had two of the balloons in the air by 4:00 p.m.. Due to the strong afternoon winds and the higher altitude of the denser smoke, sampling was terminated between 6:00 and 6:30 p.m.. Ground-based methylchloride sampling continued until 11:45 p.m.. A more detailed summary of the field test was included in our status reports (NAI, 1987; and G2E, 1988).

IV. RESULTS

Thirteen Douglas-fir and western hemlock units were preburn-inventoried for fuel consumption during 1986-1988. Only four of these units were burned and post-inventoried. Table IV-1 displays preburn fuel information and fuel consumption data from the four units burned during 1987 and 1988 field studies.

A. Measured Preburn Fuel Loading

Woody fuel loading and duff depths varied little between units. Loadings of woody fuels ranged from 43 tons per acre to 38 tons per acre (Table IV-1). The average duff depth ranged from 1.2 inches to nearly 3 inches.

The woody fuel loading values estimated by Oakridge district personnel ranged from 51 tons per acre to 38 tons per acre (Table IV-2). The average duff depth was estimated at between 1 and 2 inches in depth.

B. Measured Fuel Moisture

The four units on the Oakridge Ranger District were burned during mid-July and early August. The average unit fuel moisture measured for the large, woody material ranged from 31 percent to 23 percent (Table IV-1). The 23 percent was measured on the unit burned in August which was dominated by western red cedar residues. Western red cedar tends to have a lower fuel moisture than Douglas fir and western hemlock woody fuels.

The measured moisture of the duff ranged from over 250 percent in the lower, wet layer to 15 percent in the upper dry layer (Table IV-1). This is a very typical duff moisture range for July and August in the Pacific Northwest.

C. Measured Fuel Consumption

The diameter reduction of the large, woody fuels where consumption data could be measured ranged from 2.00 inches (10.4 tons per acre) on the Black Saddle 6 unit, which was burned early in mid-July, to 3.61 inches (19.3 tons per acre) on the Saddle Sore 3 unit burned in August (Table IV-3). Flaming fuel consumption of the large woody fuels ranged from 2.1 tons per acre on the Black Saddle 6 unit to 17.4 tons/acre on the Saddle Sore 3 unit.

Duff consumption varied from a reduction of 1.22 inches (22.8 tons per acre) to 0.71 inches (13.2 tons per acre) (Table IV-3). Flaming duff consumption ranged from 9.9 tons per acre to 15.5 tons per acre.

Table IV-1. Unit and measured fuel data summary for test burns.

Unit	Date burned	Elevation	Area	Preburn Fuels: Small fuels (0-3")	Preburn Fuels: Large fuels (>3")	Duff	Fuel Moisture: (0-1/4")	Fuel Moisture: Small fuels (1/4-1")	Fuel Moisture: (1-3")	Fuel Moisture: Large fuels (>3")	upper duff	Lower duff
		ft	acres	t/ac	t/ac	(")	-------	-------	percent	-------	-------	-------
Black Saddle #6	7/30/87	3400	35	13.3	25.1	1.22	--1/	17	18	28	15	191
Black Saddle #5	8/10/87	3200	21	16.3	24.3	2.13	--	11	19	30	21	212
Saddle Sore #3	8/12/87	3400	23	11.8	31.2	2.05	--	12	15	23	15	258
Squaw Slope #2	7/14/88	3600	39	11.4	30.1	2.99	--	7	22	31	36	314

1/ Dashes (--) indicate no data were collected.

Table IV-2. Unit and fuel data summary for test burns from burn-plan prescription.

Unit	Date burned	Elevation	Area	Preburn Fuels: Small fuels (0-3")	Preburn Fuels: Large fuels (>3")	Preburn Fuels: Duff	Fuel Moisture: (0-1/4")	Fuel Moisture: Small fuels (1/4-1")	Fuel Moisture: (1-3")	Fuel Moisture: Large fuels (>3")	Fuel Moisture: upper duff	Fuel Moisture: Lower duff
		ft	acres	t/ac	t/ac	(")	percent					
Black Saddle #6	July-Aug	3400	35	19.5	19.0	1.00	--1/	6	--	32	25	--
Black Saddle #5	July-Aug	3200	21	18.0	24.0	1.50	--	6	7	32	25	--
Saddle Sore #3	July-Aug	3400	23	11.0	31.0	1.00	--	6	7	32	25	--
Squaw Slope #2	July-Aug	3600	39	29.0	22.0	2.00	--	6	7	32	25	--

1/ Dashes (--) indicate no data were collected.

Table IV-3. Measured fuel consumption summary for test burns.

Unit	Small fuel consumption	Diameter reduction	Large Wood Fuel Consumption: Fuel consumption	Large Wood Fuel Consumption: Flaming fuel consumption	Large Wood Fuel Consumption: Smoldering fuel consumption	Duff Consumption: Duff depth reduction	Duff Consumption: Duff consumption	Duff Consumption: Flaming duff consumption	Duff Consumption: Smoldering duff consumption
		(inches)	(tons/acre)	(tons/acre)	(tons/acre)	(inches)	(tons/acre)	(tons/acre)	(tons/acre)
Black Saddle #6	13.3	2.00	10.4	2.1	8.3	0.71	13.2	9.9	3.3
Black Saddle #5	16.3	2.69	13.6	10.4	3.2	1.22	22.8	15.6	7.3
Saddle Sore #3	11.8	3.61	19.3	17.4	1.9	1.14	21.3	12.8	8.6
Squaw Slope #2	11.4	2.37	18.3	16.0	2.3	0.91	16.9	11.7	5.2

D. **Emissions Production Model (EPM) Predicted Fuel Consumption and Total Particulate Matter Emissions Using EPM and Burn Plan Inputs**

The Oakridge Ranger District developed a burn plan for each of the units to be burned. The district felt that the prescribed burn would meet their objectives if the unit was burned with a large, woody fuel moisture close to 32 percent. Using this fuel moisture content and the preburn loading estimates made by district personnel, woody fuel consumption predictions ranged from 27.9 tons per acre on Black Saddle 5 to 24.5 tons per acre on Black Saddle 6 (Table IV-4). The predicted duff consumption ranged from 16.4 tons per acre to 13.2 tons per acre.

The total particulate matter emissions predicted using the burn plan inputs ranged from 26,340 kg for Squaw Slope 2 to 12,383 kg for Black Saddle 5 (Table IV-5).

E. **Predicted Fuel Moisture**

Fuel moisture contents were predicted using the ADJ-Th fuel moisture model (Ottmar and Sandberg, 1985) and weather information from the Oakridge Ranger District weather station. The predicted fuel moisture contents for the large, woody fuels ranged from 30 percent on Squaw Slope 2 to 26 percent on Saddle Sore 3 (Table IV-6).

F. **EPM Predicted Fuel Consumption and Total Particulate Matter Emissions Using Predicted Fuel Moisture and Measured Fuel Loading Inputs**

EPM was run to predict fuel consumption using predicted fuel moisture and measured fuel loading input values. The fuel consumption ranged from a low of 30.7 tons per acre on Black Saddle 6 to 61.3 tons per acre on Saddle sore 3 (Table IV-6).

The emissions predicted to be generated using predicted fuel moisture values and measured fuel loading inputs ranged from 35,982 kg for Squaw Slope 2 to 13,685 kg for Black Saddle 6 (Table IV-7).

G. **EPM Predicted Fuel Consumption and Total Particulate Matter Emissions Using Measured Fuel Moisture and Measured Fuel Loading Inputs**

EPM predicted the total fuel consumed for the units using measured fuel moisture values and measured fuel loading inputs. The fuel consumption ranged from 30.8 tons per acre on Black Saddle 6 to 62.9 tons per acre on Saddle Sore 3 (Table IV-8).

The emissions predicted to be produced ranged from 34,585 kg from Squaw Slope 2 to 13,701 kg from Black Saddle 6 (Table IV-9).

Table IV-4. Predicted fuel consumption using TSARS, predicted fuel moisture, and burn-plan prescriptions.

Unit	Fuel moisture ADJ-TH	Small fuel consumption			Large fuel consumption			Duff consumption		
		flame	smold	total	flame	smold	total	flame	smold	total
	percent	-----tons/acre-----			-----tons/acre-----			-----tons/acre-----		
Black Saddle #6	32	14.9	0.0	14.9	9.5	0.2	9.7	12.4	3.0	15.4
Black Saddle #5	32	14.9	0.0	14.9	12.7	0.3	13.0	12.4	5.5	17.9
Saddle Sore #3	32	11.8	0.0	11.8	11.2	4.0	15.2	11.0	2.2	13.2
Squaw Slope #2	32	14.9	0.0	14.9	10.7	0.3	11.0	12.4	4.0	16.4

Table IV-5. Predicted maximum particulate matter (PM) emissions and maximum plume height using TSARS and burn plan prescriptions.

Unit	PM Emissions convec	PM Emissions non-convec	PM Emissions total	Maximum plume height	Maximum centerline concentrations D1	D2	D3	Maximum ground level concentration
	--------kilograms--------			meters	micrograms/meter3			micrograms/meter3
Black Saddle #6	14796	0	14796	387	1571	1401	1304	17
Black Saddle #5	10545	1838	12383	967	1531	1230	1060	141
Saddle Sore #3	12123	897	13020	636	469	424	292	212
Squaw Slope #2	23846	2494	26340	1084	1032	711	464	140

Table IV-6. Predicted fuel consumption using TSARS, predicted fuel moisture, and measured fuel loading on the day of the burn.

Unit	Fuel moisture ADJ-TH	Small fuel consumption			Large fuel consumption			Duff consumption		
		flame	smold	total	flame	smold	total	flame	smold	total
	percent	-----tons/acre-----			-----tond/acre-----			-----tons/acre-----		
Black Saddle #6	29	9.7	0.5	10.2	6.4	0.8	7.2	9.4	3.9	13.3
Black Saddle #5	27	14.6	0.0	14.6	15.3	0.4	15.7	13.5	13.3	26.8
Saddle Sore #3	26	12.2	0.0	12.2	15.2	3.7	18.9	12.5	17.7	30.2
Squaw Slope #2	30	12.7	0.0	12.7	13.8	2.5	16.3	12.0	15.4	27.4

Table IV-7. Predicted maximum particulate matter (PM) emissions and maximum plume height using TSARS, predicted fuel moisture, and measured fuel loading on the day of the burn.

Unit	PM Emissions convec	PM Emissions non-convec	PM Emissions total	Maximum plume height	Maximum centerline concentrations D1	D2	D3	Maximum ground level concentration
	--------kilograms--------			meters	grams/meter3			grams/meter3
Black Saddle #6	11621	2064	13685	239	1332	1116	1008	235
Black Saddle #5	11821	4210	16031	833	1664	1303	1113	193
Saddle Sore #3	14303	5753	20056	656	625	564	389	312
Squaw Slope #2	26695	9287	35982	871	1061	727	469	236

Table IV-8. Predicted fuel consumptions using TSARS, measured fuel loading and measured fuel moisture on the day of the burn.

Unit	Fuel moisture Measured	Small fuel consumption flame	Small fuel consumption smold	Small fuel consumption total	Large fuel consumption flame	Large fuel consumption smold	Large fuel consumption total	Duff consumption flame	Duff consumption smold	Duff consumption total
	percent	-----tons/acre-----			-----tons/acre-----			-----tons/acre-----		
Black Saddle #6	28	9.7	0.5	10.2	6.4	0.8	7.2	9.5	3.9	13.4
Black Saddle #5	30	14.6	0.0	14.6	13.5	0.4	13.9	12.6	12.2	24.8
Saddle Sore #3	23	12.2	0.0	12.2	15.9	3.8	19.7	12.7	18.3	31.0
Squaw Slope #2	31	12.7	0.0	12.7	12.9	2.4	15.3	11.7	14.7	26.4

Table IV-9. Predicted maximum particulate matter (PM) emissions and maximum plume height using TSARS, measured fuel loading, and fuel moisture on the day of the burn.

Unit	PM Emissions			Maximum plume height	Maximum centerline concentrations			Maximum ground level concentration
	convec	non-convec	total		D1	D2	D3	
	--------kilograms--------			meters	micrograms/meter3			micrograms/meter3
Black Saddle #6	11637	2064	13701	240	1334	1117	1009	236
Black Saddle #5	11050	3896	14946	797	1580	1229	1046	188
Saddle Sore #3	14669	5915	20584	666	641	579	399	315
Squaw Slope #2	25686	8898	34584	920	1082	745	482	216

H. EPM Predicted Total Particulate Matter Emissions Using Measured Fuel Consumption Inputs

The most accurate prediction of total particulate emissions from the prescribed fires monitored would be using actual measured fuel consumption input values. Squaw Slope 2 was predicted to produce the largest amount of emissions, which was 32,993 kg (Table IV-10). This would be expected, since Squaw Slope 2 had the largest number of acres and the largest amount of fuel consumed.

The smallest amount of emissions predicted to be produced was from Black Saddle 5. The total emissions produced was predicted at 15,726 kg. Again, this would be expected, since Black Saddle 5 had the least number of acres, although it had the most fuel consumed on a per acre basis.

