

AN ABSTRACT OF THE THESIS OF

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Title: ATMOSPHERIC TRACE ELEMENTS AND THEIR
APPLICATION IN TRACING AIR POLLUTION

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The atmospheric trace element abundances associated with several major sources of air pollution in Western Oregon, such as the paper industry, the metallurgical processing industry, the plywood industry and agricultural field burning have been measured by instrumental neutron activation analysis (INAA). Air samples were collected directly from industrial stacks and during the field burning season using high volume air samplers, tape samplers and a cascade impactor. Nuclepore filter paper and Handiwrap were used as collection media for air particulates. The results show that some of the trace elements are highly correlated with a particular source of pollution, i. e. the high concentration of Zr, Hf, Ta, As, Cl, and Br associated with the metallurgical processing company; Na, Cl, Br, Cu, V, Co, Cr and Hg with the paper company; Na, K, Cl, Cr, Cu, Br and Hg with the plywood company and Ti, Na, Al, K, and Fe with agricultural field burning. Of all these characteristic elements, only Zr, Hf, Ta

and As could be used as "natural occurring" tracers for tracing the dispersal pattern of stack effluent from a particular source. The concentrations of potentially toxic elements such as Hg, As, Se, and V emitted from these sources into the atmosphere were found to be too low to cause any health hazard in the area concerned.

The atmospheric trace element abundances in Albany (an industrial area) and in Corvallis (a rural area) were also measured. Abnormally high trace element concentrations were found in the Albany area. Most of the trace element concentrations are highly correlated to the industries in the area. The rural air in Corvallis, on the other hand, shows very low trace element concentrations and may serve as an indication of the "continental background" contribution to atmospheric abundance.

An artificial activable tracer technique using some of the rare-earth elements (Dy, Sm, La, and Ce) was also developed to monitor stack effluent. These tracers were used in testing the generalized Gaussian plume model (Gifford, 1962) and Hewson's trapping plume model (Hewson, 1958) applied to describe the dispersal pattern of stack effluent in the Albany area. These models were found to work quite well under atmospheric stabilities types D, C, and B (Pasquill's classification, 1962) and not to work well under very turbulent conditions (atmospheric stability type A or above).

These meteorological models along with the techniques of multiple regression analysis were applied to predict the emission rates of the stack effluent involving multiple sources of air pollution in the Albany area. The artificial activable tracers were used as source tracers. It was found that these models, in general, can be applied to predict the emission rates within a factor of two in multiple sources involving three stacks.

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Atmospheric Trace Elements and Their Application
in Tracing Air Pollution

by

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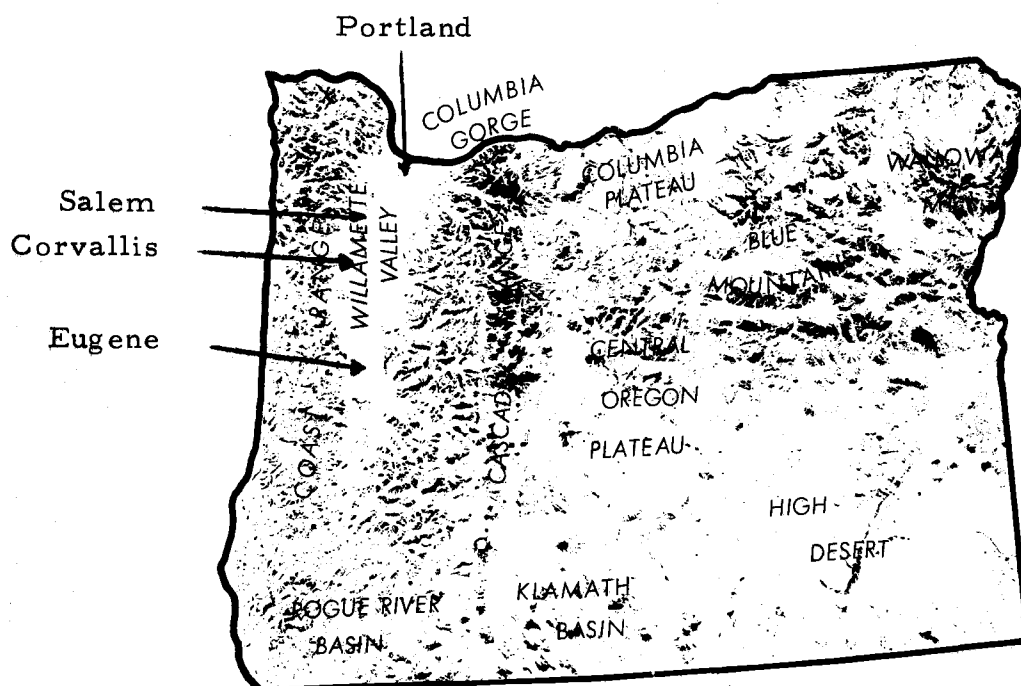
ATMOSPHERIC TRACE ELEMENTS AND THEIR APPLICATION IN TRACING AIR POLLUTION

I. INTRODUCTION

Objectives

One important cause of air pollution problems is the stagnation of air masses along with the continuous emission of pollutants which raises the concentration of air contaminants. This situation can arise when horizontal ventilation of a geographical area is limited by topographical barriers and vertical ventilation is suppressed by temperature inversion in the lower atmosphere.

The Willamette valley, located in the northwest part of Oregon, is effectively surrounded by physical barriers on three sides as shown in Map 1. To the east of the valley lies the Cascades, to the west is the coastal range and to the south is mountainous area. Its topographical barriers, with the frequent occurrence of temperature inversions in the lower atmosphere over the valley, set the geophysical stage for stagnation of a relatively small air mass. The land and sea breezes generated locally during summer provide some improvement in natural ventilation during this season. Despite the action of such local sea breezes, however, the Willamette valley is considered to have the potential for serious air pollution problems (Holzworth,



Map 1. Oregon: The air-shed in the Willamette Valley resembles a "giant room" which is ventilated through various "windows" and "doors" at Portland, N. W. of Salem, W. of Corvallis, and W. of Eugene.

1961). The only thing missing is a high rate of emission of pollutants in the valley.

At the present time, the major problem of air pollution in western Oregon is due to the emission of the suspended particulates, mostly coming from agricultural field burning, paper and wood industries, metal industry and motor-vehicles. These suspended particulates whose sizes are usually in the submicron ranges can stay in the atmosphere for a long period of time and are the major cause for visibility loss, soiling, damage to property and possible harm to human health. One of the purposes of this project is to apply a highly sensitive and reliable method to measure the trace element concentrations in the air particulates collected from some of the major sources of air pollution in western Oregon.

Methods for the study of the concentration of trace elements in the atmosphere by neutron activation analysis have recently been described by Zoller and Gordon (1970). Using the analytical methods described in their paper, one can determine the concentration of about thirty trace elements in some air particulate samples. It may be possible in some circumstances to use this technique to fingerprint the trace elements for the identification of the source of the pollutant. In order to fingerprint a pollutant source, one must establish that a source emits a unique group of trace elements in unique concentrations into the atmosphere. Then one may be able to use these

particular elements as "tracers" to study the movement of pollutants from a given source in the atmosphere. For example, under certain conditions, Na and Cl from marine air can be used as natural tracers to investigate the land and sea breezes (Rahn et al., 1971), and Pb as a tracer indicative of exhaust from motor vehicles (Winchester et al., 1967). In cases where one cannot establish that a pollutant source emits a unique group of trace elements, one must rely on the use of artificial tracers for studying pollutant dispersal. Therefore, I have attempted to develop both "naturally occurring" and artificial tracer techniques which can be applied to an area from which substantial pollution is released, such as an industrial area, to aid in monitoring air pollution dispersal. From measured tracer concentrations and appropriate meteorological data, it may be possible to apply mathematical models to estimate the contribution to the total atmospheric pollutant levels from a particular source.

The study of the concentration of the trace elements in the atmosphere is in itself important since currently there has been increasing interest in the trace elements present in the environment and their effects on human health. Therefore, it is desirable to determine the existing levels of these elements in the atmosphere to aid in establishing an air quality standard for such trace elements in the valley.

In general, the objectives of the study are summarized as follows:

1. To determine the existing levels of trace element concentrations in the atmosphere near Albany, an industrial area, and Corvallis, a rural area, in Oregon.
2. To see if one can establish trace element "fingerprints" for some sources of air pollution in the Willamette valley, such as the Wah Chang Company, (a metallurgical processing plant), the Western Kraft Company (a sulfite process paper mill), the Simpson Timber Company (a plywood Company) and agricultural field burning.
3. To develop reliable techniques utilizing "naturally occurring" and artificial tracers for tracing air pollution in an industrial area.
4. To use these tracer techniques to evaluate particular meteorological models for pollutant dispersal in situations involving multiple pollution sources and to predict the emission rate of the pollutant from the sources.

II. METHODOLOGY

General Review of Current Analytical Techniques

The determination of atmospheric aerosol trace element concentrations requires a sensitive analytical technique because of the very low atmospheric abundances of most elements. Typical atmospheric trace element concentrations are in the range of 1-1000 ng per cubic meter of air. Not only is high sensitivity needed in the analysis, but also careful handling of the samples during the analytical procedure is required.

Conventional analytical techniques, such as gravimetry or colorimetry, sometimes provide the required sensitivity for the detection of some elements in air particulates, but they are time and labor-consuming. Besides, these wet chemical procedures will destroy the samples thus preventing multi-elemental analysis and often require an experienced analyst even for routine analysis. Therefore, these methods are generally non-applicable.

The most widely used methods for measuring atmospheric trace element concentrations are atomic absorption spectrophotometry and emission spectroscopy. Although atomic absorption methods provide a sensitive technique for analysis of many elements, the disadvantages of complex sample preparation with its attendant risk of sample contamination, sample destruction and the necessity of analyzing one

element at a time (even though modern instruments have interchangeable lamps for sequential analysis of up to six elements per sample) makes this technique unsuitable for a large volume of samples.

Emission spectroscopy is a multi-element technique but requires careful sample pretreatment and is not considered to be very precise.

Another analytical technique which has shown great promise is neutron activation analysis. In current years, the technique has been developed by several authors (Zoller, et al. 1970; Dams et al., 1971; Gray et al., 1972; Keane et al., 1968, and John et al., 1973). This is a very sensitive technique (see Table 1). In general, one can measure the concentrations of about 15 to 20 trace elements in an air sample. The method is non-destructive and requires no special pretreatment of the sample. However, there are some important elements such as Pb whose concentration cannot be determined by instrumental neutron activation analysis (INAA). Also, the technique is rather expensive and requires a nuclear reactor and other facilities.

Besides INAA, the technique of X-ray fluorescence (XRF) has recently been revitalized by new instrumental developments and techniques. Research has been conducted by several groups in this respect. Cahill (1972) and Watson (1971) using an alpha particle beam as an excitation source and a high resolution Si (Li) X-ray detector incorporated with a computer system, reported that the concentrations of the atmospheric trace elements with Z higher than 11 can be

Table 1. Comparison of Sensitivities of Various Analytical Methods for Urban Atmospheric Aerosols.*

Element	Detection Limit (ng/m ³)			
	INAA	XRF	ES	AA
Na (Sodium)	1	10	3	1
Al (Aluminum)	1	3	3	200
Cl (Chlorine)	200	2	---	---
Ca (Calcium)	1000	3	3	2
V (Vanadium)	0.5	2	3	200
Mn (Manganese)	1	2	11	2
Cu (Copper)	20	3	10	
Br (Bromine)	2	3	---	---
Sc (Scandium)	0.02	---	0.2	---
Fe (Iron)	1	2	34	10
Co (Cobalt)	10	---	6.4	10
Ni (Nickel)	10	3	6.4	6
Zn (Zinc)	0.02	3	240	1
Se (Selenium)	0.02	3	---	200
Sb (Antimony)	0.01	---	40	40
Ba (Barium)	0.1	---	3	200
La (Lanthanum)	0.05	---	2	400
Ce (Cerium)	0.01	---	20	---
Sm (Samarium)	0.05	---	10	1000
Eu (Europium)	0.01	---	1	---
Yb (Ytterbium)	0.01	---	3	10
Lu (Lutecium)	0.01	---	100	---
Hf (Hafnium)	0.01	---	20	---
Th (Thorium)	0.01	---	10	---
Mg (Magnesium)	---	3	---	---
Si (Silicon)	---	3	---	---
P (Phosphorous)	---	3	---	---
As (Arsenic)	4	4	---	500
Pb (Lead)	---	1	---	---
Cd (Cadmium)	---	1	---	---
Hg (Mercury)	1	6	---	10

* This table, with minor modifications, was taken directly from Zoller and Gordon (1970).

determined qualitatively and quantitatively with high sensitivity (in the nanogram range) within several minutes. Similar research has also been performed by Jaklevic et al. (1971); Goulding et al. (1971) and Giauque (1968) using small X-ray tube or gamma-source for excitation. The detection sensitivities of this method are comparable to neutron activation analysis with the advantages of speed and low cost in the analysis. The sensitivities of the determination of trace element in air particulates by atomic absorption, emission spectroscopy, INAA and X-ray fluorescence are listed in Table 1 for comparison.

For the work described herein, I used neutron activation analysis for the determination of trace element abundances in air particulates collected from various sources of pollutants existing in western Oregon because of the availability of a nuclear reactor and the necessary associated equipment.

Sampling of Air Particulates

In general, the method of collecting air particulates is to draw a measured volume of air through a filter paper. Even though the technique is simple, one has to consider several factors in order to obtain a meaningful and representative sample. The factors to be concerned are (a) size of sample, (b) rate of sampling, (c) duration of sampling, (d) collection efficiency, (e) analytical limitation,

(f) sample handling, (g) choice of filter paper and (h) accuracy and precision required. In order to obtain accurate results, a compromise has to be made by careful consideration of the above factors. The following is brief discussion of some of the techniques used for air sampling in this study.

Air Samplers Used for Sampling

Hi-Volume Air Sampler. (Shepherd and Associates, Model 8000). This air sampler (shown in Figure 1a) is designed to sample large volume of air and is most suitable for short period sampling, such as in the study of agricultural field-burning. It was operated using one or two 12-volt batteries as a power supply. This allowed one to collect air samples at any location without relying upon other sources for electric power. The flow-rate of this air sampler ranged from 5-15 c.f.m. in the measurements described herein.

Gray et al. (1972) have reported that only 90 percent of the particulate is collected by 0.8 μm pore size Millipore filter paper at a flow-rate of about 4 c.f.m., indicating a significant amount of particulate is lost during the collection process. A study by Cohen (1973) on Hi-Volume air samplers indicated however that the loss is significant only at high flow-rates (40 to 60 c.f.m.) and is due to the loss of submicron aerosol particles through the filter pores.

