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CANADIAN MASS FIRE EXPERIMENT, 1989

James G. Quintiere

U.S. DEPARTMENT OF COMMERCE
National Institute of Standards
and Technology
National Engineering Laboratory
Center for Fire Research
Gaithersburg, MD 20899

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TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

LIST OF FIGURES

LIST OF FIGURES (continued)

LIST OF TABLES

PREFACE

In cooperation with the Ontario Ministry of Natural Resources (OMNR), the Defense Nuclear Agency (DNA) coordinated a team of researchers in making measurements of fire and smoke characteristics for a simulated mass fire initiated over 480 hectares of forest harvestation debris. The team, led by Major Richard S. Hartley, USAF, consisted of researchers from Forestry Canada, USDA Forest Service, Pacific-Sierra Research Corporation, University of Iowa, University of Washington, National Institute of Standards and Technology, and Science Applications Incorporated.

This report is intended to provide a summary of the DNA Canadian mass fire experiment. The individual team reports provide complete information on their objectives, experimental methods, analyses and results. They are listed in the References and should be consulted when necessary to determine more details of work attributed to the teams. Because the individual efforts only address aspects of the fire experiment, and are both complementary and supplementary in their relationship to each other, it was decided at the start of this project to require a summary report to integrate the team results. This summary report attempts to provide a cohesive description of the project, in particular, the Hill Township prescribed fire experiment.

The technical basis of this summary report is primarily derived from the team reports. A tentative outline of the summary report was developed with the teams in October of 1989 at a project review meeting hosted by the USDA Forest Service in Montana. The subsequently developed team reports were directed, in part, by that outline, and that outline forms the basis of this writing. This author has used his judgement as a technical editor in choosing to highlight features of the team reports, and to express his views on their significance.

In this editorial presentation there will be no overt attempt to provide further analysis of the data nor will there be any substantive attempt to evaluate the technical accuracy of the data or the technical merits of the analyses. Each result determined by the teams speak for themselves. However, it is expected that subsequent analyses by the team participants or others will pursue issues of accuracy and interpretation further, and this summary report is intended to be a road map for that enterprise.

ACKNOWLEDGEMENTS

The author gratefully wishes to acknowledge the funding support from the Defense Nuclear Agency and Maj. Richard Hartley, USAF, who led the DNA program. I also want to especially thank those participants who contributed comments and suggestions to this manuscript; namely, Darold Ward, Doug McRae, Ken Heikes, Larry Radke, and Tom Ohlemiller. I also wish to acknowledge all the members of the DNA contract participant teams and the Ontario Ministry of Natural Resources, who provided the means and results of this mass fire experiment.

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ABSTRACT

Working with Forestry Canada and the Ontario Ministry of Natural Resources, the Defense Nuclear agency carried out an extensively instrumented experiment of a prescribed burn in forest debris to simulate conditions of a mass fire. In addition to the Canadian team, a multi-institutional US team made both ground and airborne measurements of the fire and smoke conditions. The fire reported on was in Hill Township, Ontario and covered nearly 480 ha in its overall burning area. Both flaming and smoldering modes contributed to the energy and combustion products of this fire. Significant quantities measured and determined included estimations of energy release rate, emission factors for smoke particulates and specie, ground level wind and temperatures, and aspects of cloud dynamics and cloud particles. The fire caused a capping cloud to form and reach a level of 6.5 km. Rain, snow, hail and lightning were reported along with ground level fire whirls and water spouts on the adjoining lakes. Fire spread rates reached 1 m/s and fire induced winds reached 12 m/s.

Keywords: Cloud interactions, energy release rate, forest fires, mass fires, smoke emissions.

INTRODUCTION

Need for Mass Fire Research

Over the ages, large destructive fires have occurred which have involved many acres of continuous burning regions. Most notable among city fires have been London in 1666, Chicago in 1871, San Francisco in 1906, and Tokyo in 1923 (Quintiere, 1980, Pitts, 1989). The first two originated by relatively small accidental fires and were promoted to spread by high winds. When the winds died, the fire was brought under control. The last two city fires were initiated due to earthquakes. In the Tokyo fire, a large fire whirl (combusting tornado structure) was reported to have killed nearly 38,000 people who were seeking refuge in a large open field away from the main fire (Soma and Saito, 1988).

In recent times, forest fires, such as the Yellowstone fires of 1988, have been prominent in the news and demonstrate the impact of fire at the urban-wildland interface. In general, large expanses of forests can burn over very large regions for days and even weeks. Indeed, the great forest fire in China in 1987, which destroyed forest and towns over an area the size of New England, was driven by winds of 50 mph and burned for several weeks (Salisbury, 1989). In past times, on the same day as the Chicago fire, the town of Peshtigo, Wisconsin, was devastating by a surrounding forest fire killing 800 people (Lyons, 1976).

During World War II conventional weapon and nuclear air attacks on cities induced large fires, some of which have been additionally labeled as "firestorms". These firestorms were the result of very large area fires, and most likely some favorable environmental wind conditions that led to fire induced surface winds of storm-like strength. Either due to the merging of many individual fires under unstable atmospheric conditions, or ambient vorticity which caused rotation of the fire convective column, ground level induced winds of up to 100 mph were reported for the wartime fire bombing of Hamburg. The Hamburg fire covered a region of 4 - 5 miles (Murgai, 1976). In addition, it has become evident that in many of these wartime cases, the collateral fire damage was significant when compared to the direct effects of the weapons (Pitts, 1989).

These examples of catastrophic fires all have involved burning regions of a large area with numerous or continuous fuel sources. They are generally classed as "mass" fires. There is no precise definition of a mass fire, but most might accept it as a flaming region of roughly 100 m in diameter. In terms of fluid mechanics, a fire that has mass fire properties might be described in which the turbulent flame height was small compared to the diameter of the fire. Mass fires can induce high storm-like winds and can possess a rotating column -- this has been termed a firestorm. Mass fires can be driven by high winds, spawning localized fire whirls -- this has been termed a "conflagration" by Countrymen (Pitts, 1989). All of this terminology is subjective and is the jargon of this subject area for large fires.

While some attempts have been made to study large mass fires, little systematic effort has been conducted nor sustained, and their behavior can not be predicted with certainty (Pitts, 1989). During the 1960's the Office of Civil Defense, along with the Forest Service, conducted the Flambeau project which was the most significant U. S. study of mass fires. The potential to predict the consequences of fire due to earthquake or war is empirical in the least, and their accuracy are not easily assessable. Although models have been developed, they all differ in aspects of fire growth mechanisms so that without clear experimental support, it is impossible to judge their validity.

In recent years, the prospect of Nuclear Winter (a reduction in the global temperature due to the resultant smoke cloud produced by a large scale nuclear war) has prompted more research on mass fires. In addition, the realization that wartime bombing damage was accompanied by significant collateral fire damage has motivated the

Defense Nuclear Agency (DNA) to initiate research on mass fires with the overall objective of predicting their development and fire products, especially smoke and its deposition in the atmosphere.

It is in this context that this mass research effort was initiated. As with other fields involving the need to study large scale phenomena, a strategy of study must evolve that encompasses many physical scales. It is nearly impossible to conduct fully controlled experiments of realistic urban mass fires, and the cost in time and effort of analysis would be enormous if the results are to be productive. On the other hand, it is impossible to proceed with alternative strategies without making careful observations of appropriate full scale phenomena. Only then can the phenomena be dissected into tractable theoretical and laboratory studies to more intensely and completely derive the information to accurately predict the whole. In this sense, this large scale experimental effort should not be looked upon as an end in itself, but as a means to an end. It should serve as the basis for more systematic research needed to establish the principles of mass fire behavior and their prediction.

This report summarizes a large mass fire experiment that culminated from experiences gained in similar mass fires studies in recent years. Those previous studies were motivated by the need to understand the production of smoke particulates relative to the Nuclear Winter Scenario, and more generally to address issues of environmental global pollution. The current experimental study has been an attempt to develop a more complete characterization of a large urban-like mass fire.

Motivation of 1989 Experiments

Early in the Spring of 1989, a group of Canadian and U. S. researchers were invited by the Ontario Ministry of Natural Resources (OMNR) to participate in a large prescribed burn of forest harvestation debris involving an area of approximately 480 hectares (1 ha = 10,000 m2). The ignition of this region would be done rapidly to enable the resulting fire to have a mass fire character. Based on this invitation, the DNA interests, and the momentum from recent joint USA-Canada similar experiments with an experienced ensemble of potential research teams, a decision was made by DNA to support a significant portion of the experiment. The DNA incentive was to obtain more information on the ground fire behavior as well as on the plume dynamics and smoke emissions. It was also felt that the potential large size of this prescribed burn would yield significant interaction with the upper atmosphere to provide much needed data on cloud smoke scavenging. Thus, this fire could simulate many of the characteristics associated with the interests of the DNA. Since the Canadian window for conducting these experiments was between July 20 and August 31, the experimental participants had only several months to develop their plans and instrumentation for the experiments. However many of the participants had recent field experience the year before and were poised and prepared to begin. The DNA objectives for the experiment were to explore mass fire phenomena, provide a database for models, develop new instrumentation concepts, and collect a comprehensive data set.

Although two experimental sites were included in the project, only the first prescribed burn will be reviewed in this summary report. The second burn at Hornpayne was completed, but only a limited number of instruments were deployed from the first experiment in Hill Township. Also all of that data from the second test have not been analyzed nor were made available. Since the second burn was only scheduled in this project to offset any significant problems of the first burn, its lack of review here should not be of concern.

Participants of Experimental Team

The participants of the DNA project consisted of several teams from government laboratories, universities, and private industry research institutions. The teams were established by preplanning with DNA, and by review of the team work plans. Several meetings were held to coordinate the experimental operations, and to solicit advice from the team participants and other interested groups. The team organizations and principal participants are listed below:

Defense Nuclear Agency (DNA): R. Hartley

Forestry Canada (FC): B. Stocks, D. McRae

USDA Forest Service (USFS): D. Ward, R. Susott, R. Babbitt

Pacific - Sierra Research Corp. (PSRC): K. Heikes, R. Small

University of Iowa (UI): F. Weirich

University of Washington: (UW), L. Radke

National Institute of Standards and Technology (NIST): T. Ohlemiller, J. Quintiere

Science Applications Incorporated (SAIC): J. Cockayne

In addition, the prescribed burn protocol and operations were conducted by the Ontario Ministry of Natural Resources (OMNR).

OBJECTIVES OF THE EXPERIMENT

General Objectives

The Canadian prescribed burn and mass fire experiment had several general objectives. The Canadians were interested in understanding how to perform prescribed burns for more effective reforestation, and to develop more insight into the dynamics of large forest fires. The DNA objectives were to measure and elucidate the characteristics of mass fires in terms of the ground level fire dynamics and in terms of the smoke emitted. The first DNA objective relates to the need to predict the damage due to fire growth, and the second objective relates to the need to improve the ability to estimate the atmospheric smoke obscuration at high altitudes. In particular, the prospect of obtaining high altitude cloud and fire plume interactive effects on the smoke accumulations was in the offing for this large area prescribed burn.

The ground level experiments were exploratory in technique and design, and the nature of the fuel and fire spread characteristics would only partially fulfill the representation of urban-like fires. In particular, the burning of forest debris, is far different from the burning of buildings and other aspects of the built environment. They would differ in burn times, fuel types, configuration effects of burning within and outside structures, and spread mechanisms. For example, forest fires fuels usually burn on the order of several minutes, while urban structures can burn for of the order of an hour. However, the interactions of ambient winds, fire induced winds, and the large forced-ignition burn area of this prescribed forest debris burn would be of direct relevance to mass fire characteristics in general. Hence a major aspect of the project was the measurement of wind velocities at numerous locations, and the development of data and analyses to make an estimation of the energy distribution rate of the fire and its geometrical pattern as a function of time. This wind field and energy release description was a cooperative task, and many of the team participants contributed to this objective.

Anyone who has attempted to make measurements of large scale phenomena, especially when that phenomenon is transient and subject to the influence of nature, realizes that no general fundamental results are likely to emerge. In particular, these mass fire experiments are fraught with difficulties of instrument deployment and operation. They are field-based as opposed to laboratory-based, and in this case at a remote site. The geographic domain of measurement is over 1000s of meters, and the experiment is subject to the uncontrolled natural environment. Despite these limitations and challenges, the teams met their individual objectives with cooperation, efficiency and a strong dedication to safety.

It was hoped that the measurements and acute observations would serve to reveal the overall character of the fire phenomenon, to yield representative values of its significant properties, and to display features that might otherwise be overlooked by initial conceptions or small scale studies. Thus, such large scale experiments are necessary to achieve a valid realistic characterization of the phenomenon, and to provide a basis for rationale mathematical and laboratory studies.

Such a process of utilizing a large scale experiment to elucidate phenomena and develop concepts can feed more fundamental studies on various aspects of mass fire phenomena. It was hoped that this mass fire experiment would serve as the basis for a long range research program on mass fires that would eventually produce validated predictive models on urban fire spread.

Principal Objectives of the Team Participants

The Team participants will be designated throughout this summary report by the initials previously given. Each of the individual groups laid out a series of objectives based on the overall objectives of DNA, and on their expertise. Their detailed objectives are more fully described in their individual reports referenced herein, and from which this summary report was drawn. Their more principal objectives are described below.

Forestry Canada (FC): Their principal objectives were to make pre- and post-fire measurements on fuel sections in order to estimate the mass consumption rate of the fuel. This was supplemented by infrared (IR) television recordings of the fire from a hovering helicopter to capture the flaming and smoldering regions of the complete fire.

Horizontal wind speed was measured at eight locations around the perimeter of the experimentation fire region. An aircraft was also used to measure the rise of the initial fire plume.

USDA Forest Service (USFS): The principal objectives of the USFS group was to characterize the fire properties near the ground, and to test new remote measurement techniques in the harsh fire environment. Using a pentagon array of 14 m high towers, temperature, velocity, primary gas specie composition, and particulate concentration were measured. The gas and particulate sampling and instrumentation was specially designed to function in the flaming environment, yielding both real time and bag sample collection data. These data would be used to estimate the emission rates of species, soot and energy at the ground level. They continuously recorded specie data included CO, CO_2, and O_2. The design and construction of the gas and particulate instrumentation was a significant objective of the USFS team since this instrumentation was unique and tailored to the harsh particular environment of the prescribed burn fire scenario. Video records at the tower locations were also made to record the flame features.

Additional measurements were made to determine the electric field characteristics of the fire plume and resulting cloud, and stereophotography was used to determine initial characteristics of the developing fire plume.

<u>Center for Fire Research, (NIST)</u>: The NIST principal objectives were to estimate the energy release rate of the fire, and compute its associated induced wind field. Detailed analyses would be made, using the FC data and supplemental field and laboratory measurements, to estimate the fire energy release rate as a function of time. From these energy estimates, an existing model to compute fire induced winds would be executed, and the results compared to the available ground level horizontal wind measurements.

<u>Pacific-Sierra Research Corporation (PSRC)</u>: The principal objectives of the PSRC team were to develop data to support the use of a turbulent mass fire plume model, and to investigate the potential for fire growth across simulated "streets". In three L-shaped tower arrays distributed through the central experimental fire region, velocity, temperature and video data were taken. These would be used to develop turbulent modeling parameters for a mathematical model to compute the dynamics of the fire plume. Also an array of fire breaks to simulate "streets" of widths 5, 7 and 12 m were constructed and measurements were taken to examine the fire spread mechanisms for potentially breaching these "streets".

<u>University of Iowa (UI)</u>: This group assisted in executing the PSRC velocity and temperature measurements as well as deploying supplemental measurements. They also examined the calibration of the thermal anemometers, and the response of shielded versus bare thermocouples. Subsequently, they were given the task of unifying all of the ground horizontal wind speed data and overlaying it on a topographical map of the region. This wind field presentation is not available now and will be presented in a separate report later. Both the UI and PSRC towers included video cameras to record the local flame features.

<u>University of Washington (UW)</u>: A number of sophisticated measurements were made from a C-131A aircraft flying in and around the fire plume. Their principal objectives were to measure the particulate emissions, their size distribution, the cloud water droplet characteristics, their interaction with soot, and the mechanisms for soot removal from the atmosphere. They also examined gas species, and characteristics of particulates emissions, and trace species. A LIDAR was used to image soot particulates downstream of the fire plume

and capping cloud. This backscattering technique was used to gain some insight on the soot distribution in a vertical cross section of the dispersed smoke. Also an IR television camera was employed to examine the extent of visualizing ground features through the smoke column.