I. Predicted Maximum Plume Height, Centerline Emissions Concentrations and Ground Level Concentrations From TSARS Using the Four Levels of Data Input

The maximum plume height was predicted by the Tiered Smoke Air Resource System (TSARS) for each of the four burns (Figures IV-1 through IV-8). Just as with EPM, four different estimations were calculated for each burn based on the four levels of data input. The weather input data used for the model runs are displayed in Table IV-11. The measured values are displayed in Table IV-12.

The highest plume height predicted was for Squaw Slope 2 using the burn plan prescription input values (Tables IV-5, 7, 9 & 10). The maximum plume height was 1146 meters above the unit. The lowest plume height predicted was for Black Saddle 6 using predicted fuel moisture and measured fuel loadings with weather data from the day of the burn. The plume height was only 239 meters above the unit. This is what we would have expected, since the dispersion day was only fair with light winds.

The highest centerline concentration predicted during the study was for the Black Saddle 5 (1865 micrograms per cubic meter) at receptor D1 using measured fuel consumption inputs (Tables IV-5, 7, 9, & 10). The lowest centerline concentration was predicted for receptor site D3 during the Saddle Sore 3 burn (378 micrograms per cubic meters). This would seem correct since the dispersion day was excellent and the wind direction was moving the plume centerline away from the receptor.

The maximum ground level concentration predicted from TSARS was 315 micrograms per cubic meter for Saddle Sore 3 using the measured fuel moisture, fuel loading and weather variables on the day of the burn (Tables IV-5, 7, 9, & 10). The minimum ground level concentration was 18 micrograms per cubic meter. This was for Black Saddle 6, using the burn plan prescription input values.

Table IV-10. Predicted particulate matter (PM) emissions and plume height using TSARS and measured fuel consumption.

Unit	PM Emissions			Maximum plume height	Maximum centerline concentrations			Maximum ground level concentration
	convec	non-convec	total		D1	D2	D3	
	--------kilograms--------			meters	micrograms/meter3			micrograms/meter3
Black Saddle #6	16177	968	17145	377	1763	1566	1455	20.7
Black Saddle #5	12392	3334	15726	1048	1865	1521	1322	15.4
Saddle Sore #3	15128	3057	18185	668	616	556	383	285.2
Squaw Slope #2	29207	3786	32993	1131	1280	887	580	168.2

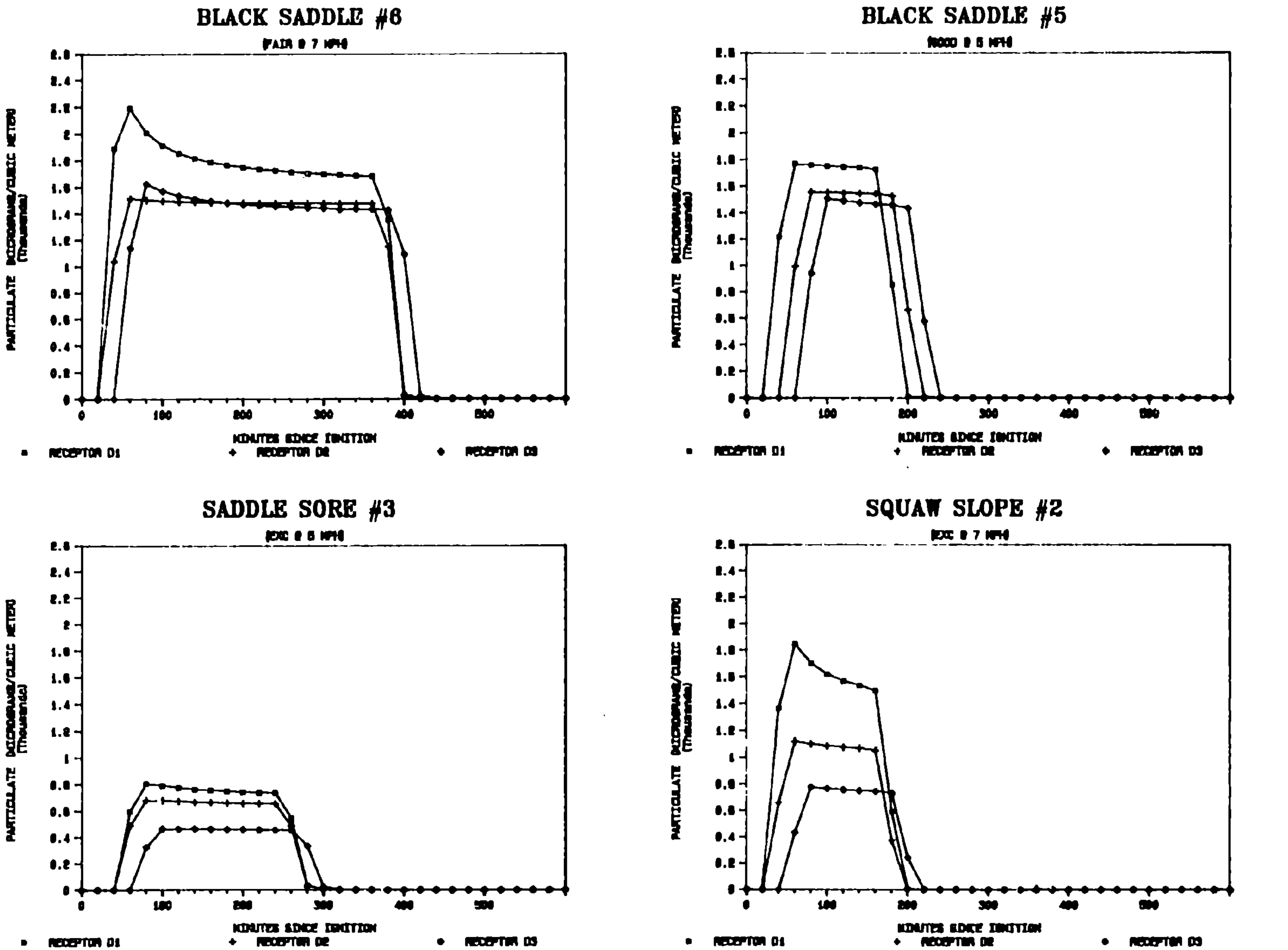


Figure IV-1. Predicted centerline concentrations using TSARS and burn plan input values for sites D1-D3.

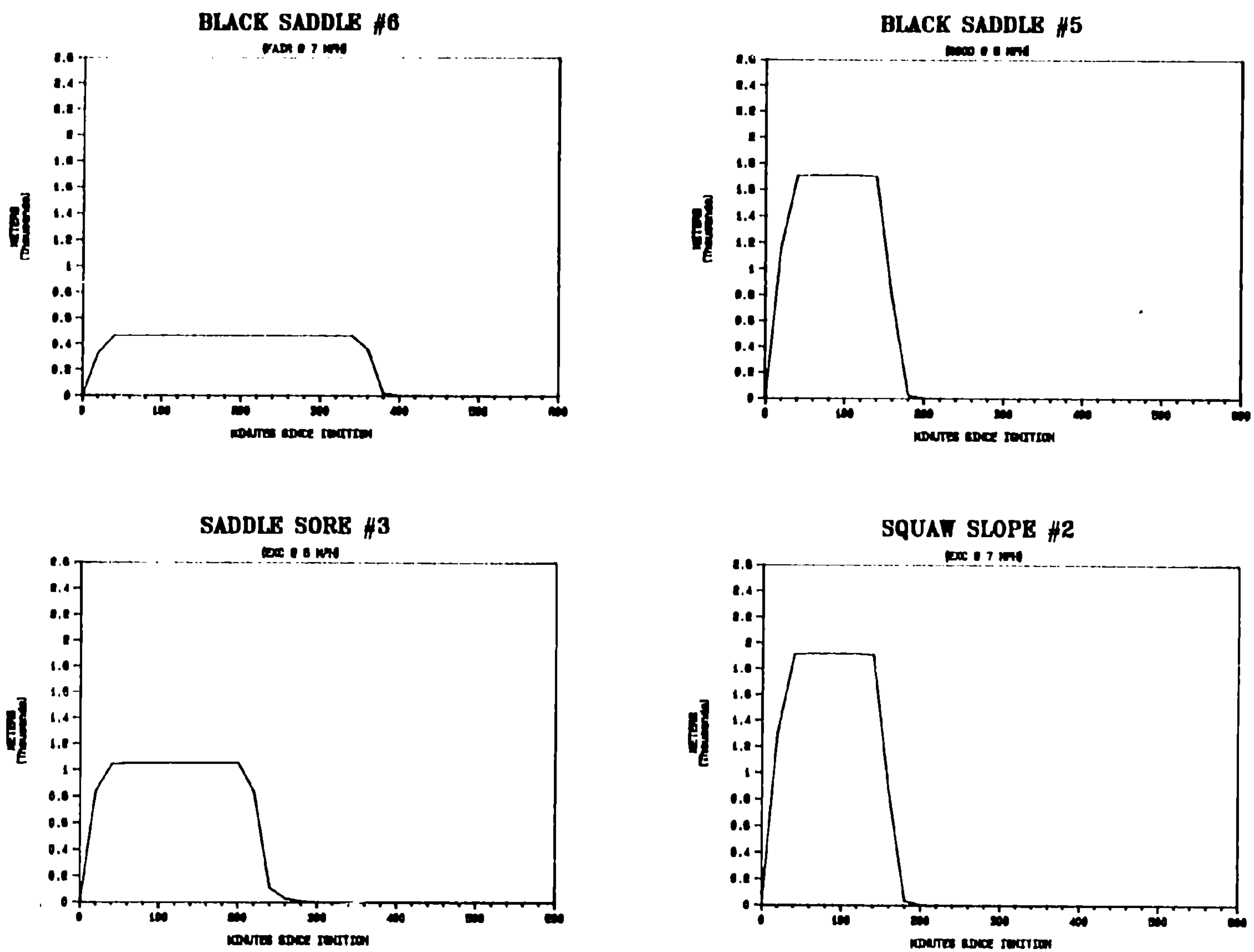


Figure IV-2. Predicted plume height using TSARS and burn plan input values.

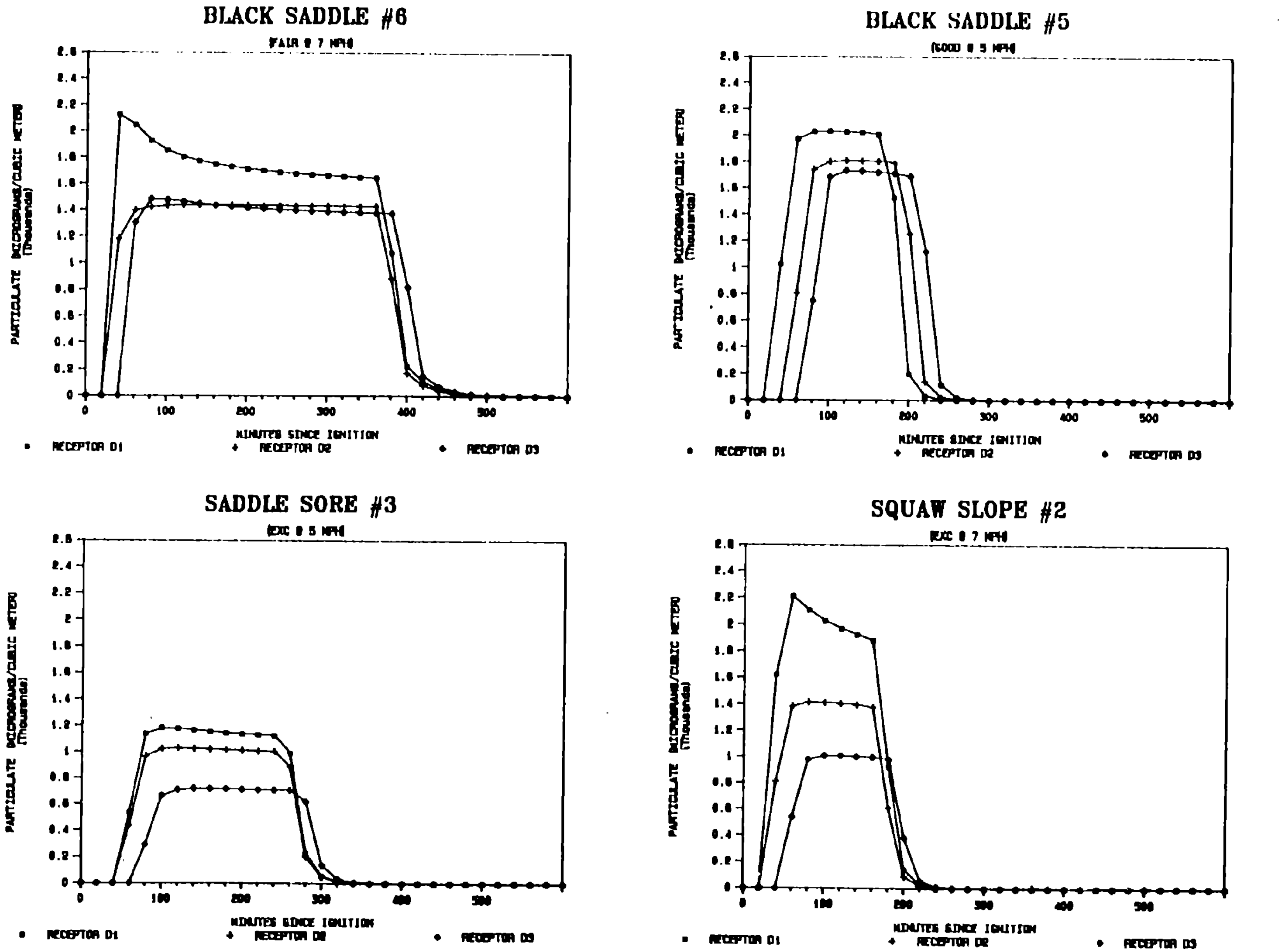


Figure IV-3. Predicted centerline concentrations using TSARS, measured fuel loading, and predicted fuel moisture input values for receptor sites D1-D3.