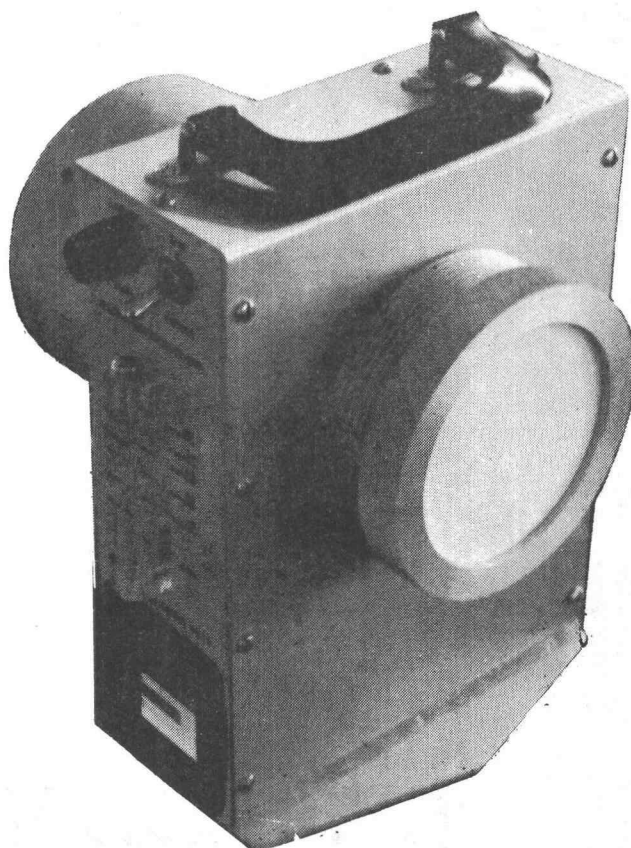


Figure 1a. High-volume air sampler (Shepherd and Associates, Model 8000) for the collection of air particulates.

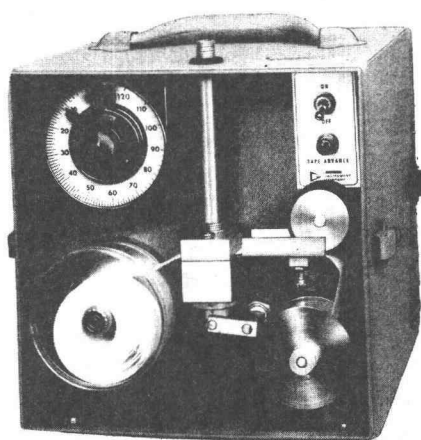


Figure 1b. Paper tape air sampler (Gelman, Catalog No. 23000) for the collection of air particulates.

In view of this controversy, a study was conducted to determine if there was significant leakage of aerosol through the filter paper during air sampling. This was done by spraying a Dy tracer into the air from the top of the O. S. U. Radiation Center and collecting an air sample downwind with a Hi-Volume air sampler operating at a flow-rate of 4.8 c.f.m. The air sampler contained two pieces of Whatman #1 filter paper attached together. The sampling period was about two hours. Upon analysis of the filter papers, it was found that the inner filter paper contained no significant amount of Dy (with upper-limit of detection less than 2 percent of Dy of the first filter paper), indicating there was no leakage of Dy through the first filter paper. This result is not consistent with the results of Gray et al. (1972).

Paper-Tape Air Sampler. (Gelman model No. 23000). This sampler (shown in Figure 1b) was operated with a 115 v. A.C. power supply. One good feature of this sampler is its automatic tape advance system which allows the sampler to remain unattended during the period of experiment. The tape is automatically rotated at a fixed rate controlled by an internal clock. This automatic advance feature is particularly useful in field work in that it allows collection of air samples at different locations at the same time. The flow-rate of this air sampler was quite low: it ranged from 0.2 to 0.9 c.f.m. in the measurements described herein.

Cascade Impactor. (Andersen model No. 23000). The function of this air sampler (shown in Figure 2a) is to fractionate the particulates according to their sizes. The sampler consists of eight stages and collection surfaces. Each stage consists of an Al plate containing many small, precisely drilled, identical holes and a collection surface. The hole diameters decrease from stage to stage. When a constant volume of air is drawn through the sampler, the velocity will increase as the air passes from stage to stage through the progressively smaller holes. After passing through each stage the air stream makes a turn and the heaviest particles have enough inertia to leave the air stream and impact on the collection surface. The particles are thus aerodynamically sized at the moment they leave the turning air stream. The range of particle sizes collected on each stage are shown in Figure 2b along with their relationship to the human respiratory system. The sampler was operated with a 12 volt battery as a power supply and drew air at 1 c.f.m. The sampler could have been modified to allow higher flow-rate. In general, the cascade impactor can be used to determine the aerodynamic particle size-weight distribution of suspended particulates, but one must be very cautious to use it to measure total suspended particulate concentration quantitatively because several studies (Gordon et al., 1973; O'Donnell et al., 1970 and Lungren, 1967) have reported that significant wall-loss could happen and the loss was quite variable due to changes in

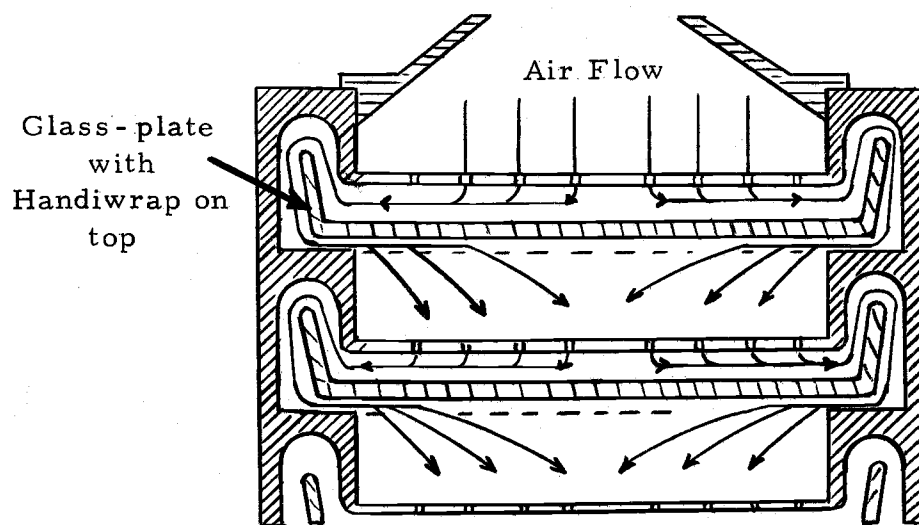


Figure 2a. Andersen cascade impactor for the fractionation of air particulates.

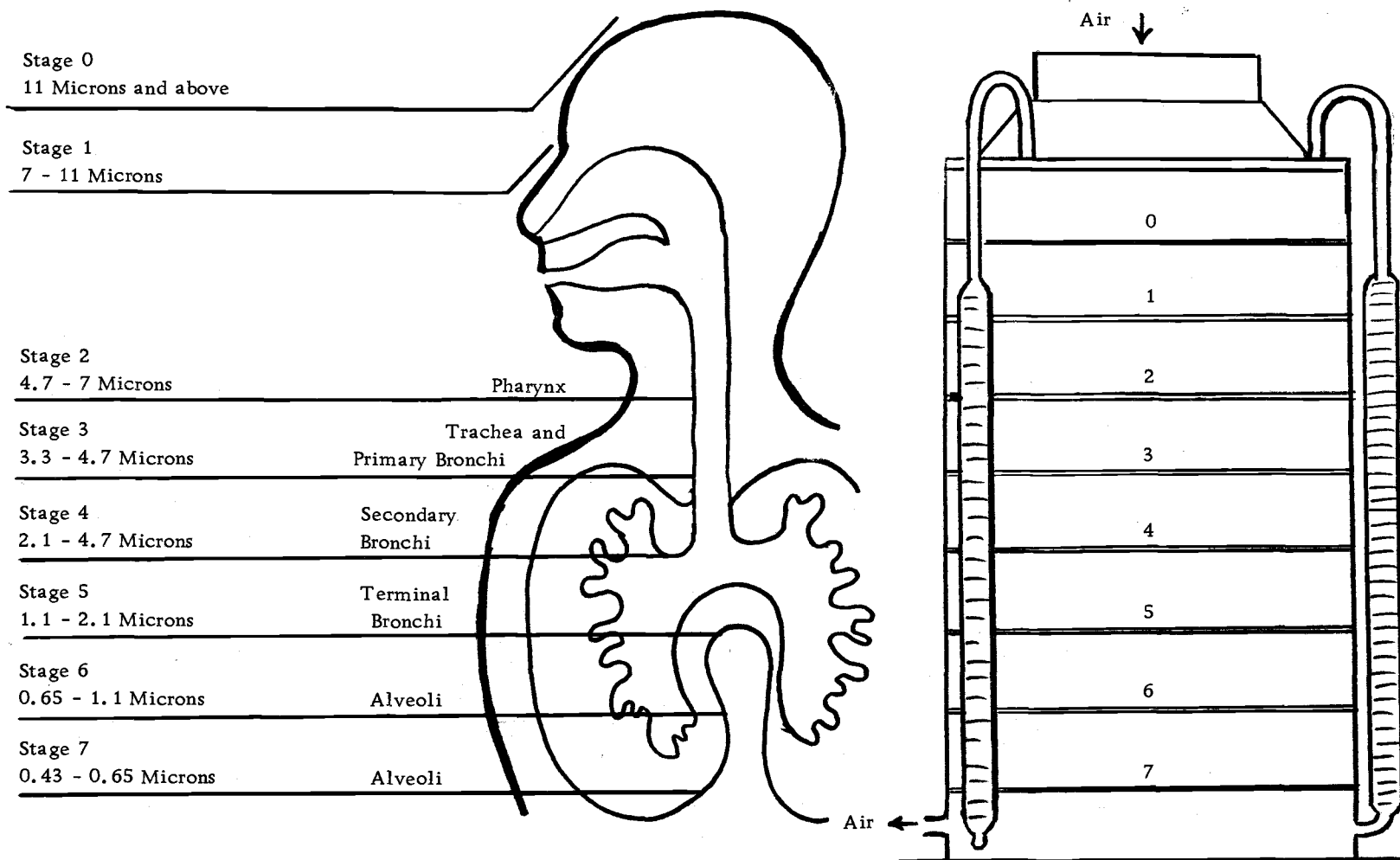


Figure 2b. Eight stage Andersen cascade impactor and the range of air particulate separated at each stage along with its relationship to human respiratory system.

atmospheric conditions, such as the humidity of the air collected and the concentration of particulates in the air. Therefore, in this work, the cascade impactor was mainly used for size fractionation of air particulates.

Measurement of Flow-Rate

In order to calculate the atmospheric concentration of any air particulate, the volume of air collected, i. e., the flow rate of the air sampler must be measured accurately. The flow-rate of the Hi-Volume air samplers used was measured directly by using a flow-meter with an accuracy of ± 10 percent error. For the paper-tape samplers, the balloon method was used. Air from the air-outlet of the sampler was sucked into a balloon for a given period of time and the volume of the balloon was calculated by measuring the diameter of the balloon. Care was taken to not fill the balloon too full causing significant back pressures. The measurement was repeated several times to get an average flow-rate. The accuracy of the measurement was estimated to be within ± 10 percent error. For long periods of air sampling, the flow-rate was measured before and after the sampling to estimate the change of flow-rate due to accumulation of air particulates on the filter paper. If the change of the flow-rate is more than 10 percent, an average flow-rate of the first and last measurement should be taken.

Most of the air sampling was done at room temperature. For samples taken at much higher temperatures such as the samples collected from industrial stacks, the volume of air collected was corrected to 25° C. using an ideal gas equation.

Choice of Collection Medium

The choice of a suitable filter paper as a collection medium for air particulate requires careful consideration and study. Because of the low concentration of trace elements in air particulate, it is critical that the filter paper chosen have very low trace element content so that the blank correction is small. The fiberglass filters used by the National Air Sampling Network to collect samples are not suitable for studies involving neutron activation analysis because of their high Na and Cl concentration. Supportive data for this conclusion is given in Table 2 which shows an analysis of a typical air sample collected with this filter. Note the large blank corrections for all the elemental abundances.

The trace element content of several types of filter papers potentially suitable as collection media were analyzed. The results are summarized in Table 3 taken from Shum and Loveland (1974). As one notes from studying Table 3, Nuclepore filter paper and Handiwrap appear to be the best collection media for air particulates.

Table 2. Trace Element Content in Fiberglass Paper and Urban Air Sample Collected at Eugene, Oregon.*

Element	Elemental Concentration ($\mu\text{g}/\text{in}^2$)		
	Fiberglass Paper	Fiberglass Paper + Air Sample	Air Sample
Mn	2.5	13.2	10.7
Cu	13.7	15.6	1.9
Na	3333.0	3607.0	274
Cl	74.0	128.5	54.5
Al	7.7	9.4	1.7
Br	1.2	27.6	26.4

* Air sample collected on 8" x 10" fiberglass filter paper from the Lane Air Pollution Authority at Eugene, Oregon.

Table 3. Trace Element Content of Filter Paper.*

Element	Handiwrap ^a	Handiwrap ^b	Elemental Concentrations (ng/cm ²)		Whatman #1 ^a	Whatman #1 ^d	0.25 μ m pore size Nuclepore ^a
			Millipore EH ^a	Millipore EH ^c			
Ti	3.2 $\pm$ 1.0	13.3	---	---	---	---	2.1 $\pm$ 0.8
Br	0.14 $\pm$ 0.04	---	66	6.2	5 $\pm$ 2	---	1.7 $\pm$ 0.1
Mn	0.73 $\pm$ 0.03	1.00	6.3	0.25	1.0 $\pm$ 0.4	2.7	0.23 $\pm$ 0.05
Na	8.7 $\pm$ 0.8	34.5	680	50	930 $\pm$ 20	1440	47 $\pm$ 2
Cl	4.8 $\pm$ 0.2	46.0	900	60	510 $\pm$ 20	900	80 $\pm$ 4
Al	2.7 $\pm$ 0.5	9.70	80	6	9.5 $\pm$ 3.6	18	2.7 $\pm$ 0.3
Sm	0.005 $\pm$ 0.001	---	0.10	---	---	---	<0.0017
Eu	0.00026 $\pm$ 0.00012	---	---	---	---	---	<0.000016

^aThis work. The reported abundance values are the weighted mean of ≥ 5 determinations and the quoted uncertainties represent population standard deviations.

^bD. Gray, D. M. McKown, M. Kay, M. Eichor, and J. R. Vogt. Determination of Trace Element Levels in Atmospheric Pollutants by Instrumental Neutron Activation Analysis, IEEE Trans. Nucl. Sci. NS-19(1), 194 (1972).