In the next section, we will begin with a description of the experiment. This will address the nature of the burn site, the principal experimental measurement arrangements of the teams, and the prescribed burn scenario. Then selective results will be presented based on measurements and analyses. The details of the measurement methods and analytical methods can be found in the team reports contained in the References. Where appropriate, results will be related and compared, but no in-depth analysis will be attempted to examine their consistency. The results will include the dynamics of the plume and cloud formation, the computation of the fuel energy release rate, the ground wind field, characteristics of the fire spread environment, and the combustion product emissions and subsequent cloud effects. Based upon the specific elements of the experiment and its general results, some conclusions and recommendations will be made.

DESCRIPTION OF THE EXPERIMENT

Mass Fire Site

Location.

The location of the prescribed burn was approximately 20 km northwest of Chapleau in Ontario, Canada. The site is in the Hill Township, and the experiments will subsequently be referred to as the Hill or Hill Township mass fire experiments of 1989. The prescribed burn site consisted of approximately 480 hectares (ha) and was divided into four blocks of nominally 80 to 140 ha each for successive burns. The general location of Hill Township and the demography of the blocks, labelled A, A1, B, and C, are shown in Figure 1 (USFS).

Forest Type and Fuel Nature (FC).

The forest fuels consisted of balsam fir, spruce, trembling aspen and white birch with shrubs of mostly mountain maple and hazel. The area had been harvested and tramped several years ago to prepare it for a prescribed burn and eventually reforestation. The tramping process levels the dead trees and in this case the bulldozing led to windrows of forest materials (slash). The windrows consisted of rough uneven rows of woody debris separated by rows of lower fuel loads. Figure 2 (NIST) shows a typical section of the fuel character in Block A. The area had also been sprayed as late as 1988 to eliminate the shrubs.

The available fuel consists of the dead branches and logs in random layers of nominally 1 m in height referred to as slash, and the accumulated leaf litter and forest floor debris known as duff. The moisture content of the slash ranged from 16 to 38 %, and increased with depth in the duff from 44 to 86 % (based on percent of the oven dry weight).

Geography (FC).

The topography of the area consisted of rolling terrain. In particular for block A where nearly all of the instrumentation was located for the ground fire measurements, transit data over the area suggest elevation changes of up to 35 m with relative flat regions throughout. Elevations relative to tower A in Figure 3 place the USFS instruments at 22 m, triangle 3 at 28 m, and triangle 10 at 30 m, for example. The general fire location is approximately at 450 m above sea level. Mal lake bounds a portion of the northern boundaries of Blocks A1 and A, and a small marshy wet region is centered in Block A.

Experimental Design and Implementation

Ground Measurements.

Figure 3 (PRSC) shows an overview of the measurement sites in Block A, the instrumented Block of the prescribed burn region. The triangles indicate the locations at which the fuel mass samplings were taken along with temperature data in order to determine the fuel consumption rates (FC). The perimeter (FC) and interior (UI) towers principally recorded horizontal wind velocities at nominally 10 m above the ground. The PSRC fire dynamic array, an L-shaped tower array (Fig. 4), and pictorially illustrated in Figure 5, measured velocities and temperatures. The USFS fire chemistry pentagon tower array (Fig. 6a) contained temperature, velocity, and gas measurement instrumentation as shown in Figure 6b (USFS). Real time measurements were made of O_2, CO_2, and CO. Particulates of less than 5 um were collected on filters, and time interval gas samples were collected for more complete subsequent analytical analysis. Several of the towers in the USFS array contained video cameras to record the local flame characteristics as they advanced through the tower monitoring stations. Video records were a vital element of the tower measurements to enable the possible correlation of the local measurements with the combusting regions. This was a key objective of the fire spread array (Fig. 3) to indicate the fire spread characteristics for traversing the simulated "streets".

The USFS team set up two additional measurement objectives. Stereophotography was employed from a distance of approximately 7.5 km from the burn site. These photographs would be used to obtain quantitative dynamic geometrical and kinematic measurements of the smoke plume. The other measurement objective was to determine the electrical charge characteristics of the fire generated smoke plume.

Airborne measurements.

The primary airborne measurements were taken from the University of Washington's Convair C-131A by Radke's team. This aircraft has been designed with a sophisticated array of specialized instruments to measure the gas species and particulate properties in the smoke column at altitudes up to the top of the fire plume and resulting cloud formation. The full array of instruments are too numerous to describe here, but more information can be obtained from the UW source report on this study. Principal measurements included particle size (0.005 to 45 um) and particulate concentrations, particulate scattering and extinction coefficients, particulate morphology and chemistry, and trace species analysis of time integrated samples. The aircraft also contained two instruments that only have been used in an exploratory and a qualitative manner. These consisted of a LIDAR imaging device employed to measure the backscattering of soot particulates in a vertical cross section along the windblown plume axis downstream of the capping cloud. The other instrument was a "forward looking infrared" (FLIR) video camera to assess the ability to see the fire through the smoke column from high altitudes.

Seven atmospheric soundings (rawinsondes) were launched during the Hill burn on August 10, 1989 at periodic intervals during the course of the fire starting at 14:23 EDT and ending at 18:42 EDT. These data included temperature, pressure, relative humidity, wind velocity and other standard weather parameters. The complete set of data are available in a report by Rangno and Radke (1989) listed in the References.

Comments on Instrumentation.

A review of the type and appropriateness of the instrumentation used by the teams will not be made in any detail here. However some comments are needed in order to gain some appreciation of the results to be presented. Needless to say, some of the instruments did not perform as intended in the harsh environment of the fire, in some cases, due to the difficulties with the use of battery powered field instrumentation and data recording. All ground instrumentation packages were self-contained with protected individual power supplies and data loggers.

The USFS team were ingenious in designing and implementing a remote automated gas and particulate instrumentation package. These survived the fire conditions and appeared to yield generally good data; however, drift was a problem with some of their continuous gas concentration monitors.

The velocity instrumentation used by the teams varied in type from turbine triaxial anemometers to standard cup vane wind monitors. Most performed well during the experiment. The PSRC team used a thermal anemometer, which did not respond well during their exposure to direct flames. Some of the other anemometers failed also due to heating, and corrections for temperature effects were not generally made to the velocity data. Improvements in techniques for measuring velocity to characterize the flow field of mass fires is sorely needed. Intrusive intensive techniques can be made to work better, but global remote techniques to address the flow field in the smoke plume need to be explored.

The empirical technique to measure the mass loss in the triangular sectors has a proven foundation, but its general accuracy or completeness in determining the fuel consumption rate is lacking (NIST). New techniques or further research on the triangle mass consumption methodology is needed.

The measurements by the UW team in the aircraft are based on years of experience with sound instruments, but the violent turbulence and cloud adverse weather conditions challenged the crew and the instruments in the Hill fire.

Ambient and Initial Conditions.

The experiment was begun on August 10, 1989 at approximately 13:55 Eastern Daylight Time (EDT). All time clocks on automated instruments and those for general field use were synchronized by Darold Ward (USFS) to EDT, and all data presentations and analyses are reported in this time base. The fire safe window for this prescribed burn was preceded by several weeks of dry weather which delayed the experiment until sufficient rain fall occurred to bring the region into a safe prescription as determined by OMNR. At the time of the test the ambient temperature was nominally 26 C with winds of approximately 3 m/s out of the west. The sky was clear with a few widely scattered cumulonimbus capillatus clouds. The rawinsonde data initiated at 14:23 EDT is most applicable to the initial period of the fire and the instrumented fire growth period. Its data indicated that the atmosphere was superadiabatic through 900 mb or over the first 300 m (an elevation above sea level from 457 to 757 m), neutrally stable up to 2.5 km above sea level, and unstable above that level. An excerpt of some of the atmospheric sounding data are listed in Table 1 (Rangno and Radke, 1989). These ambient conditions generally prevailed through the duration of the instrumented phase of the fire, except where the fire had local effects on the surroundings.

Table 1
Excerpts of Rawinsonde Data No 3.
Como Lake, Hill Township, 14:23 EDT

Elevation above Sea Level	Pressure	Air Temperature	Relative Humidity
m	mb	C	%
457	966	26.0	49
1190	887	14.4	62
2040	801	8.0	94
3020	711	0.9	78
4150	617	-6.0	55
6320	464	-18.3	34
7330	405	-26.0	15
9430	300	-43.3	43

Burn Scenario.

The nature of the ignition and fire growth scenario was dictated by the operating and safety procedures of the OMNR who were in charge of the prescribed burn. The best strategy to achieve the DNA objectives was considered, and the following scenario was implemented. The OMNR ignition technique is to drop flaming jelled gasoline from a helicopter in a radially outward spiral pattern, eg. see Figures 7 and 13. This technique leads to converging fire rings, and the radial induced fire winds tend to counteract any ambient wind that could potentially drive the prescribed fire in an undesired direction. Also this technique tends to encourage a large area fire, or simulated mass fire condition, due to the rapid ground fuel ignition and spread behavior despite the relatively short flaming time of the forest debris fuel.

Because of the prevailing westerly winds and the desire to initiate a large mass fire before the instrumented Block A was affected by flames, the east region, Block A1 was ignited first at 13:50 EDT. In approximately 40 minutes Block A1 was completely involved, and the helicopter ignition activity ceased there by 14:18 at which time the ignition process was begun in Block A. The plan for initiating the fire in Block A was to centrally begin the fire in the vicinity of triangle 10 as illustrated in Figure 7. This initial fire was developed over a several 100 - 200 m diameter circular region, then an outer ring was initiated to the north and west of the USFS and PSRC fire tower arrays. This fire arrangement together with the prevailing westerly winds would cause the outer ring fire region to spread over the tower arrays towards the centrally ignited area. This insured the desired conditions for assessing the character of the fire dynamics consistent with the ground monitoring objectives. As anticipated the fire spread from the outer ring, generally west to east, through the tower arrays and across the simulated street spaces. The flames reached the fire spread array (Figure 3) at 14:33, and that region was fully involved in flames by 14:35. Subsequently, Blocks B and C were burned, but little relevant data were taken with respect to the period of those fires. Most monitoring stations recorded data up until about 18:00, at which time the instrumented sites were examined in Block A and the data loggers and instruments were retrieved.

EXPERIMENTAL RESULTS AND ANALYSIS

As stated earlier, the major results of the mass fire experiment will be reported as described by the team reports listed in the References. Comparison of results by different sources will be presented, but no critical evaluation of their analyses or measurement techniques will be developed. We shall describe the experimental results in terms of the significant aspects of the Hill Township mass fire experiment. These features will include the dynamics of the fire plume, the determination of the fuel consumption rate and the corresponding induction of the ground winds, the characteristics of the fire spread, and the emission of gas species and particulates with the associated dynamics of the cloud processes.

Plume Dynamics

The dynamics of a plume from a large mass fire can not be separated from atmospheric effects. The two are interdependent to some extent on a local level. The plume behavior will depend on the vertical distribution of temperature, humidity, and wind velocity. The fire behavior will depend on the local ground level winds and fuel characteristics. The plume buoyancy and composition will depend on the size of the fire and its rate of burning.

The effects of wind on the trajectory of the fire plume will cause the plume to bend and its horizontal cross section to change from circular to a horseshoe shape. This is due to the interaction of the wind shear and the buoyant force of the plume. Generally a plume will rise in a stratified atmosphere until it reaches a height of neutral buoyancy at which it will flatten out and disperse in the ambient wind. Due to atmospheric moisture entrained into a plume of a large (mass) fire, a capping cloud can form at a high altitude once the plume temperature achieves the saturation point. The initial thermal energy generated by a small fire will determine the level a plume will reach in a stably stratified atmosphere. For large mass fires, this ultimate height can be considerable as illustrated by the sketches in Figure 8, and depends, as well, on the magnitude of the ambient wind and the vertical temperature and humidity distribution of the atmosphere. These latter parameters determine the stability of the ambient atmosphere which has a marked effect on the ascent of the plume. In addition, as saturation is achieved in the plume, the subsequent condensation process actually gives additional buoyancy to the plume since the thermodynamic energy of condensation is transferred to the plume gases. This condensation process led to the production of a cumulus cloud for the Hill Township fire which soared to 7 km.

Figure 9 shows the early development of the plume associated with the fire initiation in Block A1. This photograph was taken at approximately 14:10. It clearly shows the large eddy structure of the plume which is comparable in scale to its diameter. The formation of capping cloud can also be discerned in the picture. The large perimeter eddies of the plume rolled up and shed periodically. Small scale laboratory correlations, for pool fires up to 50 m in diameter, suggest that the eddy shedding frequency is inversely proportional to the square root of the diameter (Pagni, 1989). For a fire of 1000 m in diameter, the period of eddy shedding is 21 s from such a correlation, and this is consistent with observations of the Hill fire and plume conditions at this time.

A very dramatic aspect of the fire initiation was the nature and rate of the plume ascent in the atmosphere. Two measurement sources (FC and USFS) provided data on the plume elevation as a function of height with respect to sea level. These are shown in Figure 10 where the initial climb data are in close agreement, but the equilibrium position of the cloud top varies between 6 and 7 km.

An attempt to simulate some aspects of the Hill fire were conducted by the PSRC team using a two-dimensional plume model and the rawinsonde (UW) data for temperature and humidity through the depth of the atmosphere. Their computations for a 3 km base diameter fire showed a plume rise to 6 km in 30 minutes, and capping at that altitude later in time. Although this computation does not simulate all aspects of the actual fire, these results appear to be consistent with the Hill fire characteristics.

The Hill fire was of sufficient intensity to produce a mature thunderstorm. Precipitation was evident in the capping cloud very early, and light showers reported downwind of the capping cloud. By 14:54 hail of several mm in diameter was recorded by the laser camera of the UW aircraft (Fig. 11a). Shortly later, snow flakes were also observed as shown by the particulate shapes of the laser camera records in Figure 11b. At this same period, lightning discharges began to be recorded by the electric field mill monitoring station 1 km from the fire and by the Ontario Province lightning network and continued through until approximately 16:30 (USFS). Sixteen cloud to ground discharges were noted downstream of the fire plume and capping cloud. The electric field measurements indicated a positive cloud-to-ground polarity of these discharges that are not expected of normal thunderstorm systems. This phenomenon was of curious significance, and may be associated with the fire effects.

At 14:20 the fire had been underway for 30 minutes in Block A1, and the fire was ignited and began to spread in Block A. In addition to the westerly ambient wind, the fire induced winds of each fire undoubtedly produced a complex distribution of ground winds. These events are somewhat depicted in Figure 12. This shows the early dark smoke of the fire beginning in Block A and its plume affected by the ambient wind as well as the entrainment of the adjoining fire in Block A1. Even before this time, fire whirls and water spouts on the small lakes adjoining the fire blocks were noted by ground observers. The water sprays of these spouts were estimated to reach at least 10 m in the air.

Fuel Consumption Rate

The fuel consumption rate or energy release rate was viewed as one of the most important parameters of the experiment. The nature and magnitude of this energy release is the driving force of the mass fire. It is a necessary data parameter in order to characterize this fire and would be required input data for any predictive modeling of the plume. Its magnitude would allow future investigators to classify this fire in terms of its relationship to urban mass fires. The induced winds and the dynamics of the plume behavior in the atmosphere are all direct consequences of the rate and distribution of energy release.

Since the fire energy release rate is so important, and since it is impossible to make any direct measure of this dynamic parameter, it was not deemed redundant to have several of the teams pursue this estimate.

Model Variations.

The FC and NIST teams both used the mass loss data from the triangle regions (Figure 3) supplemented by thermocouple measurements, and the IR images of the FC helicopter (See Figure 13). The USFS team based their estimation on local near ground measurements of the production of carbon combustion products as measured by their gas and particulate monitors. This also required the use of their vertical velocity data, and the assumption of only a vertical carbon mass flow rate. Figure 14 shows the USFS results for the local consumption rates determined from the carbon balance method for the four tower stations in their instrumentation array. These results were averaged in their analysis.

Sources of Uncertainty in the Models.

Each of these methods of estimation have numerous points of uncertainty which affect the accuracy of the results. Despite these questions it will be seen that the estimations are in relatively reasonable agreement. Some of the sources of uncertainty include the selection of the flaming and smoldering times, their distribution over the fuel stick nominal diameters and the duff layer, the interpretation of the IR images in terms of scale dimensions and the resolution of smoldering and flaming, and the selection of the heats of combustion for these different burning modes and configurations.

1. Heats of Combustion.

In subsequent laboratory measurements of the burning characteristics of the Hill fuels, NIST found that the heat of combustion of the wood (twigs) was 12 -15 kJ/g in flaming and 16-32 in smoldering; while the duff layer samples varied from 12-14 in flaming and 6-7 in smoldering. The FC team used these nominal values, the NIST team corrected these down further to include the higher moisture levels of the actual wood under the Hill experimental conditions, and the USFS deduced and used an overall value of 19 kJ/g for all modes of burning.

2. IR Imaging.

Figure 13 is a tracing of the IR fire image in Block A several minutes after its ignition. The enclosed regions forming the spiral shape represent the flaming and smoldering fuel areas. Such plots were used to develop the burning area as a function of time. However the lack of precision in assigning flaming and smoldering times to the various size woody fuel components, creates uncertainties in the various modeling analyses.