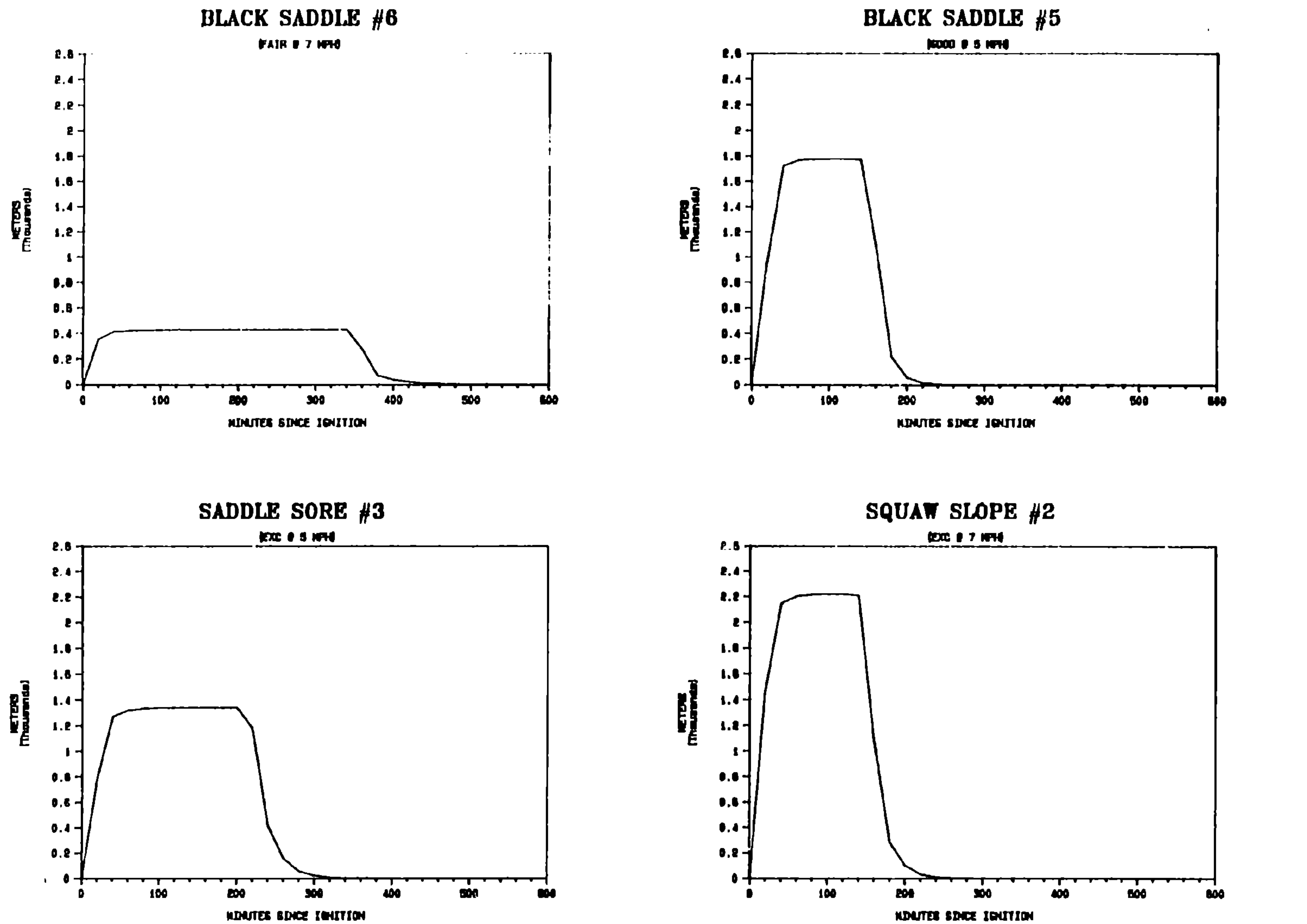


Figure IV-4. Predicted plume height using TSARS, measured fuel loading, and predicted fuel moisture input values

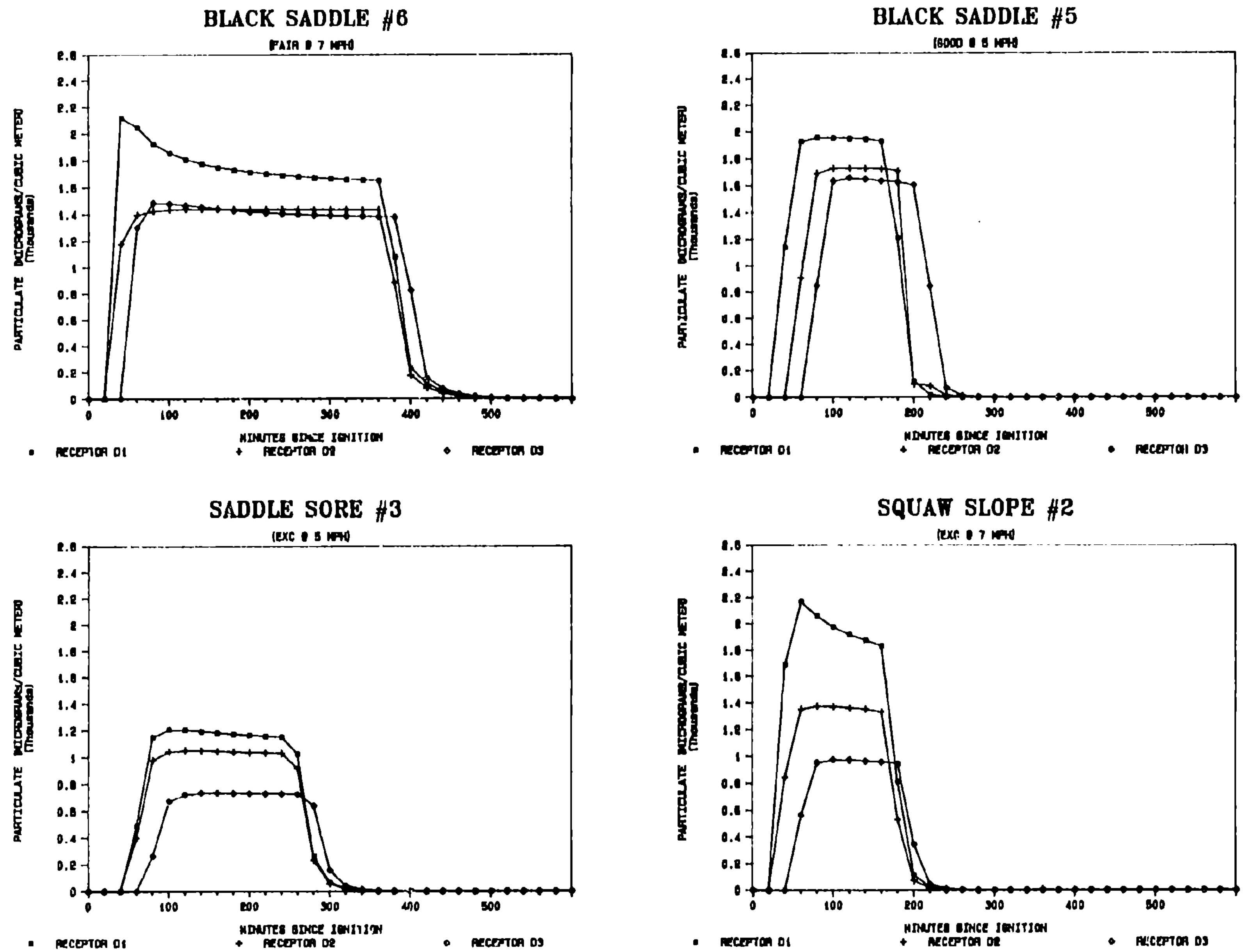


Figure IV-5. Predicted centerline concentrations using TSARS, measured fuel loading, and measured fuel moisture input values for receptor sites D1-D3.

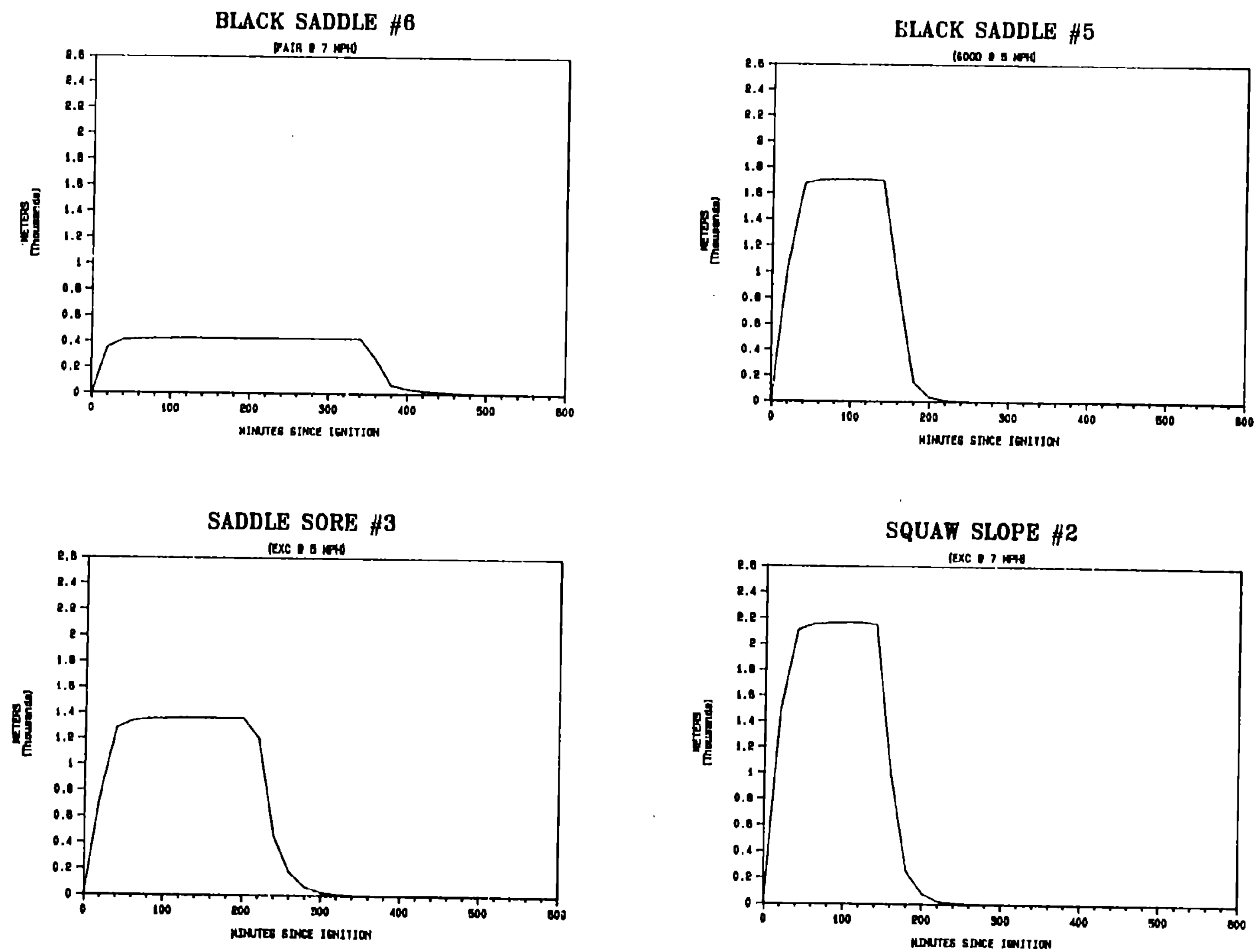


Figure IV-6. Predicted plume height using TSARS, measured fuel loading, and measured fuel moisture input values.