^cW. H. Zoller and G. E. Gordon. Instrumental Neutron Activation Analysis of Atmospheric Pollutants Utilizing Ge(Li) γ -ray Detectors, Anal. Chem. 42, 257 (1970).

^dJ. R. Keane and E. M. R. Fisher. Analysis of Trace Elements in Airborne Particulates by Neutron Activation and Gamma-Ray Spectrometry, Atmos. Env. 2, 603 (1968).

* Table taken from Shum and Loveland (Atmospheric Environment, in press).

In Table 3, the results of such analyses by other workers are included for comparison. One can observe the apparent discrepancies between analyses of the same type of material by different groups. It seems that the trace element content of these materials is extremely variable or some analyses may have suffered from contamination. As a matter of fact, our study shows the uniformity of the filter papers did vary from paper to paper from the same batch. Our analysis (see Table 4) shows that the variation of some of the trace elements in the filter paper taken from the same batch could be higher than 100 percent as compared to the averaged value. The Nuclepore filter paper also shows better uniformity than other types of filter paper. Therefore in our study, Handiwrap (manufactured by the Dow Chemical Co.) was used as impactor collection surface for the cascade impactor and Nuclepore filter paper (manufactured by the General Electric Co.) was used as collection medium for air particulates. The pore size of the Nuclepore filter paper was $0.25\text{ }\mu\text{m}$ with collection efficiency greater than 99 percent for air particulates and with flow-rates ranging from 0.05 c.f.m. to 2.4 c.f.m. depending on the type of air sampler used.

Handling of Air Samples

Due to the low trace element concentration of air particulates, special care was necessary in handling the air sample prior to

Table 4. The Variation of the Trace Element Content Among Filter Papers Taken at Random from the Same Batch.
Elemental Concentration (ng/cm²)

Nuclepore Filter Paper	Al	Cl	Na	Mn	Br
No. 1	2.7	69.0	44.0	0.15	1.7
2	2.7	79.0	47.0	0.23	1.8
3	2.7	82.0	49.0	0.25	1.6
4	2.7	80.0	46.0	0.22	1.7
5	2.7	80.0	47.0	0.23	1.7
Average	2.7	78.0	47.0	0.22	1.7
<u>Handiwrap</u>					
No. 1	3.1	4.4	13.0	0.63	0.13
2	2.4	2.8	9.2	1.26	0.22
3	2.4	5.2	11.0	1.10	0.06
4	2.4	7.5	8.4	0.31	0.26
5	3.6	5.1	7.7	0.79	0.13
Average	2.8	5.0	9.9	0.82	0.16
<u>Whatman #1 Filter Paper</u>					
No. 1	10.1	409	898	2.4	7.9
2	5.5	499	797	1.1	8.2
3	13.8	745	1025	0.9	5.1
4	4.9	797	927	0.7	2.5
5	10.0	502	920	0.8	2.5
Average	8.8	590	913	1.0	5.2

irradiation in the nuclear reactor. The air sampler was cleaned with absolute alcohol and acetone before the filter paper was inserted. The filter paper was not touched by hand. Table 5 shows the increase of trace element content of a piece of filter paper due to touching by human hands. As shown by the data of Table 5, one should always wear plastic gloves in mounting and dismounting of the filter paper. After air sampling, the sample was processed in a "clean" room immediately to avoid further contamination. In the "clean" room, the ventilated air was filtered and the walls and floor were cleaned constantly to eliminate the dust. One must wear plastic shoes, gloves and hat to avoid contamination in the processing of the air samples.

Table 5. Trace Element Contamination on Filter Paper (Whatman #1) Touched by Human Hand.

Element	Elemental Concentration (ng/cm ²)	
	Pre-Handling Initial Concentration Whatman #1	Amount Transferred by Handling
Na	913	6000
Cl	590	6063
Mn	1.0	3.0
Al	8.8	5.3
Br	5.2	64.7

Experimental Procedure for INAA of Air Particulates

In processing the air samples in a "clean" room, the samples were carefully transferred into clean polyvials and subjected to neutron activation analysis. The activation analysis procedure for measuring trace element abundances in air particulates is summarized in Table 6.

The samples or standards containing known amounts of the various trace elements were irradiated for two minutes in the pneumatic terminal of the O. S. U. TRIGA reactor in a neutron flux of 9×10^{12} n/cm²-sec. After irradiation, the sample was transferred into a new polyvial and counted immediately for 100 seconds with a 30 or 40 cm³ Ge(Li) detector incorporated with a multichannel analyzer. A Ge(Li) detector was chosen instead of a NaI (Tl) detector because of its superior resolution that allowed one to resolve the many peaks in the gamma-ray spectra. A block diagram of the counting set-up is shown in Figure 3. When the gamma radiation enter the Ge(Li) detector, the output voltage pulse is amplified by the preamplifier and amplifier and analyzed by a multichannel analyzer. The use of the Ge(Li) detector in gamma-ray spectroscopy has been treated in detail by many authors (Gordon et al., 1970; Dams et al., 1971, and John et al., 1973). Therefore, further discussion on the use of Ge(Li) detectors for gamma-ray detection will not be given here.

Table 6. Summary of Activation Analysis Procedure.

Element	Radionuclide Detected	Half-life*	Length of Irradiation	Decay Time	Count Duration	Energy of Gamma-Ray Measured* (keV)
Al	^{28}Al	2.31 min	2 min.	3 min.	100 sec.	1778.9
Ti	^{51}Ti	5.79 min.				320
V	^{52}V	3.75 min.				1434.4
Cu	^{66}Cu	5.1 min.				1039
Na	^{24}Na	14.96 hr.	2 min.	5 min.	400 sec.	1368.5
Cl	^{38}Cl	37.3 min.				1642
Mn	^{56}Mn	2.58 hr.				846.9; 1810
Br	^{80}Br	17.6 min.				617
Ba	^{139}Ba	82.9 min.				165.8
Sm	^{153}Sm	47 hr.	6 hr.	12 hr.	1 hr.	103.2
Eu	$^{152\text{m}}\text{Eu}$	9.3 hr.				121.8
Zn	$^{69\text{m}}\text{Zn}$	13.8 hr.				438.7
Br	^{82}Br	35.9 hr.				776.6
As	^{76}As	26.5 hr.				657; 1215.8; 559
Sb	^{122}Sb	2.80 day				564; 686
K	^{42}K	12.36 hr.				1524.7
La	^{140}La	40.22 hr.				486.7; 1596
Sc	^{46}Sc	83.9 day	6 hr.	15-30 d	5 hr.	889.4; 1120
Cr	^{51}Cr	27.8 day				320
Fe	^{59}Fe	45.6 day				1292
Co	^{60}Co	5.26 yr.				1173.1
Hg	^{203}Hg	46.9 day				279.1
Ce	^{141}Ce	33 day				145.4
Yb	^{169}Yb	32 day				177; 197.8
Lu	^{177}Lu	6.7 day				208.3
Hf	^{181}Hf	42.5 day				136.5
Conditions Used in Artificial Tracer Analyses						
Dy	^{165}Dy	139.2 min.	2 hr.	0	800 sec.	94.7
Sm	^{153}Sm	47 hr.	2 hr.	12 hr.	1 hr.	103.2
La	^{140}La	40.22 hr.	4 day	4 day	1 hr.	486.7; 1596
Ce	^{141}Ce	33 day	4 day	4 day	1 hr.	145.4

* Taken from Lederer *et al.* (1967)

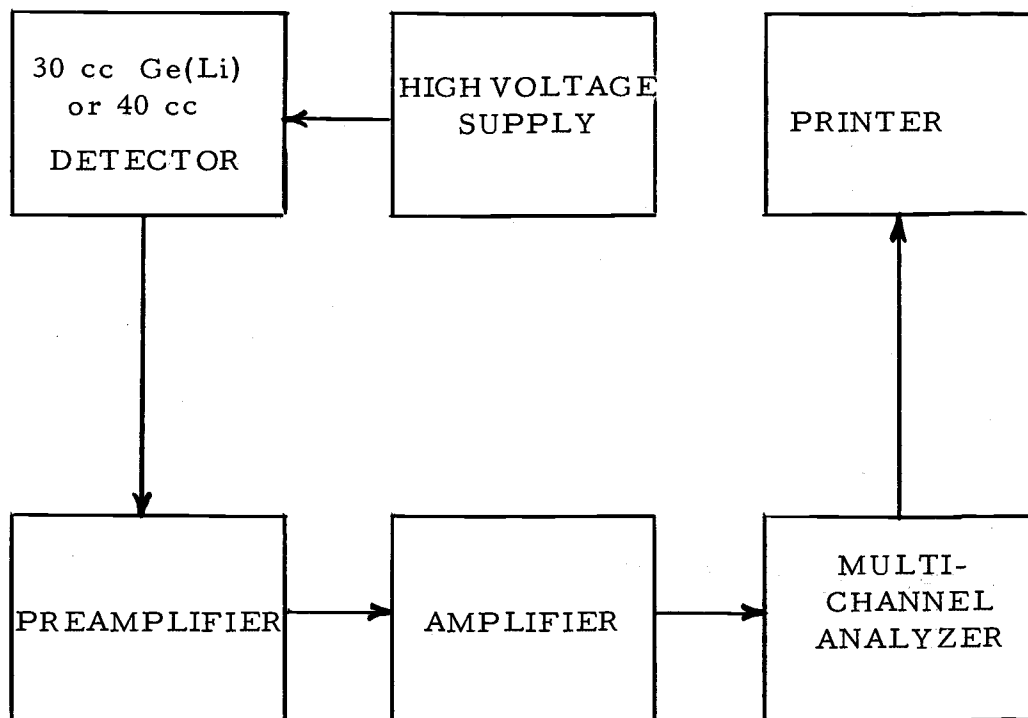


Figure 3. Schematic block diagram of electronics used in γ -ray spectroscopy.

After the first counting was done, this measurement was immediately followed by a 400 second count. Table 6 shows the elements whose concentrations are determined by the first two counts. The sample radioactivity was then allowed to decay for a week, and the sample was irradiated again in the rotating rack of the reactor at a flux of 3×10^{12} n/cm² - sec. for six hours. After cooling for 12 hours, the sample was counted for one hour. The sample was re-counted for five hours after an additional cooling period of one month. The elements whose concentrations were determined in this second irradiation are also tabulated in Table 6.

Half lives measured for all radionuclides agreed within ± 10 percent of the accepted values (Lederer et al., 1967). The energies of the gamma-rays used in the analysis of the various trace elements are listed in Table 6. Standards containing known amounts of the pure elements were irradiated along with the samples and counted under identical conditions. From the photopeak areas for samples and standards, elemental abundances were calculated for each sample. The accuracy of the standards and procedure used were evaluated by analyzing the trace element content of NBS standard reference material 1571 (orchard leaves). The measured values of the Mn, Na, Zn, As, Co, Rb, Fe, Se, Hg and Cr abundances agreed within experimental error (± 10 percent) with the accepted NBS values.

For the analysis of the samples containing the artificial tracers, i. e., Dy, Sm, La, and Ce in air samples collected for stack effluent dispersal studies, the procedures summarized in Table 6 were used. The samples and standards were irradiated in the rotating rack in a neutron flux of 3×10^{12} n/cm² - sec. for two hours. The sample was counted immediately for 800 seconds to measure the Dy abundance. The sample radioactivity was allowed to decay for 12 hours and was counted again for one hour to determine the Sm concentration. The determination of the concentrations of La and Ce requires a higher neutron flux to provide more activity. For the La and Ce analysis, the samples were wrapped in thick Al foil, packed together in an Al tube, and sent to the University of Missouri nuclear reactor where they were irradiated at a flux of 5×10^{13} n/cm² - sec. for four days. The samples were then shipped back to Corvallis by air to be counted. Only a one hour count was necessary to determine the concentrations of La and Ce.

III. ATMOSPHERIC TRACE ELEMENT CONCENTRATIONS ASSOCIATED WITH VARIOUS SOURCES OF AIR POLLUTION IN WESTERN OREGON

The Nature of Air Pollution in Western Oregon

The air pollution problems of western Oregon are not typical of the problems faced nationally. Gaseous contaminants, which cause very serious air pollution problems in other parts of the nation, do not constitute a great problem in Oregon. Photochemical smog, such as found in Los Angeles, is not threatening Oregon to any significant extent. The concentration of the photochemical smog products such as hydrocarbons, nitrogen oxides and ozone are relatively low in Oregon as compared to Los Angeles and some other parts of the nation.

The major air pollution problem in western Oregon is due to the emission of suspended particulates from various sources in the Willamette valley. These suspended particulates can stay in the atmosphere for a long period of time and are the major cause for visibility loss, soiling, and possible damage of property and harm to human health. Conditions are worse during the late summer and fall when inversion layers persist over the valley. One can observe during this period a persistent haze hanging over most of western Oregon and man-made suspended particulates are one of the major components of this haze.

According to the report of a "Rapid survey of 1968 air contaminant emission in western Oregon" by the Department of Environmental Quality in Oregon, it has been shown that 28 percent of the fine suspended particulate (with diameter less than 10 microns) comes from field burning and slash burning, 25 percent from the wood products industry, (including the pulp and paper industries), 18 percent from the metal industry, 11 percent from motor vehicles, 9 percent from heating and related fuel burning and 9 percent from other miscellaneous sources. Therefore, I have chosen the major sources of pollutants in western Oregon, such as agricultural field burning, paper, metal and plywood industries to be the subject of this study.

Agricultural Field Burning in the Willamette Valley of Oregon*

In the Willamette Valley of western Oregon, following harvest of grass seed and small grain crops, the fields containing straw and stubble are set on fire. Over a quarter million acres of land is burned during the months of August and September releasing 700,000 tons of material to the atmosphere. The reasons for this field burning are 1) to sanitize the fields (protecting them against fungus diseases, pests, etc.), 2) to dispose of the straw and stubble left

*This section with minor modifications has been taken from Shum and Loveland (Atmospheric Environment, in press).

after harvest, and 3) to prepare the seed beds for further use by destroying weeds, weed seeds and residue. Despite extensive research, no alternatives for field burning have been uncovered and the practice is expected to continue.

This study concerns measurement of the atmospheric trace element concentrations associated with field burning. We hoped to learn the magnitude and origin of these concentrations with particular emphasis being placed on those potential toxic elements such as Hg and As. Another aspect of the work was the measurement of the distribution of the particulate sizes for each of the trace elements. This is particularly important since the large particles will not pass through our respiratory system and, therefore, it is only the smaller particulates (less than 10 μm diameter) that are of concern in health consideration.