3. Flaming times.

For example, NIST interpretations of thermocouple data could suggest that flaming times of the wood slash (sticks) might be selected anywhere from 150 to 550 s corresponding to flaming temperature criteria for the gas phase thermocouples of 700 to 300 C, respectively; whereas an analysis of the video tapes suggested an overall global flaming time, based on a 50 per cent area coverage criterion, of nominally 240 +- 140 s. Hence there is some ambiguity or, at least variations for the various fuel sizes, in the flaming time.

4. Smoldering versus Flaming.

In all of the analyses, the components of energy release due to flaming and smoldering were very comparable, with smoldering surprisingly being dominant over many periods. Although the significance of the smoldering contribution is unquestionable, the NIST team questioned the conventionally available forest fire research data which states that the wood fuel logs in excess of 7 cm diameter contribute significantly to the mass consumption rate of the fuel primarily through smoldering. This was counter to the NIST experience in the smoldering of wood in the laboratory. Hence, NIST in one of its three models, the "alternative exponential model", de-emphasized the large log contribution which led to a 50 per cent reduction in their estimate for energy release rate.

Results for Block A.

A composite of the energy estimates are shown in Figure 15 in which three NIST models, varying in complexity and assumptions are presented, as well as the FC and USFS models. Although the accuracy of each are not assessable, their agreement with each other to within 50 % suggests that these results may be reasonably valid. Therefore, a mean curve has been drawn through the data to orient the reader and to suggest a representative energy output based on these approximate, but independent methods. In applying the USFS results, a starting time of 14:19 for the fire in Block A was imposed on the USFS calculations since their report started the curve at a relative time of zero. Since it would be impossible to obtain any direct measurement of this important parameter, energy release rate, these multiple calculations represent a credible base for future modeling and analysis of this mass fire experiment.

Ground Winds

The ground level winds were measured in many places within and around Block A. The UI team has an effort in progress to aggregate all of these data and present them as a function of time and position. Therefore, since that is not complete only a sample of results will be presented. The most reliable data is probably the cup anemometer results used to measure the horizontal wind velocity component. A typical trace, taken from the UI tower at Site 1 (UI-1) as shown in Figure 3 is displayed in Figure 16a along with the direction in Figure 16b. The results show the velocity is out of the west and increases from nominally 5 m/s to 12 m/s after the flames reach the tower at approximately 14:40. This is the pattern of much of the horizontal wind data, but a more detailed overview will have to await the UI compilation. It is clear that the fire caused the ambient wind field to more than double, a significant effect since in more common terms, this is of the order of 25 mph. Hence the destructive force of a large urban mass fire can clearly be appreciated.

An attempt to compute the ground wind field was made by the NIST team using a model previously developed by Baum and McCaffrey (1989). This model uses a reliable correlation for the velocity distribution of a fire plume developed from extensive comparisons with experimental data for pool fires of up to 30 m in diameter. Using this correlation to represent the energy release rate and vorticity of a series of fire plumes to simulate the distribution of this mass fire at an instant of time, it computes the velocity field in the ambient field surrounding each of the plumes near ground level. The model does not include any consideration of high altitude atmospheric effects. By superposition of this computed velocity field with the ambient initial wind, it has computed the velocity at several perimeter measurement stations of the Hill fire. Some of these FC perimeter stations, C, D and E, are shown in Figure 7. The computations have been done for three times as shown in Figures 17 a, b, and c. These represent the horizontal velocity components with the computed values indicated by the extent of the line with the half arrow head, and the measured value the other line without the arrow. The model accounts for the effect of the fire in Block A1 as well as the developing fire in Block A. In running the model, it was found that the results were somewhat dependent on the number of plumes used to describe the fire distribution. Although no definitive study was made on how to optimize this description, the best results of several iterations is shown in Figure 17. Overall, the magnitudes of the computed velocities are in good agreement with the data, and their directions are also reasonable. Indeed, the computed results for direction appear somewhat more plausible than the experimental results, but this could be due to the fact that the model does not account for topography. Incidently, the strategy of implementing the plumes was to use the least number of plumes to describe the burning pattern as derived from the IR image for Block A, and Block A1 was approximated very crudely by using five plumes. Despite the ambiguity on how best to implement the plume distribution for representing the mass fire, this model gives useful approximate results that could be used to estimate the destructive wind effects of mass fires in general.

Ground Fire Dynamics

The spareness of the ground level measurements relative to the area of fire involvement and the nearly random distribution of fuel and the flame pattern make it difficult to generalize from the tower measuring stations. The USFS, PSRC, and UI teams have developed many channels of continuous measurements of temperature, gas concentrations and velocities along with video records of the fire dynamics around the tower arrays. Correlation of these results to distinguish clearly between the combusting flame regions and the non-flaming ambient regions offers the prospect of deducing some general aspects of the burning conditions within a mass fire. Such distinctions could be relevant to the problem of urban mass fires since the urban setting would have the characteristic of discontinuous fuel arrays. However the level of effort for this program was insufficient to provide intensive analyses to better characterize the flame and local environmental conditions of this mass fire at this time. But some limited results to illuminate the internal ground level fire conditions will be reported, and more details are available in the team reports.

Flame Velocities.

The FC team report, from the IR image analysis, that the flame front velocities ranged from 0.1 to 1 m/s, and this is consistent with the USFS analysis by local tower video records. These flame propagation velocities are high and are consistent with the wind velocities of up to 12 m/s.

Flame Heights.

The flame heights are reported to have ranged from 8 to 12 m as the fire swept through the tower arrays. Thus, in many instances the highest measuring station on the towers were above or just in the tip of the flame.

Oxygen Levels.

For turbulent fire plumes in still air the amount of excess stoichiometric air relative to fuel at the flame tip is roughly 10. With increased mixing for wind blown fires, we would expect even more excess air at the flame tip. This is supported by the USFS measurements of oxygen at 8 m above the ground which showed that the oxygen concentration only dropped by 2 per cent at most.

A more important consideration on the oxygen is its availability in the local atmosphere surrounding the packets of burning fuel within the core of the fire. This is where the flame attempts to obtain its oxygen by entrainment. An example of data from the USFS ground measurements gives some insight on this issue. Figure 18 clearly shows that the oxygen sensors at 0.5 and 1.5 m above the ground are within the combusting region of the flame during the period when the temperatures are at least 500 C. The oxygen levels over that time period fall to as low as 40 per cent of that of air, or to a low of 8 % concentration. Again this concentration is indicative of high excess stoichiometric oxygen even at this low height in the flame. This figure also indicates that the flaming period is approximately 2 minutes. Following this period, the ground level temperatures are indicative of the wind blown combustion product gases and the effects of both upwind flaming and smoldering conditions. The corresponding oxygen concentrations are above 19 %, and may be nearly at air level values since electronic zero drift effects were present with these sensors. Hence these results suggest that for this fire, the atmosphere within the core of this mass fire from which available oxygen could be obtained was only sightly below normal air level concentrations.

Another indication of the vitiation or the reduction of oxygen in the surrounding flame atmosphere is the completeness of combustion. This can be reflected in the ratio of CO to CO_2 measured in the combustion products produced by the flaming and smoldering processes. Generally, for wood fuels this ratio for flaming conditions in air is of the order of 0.002, and can be as high as 2 in pure smoldering. Values measured by the USFS in their tower gas monitoring stations yield ratio of 0.02 to 0.1 which are much higher than expected for pure flaming conditions in air, but suggest the additional contribution of smoldering conditions.

Hence these experimental results for the Hill fire suggest that they are indicative of a combination of flaming and smoldering combustion products. A general characterization of the vitiated state of mass fires and their completeness of combustion can not be determined from the Hill data alone. The UW team report that in a previous prescribed forest debris burn that the CO/CO_2 correlated with oxygen concentration at or within 100 m of the ground. Of course such correlations would tend to hold in the combusting region more than in the plume itself. These previous results are shown in Figure 19. In summary, it would appear that the Hill fire had sufficient oxygen available with its core, and vitiation was not a factor. It is not apparent that this is a general characteristic of mass fires, as might be suggested by Figure 19.

Fire Spread across Gaps.

Finally, we comment on the ability of the fire under these wind conditions to jump across the simulated street breaks. These results were not conclusive since the video record in that PSRC/UI fire spread array did not produce useful data. Further analysis of the overall data in that array might produce some results on the nature and rate of spread over the breaks, but no general results are possible from the Hill data.

Smoke Emissions and Cloud Effects

Carbon Smoke Yields.

The carbon bearing particulate matter was measured both at the ground level (USFS) and in the plume-cloud system (UW). These were both done by collection of the particles on filters, and by a carbon mass balance method based on a 0.5 carbon fraction in the woody fuel. The ground level USFS measurements for particles less than 5 um ranged from 7 to 14 to 25 g/kg of fuel mass loss corresponding to their specified periods of flaming, intermediate and smoldering. These periods did not necessarily correspond to the actual times of these burning modes, but the results can be interpreted to represent the limits of smoke particulates emitted for the early flaming period and the later smoldering dominated period. No such distinction for the burning modes could be made for the cloud airborne data. These UW results for particles less than 3.5 um averaged 10 g/kg with a standard deviation of 6 g/kg. It would appear that the ground and airborne data are very consistent.

Chemical Nature of Smoke.

Chemical analysis of the particulates by USFS showed that the carbon is mostly in "organic" form rather than "graphitic" which implies that the particles are likely to be liquid tars rather than soot. This particulate composition is indicative of smoke generated under smoldering or pyrolytic, non-flaming conditions. For the Hill fire conditions, we already know that smoldering dominated the fuel consumption process so the smoke composition is consistent with those burning conditions.

Smoke Optical Properties.

The UW team also report results for the optical properties of the particulates. They determined an average scattering albedo (ratio of the scattering to extinction coefficient) of 0.84, and a value for specific absorption coefficient (or area) of 0.59 ± 0.22 m_2/g. These results correspond to a value of specific extinction area equal to 3.7 m^2/g which corresponds to "white" smokes or smoke from smoldering conditions. This value compares to a generic literature value of 4.4 which is often cited as representative of nonflaming smoke (Mulholland, 1988). In considering the above results, it was presumed that the UW measurements for these particulates are below the cloud level or that the condensed water droplets have been filtered from these smoke samples.

Smoke and Condensed Matter Size Distributions.

Size distribution measurements were made by the UW team characterizing the carbon based particulates and the water droplet formation in the capping cloud. The carbon based particles are described in Figure 20 for two times of (A) 30 and (B) 70 minutes following ignition of Block A1. The change in the distribution for particle diameter and volume could be due to the increase in smoldering for the B curves. The water droplet distribution curves are shown in Figures 21 and 22 for near cloud base at 14:30 EDT and at 14:37 EDT, 100 m above the cloud base. The UW team believe that the results at the cloud base are primarily due to ash and soil debris while the distribution at the later time is likely associated with precipitation for the millimeter sized particles.

Cloud Scavenging of Smoke .

Some preliminary analysis of the data for the Hill fire show an overall efficiency in removing carbon based particulates below 1 um at nominally 40 %. This scavenging efficiency due to cloud processing and precipitation is generally a function of particle size as illustrated in Figure 23 for another biomass fire. The UW team draw the general conclusions that supermicron smoke particles are removed in a capping cloud with high efficiency, and submicron particles are scavenged with an efficiency of 30 to 90 % in precipitating cumulus clouds. Since capping clouds are a consequence of all large fires, these results suggest that a significant amount of the smoke particles would be scavenged by the cloud. These results are important to the Nuclear Winter modeling effort and to making accurate predictions for these cloud-particle interactions.

Smoke Deposition in the Atmosphere.

Although results of the LIDAR are preliminary and still being analyzed, the data of the UW team show that the smoke particles in the Hill fire detrain, or leave the capping cloud, at an altitude of approximately 4 km. This is in contrast to the height of the capping cloud reaching 6 to 7 km which clearly shows that the smoke and the cloud boundaries do not coincide. The UW team concludes from this that if the fire capping cloud does not reach the stratosphere with its high velocity winds, then the smoke will be deposited at a much lower altitude than the top of the capping cloud.

Trace Specie.

Trace gas and element emission factors were estimated by both the UW and USFS teams based on chemical analyses of their collected samples. These include a wide range of species and elements including most notably O_3, NH_3, CH_4, NO_x, K and Ca. More details and the implications of these airborne substances can be found in the UW and USFS team reports.

SUMMARY OF RESULTS

The experimental prescribed burn began with prevailing winds from the west of 3 m/s. The fire in Block A1 caused a plume to rise to 6.5 km in 20 minutes, and achieve a nominal diameter of 1 km in a flaming and smoldering condition. The PSRC had some success at predicting the plume rise. The fire began in Block A approximately 25 minutes later and began to trigger the ground instruments. The Block A fire achieved an energy release rate of nearly 50,000 MW in 15 minutes which is believed to have been dominated by smoldering combustion. Fire whirls and water spouts were observed.

Ground level horizontal winds increased as a result of the fire to 12 m/s (approximately 25 mph) suggesting the potential destructive nature of mass fire including the possibility of fire whirls and brand transport. The NIST team exercised a model which gave fair to good results for predicting the ground wind field from the fire configuration.

The fire spread rate through the forest debris fuel bed achieved levels as high as 1 m/s under these wind conditions. Flames reached as high as 12 m. However ground level oxygen concentrations in the region surrounding the flame only dropped to 19 % at the least. The relative levels of CO/CO_2 and the specific extinction area of the smoke particulates suggest that the combusting products of this fire were significantly influenced by smoldering combustion.

The cloud effects caused precipitation, lightning, and even snow flakes. The estimation of the cloud processing in removing smoke (carbon) particulates below 1 um is nominally 40 % and perhaps higher. LIDAR data suggest that the smoke detrained at an altitude of 4 km from the capping cloud despite its ascent to nearly 7 km. Airborne trace specie samples show an interesting array of components that bear generally on global environmental effects.

Overall the experiment was a successful and safe undertaking. Most of the instruments worked and gave useful data. Analyses have been made, and a large database exists from which, it is hoped, future analyses can be developed.

CONCLUSIONS

The results of this fire provide a fairly complete description of the fire and its surroundings which should provide the basis for generalizing the characteristics of mass fires and for assessing predictive models in the future. Significant large scale phenomena have been identified that could not necessarily been identified by models or with laboratory studies alone. The quality of the data is good, and forms a fairly complete database for a simulated mass fire. The overall results appear to be reasonably consistent, especially where comparable results were obtained by different methods.

In general, a complete study of mass fires must go beyond the scope of this experiment. A large scale experiment falls short because it does not provide the means to systematically study the important phenomena over a range of the variables that apply. Such experiments are not sufficient in themselves to shed needed information for constructing sound and complete predictive models. Aspects of this mass fire experiment and its results must be dissected and studied in the laboratory and analyzed through focused mathematical models. Scaling studies can be fruitful for some features of the phenomena. Before significant new large scale experiments are considered, it would be desirable to review the quality of the instrumentation currently available, explore new concepts in instrumentation, and consider the best configuration and scale to match the urban fuel environment. There is no doubt that the Hill Township fire was a successful enterprise and the results contained in the team reports should be studied further and critically reviewed in planning new experiments or projecting new analyses.