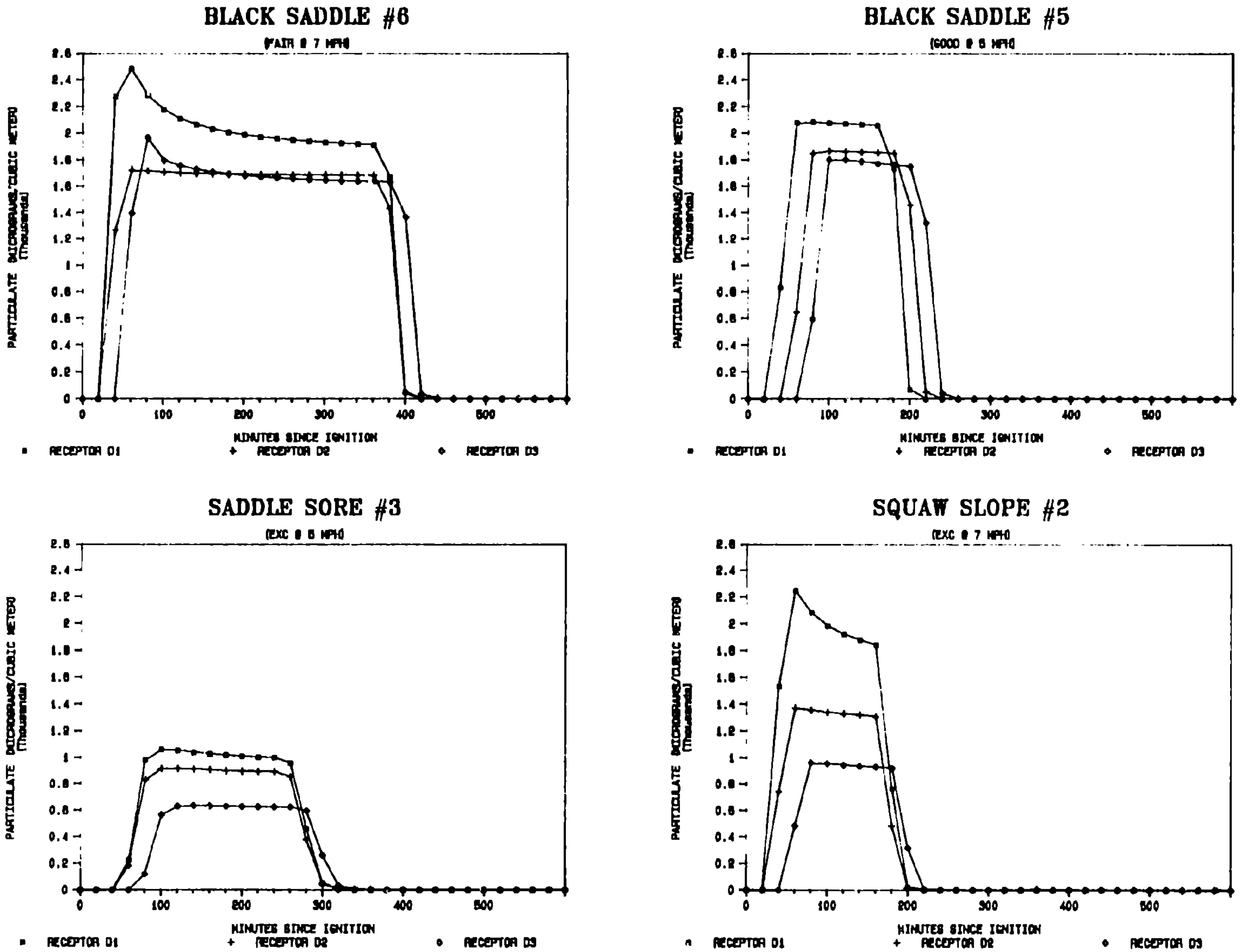


Figure IV-7. Predicted centerline concentrations using TSARS and measured fuel consumption input values for receptor sites D1-D3.

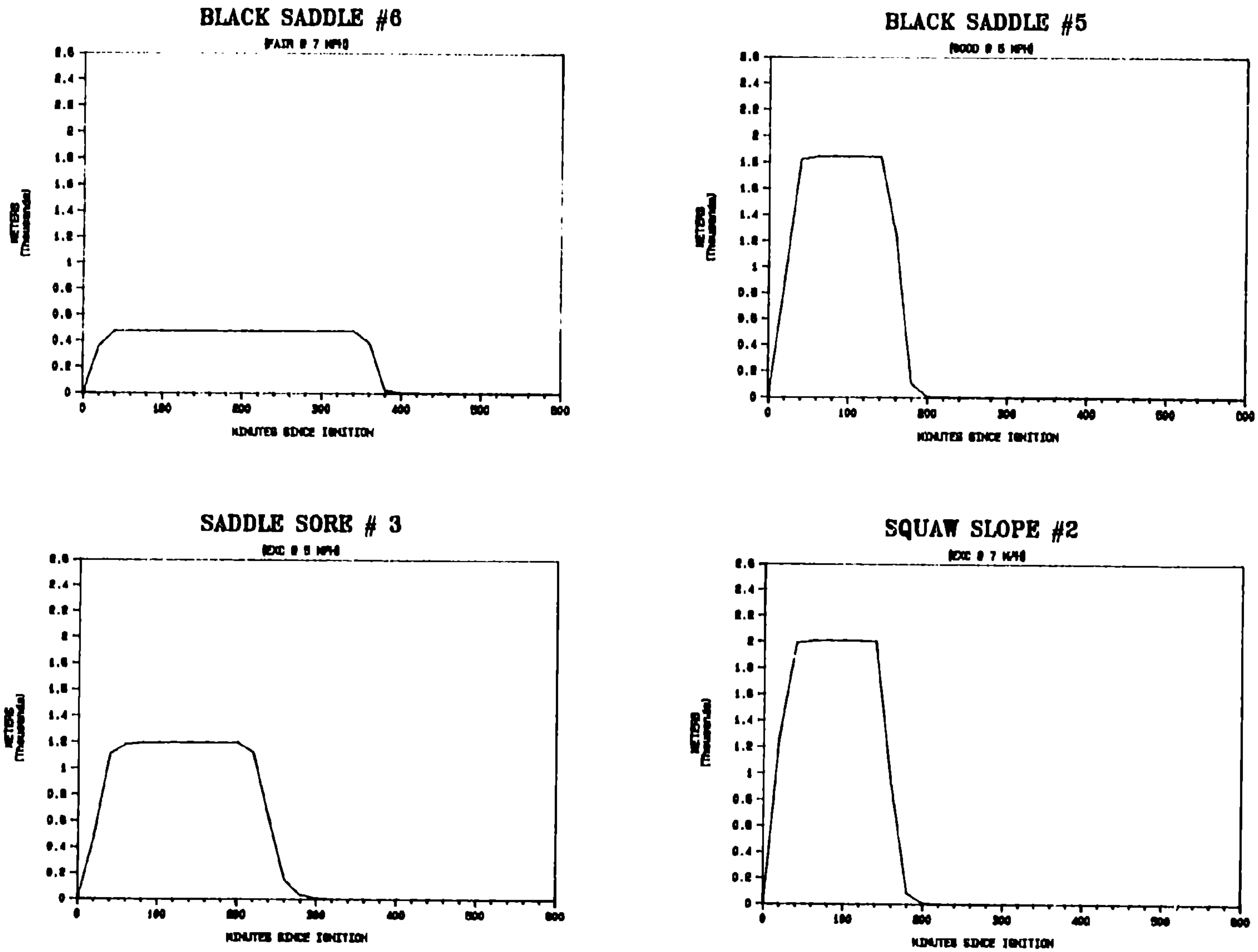


Figure IV-8. Predicted plume height using TSARS and measured fuel consumption input values.

Table IV-11. Measured weather data and receptor information on the day of the burn.

Unit	Average wind speed	Average wind direction	Dispersion day	Mixing height	Distance to receptor D1	D2	D3
	miles/hour			meters	----miles---		
Black Saddle #8	6-9	W	Fair	1372	2.8	4.4	5.6
Black Saddle #5	3-6	NW	Good	1372	3.2	4.8	6.0
Saddle Sore #3	3-6	N	Excellant	1372	4.0	4.4	6.2
Squaw Slope #2	5-10	NW	Excellant	1372	2.8	4.1	6.2

Table IV-12. Measured maximum plume height and downwind emissions. concentrations.

Unit	Maximum plume height	Maximum centerline concentrations D1	D2	D3	Maximum ground level concentration D1		
	meters	ug/meter3			ug/meter3		
Black Saddle #6	653	110	83	34	34	--	--
Black Saddle #5	--	136	108	115	127	--	--
Saddle Sore #3	--	--	--	--	--	--	--
Squaw Slope #2	--	--	--	--	--	--	--

J. Ambient Measurement Results

The ambient data collected during the four prescribed burn samples are reported in this Section. The measured weather data and ambient sampling site information for the four tests are listed in Table IV-11. Adverse field conditions allowed only in-plume particulate sampling for the first two tests. The measured maximum plume height and average downwind particulate concentrations for the two tests at Black Saddle 6 and Black Saddle 5 are listed in Table IV-12. For Black Saddle 6, enough measurements were made to plot the plume height against the time of day (Figure IV-9).

Upwind particulate concentrations of 34 $\mu g/m^3$ was measured for the Black Saddle #6 test. For the second test at Black Saddle 5, upwind concentrations of 13 $\mu g/m^3$ was measured. Details of the particulate concentrations by test unit and sampling site are in Table IV-13.

Ambient gaseous samples were collected and analyzed for three tests. Tables IV-14 & 15 and Figure IV-10 show the methyl chloride concentrations for the three tests. Methyl chloride and other gaseous concentrations vary from site D_1 to D_3 as anticipated. In-plume or near-plume concentrations were found to be much above background concentrations.

Results of the x-ray flourescences (XRF) and Carbon analysis on the filters from Black Saddle 5 and Black Saddle 6 are included in Appendix A. In general the filters were lightly loaded. In spite of the longer XRF analysis counting protocol, most of the elements were below their uncertainties. In plume samples were more than 50 percent carbon, as expected. These samples can be compared with other source samples collected for prescribed burning.

Figure IV-9. Plume height vs. time of day, Black Saddle 6 burn.

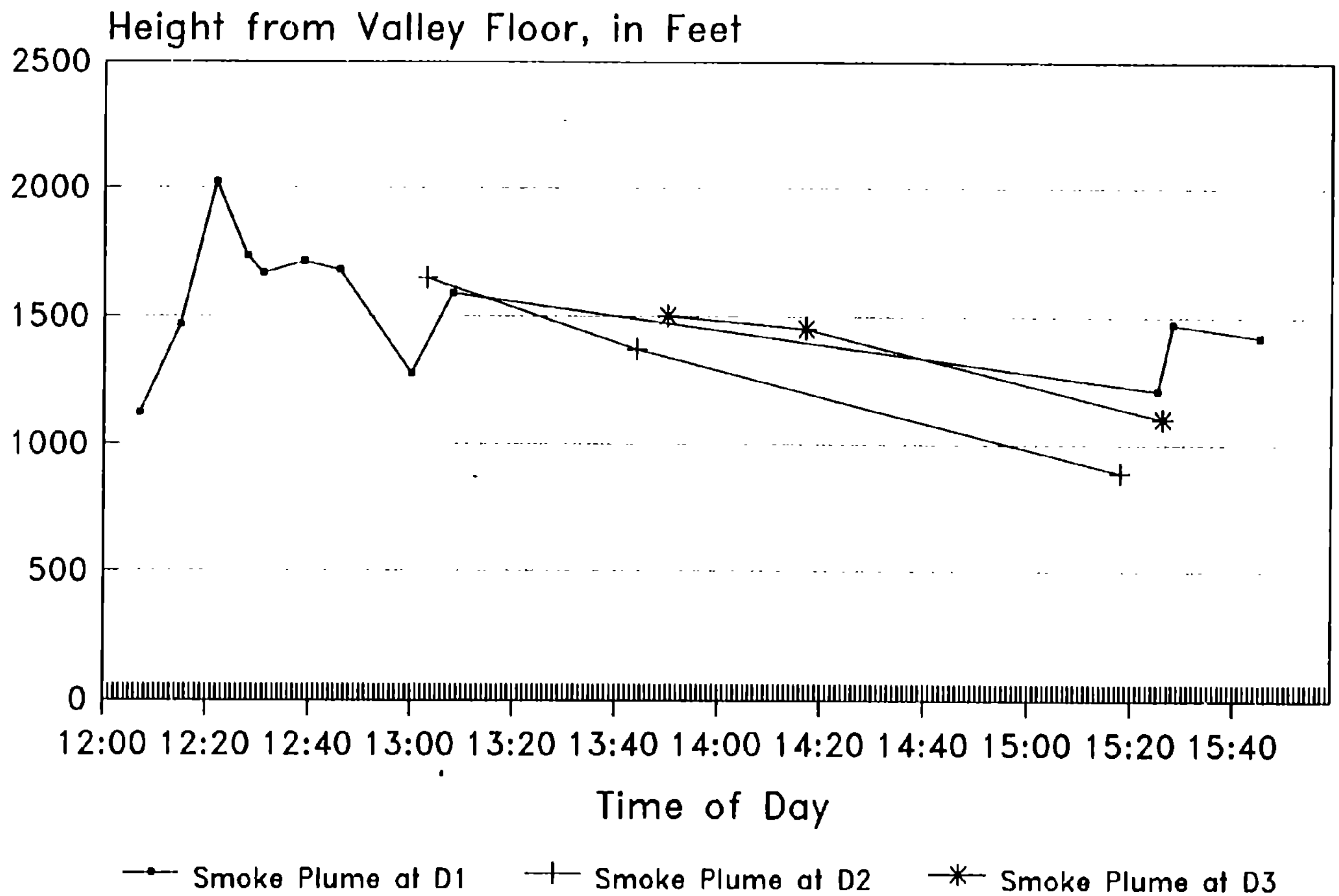


Table IV-13. Particulate Concentration for the two tests.