Experimental

Ground level air samples were collected during the burning of five different grass fields in the vicinity of Corvallis, Oregon during August, 1972. Samples were collected in the smoke plume from the burning field and were taken at a distance of 50-100 yards away from the periphery of the field where burning was taking place. A gross particulate sample was collected using a Hi-vol. air sampler and a collection medium of Nuclepore filter paper (manufactured by the

General Electric Company). Nuclepore filter paper with a $0.25\text{ }\mu\text{m}$ pore size was selected as the collection medium for the sample because of its low concentrations of trace elements as shown in Table 3 and its high collection efficiency ($>99\%$) for particulates. This gross particulate sample was analyzed for the determination of the atmospheric trace element concentrations. Samples in which the atmosphere particulates were fractionated by particle size were also collected using an 8-stage Andersen cascade impactor. The impaction medium for these samples was a piece of Handiwrap (Dow Chemical Co.). Handiwrap is also known to have a low trace element content (see Table 3). The volume of air collected for each sample was approximately $2\text{--}20\text{ m}^3$. Samples of ordinary rural air were taken at the same locations a month later for comparison purposes. At the same time, samples of unburned grass stubble and soil were gathered for further analysis. The procedure for multielemental analysis of the samples is discussed in detail under the "Methodology" section of this thesis. One point to be mentioned here is the magnitude of the filter paper blank corrections. For the field burning air samples, the blank corrections ranged in magnitude from 0-45 percent for various trace elements with the average blank correction being about five percent. For the rural air samples, the blank corrections were far more significant ranging in magnitude from 0-60 percent and having an average value of 27 percent.

Results and Discussion

Table 7 shows the relative atmospheric trace element concentrations found in the field burning air samples (arbitrarily normalized to Ti = 10,000). (All atmospheric trace element concentrations reported in this section refer to an air temperature of 25° C). The relative concentrations represent averages of the concentrations in all the air samples collected. Because of the different quantities of material being burned and varying sampler locations at the five fields, it is difficult to extract a meaningful absolute atmospheric trace element concentration associated with field burning from the data. The most meaningful data are therefore the relative trace element concentrations which serve as a "fingerprint" for field burning. However, as a point of interest, one can average the absolute concentrations observed at the various locations and obtain a rough estimate of the absolute atmospheric trace element abundances associated with agricultural field burning. This has been done and the data are shown in Table 7. Also shown in Table 7 are the average absolute atmospheric trace element concentrations in ordinary rural air in the Corvallis, Oregon area.

Firstly we note that the contribution of the ordinary rural air "background" to the atmospheric trace element concentrations associated with field burning is negligible (~1-5%) in almost all cases.

Table 7. Gross Atmospheric Trace Element Concentrations.

Element	Relative Trace Element Concentration Associated with Field Burning (normalized to Ti = 10^4)	Absolute Trace Element Concentration Associated with Field Burning (ng/m ³)	Absolute Trace Element Concentration in Ordinary Rural Air (ng/m ³)
Al	71,000 $\pm$ 23,000	16,700 $\pm$ 5,400	450 $\pm$ 180
Fe	39,000 $\pm$ 25,000	9,100 $\pm$ 5,800	160 $\pm$ 70
Na	62,000 $\pm$ 20,000	14,400 $\pm$ 4,600	340 $\pm$ 20
K	22,000 $\pm$ 7,000	5,200 $\pm$ 1,700	85 $\pm$ 8
Ti	10^4	2,330 $\pm$ 100	69 $\pm$ 5
Mn	2,800 $\pm$ 800	650 $\pm$ 190	2.7 $\pm$ 0.5
Ba	<130*	<30	<22
V	280 $\pm$ 120	70 $\pm$ 30	2.8 $\pm$ 0.1
Cl	42,300 $\pm$ 1,900	9,840 $\pm$ 450	240 $\pm$ 20
Cr	265 $\pm$ 40	62 $\pm$ 9	6 $\pm$ 1
Ce	80 $\pm$ 30	19 $\pm$ 7	<0.9
Cu	<215	<50	<35
La	70 $\pm$ 30	16 $\pm$ 7	1.4 $\pm$ 0.2
Co	50 $\pm$ 25	11 $\pm$ 6	<0.1
Sc	180 $\pm$ 100	42 $\pm$ 24	0.07 $\pm$ 0.02
Sm	16 $\pm$ 6	3.7 $\pm$ 1.4	0.095 $\pm$ 0.02
Yb	16 $\pm$ 9	3.6 $\pm$ 2.1	<0.7
Hf	9.5 $\pm$ 3.4	2.2 $\pm$ 0.8	<0.4
Br	560 $\pm$ 220	130 $\pm$ 50	2.9 $\pm$ 0.4
As	120 $\pm$ 55	28 $\pm$ 13	<0.35
Eu	7.7 $\pm$ 2.1	1.8 $\pm$ 0.5	0.019 $\pm$ 0.002
Lu	1.3 $\pm$ 0.4	0.3 $\pm$ 0.1	<0.2
Sb	210 $\pm$ 70	50 $\pm$ 17	0.3 $\pm$ 0.2
Hg	120 $\pm$ 70	27 $\pm$ 15	<1.4

*The upper limit is taken as $2\sigma_b$ where σ_b is the background standard deviation. This definition of an upper limit applies to all other trace elemental analyses reported in this work.

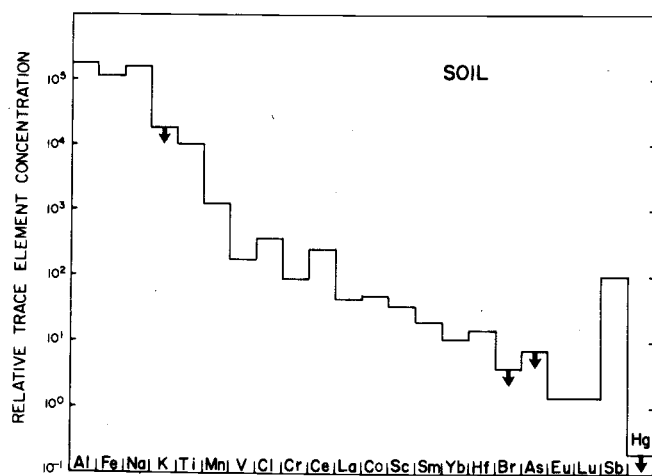
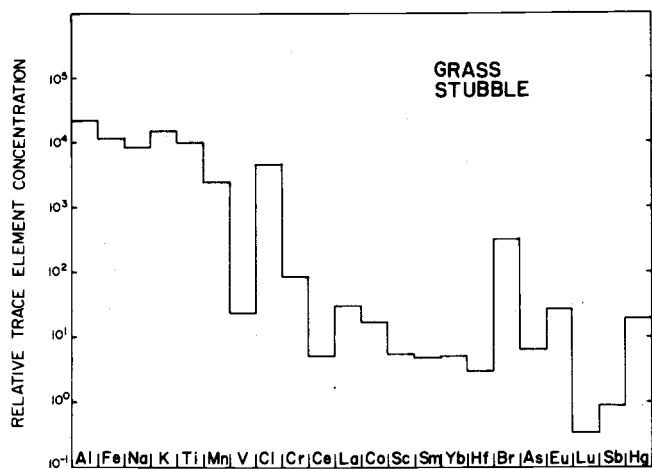
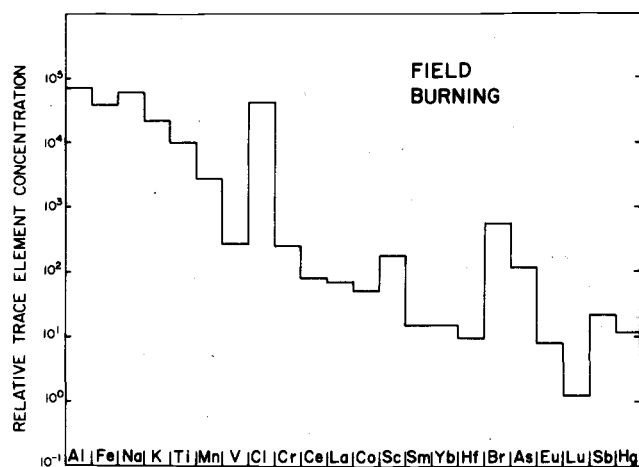
Secondly, we note that the trace element concentrations associated with field burning are not large by contemporary standards. For example, if we consider the toxic elements Hg and As, the reported atmospheric concentrations of 27 ± 15 and $28 \pm 13 \text{ ng/m}^3$, respectively, are very small when compared to the threshold limit value for atmospheric concentrations of Hg vapor and inorganic Hg and As of 100 and $500 \text{ } \mu\text{g/m}^3$ set by the American Conference of Governmental Industrial Hygienists. [ACGIH] The threshold limit values are the time-weighted average concentration for a normal workday to which it is believed that workers may be exposed without adverse effect. Even if we were to consider all the Hg detected in our experiments to be in the form of organic Hg compounds, the concentration values found are still a trivial fraction of the threshold limit value for organic Hg in the air which is $10 \text{ } \mu\text{g/m}^3$. Furthermore, we recognize that the concentrations shown in Table 7 represent concentrations present in the smoke in the burning field, and not the much smaller concentrations inhaled by the residents of the Willamette Valley. Lastly as we shall show, most of the trace elements are concentrated on the larger smoke particles (diameter $> 10 \text{ } \mu\text{m}$) and are not expected to significantly enter the human respiratory system.

As mentioned previously, the relative trace element concentrations form a "fingerprint" for air pollution derived from field burning. To help understand the origin of the trace element

concentrations associated with field burning, we have analyzed the trace element content of the dry grass stubble being burned and the soil in the field being burned. These relative trace element concentrations are shown in Figure 4. One notes that the air pollution associated with field burning shows the high abundances of Ti, Na, Al, K, and Fe characteristic of the dry grass stubble. The soil on the other hand, while having high abundances of some of these elements, is very depleted in Br, Cl, and the rare earths relative to the abundances observed in field burning air. A least squares analysis of the atmospheric trace element abundances associated with field burning based upon the assumption that the atmospheric abundances were derived solely from the grass and the soil showed a 95 percent contribution of the grass and a five percent contribution of the soil to the atmospheric abundances. This assignment of the origin of the air particulate primarily to one source is further supported by the calculation of the linear correlation coefficients for the atmospheric trace element concentrations measured at the five collection sites. The concentrations of the elements Fe-Co-Hg-Hf-Lu-Yb-Ce-As-K-Sm-V-Cl and Ti were found to correlate linearly at the 95 percent confidence level. This, we believe, supports the notion of a common origin for the trace elements in field burning smoke.

Figure 4. Relative trace element concentrations (normalized to $Ti = 10^4$) associated with field burning.

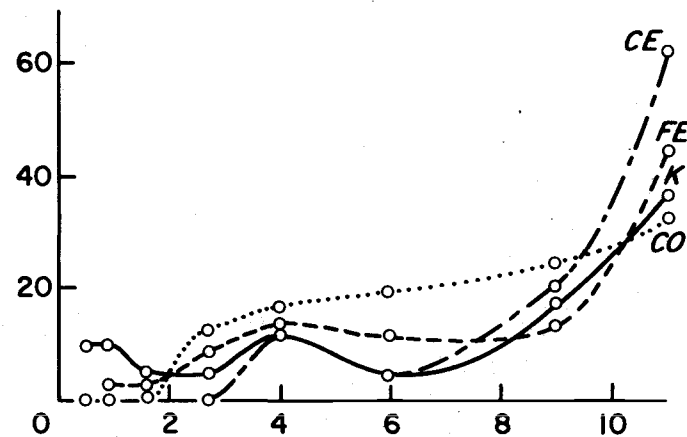
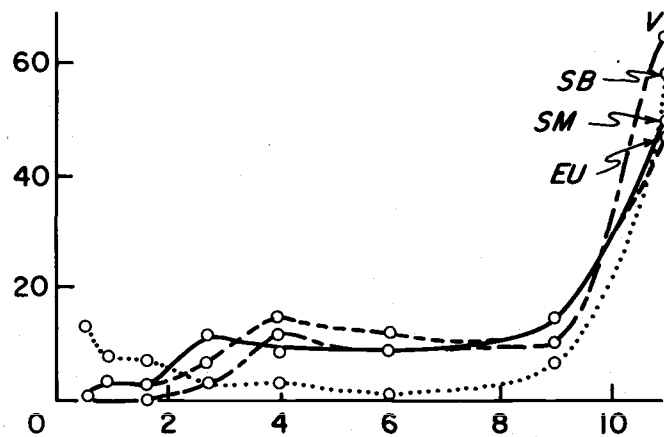
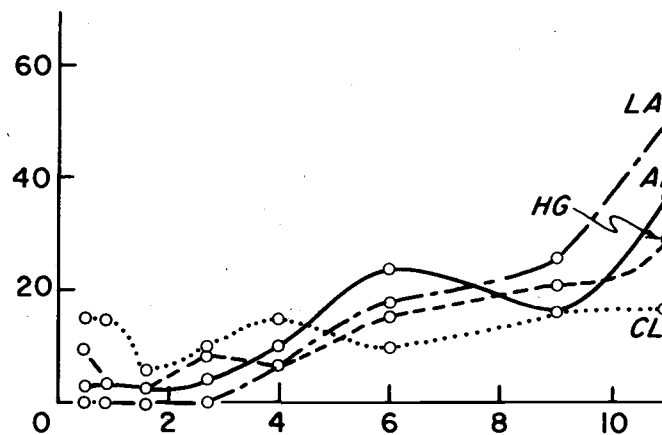
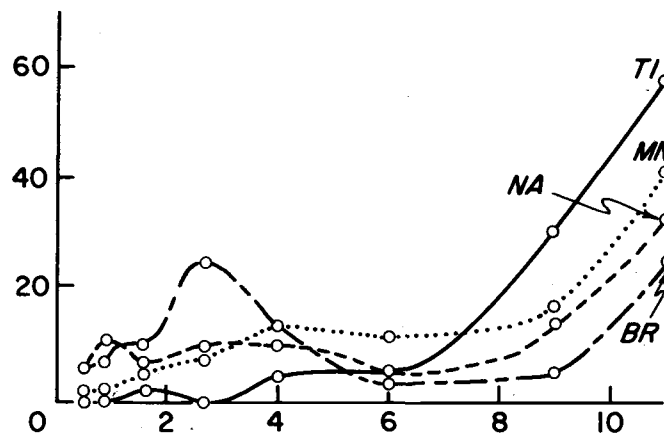
- (a) The trace element concentrations in the smoke from field burning.
- (b) The trace element content of some samples of dry grass stubble from the fields being burned.
- (c) Trace element concentrations in the soil of the fields being burned. Downward arrows indicate upper limits for elemental concentrations (The upper limits are taken as $2\sigma_b$ where σ_b is the background standard deviation). The concentration of the element Fe was taken from the work of Vinogradov (normalized to our measured Al content) (Vinogradov, 1959).