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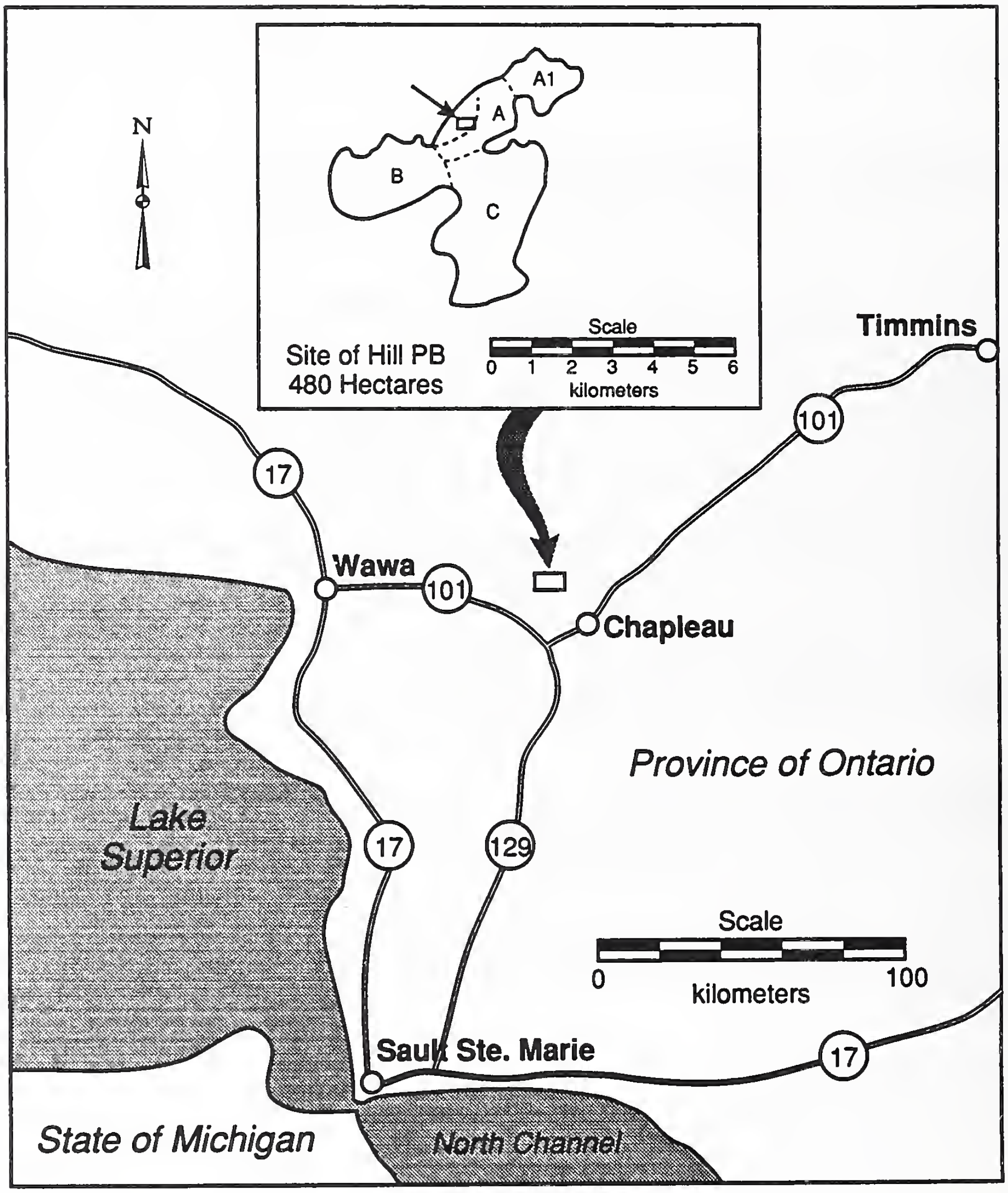

Figure 1. Location of the Hill Township prescribed burn relative to Chapleau and Sault Ste. Marie, Ontario, Canada (FC).

Figure 2. Nature of the fuel load (NIST).

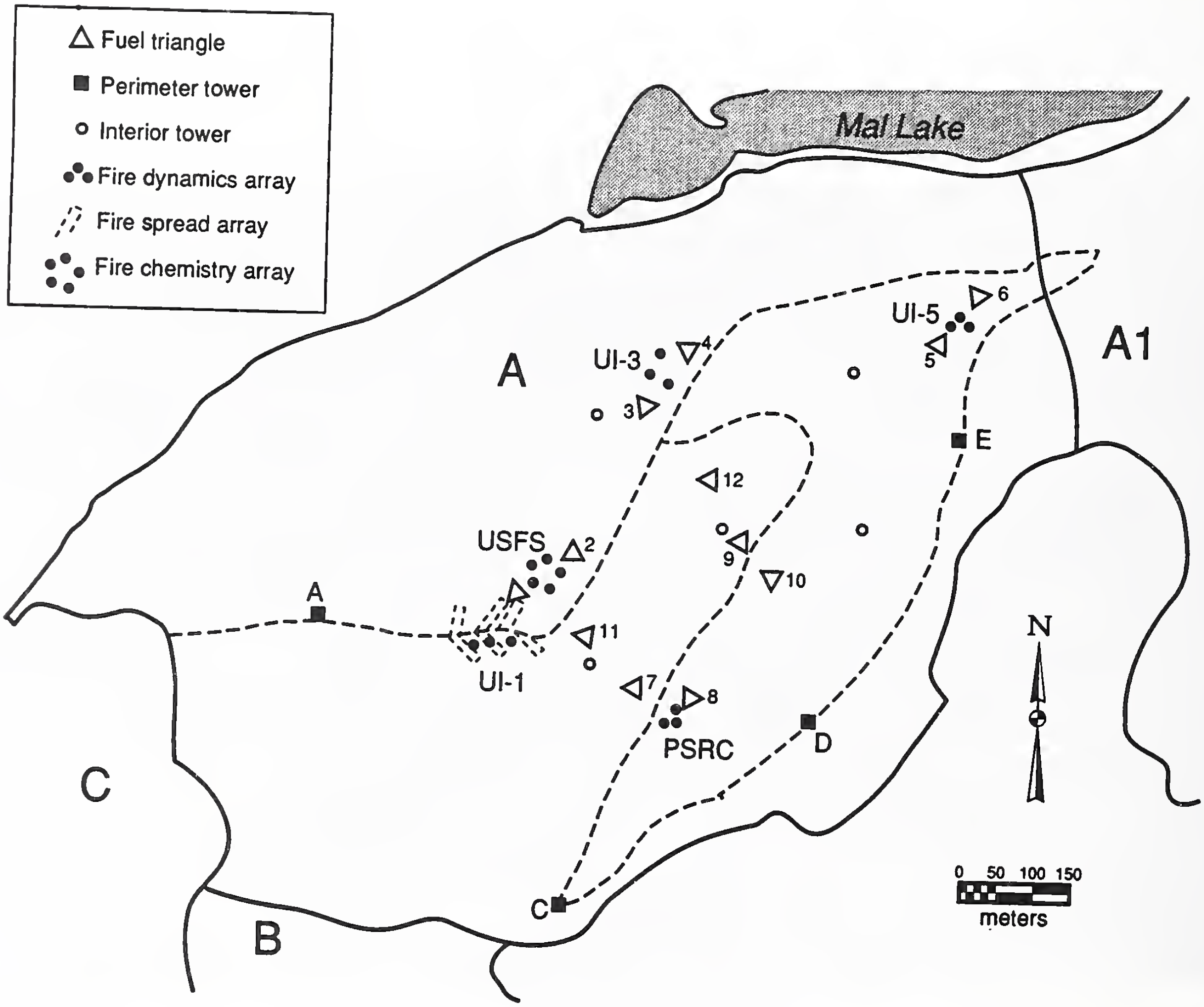

Figure 3. Ground instrumentation locations in Block A (PSRC).

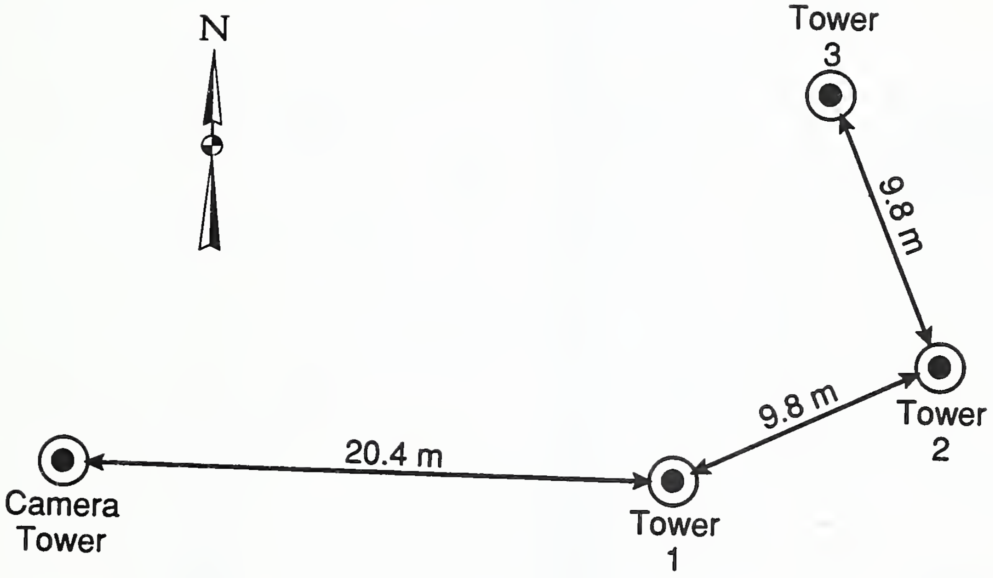

Figure 4. PSRC fire dynamics array -- Hill tower designation and placement (PSRC).

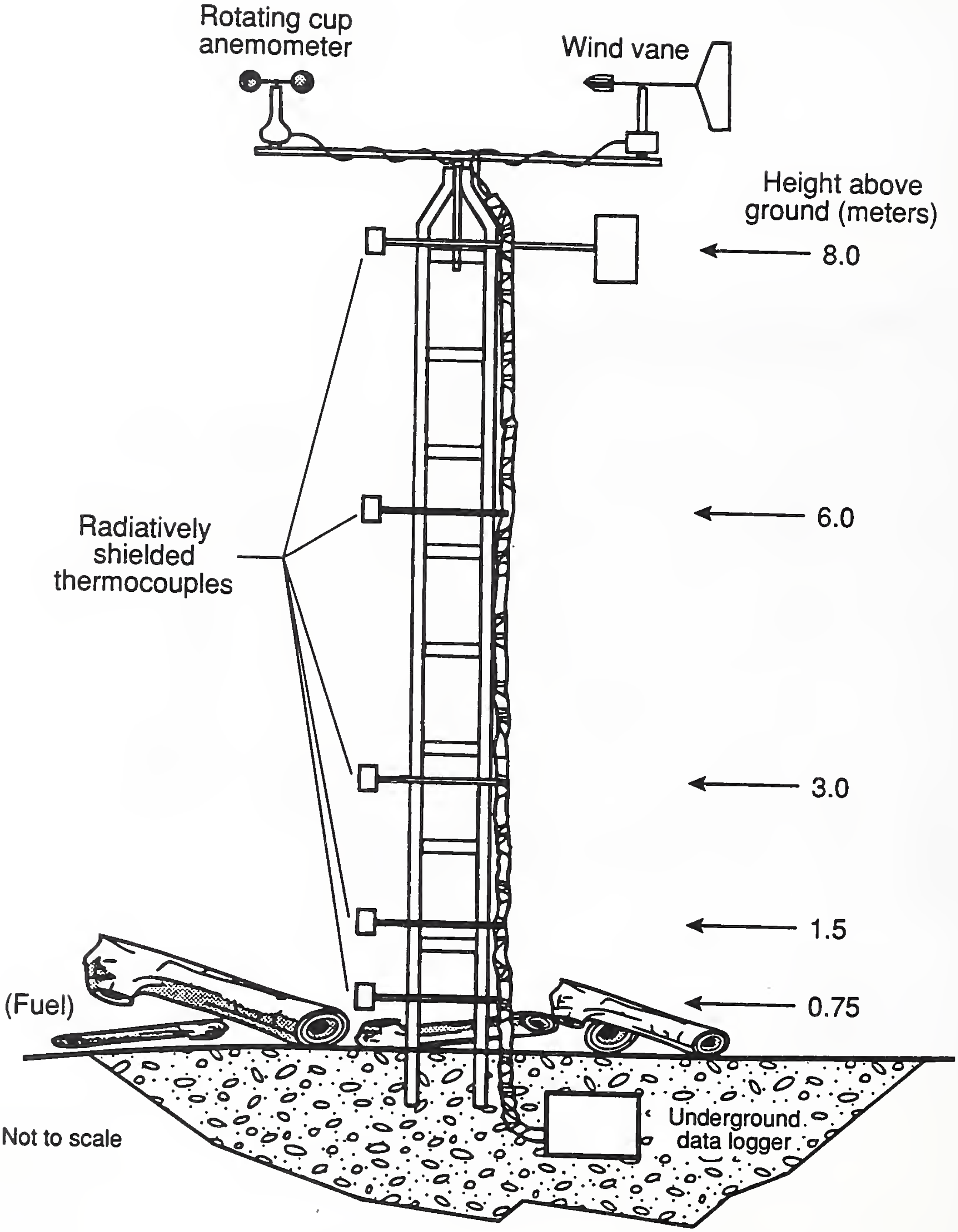

Figure 5. PSRC measurement tower (PSRC).

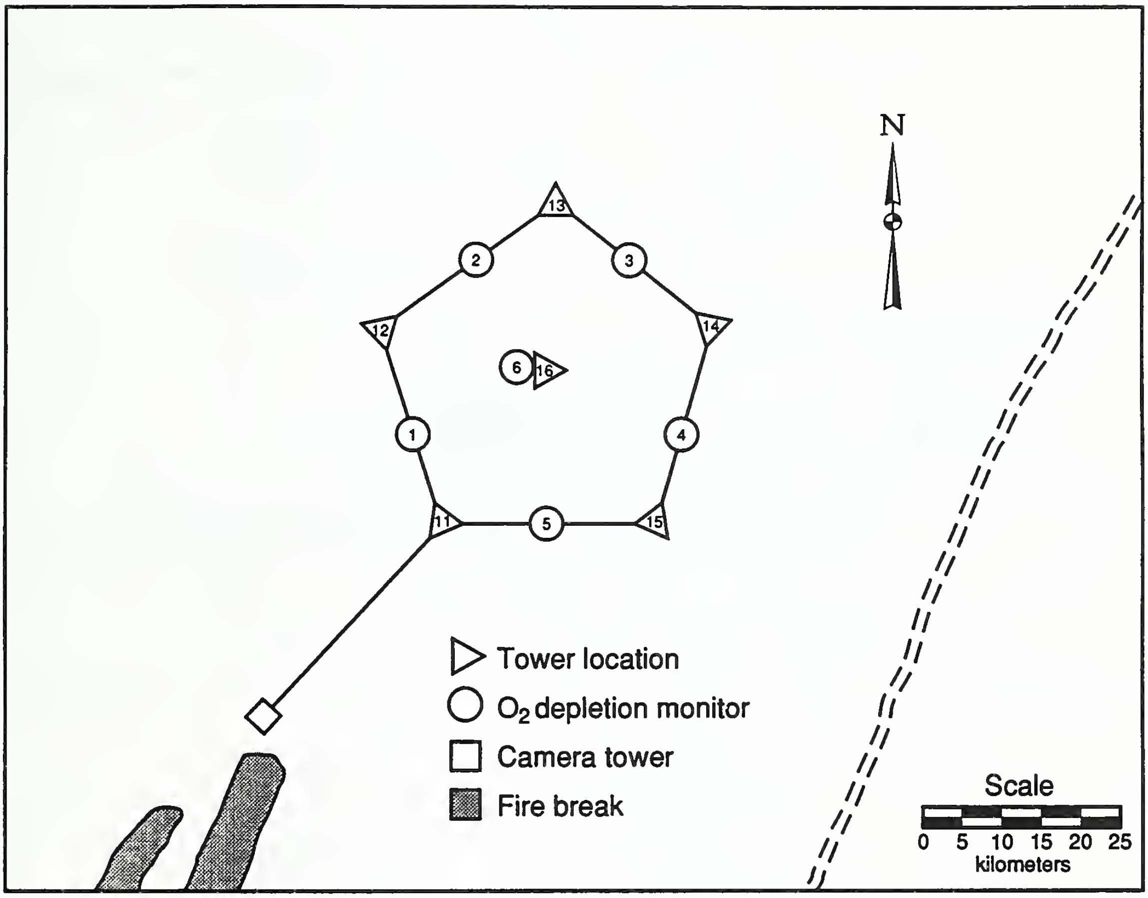

Figure 6a. USFS ground instrumentation array (USFS).

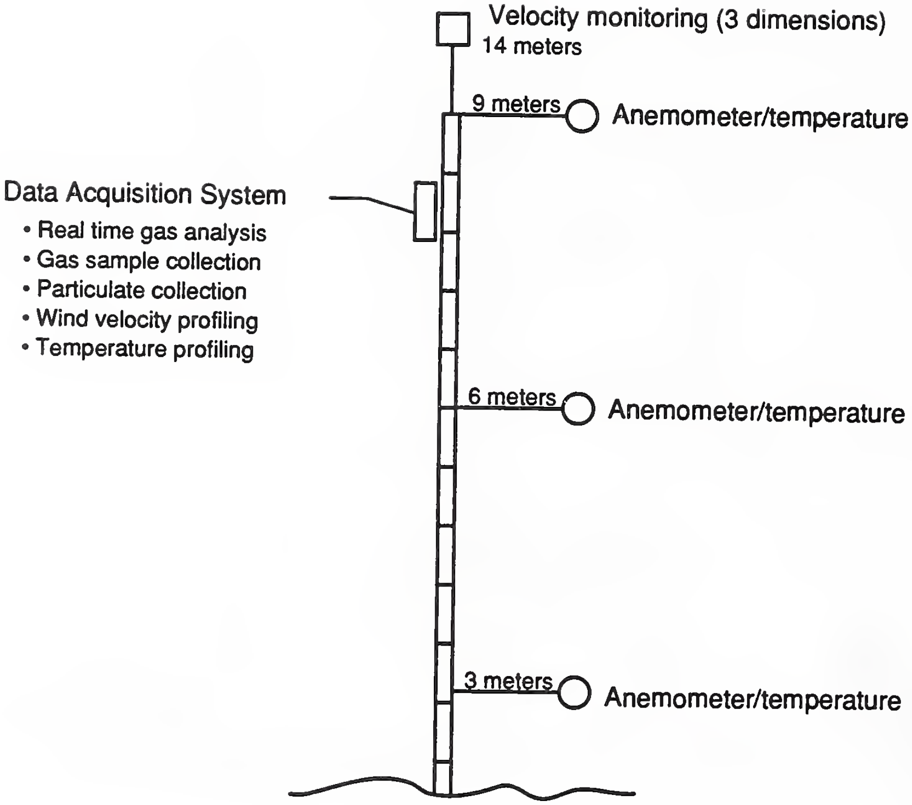

Figure 6b. USFS measurement tower (USFS).