Date	Unit I.D.	Site I.D.	Time (Minutes)	Concen. (ug/m^3)
7/30/87	B.S.6	U1G	375	34
7/30/87	B.S.6	U1G	614	34*
7/30/87	B.S.6	D1G	422	58
7/30/87	B.S.6	D1G	693	23*
7/30/87	B.S.6	D1P	248	110
7/30/87	B.S.6	D2P	308	83
7/30/87	B.S.6	D3P	308	34
8/10/87	B.S.5	U1G	475	9
8/10/87	B.S.5	U1G	180	16 *
8/10/87	B.S.5	D1G	310	127
8/10/87	B.S.5	D1G	335	10 *
8/10/87	B.S.5	D1P	125	136
8/10/87	B.S.5	D2P	131	108
8/10/87	B.S.5	D3P	110	115

* Samples collected during "smoldering" phase of burn.

TABLE III-14. Methyl Chloride data for Black Saddle 5 and 6.

Site	Acc. No.	SN	Date	Time	Bag No.	Comment	CH3Cl pptv	Unit
D_1P	1	TV704	30-Jul-87	1156 1407	3	AM	641	Black Saddle 6
D_2P	2	TV254	30-Jul-87	1200 1450	4	AM	573	Black Saddle 6
D_2P	3	TV943	30-Jul-87	1509 1728	4	PM	601	Black Saddle 6
D_3P	4	TV125	30-Jul-87	1205 1454	1	AM	626	Black Saddle 6
D_3P	5	TV250	30-Jul-87	1514 1731	1	PM	664	Black Saddle 6
D_1G	6	CQ168	30-Jul-87	1118 1820			663	Black Saddle 6
D_1G	7	CQ094	30-Jul-87 31-Jul-87	1825			598 558	Black Saddle 6
D_2P	8	BZ881	10-Aug-87	949 1200	2		733	Black Saddle 5
D_3P	9	BZ68	10-Aug-87	1016		NAI Sample	681	Black Saddle 5
D_1P	10	TV589	10-Aug-87	940 1145		NAI Sample	744	Black Saddle 5
U_1G	11	CQ57	10-Aug-87	505 1316			526	Black Saddle 5

Table IV-15. Results of the Gaseous Samples for Squaw Slope 2.

Sample No.	S/N	Date	Time Start	Time End	Location	H2 ppbv	CO ppbv	CO ppbv	CH4 ppbv	CO2 ppmv	N2O ppbv	F-12 pptv	F-11 pptv	CH3Cl pptv
1	TV695 B	14-Jul-88	1645			550	160	176	1730	346	340.3	1020	277	772
2	TV881 B	14-Jul-88	1730			1419	316	356	1805	686	341.3	654	474	740
3	G1 CT	14-Jul-88	1500	1900	Squaw Slope 2	568	254	273	1761	349	340.7	649	656	586
4	CQ510 CT	14-Jul-88	1500	1906	Squaw Slope 2 burning	505	78	73	1734	344				552
5	CQ384 CT	14-Jul-88	1917	2345	Squaw Slope 2 smoldering	439	77	78	1734	389				701
6	G2 CT	14-Jul-88	1900	2400	Squaw Slope 2	702	841	919	1784	350				557

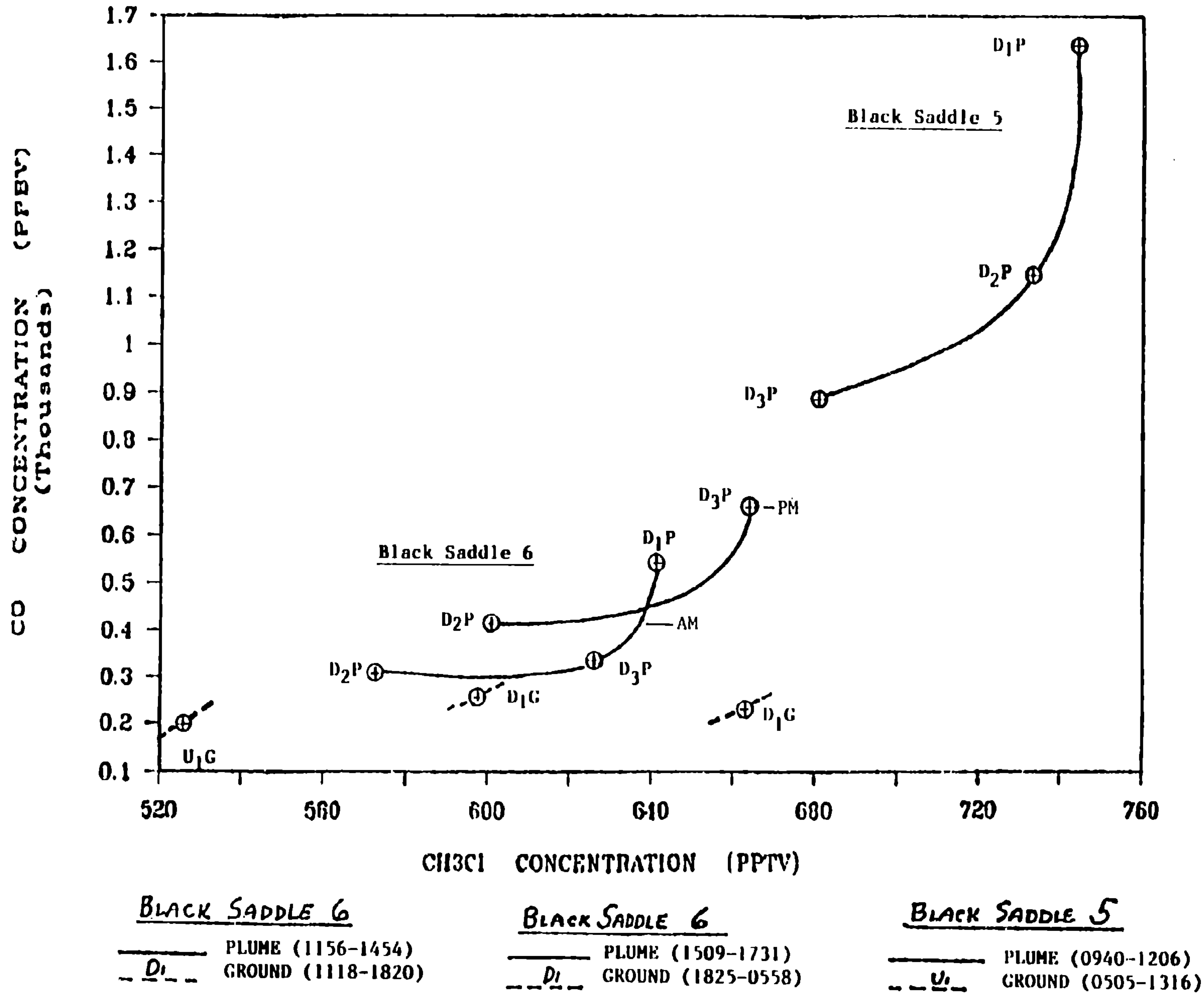


FIGURE IV - 10 METHYL CHLORIDE CONCENTRATIONS FOR TWO TESTS

V. DISCUSSION

A. Predicted vs. Measured Fuel and Emission Results

Thirteen prescribed burns were located and inventoried by the Fire and Air Resource Management Project for this study. Due to the adverse weather conditions, only 4 of those burns could be evaluated for fuel consumption. In-plume samples downwind of the burn were obtained for only 2 of the 4 units.

Of the units which were burned, evaluation of the fuel moisture contents, fuel consumed, predicted emissions, and predicted plume heights proceeded as planned. Each unit had uniform fuels and were burned under conditions the models were developed for. It is important to remember, however, that the measured emissions data base is very small and it is difficult to make any conclusions as to how well the Tiered Air Resources System (TSARS) model predicted downwind emissions concentrations.

B. Evaluation of EPM

Several comparisons were made to help us determine the level of accuracy which could be expected for different levels of data input effort.

First, using current weather data, the large, woody fuel moisture contents were predicted within 3 percent of the measured values. This is well within the ± 5 percent error associated with the ADJ-Th which is a meteorological based fuel moisture model.

Second, the line intersect procedure was used to obtain the best fuel loading information. This information was placed into the fuel consumption models within the Emission Production Model (EPM). EPM predicted the measured woody fuel and duff consumption within an error range of 4-17 percent (Table V-1). Again, this is well within the error which is associated with the fuel consumption algorithms. We feel this evaluation has shown that the fuel moisture and fuel consumption models are satisfactorily predicting values for the prescribed burning situations which they were developed for.

Third, the Ranger District burn plan information was used as input into EPM. The models continued to predict very well although the difference between the measured and predicted were slightly larger (9 to 23 percent).

For these four burns, the burn plan prescriptions inputs would be adequate for use by the models.

C. Evaluation of TSARS

Plume height measurements were attempted for both the Black Saddle 6 and Black Saddle 5 prescribed fires; however, reliable data were collected for only the Black Saddle 6 prescribed fire. Downwind centerline and ground level emissions concentration measurements were collected on the Black Saddle 6 and Black Saddle 5 units. The

Table V-1. Summary table of predicted versus measured fuel moisture and fuel consumption.

Unit	Predicted large fuel moisture	Measured large fuel moisture	Predicted consumption1/	Measured consumption
	percent	percent	tons/acre	tons/acre
Black Saddle #6	29	28	30.8	36.9
Black Saddle #5	27	30	53.3	51.2
Saddle Sore #3	26	23	62.9	52.4
Squaw Slope #2	30	31	54.4	46.6

1/ Predicted fuel consumption using measured preburn loading and fuel moisture values.

measured and predicted plume heights and emission concentrations were compared. The predicted values were determined from using measured fuel consumption inputs.

The plume height predictions were within 40 percent of the measured values for Black Saddle 6. We believe that TSARS would have better predicted the actual plume height had improved input for weather data.

The plume centerline concentrations predicted for Black Saddle 6 and Black Saddle 5, were 10 to 15 times higher than the highest concentration measured. This is in line with the initial intention of the TSARS model, which was to provide the managers with a simple, screening tool which always overpredicts. It is also important to note that this is the first test with a very simple model in complex terrain and that the tethered balloons that collected the concentration samples were not always exactly in the center of the plume during the sampling period.

The maximum ground level concentrations downwind from the prescribed fire for each the receptor sites was also predicted by the TSARS model. Ground sample data at receptor D1 for Black Saddle 6 and Black Saddle 5 burn were collected. The predicted ground level concentration for the Black Saddle 6 receptor D1 was within 40 percent of the measured (Table V-2). The predicted ground level concentration for receptor D1 during the Black Saddle 5 burn was lower by a factor of 9 than what was measured. No ground level concentrations were measured for the Saddle Sore 3 and Squaw Slope 2 prescribed burns.

D. Emissions from Prescribed Fires

A cable and tower system has been developed and implemented by the Fire and Air Resource Mangement project to obtain discrete measurements for each of two to three phases of combustion during tests in logging slash fires. A system of samplers is suspended from elevated cables and allows for the collection of five replicate samples of combustion products for each phase of combustion as well as continuous, real time measurements of certain combustion parameters and products.