Another important aspect of the study of the particulate trace element concentrations associated with field burning is their size fractionation. Figure 5 shows the concentrations of some of the trace elements in field burning air particulate plotted as a function of the particulate size. Note that most of the trace elements are associated with larger sized particles (diameter $\geq 11 \mu\text{m}$). The large particle diameters associated with field burning air particulate are believed to be the product of the incomplete combustion of the stubble in field burning. (This result is not in agreement with the less detailed microscopic study of Meland and Boubel (1966) who found a mean particle size of $0.5 \mu\text{m}$ for the field burning air particulate.) Interestingly, the halogens Cl and Br show more uniform distributions with Br showing a definite peak in the particle size distribution at a particle size of 2.7μ . If, as argued earlier from mixing model and linear correlation coefficient arguments, Br originates in the plant stubble, this data then serves to caution one that the mere observation of Br concentrating on small-sized particles in air samples is not sufficient evidence by itself that the Br originated from the burning of gasoline as has been claimed previously (Gordon, 1971). The large particle sizes found for the air particulate from field burning further emphasize that the atmospheric trace element concentrations associated with field burning are not significant in regard to human health considerations. Particles with diameters $\geq 11 \mu\text{m}$ are not easily respired by

Figure 5. Percent of the total elemental particulate mass with a given particle diameter vs. particle diameter for each trace element studied in field burning air. Measurements were taken for mean particle diameters of ≥ 11 , 9, 6, 4, 2.7, 1.6, 0.9 and 0.5 μ m. Uncertainties in each point are of the same order as the uncertainties shown in Table 7 for the gross elemental concentrations. (To obtain concentrations of each element, one need only multiply the percentages shown in this Figure by the absolute total elemental concentrations shown in Table 7).

% TOTAL ELEMENTAL MASS WITH GIVEN DIAMETER



MEAN PARTICLE DIAMETER (μm)

humans and therefore from the point of view of human health, the trace element concentrations reported in Table 7 are in general a factor of ~ 2 higher than the concentrations that enter the human respiratory system.

An interesting sidelight of this study has been the measurement of the atmospheric trace element abundances associated with ordinary rural air in the Corvallis, Oregon area. These abundances are tabulated in Table 8 along with similar measurements of atmospheric trace element abundances in other representative American cities, rural and residential areas. The first thing one notes upon examination of the data in Table 8 is that the atmospheric trace element concentrations in Oregon rural air are extremely low when compared to similar concentrations measured in major urban areas or in other rural environments such as Columbia, Missouri. The measurements reported here were taken at the end of a dry summer period (August, September, 1972) and were taken in rural areas with many open, plowed fields. The air in the Willamette Valley does not turn over rapidly but sloshes back and forth in the valley between the Cascade Mountain Range and the Pacific Coast mountain range. In short, the air at the time of our measurements should have represented "the continental background" due to the contribution of soil and rock dust to the air. In fact, the atmospheric elemental abundances do remarkably resemble the relative elemental abundances in the earth's

Table 8. Atmospheric Trace Element Abundances in Various American Locations (ng/m³).

Element	Corvallis, Ore. Rural Air	San Francisco Bay Area ^a	Gary-E. Chicago Indiana ^b	Chicago Illinois ^c	Cambridge Mass. ^d	Columbia Mo. ^e	Portland Ore. ^f
Al	450 ± 180	863	1950	1900	700	1460	-
Fe	160 ± 70	1670	3900	4800	1000	1100	800
Na	340 ± 20	3520	285	560	800	319	-
K	85 ± 8	-	1150	-	-	5100	-
Ti	69 ± 5	-	175	-	-	150	10
Mn	2.7 ± 0.5	17	130	700	20	28.8	140
Ba	< 22	12	-	-	-	-	-
V	2.8 ± 0.3	5.4	7.4	24	600	5	18
Cl	240 ± 20	2930	-	5900	500	700	-
Cr	6 ± 1	8.2	21	25	-	2.9	4
Ce	< 0.9	2.5	3.8	20	0.2	0.02	-
Cu	< 35	50	180	-	50	-	80
La	1.4 ± 0.2	1.4	2.4	3.7	0.3	0.9	-
Co	< 0.1	1.0	1.1	4.5	0.2	0.85	-
Sc	0.07 ± 0.02	1.4	1.6	0.9	0.8	0.4	-
Sm	0.095 ± 0.02	0.22	0.34	-	0.2	0.53	-
Yb	< 0.7	-	-	-	-	-	-
Hf	< 0.4	-	-	-	-	-	-
Br	2.9 ± 0.4	220	66	270	150	65	-

Table 8. Continued.

Element	Corvallis, Ore. Rural Air	San Francisco Bay Area ^a	Gary-E. Chicago Indiana ^b	Chicago Illinois ^c	Cambridge Mass. ^d	Columbia Mo. ^e	Portland Ore. ^f
As	< 0.35	-	4.4	-	-	1.8	-
Eu	0.019 ± 0.002	0.05	0.09	0.22	0.3	0.09	-
Lu	< 0.2	-	-	-	-	-	-
Sb	0.3 ± 0.2	2.1	6.3	45	0.5	0.08	-
Hg	< 1.4	2.7	-	-	-	-	-

^aJohn, W., Kaifer, R., Rahn, K., and Wesolowski, J. J., Atmos. Env. 7, 107 (1973).

^bDams, R., Robbins, J. A., Rahn, K., and Winchester, J. W., Nuclear Techniques in Environmental Pollution (IAEA, Vienna, 1971).

^cBray, S. S., Nelson, D. M., Kanabrocki, E. L., Moore, C. E., Bwinham, C. D. and Hattori, D. M., Env. Sci. and Tech. 4, 50 (1970).

^dZoller, W. H. and Gordon, G. E., Anal. Chem. 42, 257 (1970).

^eGray, D., McKown, D. M., Kay, M., Eicher, M., and Vogt, J. R., IEEE Trans. Nucl. Sci. NS-19(1), 194 (1972).

^fOregon Dept. of Environmental Quality, Report on Air Quality, December, 1969.

crust as shown in Figure 7. The low abundances seen in this work may be due to gravitational settling in our stagnant air of many of the soil and dust particles which are expected to have larger sizes.

[Butcher and Charlson, 1972] We believe that apart from a few exceptions to be commented upon later, our Oregon rural air elemental abundances represent "the continental background" of relative trace element abundances.

Some deviations from the crustal abundance patterns observed in Oregon rural air can be understood. For example, the Na/Br ratio observed in Oregon rural air agrees within experimental error with the known Na and Br abundances in sea salt (Mason, 1966). The Cl abundance observed is lower than that expected assuming the Na and Br are from a marine aerosol. This depletion of Cl in what presumably is a marine aerosol was also noted by John et al. (1973) and was explained in terms of Cl loss by the aerosol as it ages.

Further interesting views of this fairly clean "continental background" air can be obtained by examining the particle size distribution found in Oregon rural air. This size is shown in Figure 6 for a few typical trace elements found in Oregon rural air. As expected, the continental indicator elements, Mn and Al, are concentrated on larger sized particles. However, the Na, Br and Cl, which their abundances indicate originate in sea salt, show a relatively uniform particle size distribution. This is not in agreement with the particle

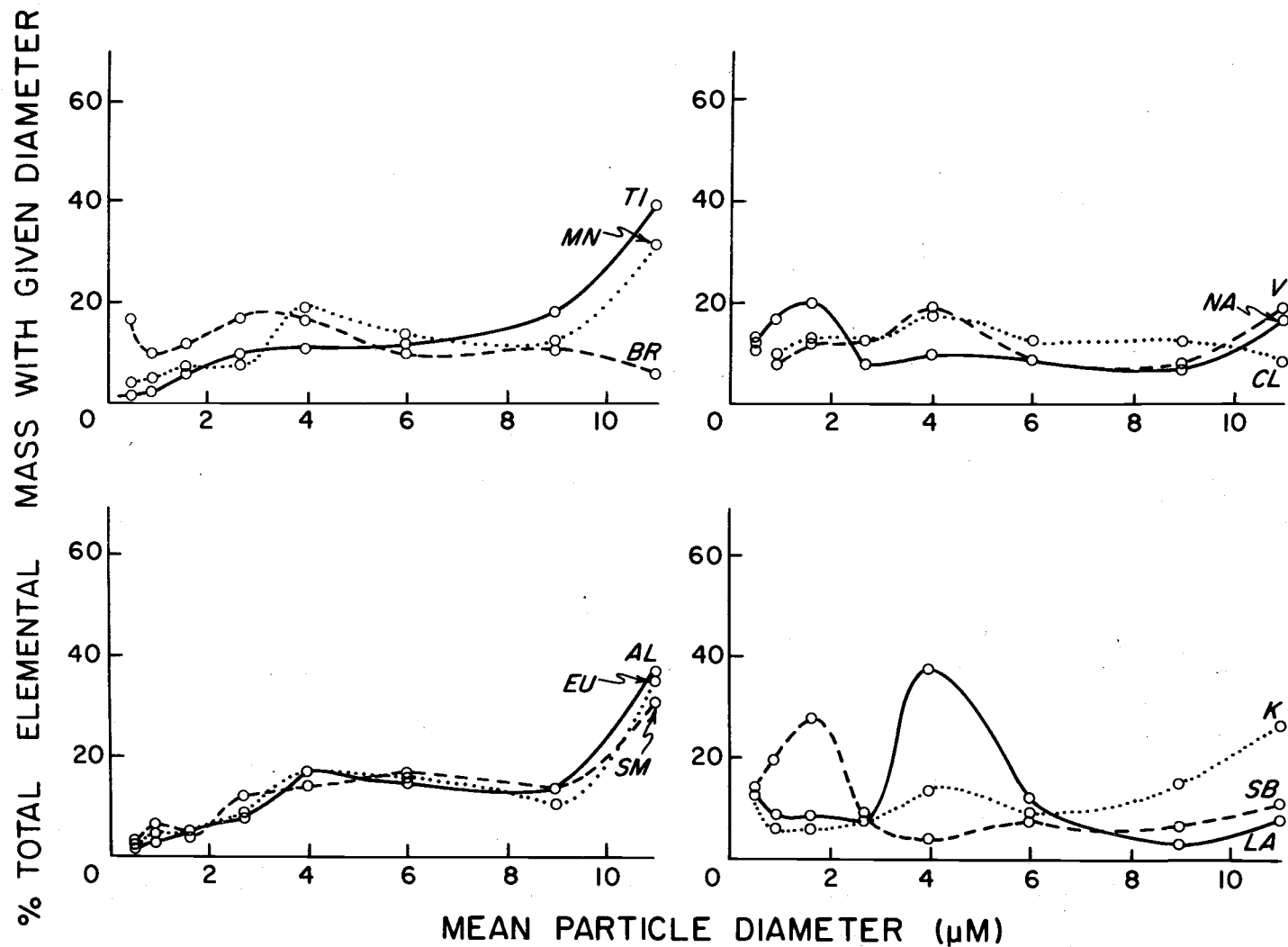


Figure 6. Percent of the total elemental particulate mass with a given particle diameter vs. particle diameter for the trace elements found in Oregon rural air. See Figure 5 for further description.

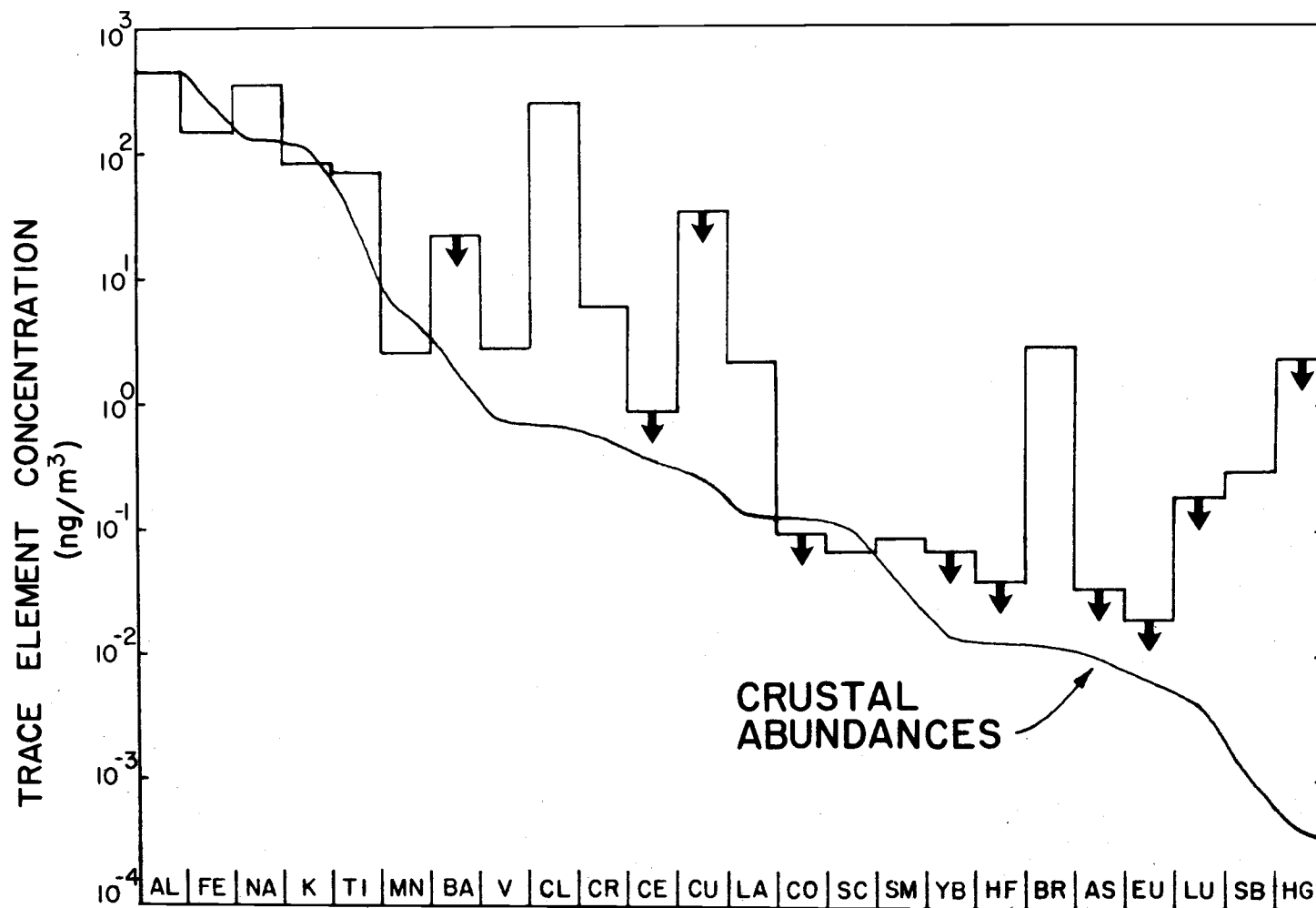


Figure 7. Absolute atmospheric trace element concentrations in Corvallis, Oregon rural air. Also shown is the relative pattern of average trace element abundances in the earth's crust normalized to our Al abundance. The values of the crustal trace elemental abundances are taken from Taylor [1964] assuming a 1:1 mixture of granite and basalt. Downward arrows indicate upper limits for elemental concentration. (The upper limits are taken as $2\sigma_b$ where σ_b is the background standard deviation.)

size distributions observed in fresh marine aerosols. Perhaps during the aging of the aerosol, the larger particles will settle out leaving a more uniform size distribution in the aerosol. Interestingly, the rare earths Sm and Eu seem to be concentrated on the larger sized particles while La is not. The reasons for this are not well understood. Sb and V concentrations in urban air are usually taken as indicative of the burning of fuel oil and Sb and V concentrate on the smaller particles. In rural air we observe the concentration of Sb on the smaller sized particles but not that of V. The origin of these elements in rural air is not clear.