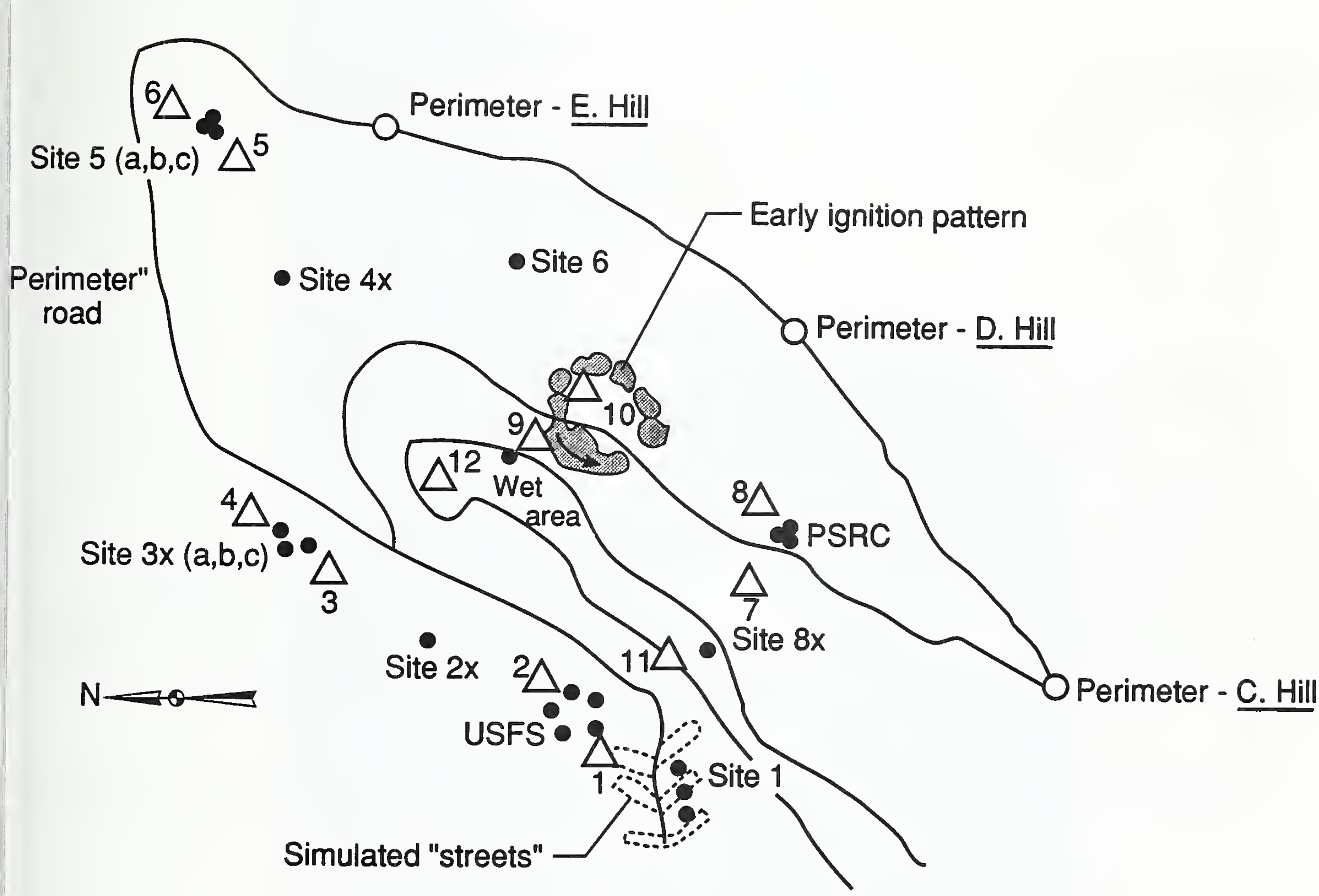

Figure 7. Layout of instrumentation in Block A relative to roads on site. Darkened, irregular circle indicates first area ignited by helitorch (NIST).

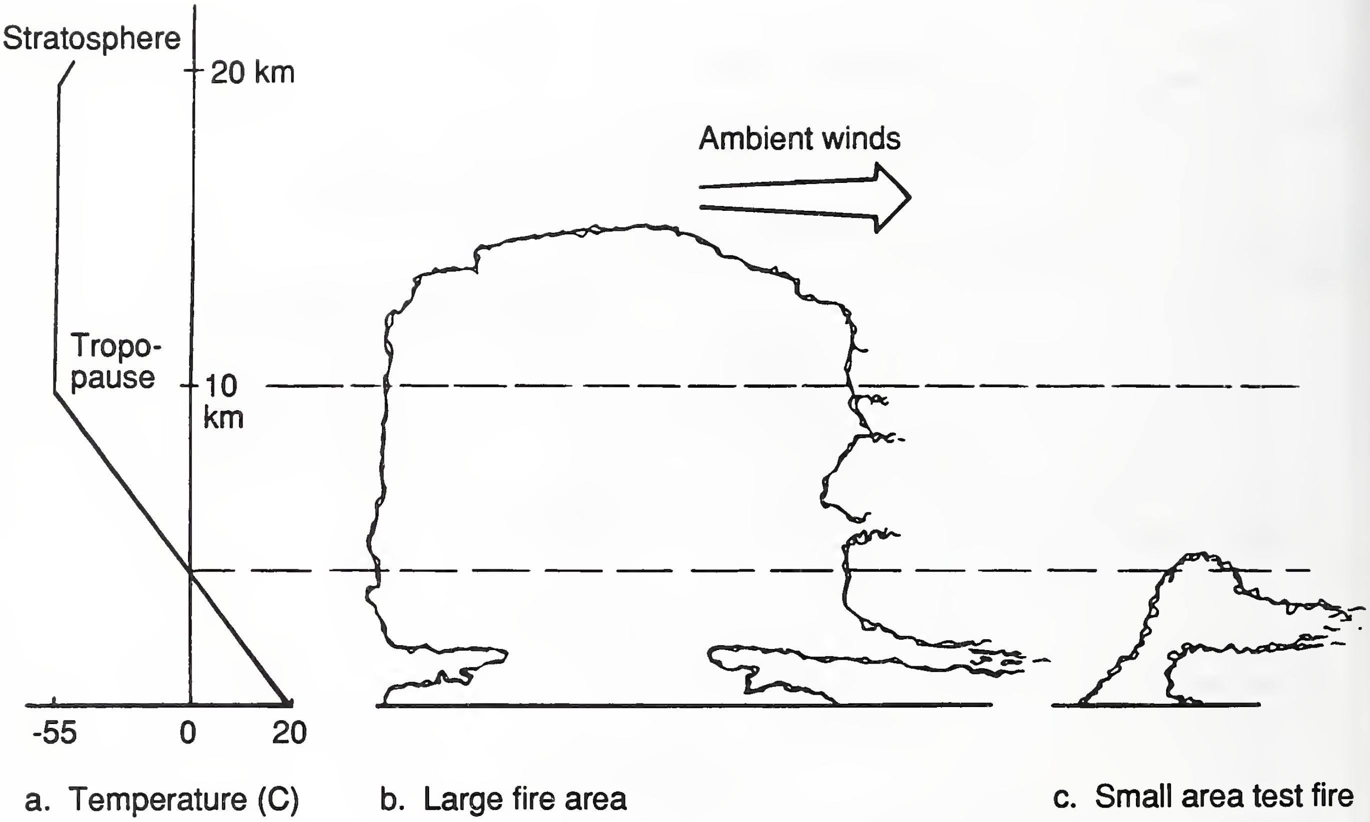

Figure 8. Illustration of mass fire plume in the atmosphere (PSRC).

Figure 9. Photograph of the capping cloud formed after igniting Block A1 at approximately 15 minutes after ignition (NIST).

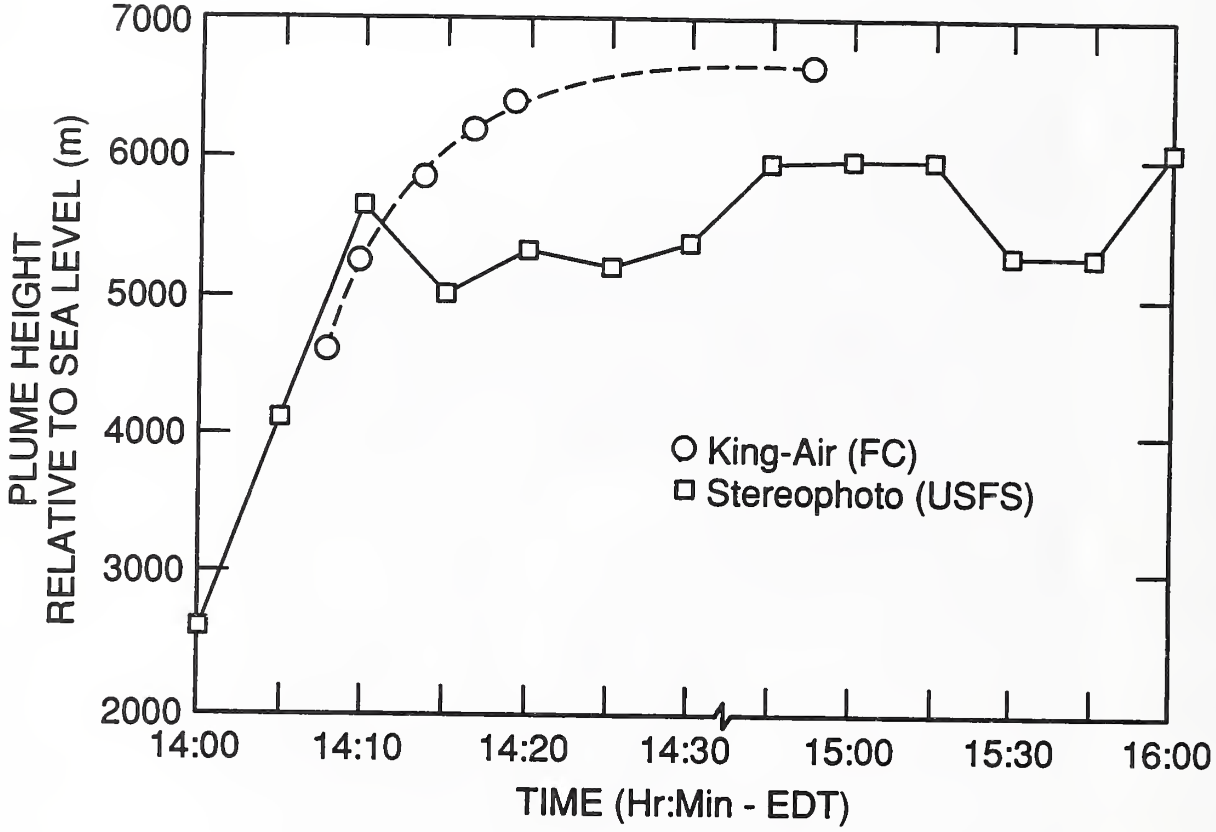

Figure 10. Plume rise as a function of time.

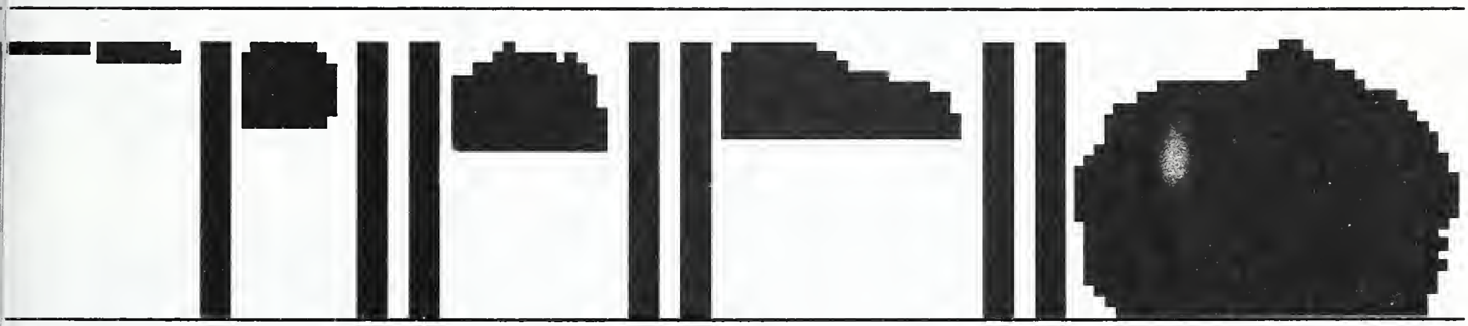

Figure 11a. Laser camera images of small hail at 14:54 EDT in the Hill fire's cumulus cloud. The vertical bars are 3.2 mm high (UW).

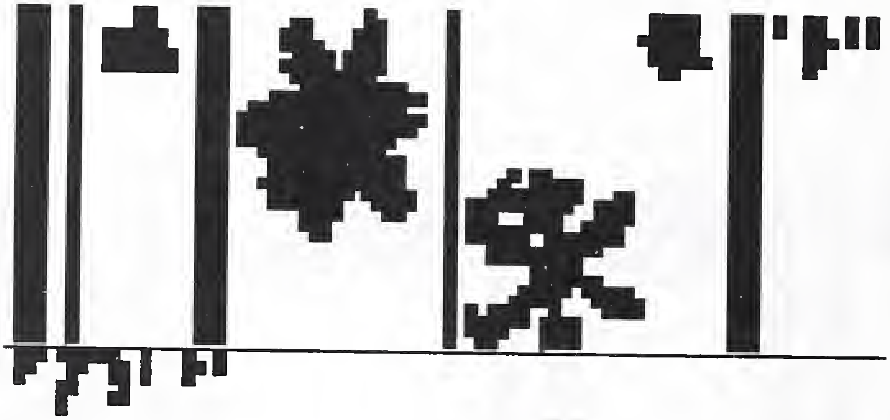

Figure 11b. Typical snowfall imaged by the laser cameras downwind of the Hill fire towering cumulus cloud. The vertical bars are 3.2 mm high (UW).

Figure 12. Photograph showing the initiation of Block A at approximately 14:20 EDT (NIST).

Figure 13. Example of early burning area spatial distribution in Block A at 14:22:24. Blace dot locates the estimated center of the ignition area (NIST).