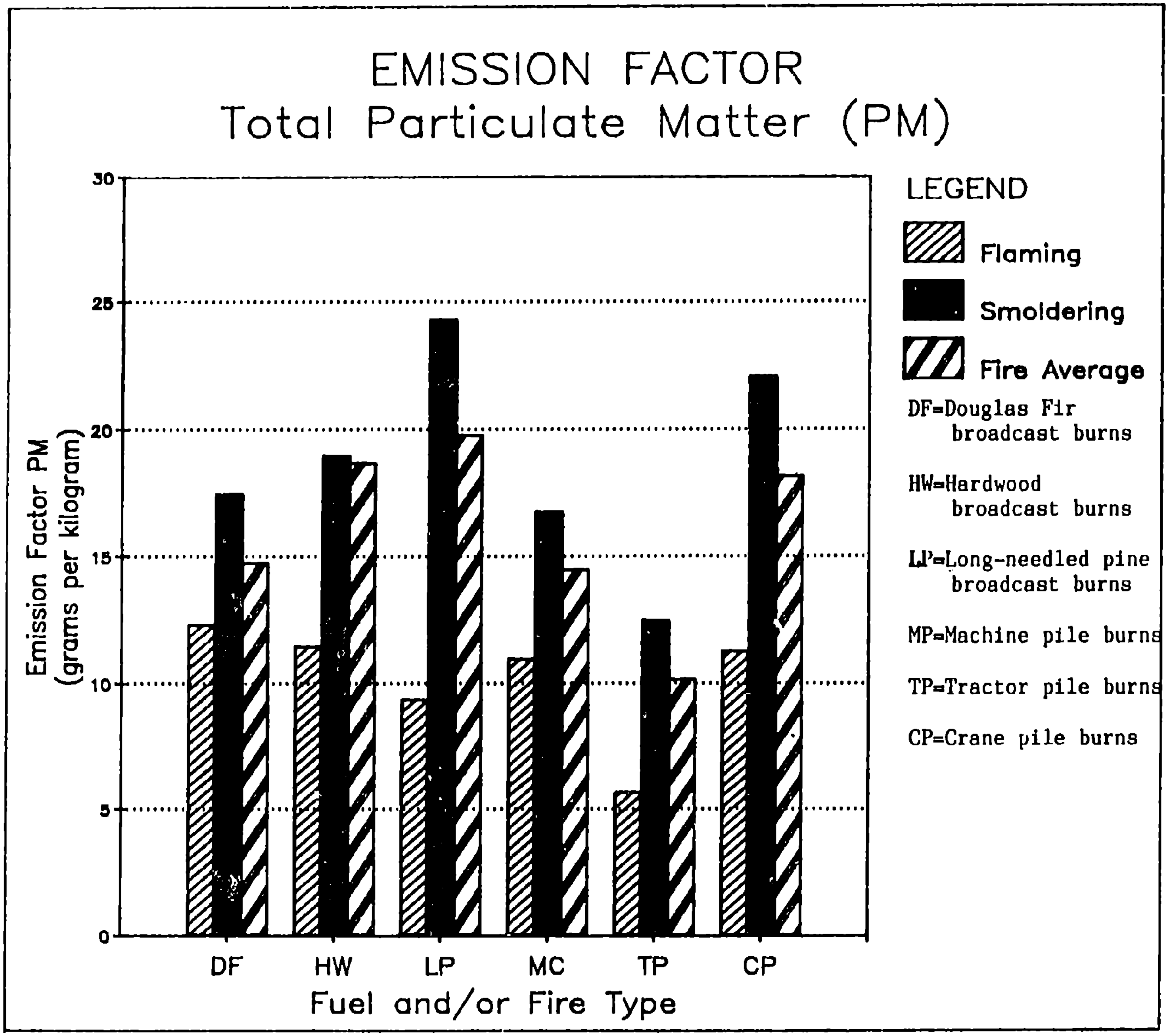
Total particulate matter emission factors (EFPM) represents the ratio of particles produced to fuel consumed measured at 20 meters above the fire during the flaming stage and 10 meters above the fire during the smoldering stage. The EFPM values were always lowest for the flaming combustion phase and highest for the smoldering combustion phase, regardless of fuel type. Between fuel types, the lowest emission factors were measured for tractor-piled conifer slash and the highest for eastside long-needled pine broadcast burn units during the smoldering combustion phase. Figure V-1 illustrates these relative differences as a function of phase of combustion and fuel type for the average values (Sandberg and others, 1989).

Table V-2. Summary Table of predicted versus measured maximum plume height, maximum centerline concentration, and maximum ground level concentrations.

Unit	Predicted1/ maximum plume height	Measured maximum maximum plume height	Predicted maximum1/ centerline concentration			Measured maximum centerline concentration			Predicted maximum1/ ground level concentration	Measured maximum ground level concentration
			D1	D2	D3	D1	D2	D3	D1	D1
	meters	meters	μgrams/meter³			μgrams/meter³			μgrams/meter³	μgrams/meter³
Black Saddle #6	377	653	1763	1566	1455	10	83	34	21	34
Black Saddle #5	1048	--	1865	1521	1322	135	108	115	15	127
Saddle Sore #3	668	--	616	556	383	--	--	--	285	--
Squaw Slope #2	1131	--	1280	887	580	--	--	--	168	--

1/ Predicted maximum plume height, predicted centerline concentration, and predicted maximum groudlevel concentration using measured fuel consumption values.

Figure V-1. Fire average values of particulate matter for various burns.



Gaseous and particulate matter samples were collected and analysized for trace elements. The coefficient of variation for the trace materials was generally the lowest for K, Cl, and S and ranged higher for Ca, Fe, and Pb. The trace elements for samples of PM2.5 for the six different fuel types are shown by combution phase in Table V-3 (Ward and Hardy, 1989).

Table V-3. Percentage content of PM2.5 for trace elements and carbon for the Pacific Northwest fuel types by phase of combustion.

Profile	Conifer F	Conifer S	Hardwood F	Hardwood S	P.pine F	P.pine S	Tractor-piled F	Tractor-piled S	Crane-piled F	Crane-piled S	Chaparral F	Chaparral S
Na	2.734	0.732										
Al	0.120	0.101	0.280	0.181	0.081	0.105	0.181	0.056	0.025	0.013	0.261	0.077
Si	0.091	0.167	0.427	0.336	0.152	0.148	0.348	0.052	0.016	0.013	0.699	0.238
P			0.237	0.093	0.088	0.048	0.128	0.039	0.011	0.007	0.209	0.096
S	0.341	0.114	1.118	0.503	0.556	0.162	0.950	0.228	0.229	0.125	2.297	0.838
Cl	0.556	0.118	2.703	0.466	0.554	0.226	0.921	0.227	0.196	0.107	4.323	1.549
K	1.419	0.126	5.014	0.577	2.103	0.501	3.895	0.606	1.195	0.818	9.896	3.988
Ca	0.182	0.127	0.181	0.183	0.112	0.073	0.619	0.071	0.074	0.077	0.581	0.268
Ti	0.218	0.124	0.019	0.013	0.010	0.005	0.018	0.002	0.001	0.002	0.015	0.010
V	0.069	0.031	0.008	0.004	0.003	0.002	0.007	0.001	0.001	0.000	0.004	0.002
Cr	0.113	0.024	0.018	0.003	0.003	0.000	0.000	0.000	0.000	0.001	0.006	0.000
Mn	0.038	0.020	0.023	0.011	0.016	0.008	0.045	0.005	0.019	0.018	0.010	0.014
Fe	0.057	0.061	0.107	0.062	0.010	0.057	0.030	0.003	0.006	0.007	0.121	0.020
Ni	0.009	0.010	0.024	0.003	0.035	0.002	0.011	0.027	0.000	0.000	0.002	0.001
Cu	0.009	0.010	0.021	0.001	0.000	0.000	0.007	0.000	0.001	0.001	0.003	0.000
Zn	0.118	0.010	0.154	0.014	0.115	0.025	0.389	0.012	0.054	0.012	0.181	0.040
Br	0.048	0.025	0.124	0.019	0.033	0.008	0.146	0.012	0.004	0.002	0.110	0.035
Ag			0.077	0.030	0.028	0.018	0.172	0.008	0.005	0.004	0.097	0.026
Cd			0.169	0.066	0.045	0.014	0.066	0.015	0.001	0.004	0.055	0.015
Sn			0.086	0.043	0.013	0.018	0.196	0.000	0.005	0.000	0.031	0.000
Pb	0.154	0.078	0.211	0.031	0.068	0.019	0.234	0.010	0.007	0.003	0.425	0.082
Carbon												
Organic	36.4	51.9	60.3	61.7	55.1	61.0	49.0	53.1	59.8	60.4	48.0	63.9
Elemental	18.6	3.4	8.3	2.7	10.9	4.1	8.2	2.9	2.3	1.1	9.2	7.8
Total	55.0	55.3	68.6	64.4	66.0	65.1	57.2	56.0	62.1	61.4	57.2	71.7

F=Flaming S=Smoldering

VI. CONCLUSIONS

As a result of this study, the fuel moisture models used by forest managers and the fuel consumption models built into the emissions production model of the Tiered Smoke Air Resource System (TSARS) were evaluated. In-plume sampling procedures using tethered equipment for sampling of particulate and gaseous pollutants were designed, developed, acquired, and tested during this study. In addition, the first quantitative look at the simple dispersion model, a Simple Approach Smoke Estimation Model (SASEM), was provided.

The fuel moisture and fuel consumption models are predicting well within the models' error bounds even when less accurate burn plan inputs are used. TSARS was shown to substantially over-predict observed emission concentrations downwind from the plume from the two burns sampled. More specific conclusions from this study include:

1. The fuel moisture models predicted the measured fuel moisture values for the units on the day of the burn. In all cases, the model predicted within 3 percent of the measured fuel moisture contents for each of the four burns monitored. The model was designed to estimate the average, unit fuel moisture within 5 percent.

2. The average woody fuel and duff consumption which were predicted by the fuel consumption models were within 4 to 17 percent of the measured values. This is well within the errors bounds associated with the fuel consumption models.

   The Ranger District burn plan information also provided adequate input into EPM. The models continued to predict very well although the difference between the measured and predicted were slightly larger (9 to 23 percent) than if the measured fuel loadings and measured fuel moisture values had been used. For these four burns, the burn plan prescriptions inputs would be adequate for use by the models.

   The errors are within the error bounds shown to exist with the fuel consumption models. This validation portion of the study has shown that the fuel consumption models built within the TSARS framework are adequate for the prescribed fires that are accomplished when the small fuels are generally totally consumed. There are limitations, however, which did not play a role during these burns. These include:

   The fuel consumption models will over-predict consumption if the small fuels are wet and do not entirely consume, if the unit is flat and small (less than 2 acres), or if the fuel bed is non-uniform. The fuel consumption models will under predict if very windy conditions persist that serve to extend the smoldering stage. Units that are burned shortly after harvest may be considered uncured and a different relationship will then exist between fuel moisture and consumption.

   Although the total consumption for all the fuel types was predicted reasonably well by the fuel consumption models, in many cases the models show a trend toward being conservative. As we fine tune the models and can account for spring burning, uncured slash, and helicopter ignition, the models will become less conservative.

3. The plume height prediction of the TSARS model was within 40 percent of measured value from one burn. This is encouraging, although additional validation tests need to be set up before a conclusive statement can be made.

4. Black Saddle 6 and Black Saddle 5 were the only prescribed burns where emission concentration samples were collected. With only two burns of data, it is difficult to establish a conclusive statement about the prediction capability of TSARS. We can only say that TSARS was very conservative for these burns and over predicted the concentrations measured by 10 to 15 times.

TSARS was designed to be conservative, since it is to be used as a screening tool by forest managers. However, the difference between the measured values and the predicted values may have been inflated because the balloon samplers employed were not always in the center of the plume during the sampling period.

5. In-plume sampling is possible, and it provides an excellent opportunity to obtain long-term samples and allow dispersion model validation. An airborne sampling unit was designed and assembled to sample in the smoke plume by an airplane. All the problems encountered during the project also point out the difficulties associated with field studies of this nature. We are now better prepared than ever to carry out further research in this area.

VII. RECOMMENDATIONS

The following recommendations are based on the four field tests and observations during the field study.

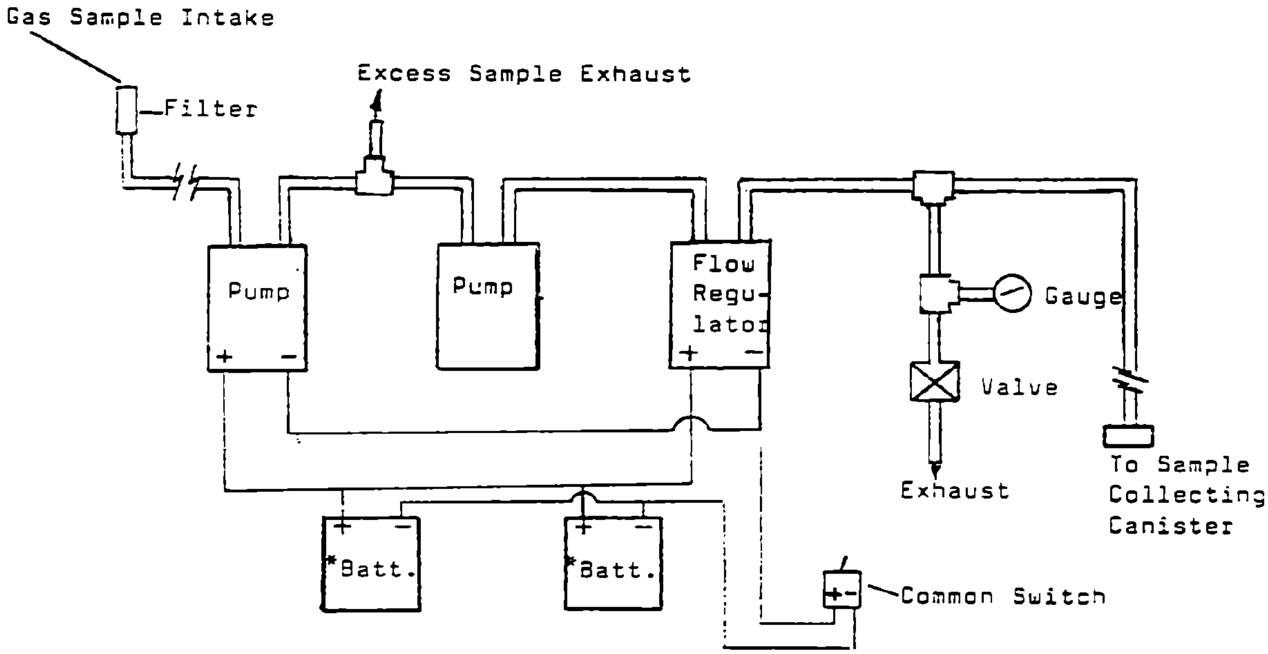
1. Any future testing must be done during spring to ensure that extreme dry or wet weather conditions that hampered this field study do not reoccur.