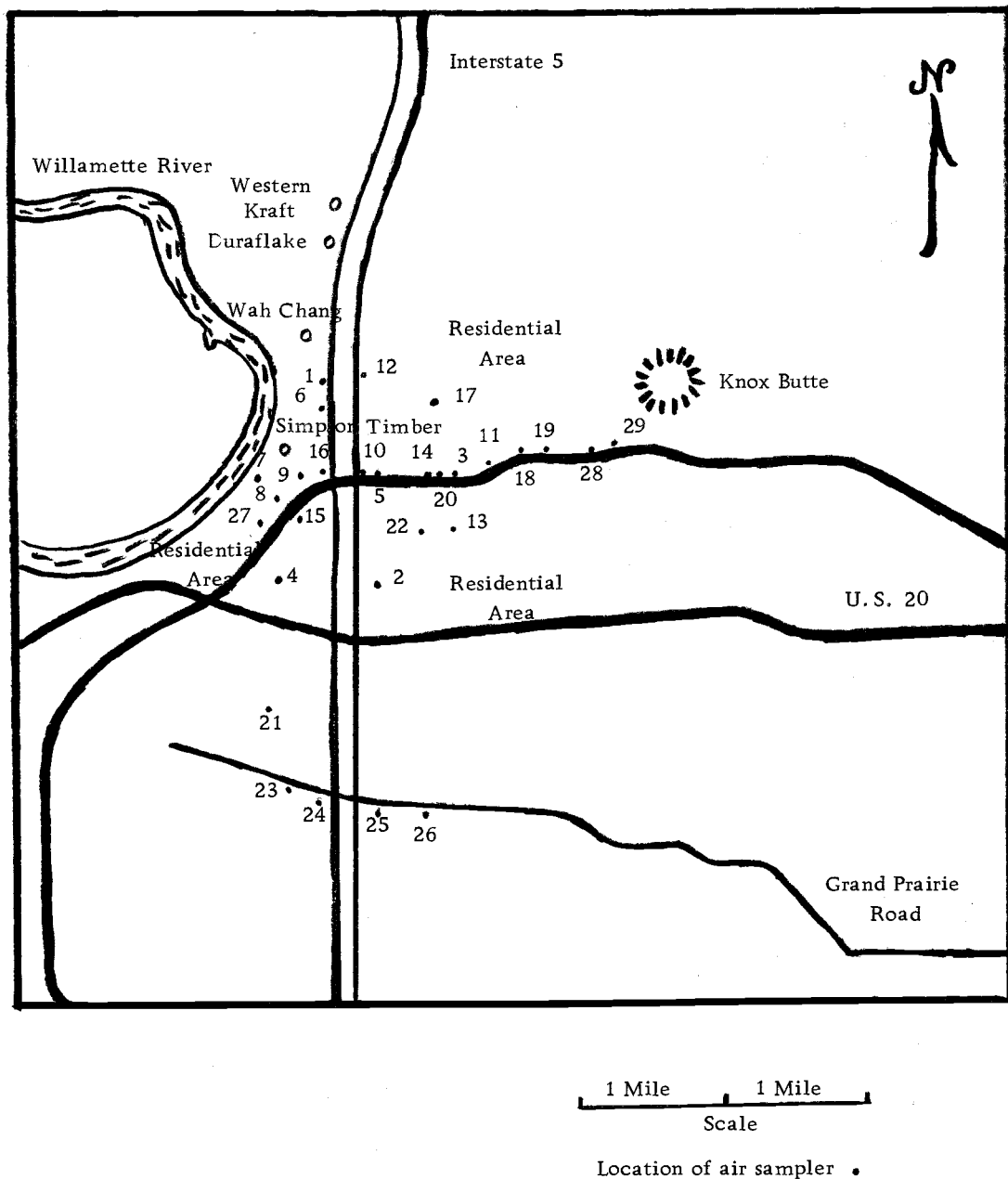
In general, what we have learned from our studies of field burning is that:

1. The atmospheric trace element abundances associated with field burning do not represent a significant health hazard and are primarily due to the trace element content of the stubble being burned.
2. As far as particulate size is concerned, the trace elements associated with field burning air particulate are concentrated in the large particles, probably due to incomplete combustion.
3. The total trace element content of Oregon rural air is very low compared with other areas of the country, and may

serve as an indication of the "continental background" contribution to atmospheric abundances.

Atmospheric Trace Element Concentrations Associated
with Various Industries in Albany, Oregon

The purpose of this phase of the study is to attempt to establish a trace element "fingerprint" for some major sources of air pollution in Albany, Oregon. A paper manufacturing company (Western Kraft), a metallurgical processing company, (Teledyne Wah Chang), and a plywood company (Simpson Timber Company) were chosen for this study. They not only represent different industries in this area, but they are also physically very close to each other as shown in Map 2. This is an ideal situation for a study of multiple sources of air pollution. In order to establish a chemical fingerprint for a given industry, we must establish that the industry's effluent contains a unique trace element abundance distribution. We can then use these trace elements as tracers to monitor the dispersal of the stack effluent and with the use of a suitable meteorological model, we would be able to predict the emission rate of the effluent discharged from the plants. This "fingerprinting" method could be particularly important when it is difficult to gain access to the plant to measure the emission of effluent or to insert a particular artificial tracer to monitor the stack effluent dispersal. To test the usefulness of these "natural"



Map 2. Location of air samplers with reference to the Western Kraft, Wah Chang and Simpson Timber Companies in Albany, Oregon.

industrial tracers as a means of monitoring stack effluent, we collected air samples at various locations downwind from these sources and measured the trace element concentrations. At the same time, we also released some artificial tracers from the stack for comparison purposes. Here we can appreciate the beauty of instrumental neutron activation analysis. Because of its non-destructive nature, we can simultaneously measure the concentrations of the artificial and "naturally-occurring" tracer in the same air samples.

Experimental

Air samples were collected directly from industrial stack effluent with tape samplers (flow-rates ranged from 0.001 to 0.005 c.f.m.). Nuclepore filter paper with pore-size of $0.25\ \mu\text{m}$ was used as collection medium. The period of sampling ranged from two to six days. (Volume of air collected ranged from 0.2 to 2 cubic meters.) Three stacks representing the three different industries were monitored for a period of about four months. (October, 1972 to February, 1973). A glass-tubing with diameter of 1 cm. and connected with a two foot plastic tubing to the air sampler was inserted into the stack through a hole drilled at the side of the stack. The glass-tubing was tilted downward to avoid any condensation inside the tube. Since this study was to obtain an average trace element

concentration in the stack effluent with the emphasis to fingerprint the trace element pattern from each industry, an exact method for stack sampling which requires special equipment such as a pitot-static tube for isokinetic sampling was not required. Besides that, the error associated with nonisokinetic air sampling was small as the sizes of the particulates emitted were mostly in the submicron ranges (Augustine, 1973). During air sampling, the temperature of the stack effluent was measured and the volume of air collected was corrected to a temperature reference of 25⁰ C assuming that the static pressure of the effluent to be the same as ambient air and also neglecting the cooling of the effluent along the collection tubing. The errors associated with this measurement and corrections are estimated to be small as compared to the wide variations of the concentration of trace elements from individual measurement (see Appendix I). Air samples were also collected at different periods downwind from one to three miles from the sources along with the "artificial" tracer studies. Paper tape samplers utilizing Whatman #1 paper tape as the collection medium were used. The meteorological conditions during the time of collection are summarized in Table (12a, b) in the following section. The procedures for multielemental analysis in air particulates are referred to in the "Methodology" section. The blank corrections of the various trace elements in the filter paper were, in general, negligible as compared to the high concentration of trace

elements in the stack effluent. For the atmospheric trace element concentrations measured downwind, the blank correction on the average was about five percent of the atmospheric trace element concentrations.

Industrial Processes in Relation to Stack Effluent Discharged

Before we proceed to the discussion of the trace element "fingerprint" of each source of pollution, it will be helpful to understand the industrial processes that lead to the discharge of the effluent in the stack.

In the Western Kraft Paper Company, wood chips are converted into "pulp" or paper by the Kraft process. The first step is the cooking process in which wood chips are cooked in a solution of sodium sulfide and sodium hydroxide called "white liquor" in a digester. The wood chips are reduced to cellulose fiber, called "pulp" and are separated from the solution now called "black-liquor." The pulp is then washed and processed to produce the desired product and formed into sheets. During the digestion process, gases mainly in the form of hydrogen sulfide, methyl sulfide, and mercaptans are released. Most of the particulate discharge comes from the recovery process in which the "black-liquor" is transformed into sodium carbonate and sodium sulfide. The "black-liquor" is first concentrated

through an evaporation process and transferred to a mixing tank into which sodium sulfate is added. The liquor is pumped into a recovery furnace where the organic substances in the liquor are burned. As a result, sodium sulfate is reduced to sodium sulfide. The sodium salts are recovered as molten ash in the form of carbonates and sulfides. During this process, considerable amounts of particulate matter in the flue gas are released even though more than 90 percent of it is controlled by an electrostatic precipitator. The output from the recovery process, consisting of sodium carbonate and sodium sulfide, is dissolved in water to form "green-liquor" and calcium hydroxide is added to yield "white-liquor." The precipitate of calcium carbonate is then calcined in a lime kiln to regenerate calcium oxide. Particulate matter is also emitted during this process. The effluent from these processes are combined and discharged into the tall stack from which air samples were collected.

The Teledyne Wah Chang metallurgical processing company is the world's largest operation for the production of zirconium and other rare metals. An operation process for the production of zirconium is summarized on the flow chart in Figure 8 offered by the company. Air samples were collected at the stack of the separation tower. The function in the separation tower as represented in steps 5-7 in the flow-chart is to separate Zr and Hf from the other raw materials through the liquid-liquid chemical separation plant.

The Zr and Hf hydroxides coming out of step 7 as precipitates are transferred to a calciner to convert the hydroxides to their oxides. During this process particulate matter are discharged into this stack. A detailed description of the chemical separation process is regarded as proprietary information by the company and was not available.

In the process of making plywood in the Simpson Timber Company, the logs used are first debarked and turned into veneer by sawing or slicing. The veneer is then mixed with glue and pressed to form wood sheets. The sheets are then trimmed and sanded. All these processes produce unusable bark, wood chips and saw dust. The solid wastes are usually disposed of by burning in a furnace. This resembles the wigwam burners which are commonly used to dispose of waste wood products in Oregon. Air samples were collected directly at the outlet of the furnace where the waste wood products are burned.

Results and Discussion

Table 9 shows the atmospheric trace element concentrations associated with the Western Kraft, Wah Chang and Simpson Timber Companies. Six air samples were collected at Western Kraft and Wah Chang Companies and eight samples were collected at Simpson Timber Company. Since we did not have enough samples to obtain a

Table 9. Concentration of Trace Elements in Stack Effluent ($\mu\text{g}/\text{m}^3$)

Element	Wah Chang Metallurgical Processing Company			Western Kraft Paper Company			Simpson Timber Company		
	Geometric Mean	Arithmetic Mean	Range	Geometric Mean	Arithmetic Mean	Range	Geometric Mean	Arithmetic Mean	Range
	$\pm$ G. S. D.	$\pm$ S. D.		$\pm$ G. S. D.	$\pm$ S. D.		$\pm$ G. S. D.	$\pm$ S. D.	
Al	8.1 (+11.5;-4.8)	11.0 $\pm$ 9.5	2.0-28.5	58.1 (+75.4;-32.8)	81.3 $\pm$ 83.0	23.3-243.6	56.3 (+63.2;-29.8)	69.0 $\pm$ 8.4	12.0-115.0
Fe	9.2 (+10.9;-5.0)	10.6 $\pm$ 5.4	5.3-16.0	14.6 (+17.2;-7.9)	12.2 $\pm$ 11.7	3.0-25.3	16.8 (+21.2;-9.4)	29.6 $\pm$ 19.7	11.0-43.1
Na	29.6 (+17.2;-10.9)	32.0 $\pm$ 13.2	15.5-46.7	1001 (+581;-367)	1096 $\pm$ 530	601-1997	252 (+232;-121)	299 $\pm$ 176	73-580
K	3.1 (+2.6;-1.4)	3.7 $\pm$ 2.8	1.7-9.2	41.5 (+33.3;-18.6)	47.6 $\pm$ 26.5	17.7-91.1	112 (+64;-41)	123.2 $\pm$ 50.7	58-211
Ti	---	<2.8	---	---	<3.8	---	---	<5.0	---
Mn	0.45 (+0.48;-0.23)	0.56 $\pm$ 0.38	0.17-1.23	0.91 (+0.88;-0.45)	1.1 $\pm$ 0.5	0.38-1.97	7.0 (+7.6;-3.6)	8.7 $\pm$ 2.9	2.2-19.6
Zr	2214 (+7718;-1689)	3863 $\pm$ 3252	188-8067	---	<15	---	---	<95	---
V	---	<0.02	---	22.5 (+26.1;-12.1)	28.1 $\pm$ 19.0	7.0-52.5	0.39 (+0.29;-0.17)	0.45 $\pm$ 0.22	0.18-0.80
Cl	3857 (+1486;-1072)	4016 $\pm$ 1139	2173-5172	524 (+253;-171)	562 $\pm$ 252	344-1039	196 (+123;-76)	215.5 $\pm$ 9.4	89-369
Cr	0.61 (+0.70;-0.33)	0.76 $\pm$ 0.26	0.27-1.53	1.4 (+0.3;-0.3)	1.4 $\pm$ 0.3	1.0-1.7	2.0 (+4.9;-1.4)	3.2 $\pm$ 3.5	0.6-7.2
Ni	---	<2.2	---	---	<2.2	---	---	<2.5	---
Zn	---	<0.5	---	---	<0.9	---	---	<3.8	---
Cu	---	<3.9	---	14.3 (+12.2;-6.6)	17.3 $\pm$ 14.2	9.6-43.0	8.2 (+8.2;-4.1)	11.5 $\pm$ 7.5	4.1-21.5
La	---	<0.006	---	---	<0.017	---	---	<0.020	---
Co	0.036 (+0.069;-0.024)	0.054 $\pm$ 0.044	0.010-0.110	1.1 (+0.5;-0.3)	1.2 $\pm$ 0.5	0.8-2.1	0.064 (+0.069;-0.033)	0.051 $\pm$ 0.017	0.025-0.225
Sc	0.022 (+0.056;-0.016)	0.044 $\pm$ 0.059	0.005-0.055	---	<0.03	---	---	<0.009	---
Sm	---	<0.002	---	---	<0.003	---	0.025 (+0.027;-0.013)	0.032 $\pm$ 0.027	0.014-0.079
Hf	1.9 (+2.3;-1.0)	2.5 $\pm$ 1.6	0.60-4.32	---	<0.004	---	---	<0.03	---
Br	31.2 (+41.6;-17.8)	39.2 $\pm$ 24.3	6.7-57.5	11.5 (+6.3;-4.1)	12.5 $\pm$ 5.8	6.8-22.2	14.5 (+29.8;-9.7)	21.5 $\pm$ 16.9	1.8-47.6
Ta	0.22 (+0.41;-0.14)	0.37 $\pm$ 0.46	0.05-1.30	---	<0.01	---	---	<0.05	---
As	6.5 (+11.2;-4.1)	10.2 $\pm$ 11.2	2.8-31.0	---	<0.5	---	---	<1.1	---
Sb	---	<0.05	---	---	<0.03	---	---	<0.03	---
Hg	---	<0.05	---	0.5 (+0.4;-0.2)	0.6 $\pm$ 0.5	0.25-0.87	1.3 (+1.4;-0.7)	1.8 $\pm$ 1.1	0.59-3.21
Se	0.19 (+0.27;-0.11)	0.25 $\pm$ 0.16	0.05-0.42	---	<0.02	---	---	<0.02	---
Au	---	<0.0001	---	---	<0.0002	---	---	<0.0002	---