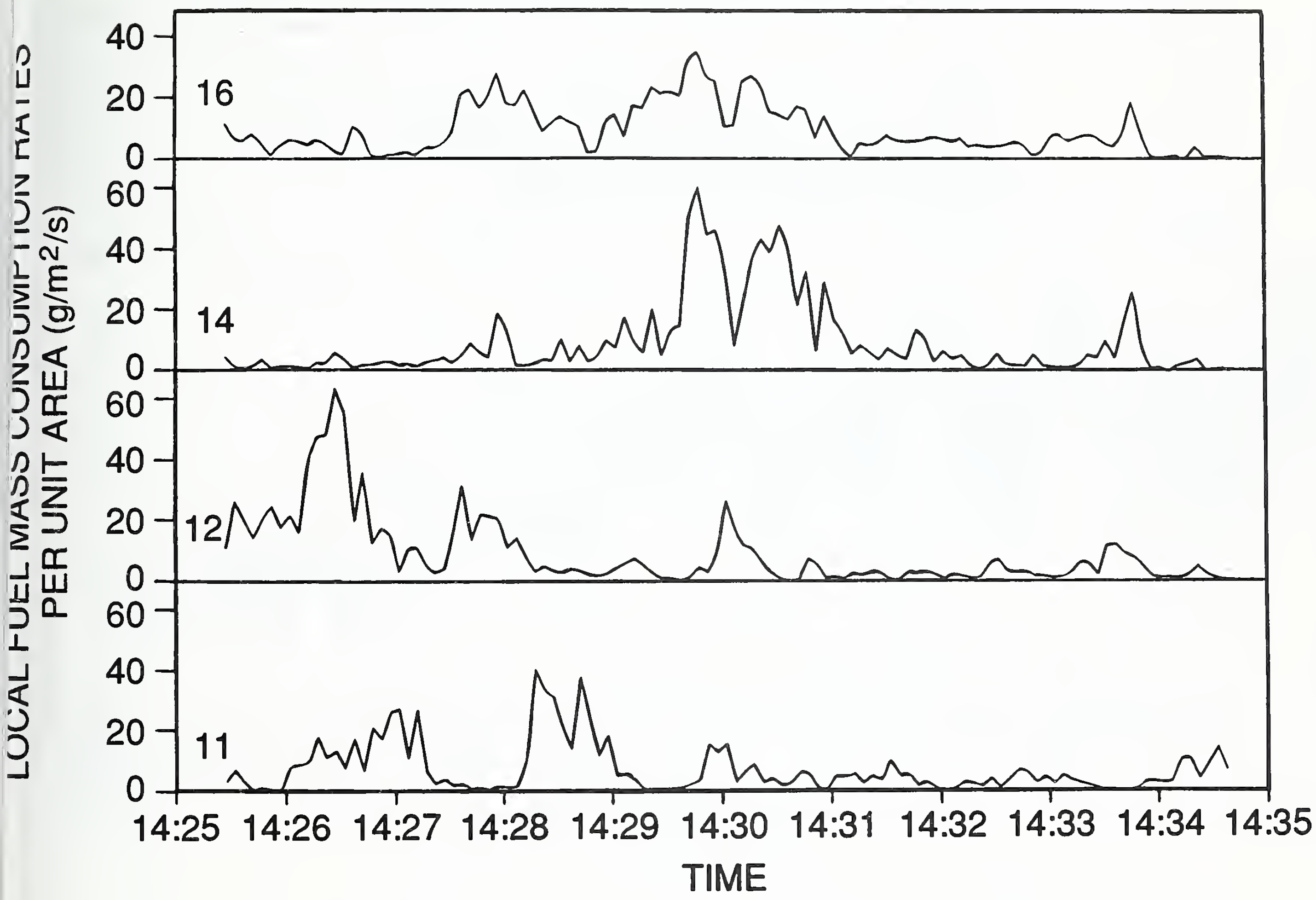

Figure 14. Calculated rate of fuel consumption based on carbon flux measurements for packages 11, 12, 14, and 16 (USFS).

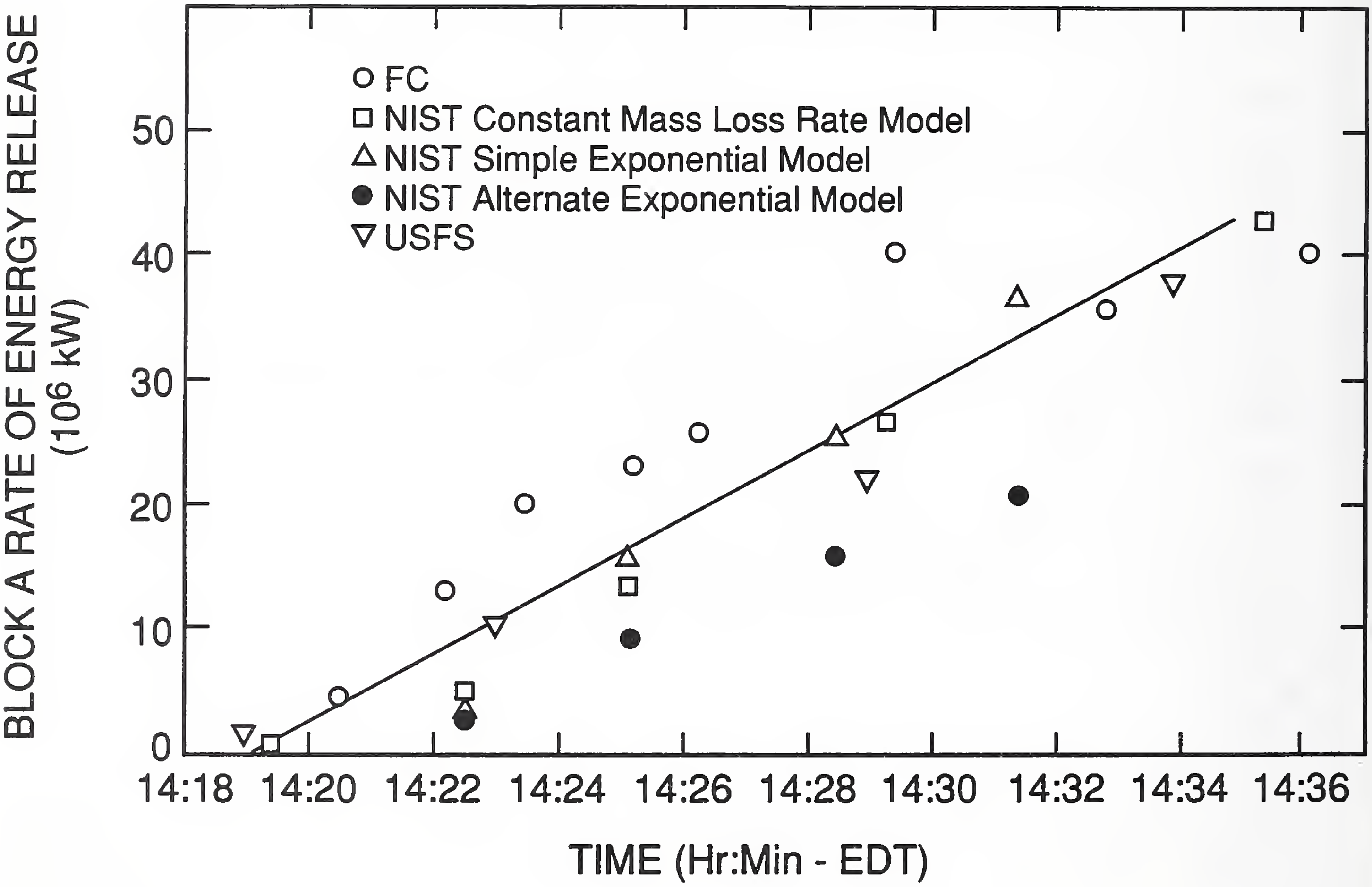

Figure 15. Estimated energy release rates of Block A.

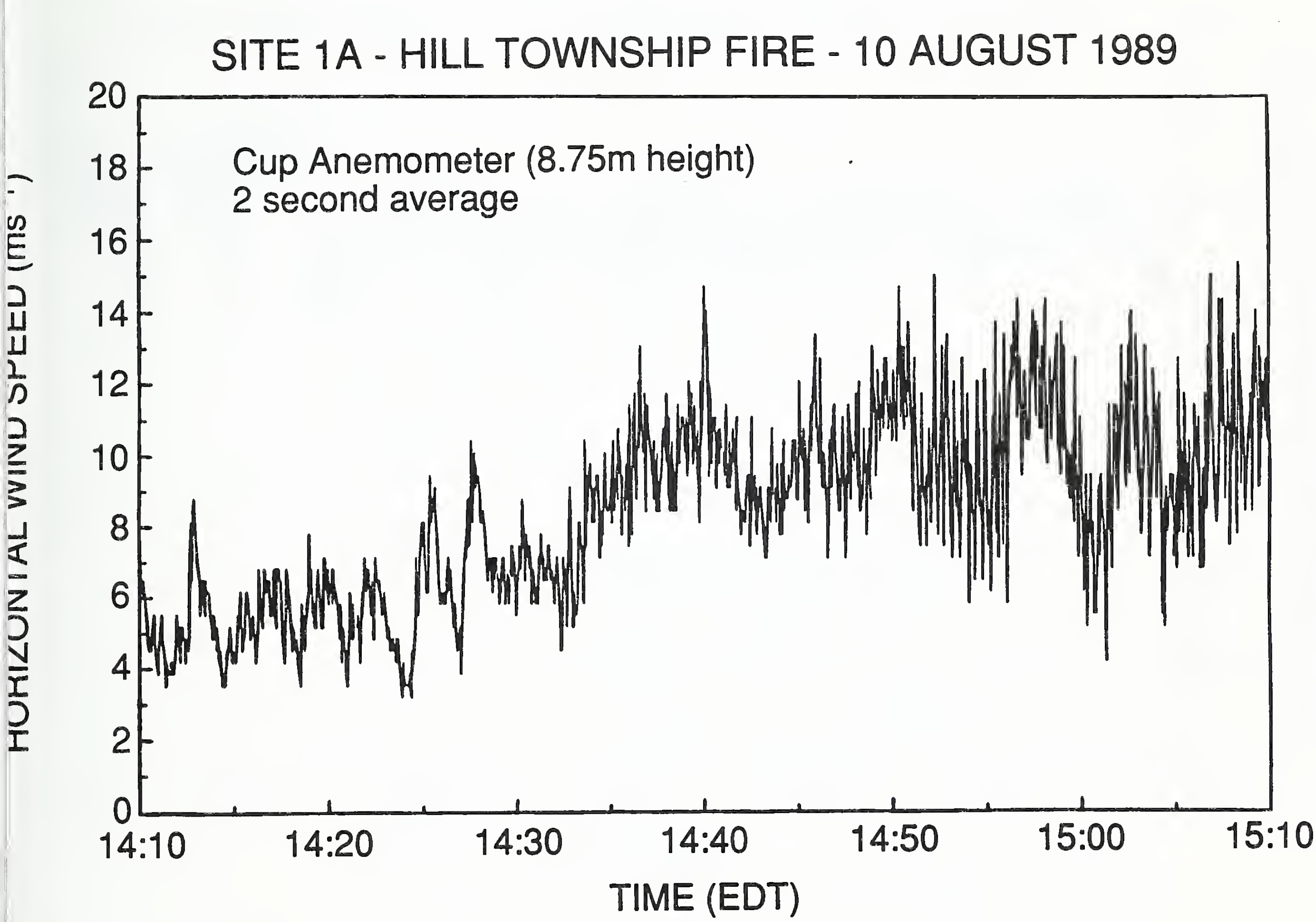

Figure 16a. Example of wind speed at the UI-1 site (UI).

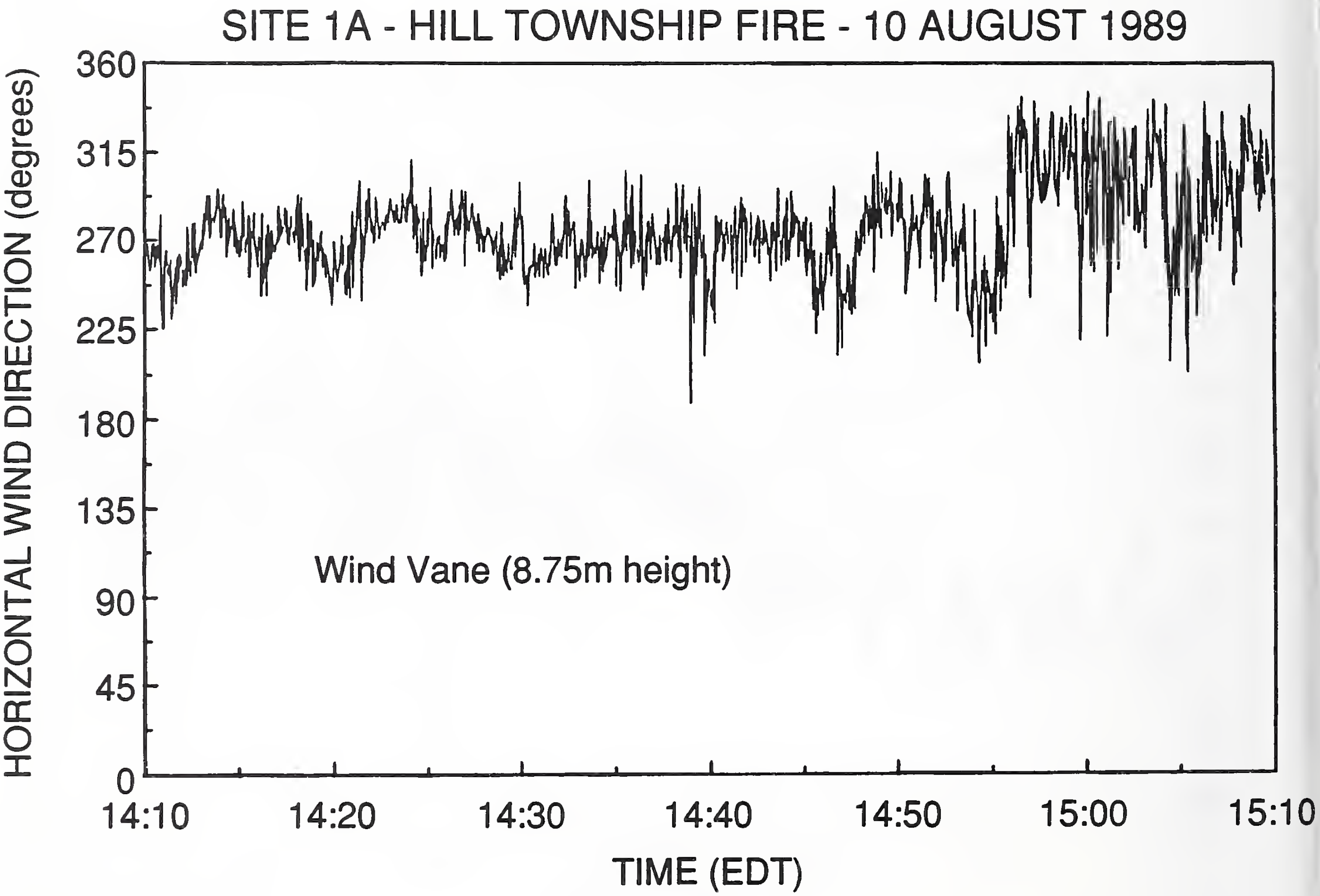

Figure 16b. Corresponding wind direction at UI-1 site. 360 is north (UI).

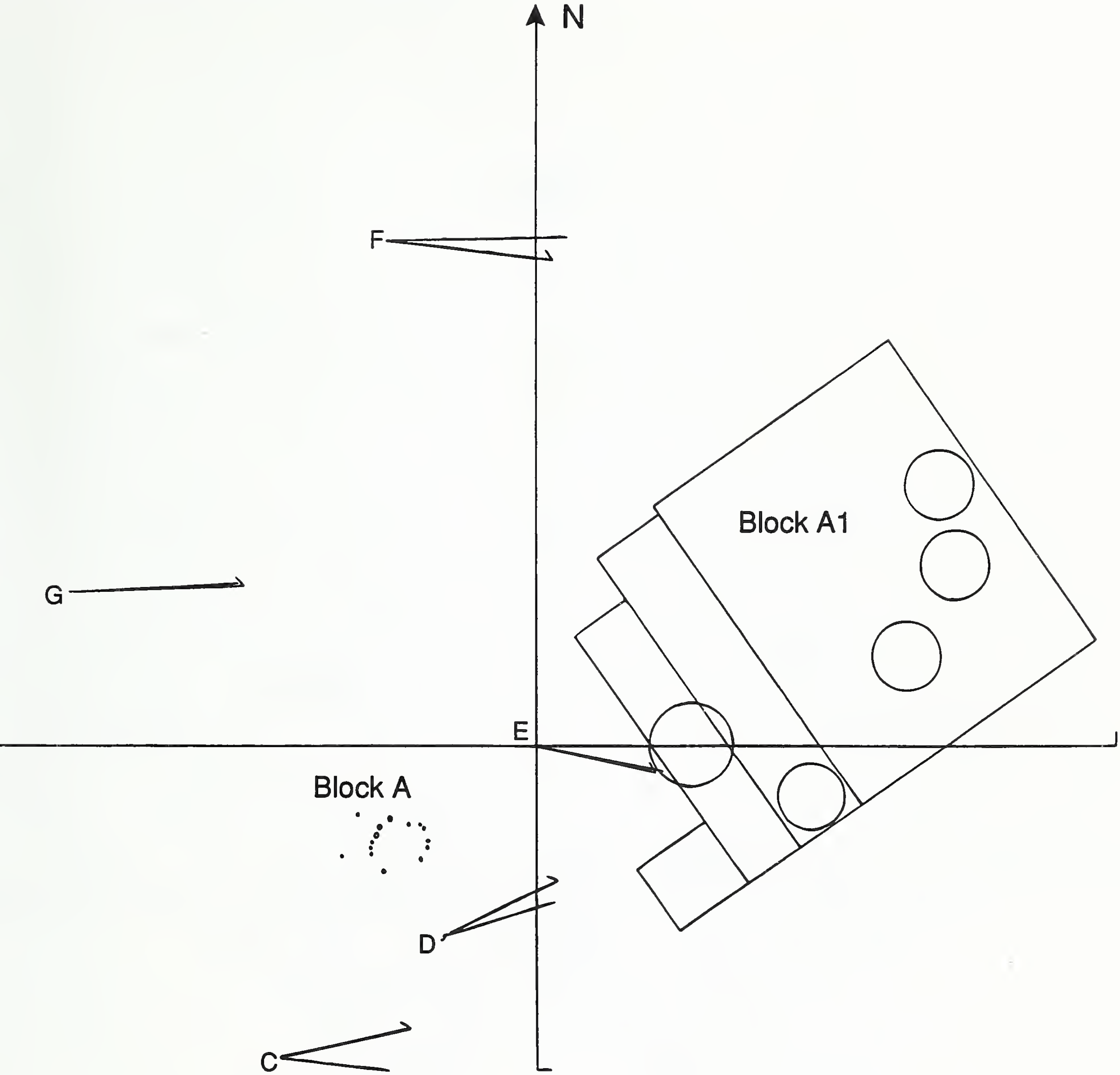

Figure 17a. Computed (arrow head) and measured (no head) velocities at ground level as a function of circular plume simulated fire configurations, 14:19:20 EDT (NIST).