2. More burns may have to be monitored than originally planned. Ground level sampling has the distinct advantage of being able to maintain a more or less stationary point in the plume (which aircraft can't), but has the disadvantage of not being able to reach high smoke plumes. Thus, one may need to monitor as great a number of burns as possible to ensure high enough success ratio. Also, the prescribed burn sites and potential sampling sites should be selected to facilitate reaching the plume.

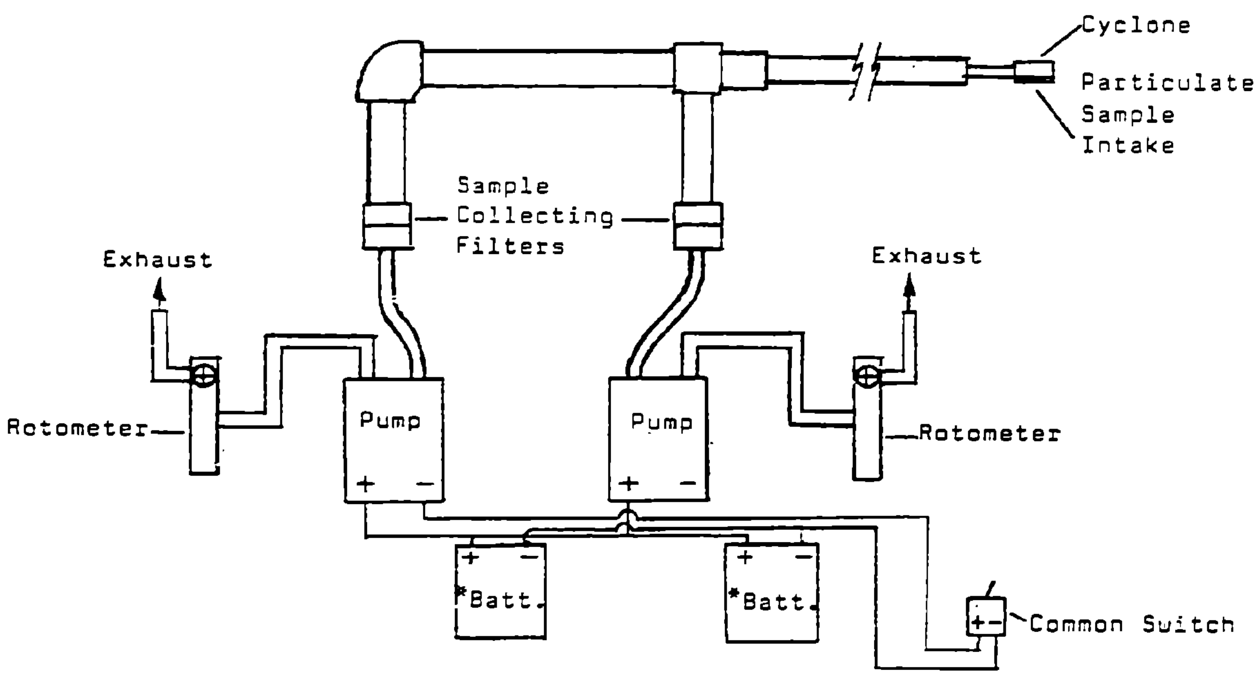
3. A major problem in the 1988 sampling was not knowing exactly where the smoke plume was going. The two theodolite observers were helpful in advising the balloon teams as to elevation needed to enter the plume, but were not able to accurately advise on the plume direction. After reviewing the situation, it was agreed that a "spotter" airplane could obtain a very good overall view of direction and elevation. The pilot/observer would be in radio contact with the Operations Manager so that balloon teams could be located in line with the early plume and be ready to deploy the balloon when the dense plume developed.

4. In addition to the task of observing and tracking the smoke plume, the airplane could carry an airborne sampling unit designed to sample the atmosphere near the smoke plume (Figure VII-1). The unit could be turned on and off as necessary to obtain a total sample with the sampling period duration needed. The unit would be strapped in the cockpit in place of the co-pilot's seat, and operated by the observer. Two hoses would run out of an air vent, through the core of the airplane's wing, and out an air intake hole in the leading edge of the wing. The intake end of the hoses would be strapped to a wing strut far enough away from the body of the airplane so that no fumes would contaminate the samples. Both methylchloride and particulate samples would be obtained. This unit was designed and ready for the second burn in 1988 but was never used, as the program was shutdown by extensive forest fires and extremely hazardous fire conditions in the forest, followed by an extended rainy season.

5. Further efforts to validate the model are warranted before FS can effectively use the models developed for smoke management.



METHYLCHLORIDE SAMPLER



* Two 12-Volt Batteries Are Common to Both Samplers.

PARTICULATE SAMPLER

Figure VII-1. Aircraft samplers schematics.

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APPENDIX A

Results of the Chemical Analysis for the Samples from Black Saddle 5 and 6

Table 1
G2E/J. Shah
Ambient Sample Analysis Results

Date : 07/30/87
Filters: NT0700419 NQ0200405 Burn ID: Black Saddle 6
Volumes: 1.1760 m3 1.1760 m3 Site ID: D1 Plume

Flags : TFFLG QFFLG MTGF ANIF N4CF NAAF MGAF KPAF OETF ELXF
PM2.5 :

****

Species	PM2.5 (µg/m3) Conc.	± Unc.
Mass	113.9456	10.2356
Na	0.0000	2.2341
Mg	0.0000	1.1368
Al	0.0000	0.2854
Si	0.2466	0.2987
P	0.0000	0.0738
S	0.6702	0.0528
Cl	0.0270	0.2769
K	0.2824	0.0959
Ca	0.1585	0.2209
Ti	0.0000	0.2596
V	0.0000	0.1062
Cr	0.0000	0.0258
Mn	0.0147	0.0219
Fe	0.1088	0.1173
Co	0.0000	0.0109
Ni	0.0004	0.0099
Cu	0.0003	0.0143
Zn	0.0128	0.0161
Ga	0.0281	0.0333
As	0.0005	0.0304
Se	0.0000	0.0169
Br	0.0021	0.0138
Rb	0.0000	0.0164
Sr	0.0000	0.0203
Y	0.0000	0.0222
Zr	0.0197	0.0302
Mo	0.0000	0.0556
Pd	0.0354	0.1074
Ag	0.0000	0.1266
Cd	0.0000	0.1248
In	0.0000	0.1474
Sn	0.0000	0.1984
Sb	0.0398	0.2358
Ba	0.2540	0.8444
La	0.0000	0.9078
Au	0.0000	0.0566
Hg	0.0099	0.0363
Tl	0.0000	0.0336
Pb	0.0023	0.0476
U	0.0000	0.0463
OC	57.2279	6.6477
EC	7.8656	1.4952
Sum	67.0071	7.4049

Table 1, continued
G2E /J. Shah
Ambient Sample Analysis Results

Date : 07/30/87
Filters: NT0700422 NQ0200407
Volumes: 1.3860 m3 1.1396 m3

Burn ID: Black Saddle 6
Site ID: D3 Plume

Flags : TFFLG QFFLG MTGF ANIF N4CF NAAF MGAF KPAF OETF ELXFil
PM2.5 :

****

Species	PM2.5 (µg/m3) Conc.	± Unc.
Mass	33.1890	7.4034
Na	0.2993	1.8471
Mg	0.1234	0.9516
Al	0.0996	0.2384
Si	0.3868	0.2542
P	0.0234	0.0564
S	0.2675	0.0363
Cl	0.1919	0.2201
K	0.1815	0.0806
Ca	0.3109	0.1882
Ti	0.0071	0.2150
V	0.0098	0.0880
Cr	0.0053	0.0218
Mn	0.0216	0.0089
Fe	0.1711	0.0999
Co	0.0000	0.0095
Ni	0.0045	0.0084
Cu	0.0038	0.0118
Zn	0.0729	0.0077
Ga	0.0027	0.0271
As	0.0000	0.0252
Se	0.0012	0.0141
Br	0.0084	0.0117
Rb	0.0000	0.0137
Sr	0.0019	0.0170
Y	0.0000	0.0185
Zr	0.0009	0.0248
Mo	0.0000	0.0465
Pd	0.0000	0.0877
Ag	0.0000	0.1059
Cd	0.0000	0.1024
In	0.0029	0.1227
Sn	0.0000	0.1650
Sb	0.0377	0.1966
Ba	0.0000	0.6984
La	0.0000	0.7576
Au	0.0108	0.0479
Hg	0.0000	0.0297
Tl	0.0000	0.0281
Pb	0.0013	0.0395
U	0.0227	0.0391
OC	32.7308	4.1059
EC	5.0456	1.0542
Sum	40.0473	4.8736

Table 1, continued
G2E /J. Shah
Ambient Sample Analysis Results

Date : 07/30/87
Filters: NT0700423 NQ0200402 Burn ID: Black Saddle 6
Volumes: 3.4650 m3 3.4650 m3 Site ID: D1 Ground, No. 2
Smoldering Phase

Flags : TFFLG QFFLG MTGF ANIF N4CF NAAF MGAF KPAF OETF ELXF
PM2.5 :

****

Species	PM2.5 (µg/m3) Conc.	± Unc.
Mass	23.3766	3.1138
Na	0.0000	0.7592
Mg	0.1308	0.3903
Al	0.0879	0.0705
Si	0.2763	0.1026
P	0.0118	0.0331
S	0.5203	0.0303
Cl	0.0652	0.0881
K	0.4385	0.0402
Ca	0.2509	0.0763
Ti	0.0115	0.0882
V	0.0035	0.0361
Cr	0.0000	0.0087
Mn	0.0032	0.0074
Fe	0.1882	0.0410
Co	0.0000	0.0050
Ni	0.0007	0.0034
Cu	0.0005	0.0049
Zn	0.0112	0.0027
Ga	0.0006	0.0113
As	0.0027	0.0106
Se	0.0020	0.0059
Br	0.0017	0.0048
Rb	0.0008	0.0057
Sr	0.0000	0.0069
Y	0.0000	0.0076
Zr	0.0009	0.0103
Mo	0.0025	0.0192
Pd	0.0166	0.0366
Ag	0.0025	0.0434
Cd	0.0000	0.0414
In	0.0000	0.0487
Sn	0.0000	0.0671
Sb	0.0275	0.0803
Ba	0.0897	0.2863
La	0.0000	0.3082
Au	0.0000	0.0195
Hg	0.0000	0.0123
Tl	0.0000	0.0114
Pb	0.0017	0.0165
U	0.0000	0.0158
OC	13.1602	1.5937
EC	2.3521	0.4555
Sum	17.6620	1.9280

Table 1, continued
G2E /J. Shah
Ambient Sample Analysis Results

Date : 07/30/87
Filters: NT0700424 NQ0200403
Volumes: 2.1100 m3 2.1100 m3

Burn ID: Black Saddle 6
Site ID: D1 Ground, No. 1
Active Phase

Flags : TFFLG QFFLG MTGF ANIF N4CF NAAF MGAF KPAF OETF ELXF
PM2.5 :

****

Species	PM2.5 (µg/m3) Conc.	± Unc.
Mass	58.2938	5.5639
Na	0.0000	1.2603
Mg	0.0000	0.6346
Al	0.0308	0.1662
Si	0.4969	0.1687
P	0.0000	0.0416
S	0.3797	0.0299
Cl	0.0060	0.1530
K	0.1081	0.0529
Ca	0.2494	0.1239
Ti	0.0152	0.1428
V	0.0046	0.0584
Cr	0.0005	0.0142
Mn	0.0127	0.0058
Fe	0.2124	0.0663
Co	0.0000	0.0070
Ni	0.0017	0.0055
Cu	0.0000	0.0077
Zn	0.0083	0.0042
Ga	0.0000	0.0178
As	0.0000	0.0167
Se	0.0009	0.0094
Br	0.0049	0.0077
Rb	0.0000	0.0091
Sr	0.0000	0.0112
Y	0.0000	0.0122
Zr	0.0089	0.0167
Mo	0.0000	0.0307
Pd	0.0034	0.0588
Ag	0.0000	0.0691
Cd	0.0000	0.0691
In	0.0000	0.0807
Sn	0.0056	0.1108
Sb	0.0000	0.1288
Ba	0.0421	0.4635
La	0.0000	0.4985
Au	0.0007	0.0316
Hg	0.0000	0.0198
Tl	0.0000	0.0187
Pb	0.0000	0.0261
U	0.0000	0.0255
OC	11.4692	1.6294
EC	2.6303	0.5552
Sum	15.6924	2.3664

Table 1, continued
G2E /J. Shah
Ambient Sample Analysis Results

Date : 07/30/87 Burn ID: Black Saddle 6
Filters: NT0700425 NQ0200411 Site ID: V1, No. 2
Volumes: 2.2104 m3 2.7937 m3 Smoldering Phase

Flags : TFFLG QFFLG MTGF ANIF N4CF NAAF MGAF KPAF OETF ELXF
PM2.5 :