distribution curve of the trace elemental concentration, we decided to report the concentration as geometric and arithmetic means along with the range of the concentrations. For the interest of the reader, the individual concentrations are included in Appendix I.

One notes from Table 9 that high concentrations of Zr, Cl, Hf, Ta, As, Br and Hg are associated with the metal processing company. These elements are directly related to the chemical processes used in the plant. The high concentrations of V, Hg and Co in the stack effluent at the paper company may be due to the burning of fuel-oil or due to the chemicals used in the cooking process. The stack effluent of the plywood company is characterized by its high concentration of Na, K, Cl, Br, Cu and Hg. Some of these elements are typical trace elements in wood products.

In order to establish the trace element "fingerprint" of an industrial source, the average trace element concentration in Table 9 were normalized to Al. With the crustal abundances also normalized to Al, one can define the enrichment factor of the element (Gordon, 1973b), Ef, as

$$Ef = \frac{(\text{Conc. of element/Conc. of Al})_{\text{atmos.}}}{(\text{Conc. of element/Conc. of Al})_{\text{crustal}}}$$

Figures 9, 10, and 11 are plots of elemental abundances for each industrial stack effluent with crustal normalization to show the

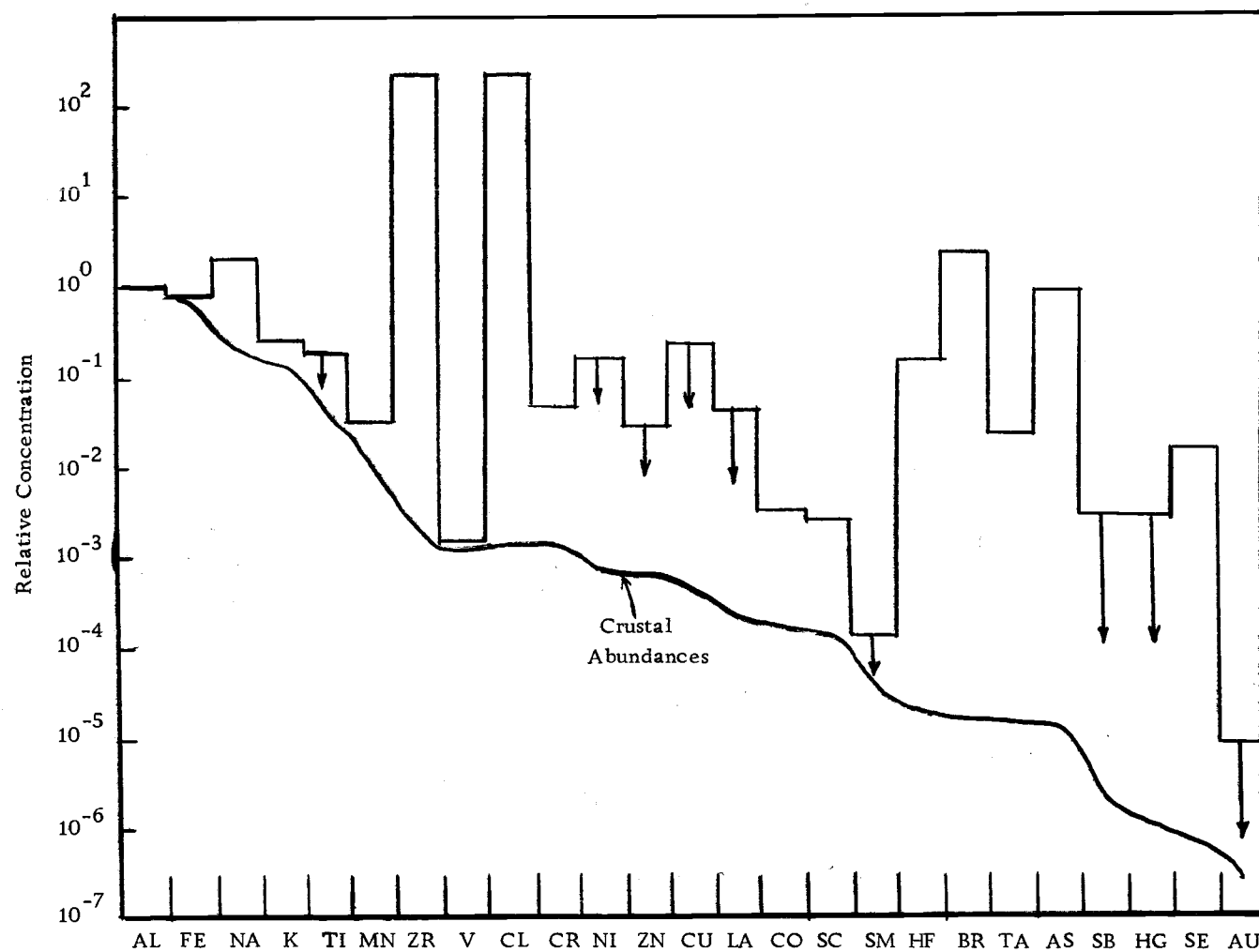


Figure 9. Relative concentration of trace elements of stack effluent at the Wah Chang metallurgical processing company. (Downward arrows indicate upper limit for elemental abundances; concentration of trace elements are normalized to Al = 1.0).

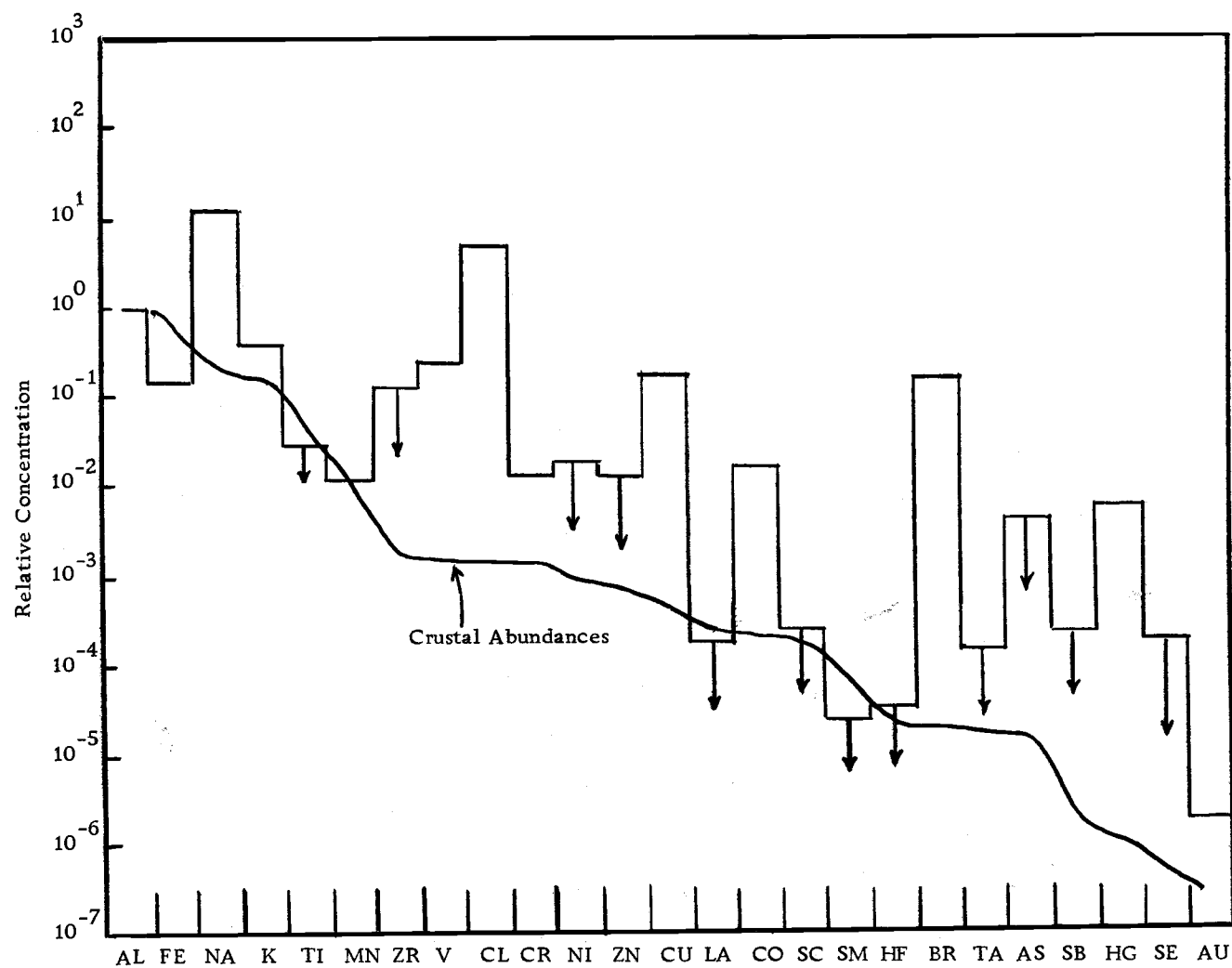


Figure 10. Relative concentration of trace elements of stack effluent at the Western Kraft Corporation. (Downward arrows indicate upper limit for elemental abundances; concentration of elements are normalized to Al = 1.0).

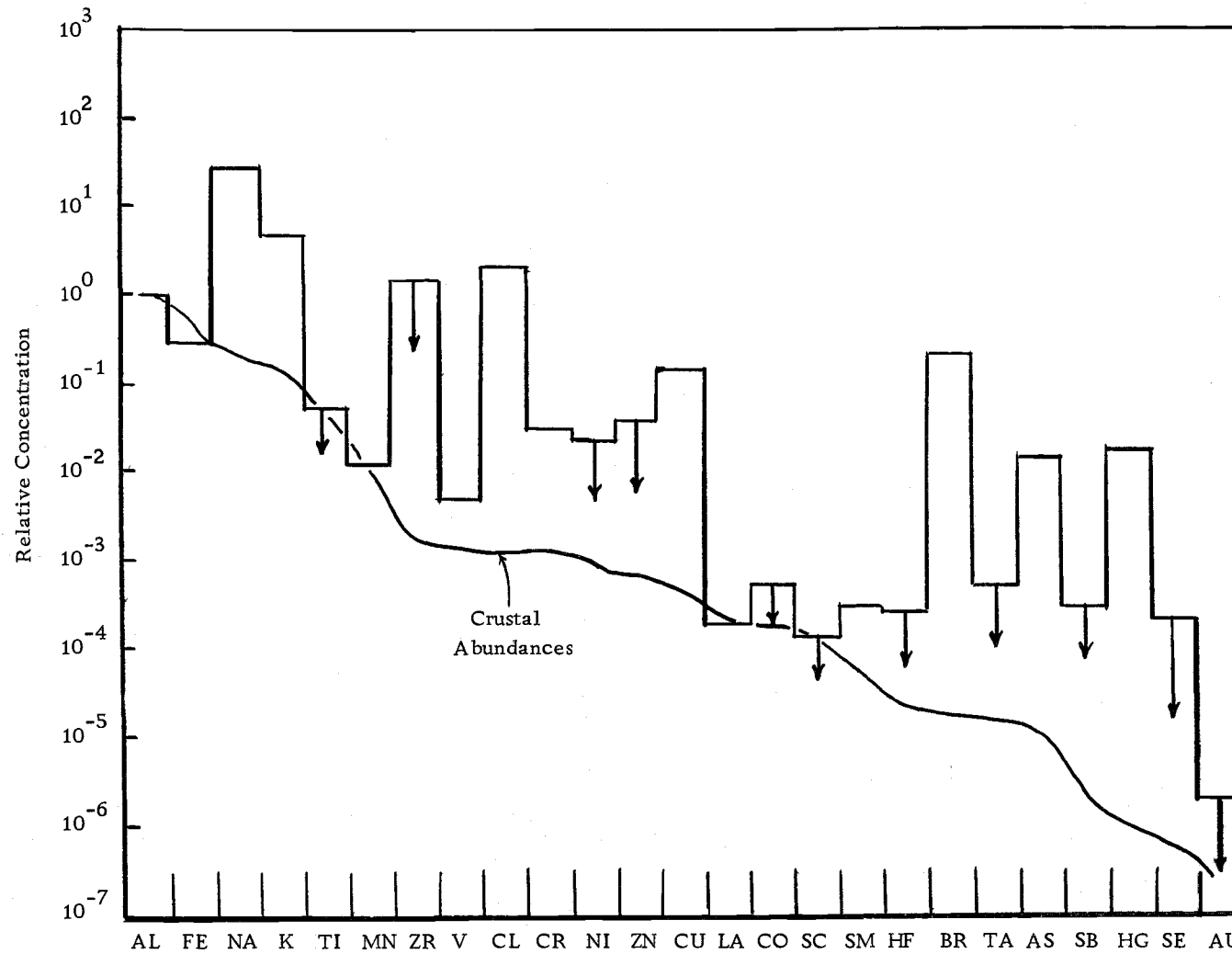


Figure 11. Relative concentration of trace elements of stack effluent at the Simpson Timber Company. (Downward arrows indicate upper limit for elemental abundances; concentration of trace elements are normalized to Al = 1.0).

enriched elements. The crustal abundances were taken from Taylor (1964). The tabulations of the enrichment factors for each element are shown in Appendix II. With reference to Figure 9 for the Wah Chang metallurgical company stack effluent, the enriched elements are Zr, Cl, Br, As, Hf, Ta, Se, Na, Cr, Co, and Sc. The concentration of the elements Hf-Ta-Cr-Sc-Cl were found to correlate linearly at the 95 percent confidence level while Zr was not correlated with these elements, indicating that Zr may come from a different chemical process in the plant with a different production rate. The elements such as Zr, Hf and Ta are rare metals which can be used as "natural occurring" stack tracers. In Figure 10, the stack effluent of the paper company is characterized by its high concentration of Na, Cl, Br, Cu, V, Co, Cr and Hg. The concentration of trace elements K-Cu-Co-Br-V-Hg-Cr, Na-Cl were found to correlate linearly at the 95 percent confidence level. Among these enriched elements, V, Co and Hg are potential candidates for natural stack tracers. The results of their application in tracing stack effluent will be discussed in the next section. In Figure 11, the stack effluent associated with the plywood company is characterized by its high concentration of Na, K, Cl, Cr, Cu, Br and Hg. Since all these enriched elements except Hg are common elements which can come from many other sources, their application as natural stack tracers in tracing stack effluent is quite limited.