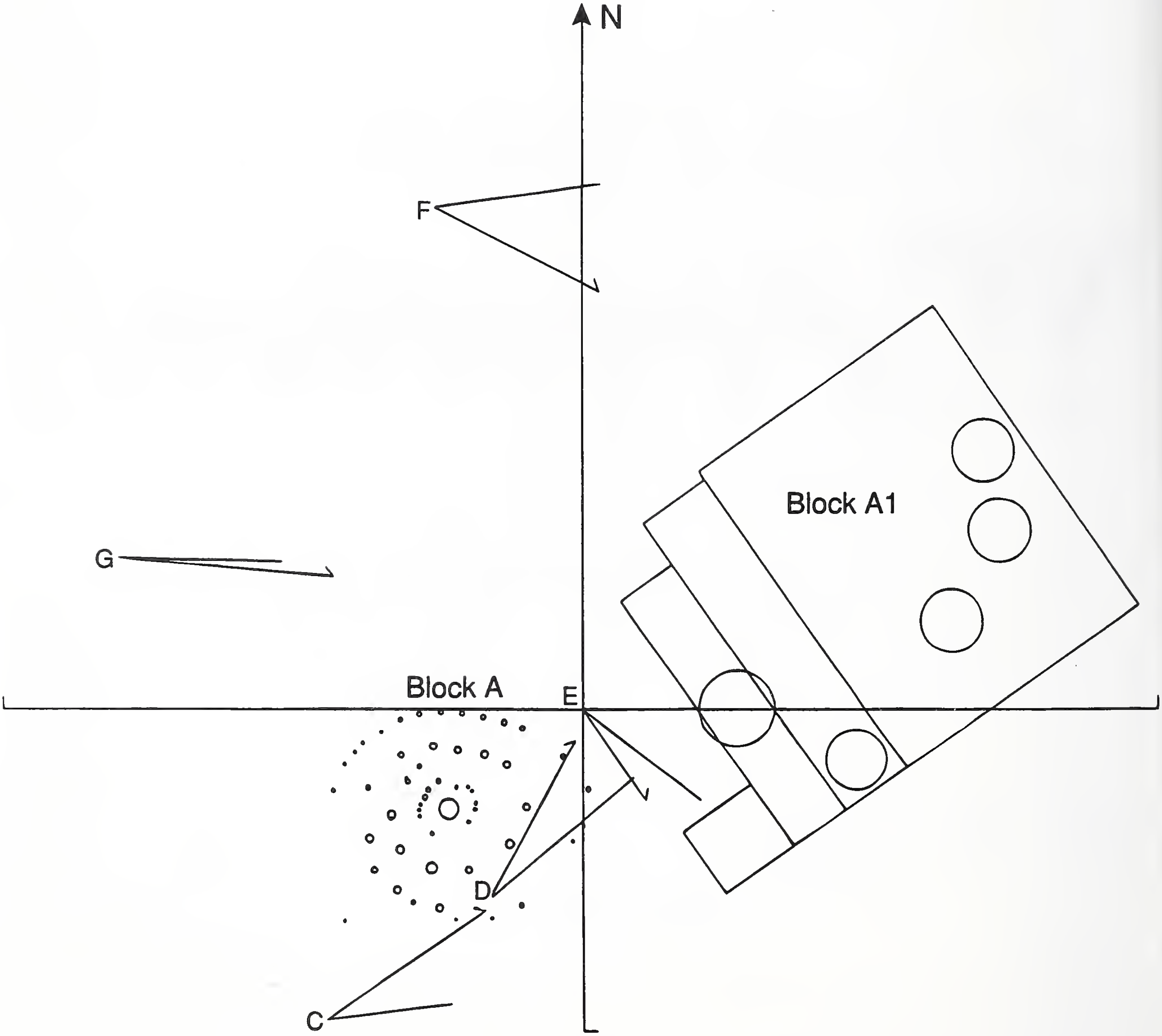

Figure 17b. Velocities and fire at 14:22:24 (NIST).

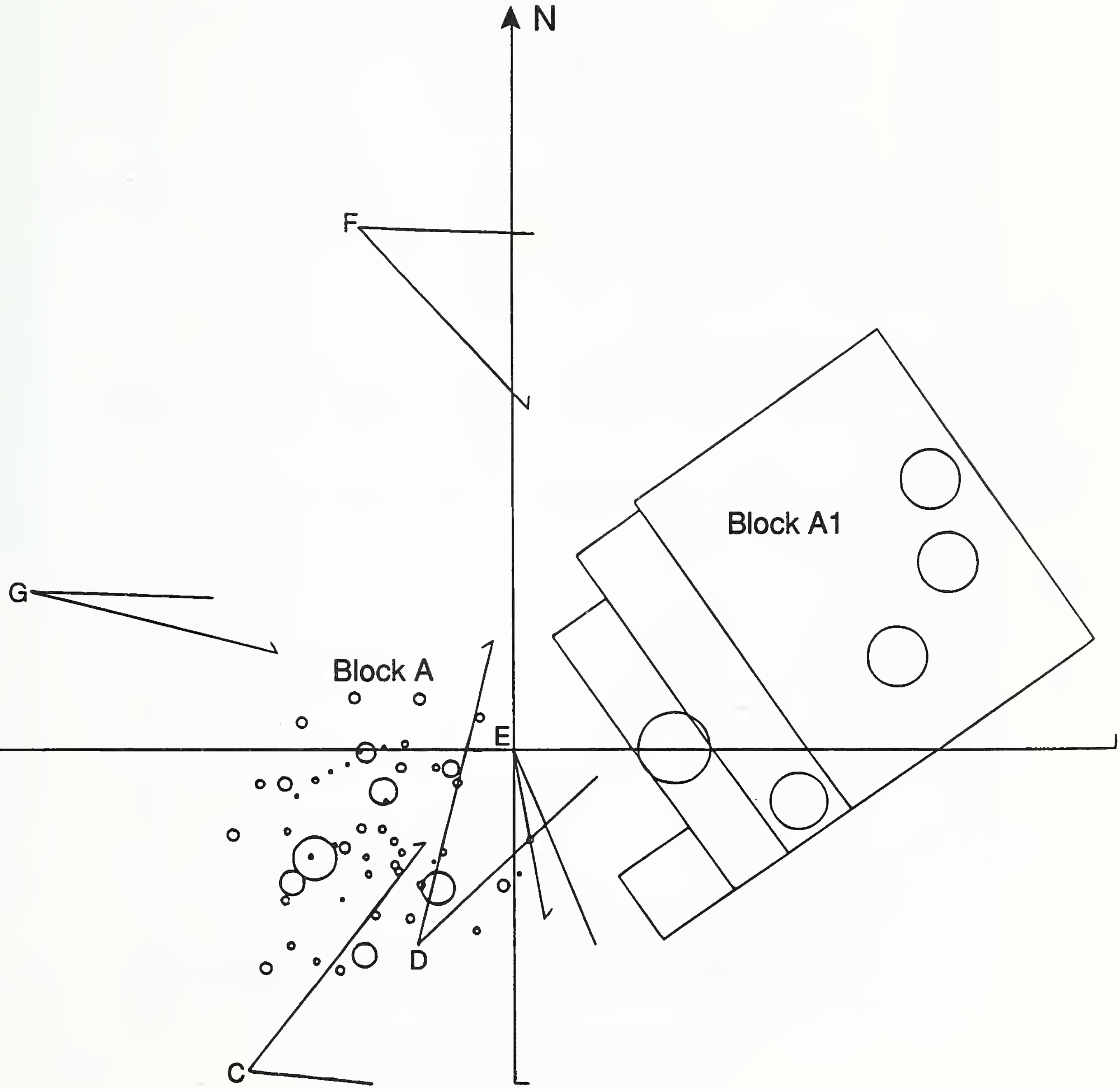

Figure 17c. Velocities and fire at 14:25:05 (NIST).

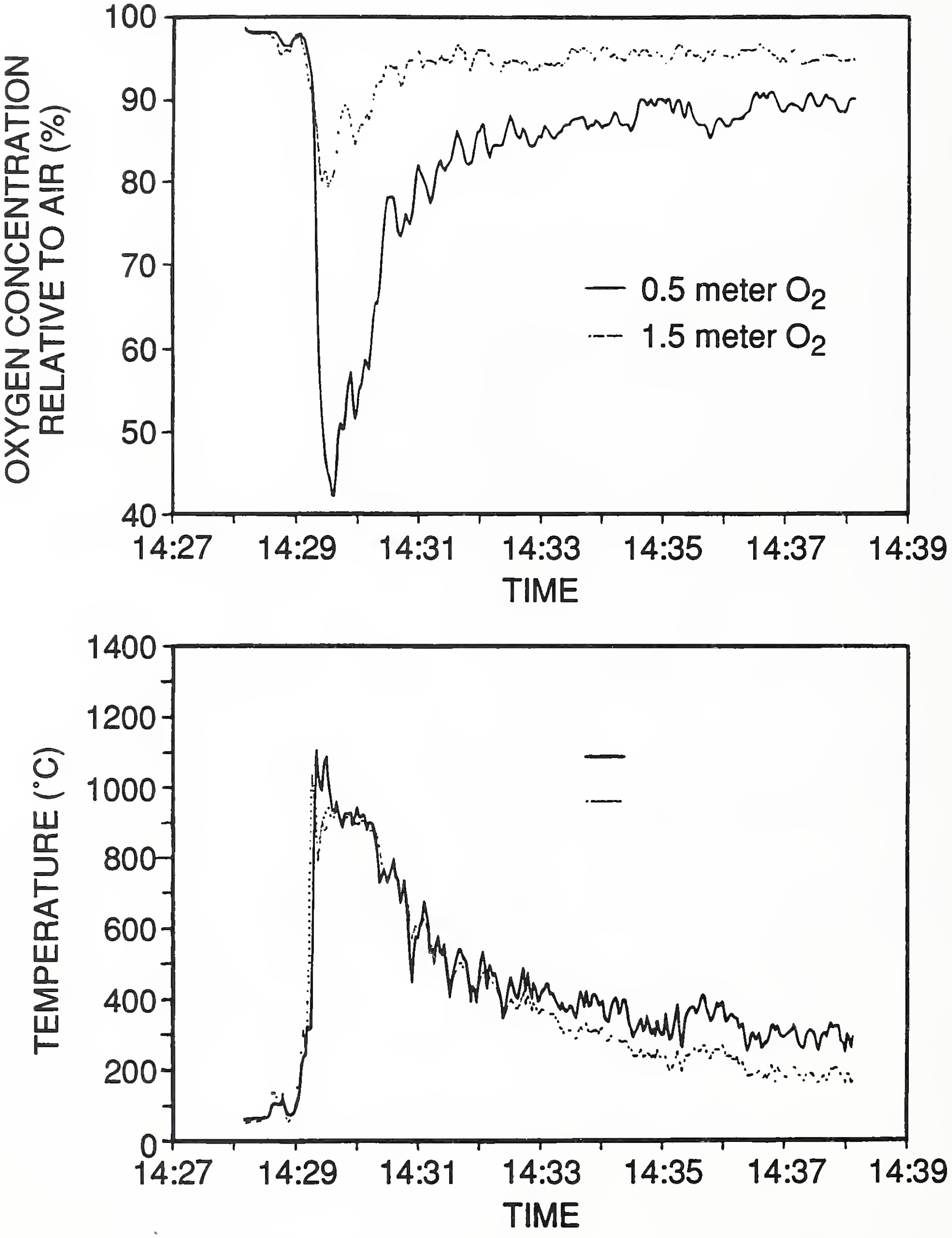

Figure 18. Real time measurements for ground level oxygen depletion relative to ambient air and air temperature (USFS).

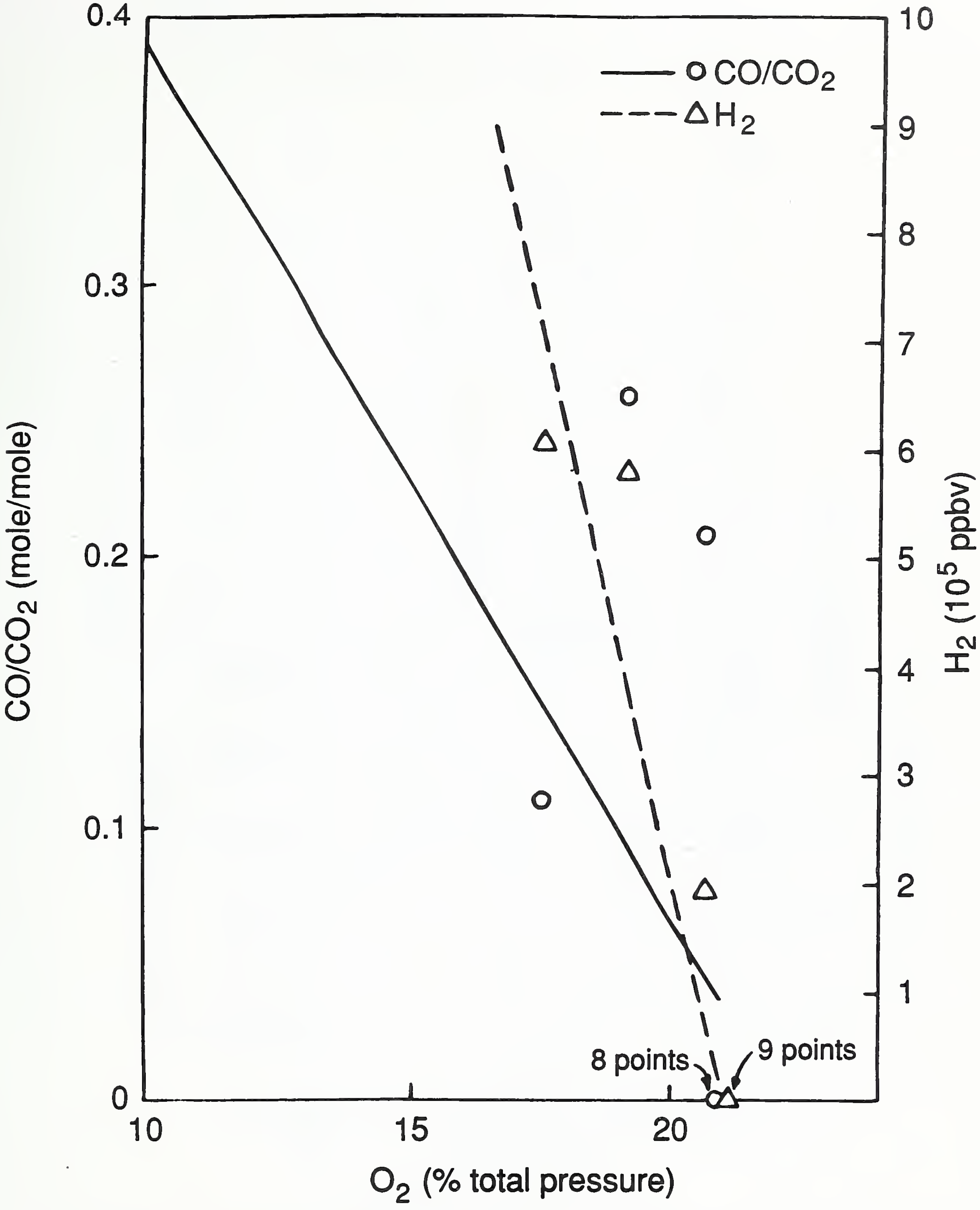

Figure 19. Concentration ratio of CO/CO2 and H2 concentration versus O2 in the plume from the Battersby fire. The data were obtained at or within 100 m of the ground. The lines shown are linear regressions (UW).