****

Species	PM2.5 (µg/m3) Conc.	± Unc.
Mass	33.4781	4.8237
Na	0.0000	1.1531
Mg	0.0000	0.6014
Al	0.0233	0.1515
Si	0.1363	0.1589
P	0.0037	0.0405
S	0.4381	0.0313
Cl	0.0153	0.1460
K	0.4178	0.0556
Ca	0.0491	0.1174
Ti	0.0000	0.1333
V	0.0000	0.0545
Cr	0.0000	0.0129
Mn	0.0052	0.0111
Fe	0.0809	0.0625
Co	0.0000	0.0058
Ni	0.0004	0.0052
Cu	0.0021	0.0073
Zn	0.0056	0.0081
Ga	0.0000	0.0167
As	0.0048	0.0158
Se	0.0000	0.0086
Br	0.0046	0.0072
Rb	0.0037	0.0086
Sr	0.0000	0.0105
Y	0.0000	0.0114
Zr	0.0038	0.0154
Mo	0.0000	0.0288
Pd	0.0110	0.0552
Ag	0.0000	0.0651
Cd	0.0048	0.0652
In	0.0000	0.0745
Sn	0.0000	0.1021
Sb	0.0065	0.1214
Ba	0.0310	0.4336
La	0.0000	0.4690
Au	0.0000	0.0292
Hg	0.0000	0.0180
Tl	0.0000	0.0173
Pb	0.0028	0.0246
U	0.0005	0.0239
OC	4.0806	0.8858
EC	0.1611	0.2296
Sum	5.4930	1.7601

Table 1, continued
G2E /J. Shah
Ambient Sample Analysis Results

Date : 07/30/87
Filters: NT0700426 NQ0200408
Volumes: 1.7063 m3 1.3500 m3

Burn ID: Black Saddle 6
Site ID: V1, No. 1 Active Phase

Flags : TFFLG QFFLG MTGF ANIF N4CF NAAF MGAF KPAF OETF ELXF
PM2.5 :

****

Species	PM2.5 (µg/m3) Conc.	± Unc.
Mass	33.9917	6.1020
Na	0.0000	1.4842
Mg	0.0000	0.7688
Al	0.0000	0.1943
Si	0.1037	0.2057
P	0.0000	0.0466
S	0.2540	0.0302
Cl	0.0082	0.1875
K	0.0689	0.0647
Ca	0.0265	0.1554
Ti	0.0000	0.1716
V	0.0052	0.0702
Cr	0.0031	0.0170
Mn	0.0045	0.0140
Fe	0.0607	0.0808
Co	0.0000	0.0070
Ni	0.0022	0.0065
Cu	0.0088	0.0094
Zn	0.0071	0.0103
Ga	0.0000	0.0205
As	0.0000	0.0201
Se	0.0012	0.0111
Br	0.0079	0.0092
Rb	0.0000	0.0107
Sr	0.0000	0.0132
Y	0.0002	0.0145
Zr	0.0025	0.0195
Mo	0.0069	0.0366
Pd	0.0000	0.0696
Ag	0.0380	0.0868
Cd	0.0000	0.0819
In	0.0000	0.0972
Sn	0.0000	0.1329
Sb	0.0000	0.1546
Ba	0.0000	0.5582
La	0.0000	0.6046
Au	0.0248	0.0383
Hg	0.0029	0.0234
Tl	0.0000	0.0221
Pb	0.0127	0.0314
U	0.0139	0.0305
OC	8.1481	1.8163
EC	1.4444	0.5364
Sum	10.2567	2.7063

Table 1, continued
G2E /J. Shah
Ambient Sample Analysis Results

Date : 07/30/87 Burn ID: Black Saddle 6
Filters: NT0700427 NQ0200406 Site ID: D2 Plume
Volumes: 1.2628 m3 1.2628 m3

Flags :	TFFLG	QFFLG	MTGF	ANIF	N4CF	NAAF	MGAF	KPAF	OETF	ELXF
PM2.5 :										il

****

Species	PM2.5 (µg/m3) Conc.	± Unc.
Mass	86.3161	9.0173
Na	0.0000	1.9147
Mg	0.1161	1.0214
Al	0.1421	0.2537
Si	0.2129	0.2781
P	0.0000	0.0620
S	0.5185	0.0453
Cl	0.0219	0.2517
K	0.2261	0.0884
Ca	0.2415	0.2058
Ti	0.0000	0.2184
V	0.0102	0.0892
Cr	0.0000	0.0208
Mn	0.0268	0.0094
Fe	0.1587	0.1094
Co	0.0031	0.0095
Ni	0.0040	0.0082
Cu	0.0162	0.0045
Zn	0.0141	0.0067
Ga	0.0000	0.0283
As	0.0000	0.0264
Se	0.0025	0.0139
Br	0.0055	0.0112
Rb	0.0027	0.0135
Sr	0.0027	0.0167
Y	0.0011	0.0179
Zr	0.0086	0.0243
Mo	0.0340	0.0466
Pd	0.0125	0.0894
Ag	0.0000	0.1065
Cd	0.0315	0.1059
In	0.0169	0.1227
Sn	0.0000	0.1657
Sb	0.0770	0.1996
Ba	0.0000	0.7111
La	0.0000	0.7736
Au	0.0309	0.0490
Hg	0.0096	0.0293
Tl	0.0084	0.0283
Pb	0.0445	0.0176
U	0.0000	0.0375
OC	38.0108	4.5692
EC	3.6823	0.8244
Sum	43.6935	5.2748

Table 1, continued
G2E /J. Shah
Ambient Sample Analysis Results

Date : 07/30/87 | Burn ID: Black Saddle 5
Filters: NT0700430 NQ0200417 | Site ID: D3 Plume
Volumes: 0.5115 m3 0.3960 m3

Flags : TFFLG QFFLG MTGF ANIF N4CF NAAF MGAF KPAF OETF ELXF
PM2.5 :

****

Species	PM2.5 (µg/m3) Conc.	± Unc.
Mass	115.3470	20.3849
Na	0.0000	5.1397
Mg	0.0000	2.6198
Al	0.0000	0.6650
Si	0.3810	0.6861
P	0.0000	0.1610
S	0.9341	0.1024
Cl	0.0082	0.6299
K	0.3754	0.2174
Ca	0.5683	0.5085
Ti	0.0000	0.5836
V	0.0000	0.2385
Cr	0.0000	0.0581
Mn	0.0364	0.0495
Fe	0.1935	0.2696
Co	0.0000	0.0242
Ni	0.0117	0.0231
Cu	0.1501	0.0153
Zn	0.0217	0.0360
Ga	0.0000	0.0745
As	0.0000	0.0696
Se	0.0000	0.0383
Br	0.0000	0.0317
Rb	0.0000	0.0379
Sr	0.0000	0.0465
Y	0.0000	0.0512
Zr	0.0031	0.0690
Mo	0.0000	0.1277
Pd	0.0225	0.2399
Ag	0.1580	0.2953
Cd	0.0000	0.2792
In	0.0000	0.3281
Sn	0.0000	0.4506
Sb	0.0000	0.5296
Ba	0.0000	1.8976
La	0.0682	2.0628
Au	0.0000	0.1302
Hg	0.0022	0.0829
Tl	0.0000	0.0772
Pb	0.0000	0.1091
U	0.0066	0.1069
OC	87.6263	11.1657
EC	10.2273	2.4223
Sum	100.7947	13.2179

Table 1, continued
G2E /J. Shah
Ambient Sample Analysis Results

Date : 07/30/87 Burn ID: Black Saddle 5
Filters: NT0700432 NQ0200412 Site ID: D1 Ground, No. 1
Volumes: 1.5500 m3 1.5500 m3

Flags : TFFLG QFFLG MTGF ANIF N4CF NAAF MGAF KPAF OETF ELXF
PM2.5 :

****

Species	PM2.5 (µg/m3) Conc.	± Unc.
Mass	127.0968	9.0558
Na	0.0000	1.6727
Mg	0.0000	0.8664
Al	0.0000	0.2211
Si	0.2612	0.2270
P	0.0000	0.0603
S	0.6796	0.0465
Cl	0.0027	0.2077
K	0.2114	0.0726
Ca	0.2025	0.1679
Ti	0.0000	0.1883
V	0.0105	0.0771
Cr	0.0013	0.0186
Mn	0.0137	0.0158
Fe	0.0708	0.0890
Co	0.0000	0.0076
Ni	0.0029	0.0072
Cu	0.0020	0.0102
Zn	0.0268	0.0059
Ga	0.0000	0.0234
As	0.0032	0.0217
Se	0.0000	0.0121
Br	0.0000	0.0098
Rb	0.0049	0.0121
Sr	0.0000	0.0147
Y	0.0000	0.0159
Zr	0.0010	0.0215
Mo	0.0000	0.0404
Pd	0.0000	0.0770
Ag	0.0046	0.0935
Cd	0.0000	0.0896
In	0.0350	0.1086
Sn	0.0000	0.1448
Sb	0.0000	0.1705
Ba	0.1120	0.6127
La	0.0000	0.6562
Au	0.0176	0.0422
Hg	0.0021	0.0259
Tl	0.0000	0.0243
Pb	0.0000	0.0338
U	0.0140	0.0339
OC	52.5161	5.0289
EC	8.2903	1.5253
Sum	62.4864	6.5845

Table 1, continued
G2E /J. Shah
Ambient Sample Analysis Results

Date : 07/30/87 Burn ID: Black Saddle 5
Filters: NT0700434 NQ0200419 Site ID: D2 Plume
Volumes: 0.5738 m3 0.5738 m3

Flags : TFFLG QFFLG MTGF ANIF N4CF NAAF MGAF KPAF OETF ELXF
PM2.5 :

****

Species	PM2.5 (µg/m3) Conc.	± Unc.
Mass	108.0516	18.2464
Na	0.0000	4.3917
Mg	0.1751	2.2940
Al	0.0000	0.5657
Si	0.2551	0.6115
P	0.0261	0.1424
S	1.1373	0.1007
Cl	0.0073	0.5610
K	0.5802	0.1961
Ca	0.2447	0.4524
Ti	0.0000	0.5173
V	0.0038	0.2112
Cr	0.0127	0.0511
Mn	0.0284	0.0424
Fe	0.1119	0.2400
Co	0.0000	0.0204
Ni	0.0000	0.0188
Cu	0.0014	0.0277
Zn	0.0535	0.0157
Ga	0.0523	0.0659
As	0.0141	0.0605
Se	0.0096	0.0338
Br	0.0160	0.0277
Rb	0.0000	0.0328
Sr	0.0000	0.0399
Y	0.0000	0.0439
Zr	0.0000	0.0587
Mo	0.0000	0.1105
Pd	0.0000	0.2104
Ag	0.0176	0.2567
Cd	0.0000	0.2484
In	0.0000	0.2928
Sn	0.0000	0.3986
Sb	0.0000	0.4659
Ba	0.2743	1.6836
La	0.0000	1.8126
Au	0.0244	0.1149
Hg	0.0108	0.0713
Tl	0.0016	0.0676
Pb	0.0000	0.0941
U	0.0193	0.0924
OC	81.3872	9.8223
EC	9.4981	2.0157
Sum	93.9631	11.5573

Table 1, continued
G2E/J. Shah
Ambient Sample Analysis Results

Date :	07/30/87		Burn ID: Black Saddle 5
Filters:	NT0700435	NQ0200421	Site ID: D1 Plume
Volumes:	0.6125 m3	0.6125 m3	

Flags :	TFFLG	QFFLG	MTGF	ANIF	N4CF	NAAF	MGAF	KPAF	OETF	ELXF
PM2.5 :										j

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Species	PM2.5 (µg/m3) Conc.	± Unc.
Mass	135.5102	17.6745
Na	0.0000	4.1091
Mg	0.0000	2.1657
Al	0.0000	0.5383
Si	0.2722	0.5731
P	0.0000	0.1543
S	1.9469	0.1264
Cl	0.1758	0.5269
K	0.5922	0.1841
Ca	0.6478	0.4254
Ti	0.0000	0.4767
V	0.0042	0.1948
Cr	0.0245	0.0483
Mn	0.0467	0.0197
Fe	0.1486	0.2251
Co	0.0000	0.0194
Ni	0.0052	0.0181
Cu	0.0111	0.0258
Zn	0.0532	0.0146
Ga	0.0000	0.0607
As	0.0088	0.0550
Se	0.0083	0.0309
Br	0.0149	0.0252
Rb	0.0000	0.0297
Sr	0.0046	0.0369
Y	0.0000	0.0398
Zr	0.0047	0.0537
Mo	0.0473	0.1017
Pd	0.0281	0.1956
Ag	0.0000	0.2325
Cd	0.0000	0.2286
In	0.0000	0.2681
Sn	0.0000	0.3660
Sb	0.2676	0.4392
Ba	0.0000	1.5505
La	0.0971	1.6833
Au	0.0508	0.1062
Hg	0.0113	0.0648
Tl	0.0000	0.0607
Pb	0.0119	0.0860
U	0.0000	0.0826
OC	128.0000	14.7217
EC	21.7959	3.9993
Sum	154.2798	16.1743