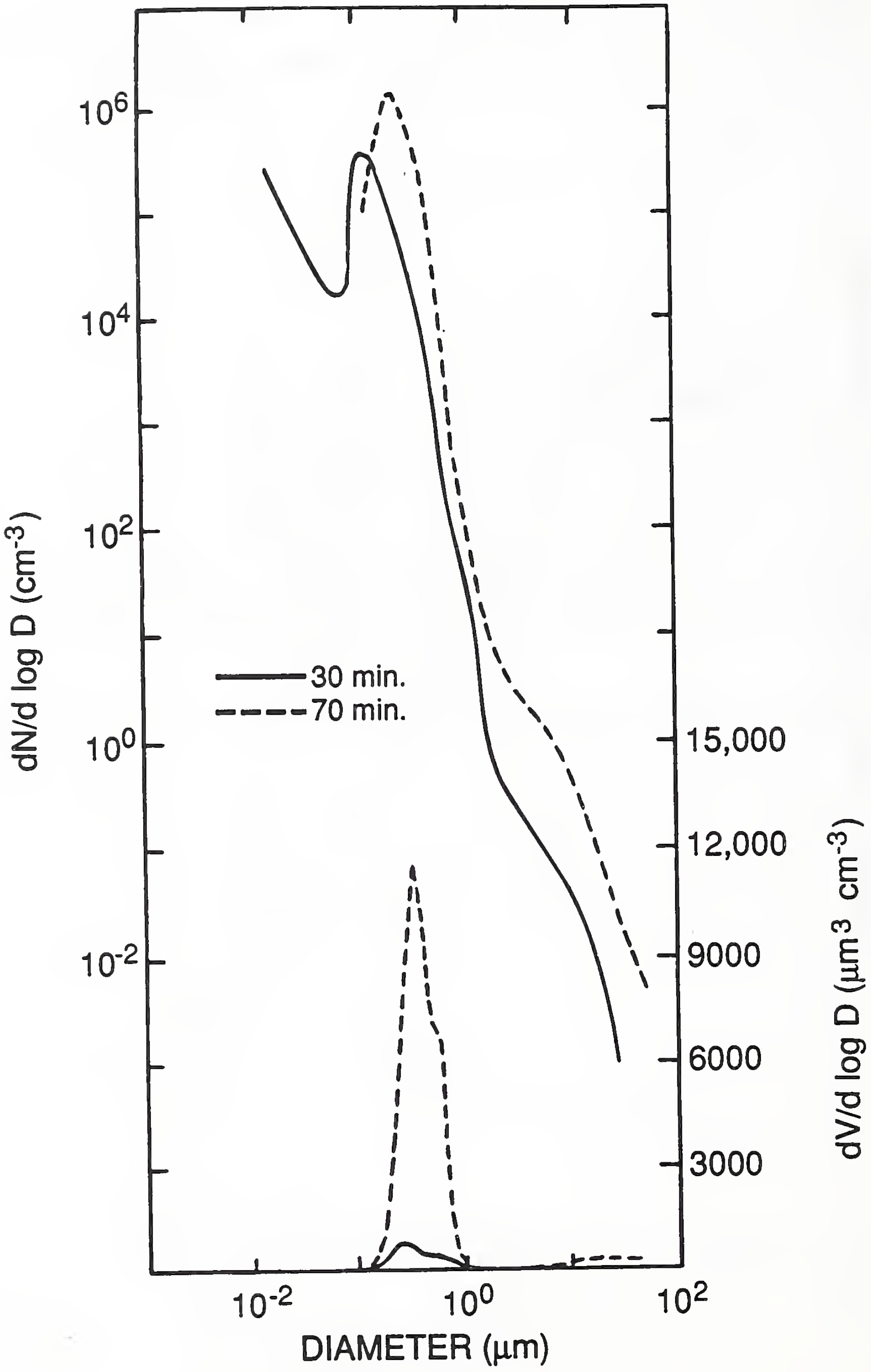

Figure 20. Mean particle number and volume spectra measured in two column samples (A) and (B) at the Hill fire taken 30 minutes and 70 minutes following ignition of Block A, respectively (UW).

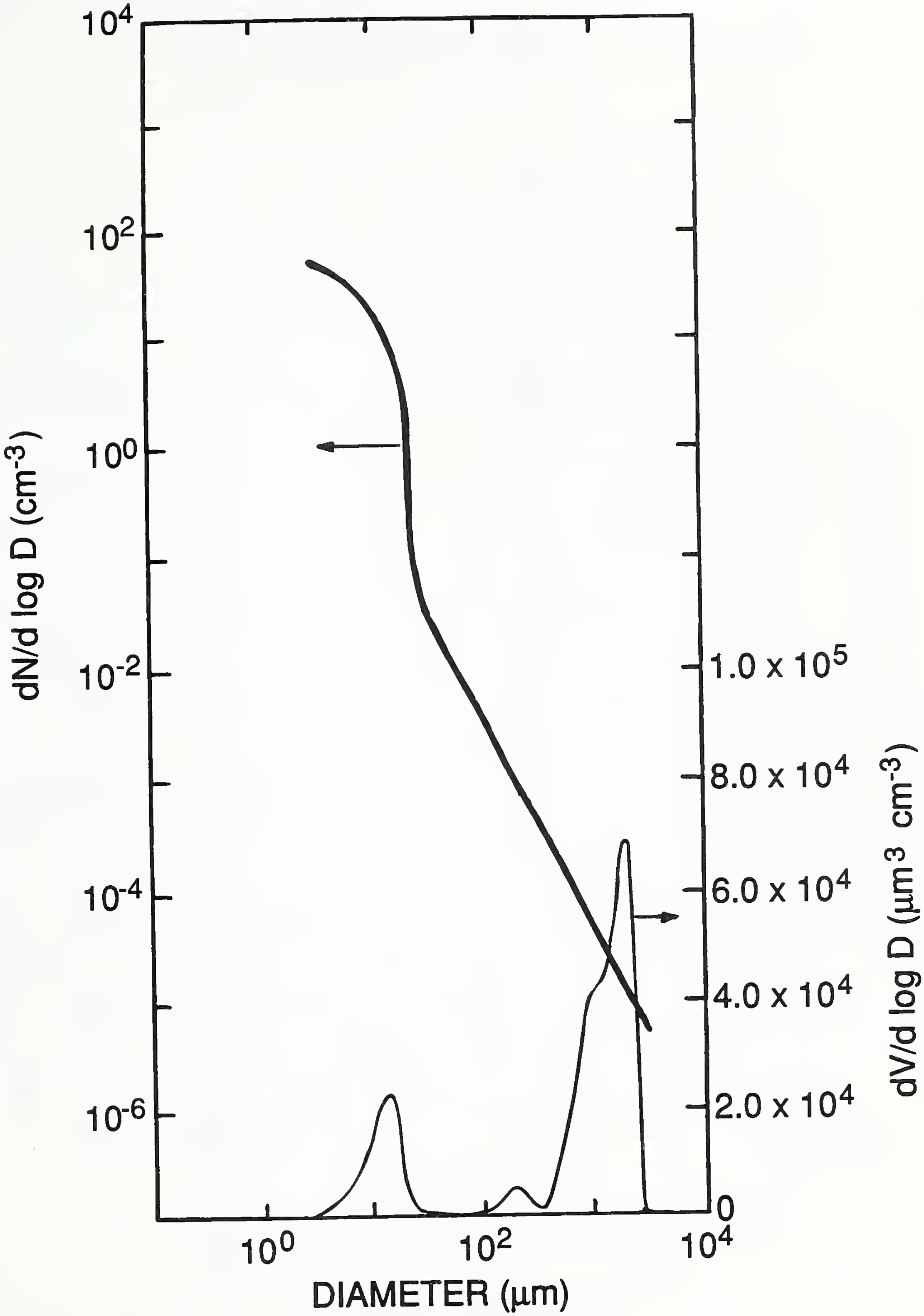

Figure 21. Droplet number and volume spectra at 14:30 EDT near cloud base in the ascending smoke column at the Hill fire (UW).

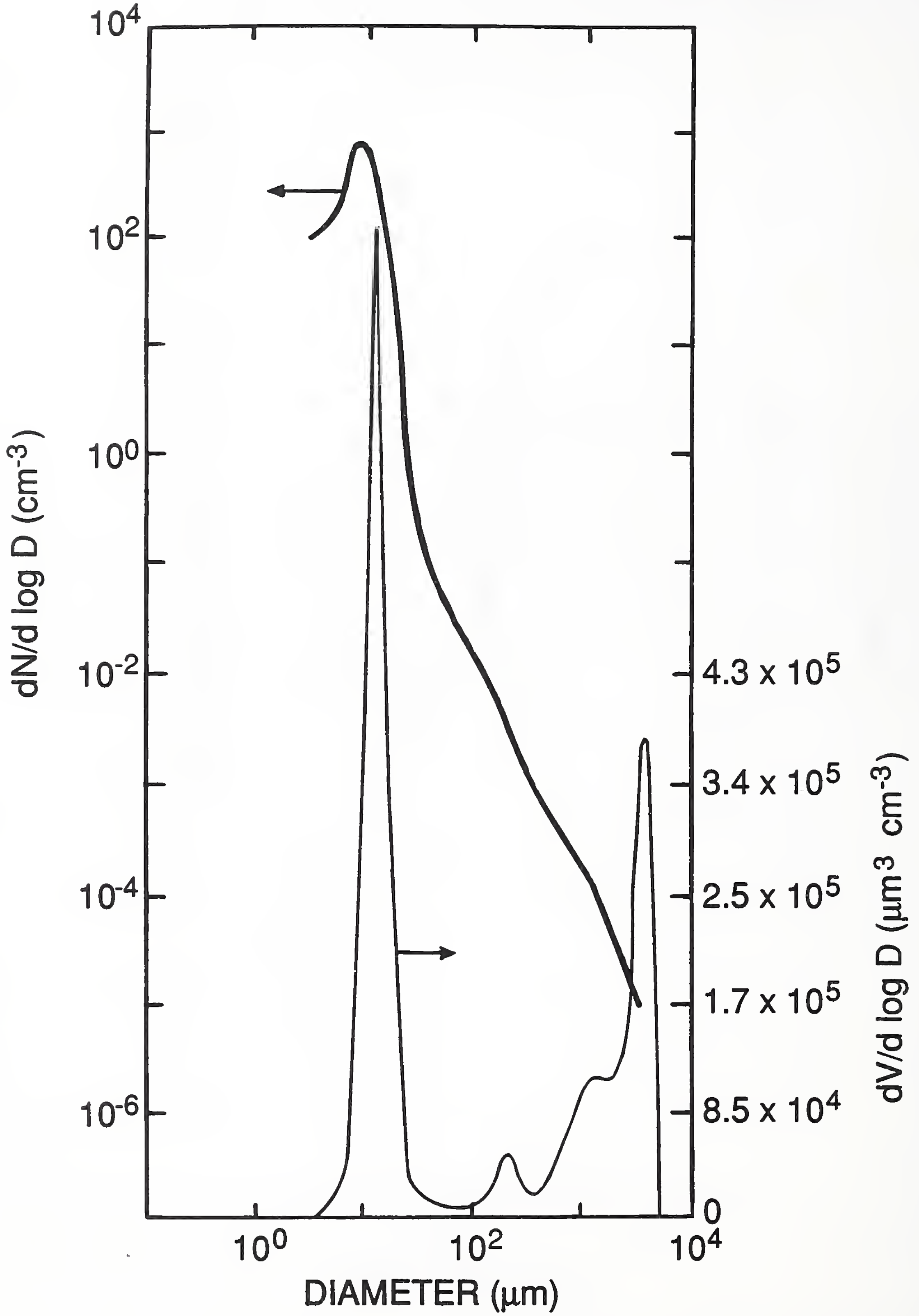

Figure 22. Droplet number and volume spectra at 14:37 EDT approximately 100 m above cloud base at the Hill fire (UW).

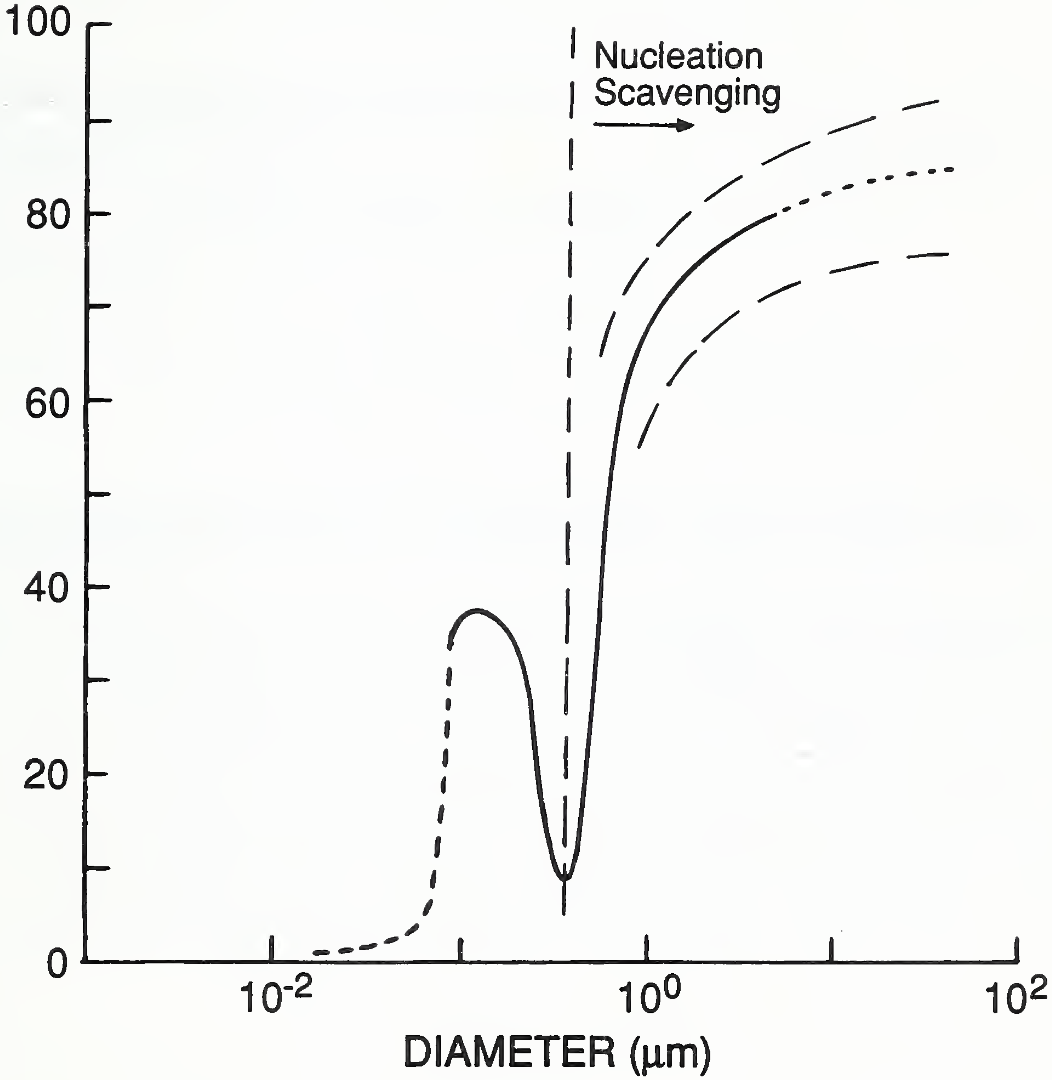

Figure 23. Smoke removed by cloud and precipitation scavenging as a function of smoke particle size over the Hardiman biomass fire (UW).

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11. ABSTRACT (A 200-WORD OR LESS FACTUAL SUMMARY OF MOST SIGNIFICANT INFORMATION. IF DOCUMENT INCLUDES A SIGNIFICANT BIBLIOGRAPHY OR LITERATURE SURVEY, MENTION IT HERE.)

Working with Forestry Canada and the Ontario Ministry of Natural Resources, the Defense Nuclear agency carried out an extensively instrumented experiment of a prescribed burn in forest debris to simulate conditions of a mass fire. In addition to the Canadian team, a multi-institutional US team made both ground and airborne measurements of the fire and smoke conditions. The fire reported on was in Hill Township, Ontario and covered nearly 480 ha in its overall burning area. Both flaming and smoldering modes contributed to the energy and combustion products of this fire. Significant quantities measured and determined included estimations of energy release rate, emission factors for smoke particulates and species, ground level wind and temperatures, and aspects of cloud dynamics and cloud particles. The fire caused a capping cloud to form and reach a level of 6.5 km. Rain, snow, hail and lightning were reported along with ground level fire whirls and water spouts on the adjoining lakes. Fire spread rates reached 1 m/s and fire induced winds reached 12 m/s.

12. KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)
cloud interactions; energy release rate; forest fires; mass fires; smoke emissions

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