As far as toxic elements are concerned, Table 9 shows that some of the potentially toxic elements, such as As, Se, Hg and V were emitted from the industrial stacks. The threshold limit values based on the exposure time of eight hours per day for five days per week of these elements in air compared to the range of undiluted concentrations we measured from the stacks are listed in Table 10. From Table 10, one notes that the concentrations of the toxic elements are very low as compared to the threshold limit values. Even though if we consider a longer exposure of 24 hours a day for the nearby residents, and disregard the fact that the plume will be diluted, the concentrations are still not sufficient to cause a significant health hazard.

Table 10. Toxic Element Concentrations in Undiluted Stack Effluent Compared to Threshold Limit Values (T. L. V.) in Air.

Element	Concentration ($\mu\text{g}/\text{m}^3$ of air)	
	Undiluted Effluent	T. L. V. *
As	8.3	500
Se	0.17	200
Hg	1.2	100
V	20.0	---

* Based on the limit set by the American Conference of Governmental Industrial Hygienists (1966).

Table 11 shows the atmospheric trace element concentrations in the Albany area. For reasons as discussed in the last section, the results represent the arithmetic and geometric means along with the range of the concentration of the trace elements in all the air samples collected at different locations as shown in Map 2. (Detailed information for individual measurements is shown in Appendix III.) The wind direction during the period of collection was eitherly northerly or northwesterly which were the prevailing winds in this season (July-September). At the same time, artificial tracers were emitted from the industrial stacks for meteorological model testing. Therefore, all the air samplers were generally located near the center-line of the plumes. From Table 11, one observes an abnormally high concentration of most of the atmospheric trace elements in the area. Their concentrations are also compared with some of the industrial and urban areas in the United States as summarized in Table 11. The arithmetic mean concentrations of Al, Fe, Na, Ti, Zr, Cl, Cr, Hf, Ta and As in the Albany area are generally higher by a factor of two to six than the concentrations of other cities. These high trace element concentrations may reflect that the concentrations of the other potential toxic pollutants, such as SO_2 , H_2S and oxides of nitrogen in the Albany area are higher than the concentrations observed in other cities by the same order of magnitude.

Figure 12 shows the normalized atmospheric trace elemental abundances in Albany as compared to crustal abundances. (The

Table 11. Atmospheric Trace Element Abundances in Albany, Oregon as Compared to Other Cities in the United States.

Element	Albany, Oregon (nanograms/cu. meter)			San Francisco Bay Area ^a	Gary--E. Chicago Indiana ^a	Chicago Illinois ^a	Cambridge Mass. ^a	Portland Oregon ^a
	Geometric Mean ± G. S. D.	Arithmetic Mean ± S. D.	Range					
Al	7681 (+13100;-4842)	11822 ± 13222	2300-34700	863	1950	1900	700	-
Fe	3279 (+6089;-2131)	5105 ± 3712	536-14827	1670	3900	4800	1000	800
Na	7519 (+5193;-3071)	7172 ± 4929	500-19800	3520	285	560	800	-
K	1919 (+1542;-855)	1927 ± 1367	550-4968	-	1150	-	-	-
Ti	1725 (+1450;-788)	2150 ± 982	700-4500	-	175	-	-	10
Mn	115 (+189;-71)	122 ± 107	30-450	17	130	700	20	140
Zr	1074 (+1319;-592)	1517 ± 1802	356-8708	-	-	-	-	-
V	3.0 (+10.4;-2.3)	8.9 ± 12.2	0.3-57	5.4	7.4	24	600	18
Cl	5884 (+7565;-3310)	6894 ± 5689	1500-24700	2930	-	5900	500	-
Cr	141 (+113;-63)	168 ± 111	62-422	8.2	21	25	-	4
Ni	298 (+281;-145)	356 ± 195	73-703	-	-	-	-	-
Zn	394 (+698;-252)	595 ± 544	31-2323	-	-	-	-	-
La	6.1 (+5.4;-2.9)	5.0 ± 4.0	0.6-10.1	1.4	2.4	3.7	0.3	-
Co	2.4 (+3.3;-1.4)	3.4 ± 2.2	0.3-7.8	1.0	1.1	4.5	0.2	-
Sc	0.47 (+0.77;-0.29)	0.70 ± 0.89	0.08-3.3	1.4	1.6	0.9	0.8	-
Sm	0.8 (+1.3;-0.5)	1.2 ± 1.2	0.3-3.5	0.22	0.34	-	0.2	-
Hf	2.9 (+6.3;-2.0)	4.4 ± 4.9	0.6-21.9	-	-	-	-	-
Br	195 (+246;-109)	256 ± 192	63-560	220	66	270	150	-
Ta	66 (+66;-33)	82 ± 48	33-211	-	-	-	-	-
As	20.3 (+12.0;-7.5)	20.4 ± 8.6	10.0-35.0	-	4.4	-	-	-
Sb	25.8 (+17.0;-10.2)	24.5 ± 13.9	7.5-42.7	2.1	6.3	45	0.5	-
Hg	168 (+276;-104)	323 ± 608	55-2858	2.7	-	-	-	-
Se	4.8 (+7.2;-2.7)	7.8 ± 14.3	2-69	-	-	-	-	-
Au	0.7 (+0.6;-0.3)	0.8 ± 0.6	0.4-2.0	-	-	-	-	-

^a Taken from Table 8.

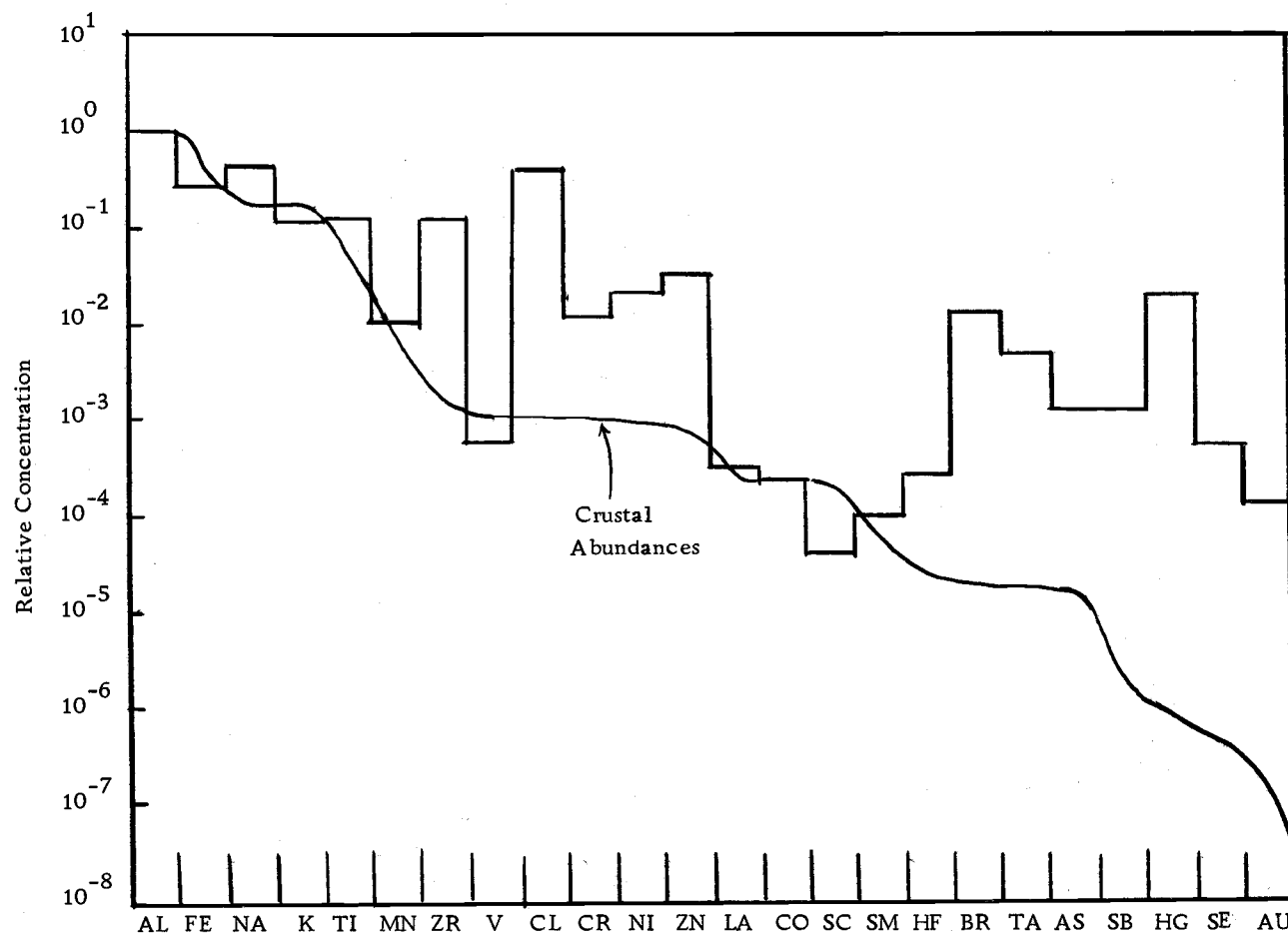


Figure 12. Relative atmospheric trace element abundances in Albany, Oregon. (Concentration of trace elements are normalized to Al = 1.0).

calculation of the enrichment factors for each element is shown in Appendix III.) One observes from Figure 12 the enriched elements such as Zr, Cl, Cr, Hg, Br, Zn, Ni, Hf, Ta, As, Sb, Se and Au. Most of these elements were identified as characteristic elements from the three stacks studied. The concentrations of the elements Hf-Zr-Ta-Au-Sb-Cl; Br-As; Zn-Se and Co-Hg were found to correlate linearly at the 95 percent confidence level, indicating that these groups of elements may come from source of a particular industry. (In the study of stack effluent, we found that Zr was not correlated with Hf and Ta. This indicates that the stack at the separation tower of the metal company may not be the representative stack in the plant for the emission of these elements.) The application of these natural stack tracers to trace the dispersal of stack effluent is discussed in the following section.

The Application of "Naturally Occurring" Industrial Tracers to the Monitoring of Stack Effluents

From the measurements of the trace element "fingerprints" of various sources of air pollution discussed in the preceding section, it is found that some of the trace elements are highly correlated with particular sources of pollution. These elements may be used to identify the source and to trace the dispersal of the pollutants from the source. Under certain meteorological conditions and with the

application of a suitable diffusion model, one should be able to predict the emission rate of the tracer from the stack which in turn should provide us with an estimate of the rate of effluent discharge.

Tables 12a and 12b are summaries of the experiments performed to measure the concentrations of Zr, Ta, Hf, Au, Sb, V, Co and Hg downwind from Wah Chang and Western Kraft Companies. These elements are the most characteristic elements from the stack effluent of these companies. The meteorological conditions pertaining to these measurements are summarized in Tables 12a and 12b. The generalized Gaussian plume model as modified by Gifford (1962) and discussed in detail in the succeeding sections was applied to calculate the emission rates of Zr, Ta, Hf, Au, Sb, V, Co and Hg from the stacks in question. From the measured concentrations of the tracer at a number of locations, one can use the formula to calculate the emission rate of the tracer. One notes from Table 12a that in the case of Zr, Ta, Hf, Au and Sb, the emission rates calculated from the measurements at each location are quite constant, indicating that Zr, Ta, Hf, Au and Sb came from the stacks at Wah Chang Company. This is further supported by the fact that the concentrations of Ta-Hf-Zr-Au and Sb are linearly correlated at the 95 percent level from the study on the measurements of the atmospheric trace elements in the Albany area. Also the ratios of these elements calculated from the

Table 12(a). Summary of Experimental Results for the Estimation of Emission Rates of Zr, Ta, Hf, Au and Sb from Wah Chang Teledyne Metallurgical Company

Date of Experiment	Sample Number	Location of Air Sampler (1)	Mean Wind Direction (2) and Fluctuation (σ_θ) (3)	Mean Wind Speed (m/sec)	Time of Collection	With Reference to Wah Chang Co.					Measured Trace Element Concentration ($\mu\text{g}/\text{m}^3$)					Calculated Emission Rates (gm/sec)				
						x	y	σ_y	σ_z	A_n	Zr	Ta	Hf	Au	Sb	Zr	Ta	Hf	Au	Sb
						----- (in meters) -----														
8/28/72	1	1	360° ($\sigma_\theta=9^\circ$)	5.3	1244-1500	847	283	115	100	2.4×10^{-7}	2.42 ± 0.79	0.17 ± 0.02	0.0094 ± 0.0017	0.0020 ± 0.0003	0.043 ± 0.002	(10.0 ± 3.3)	(0.71 ± 0.08)	(0.039 ± 0.007)	(0.0083 ± 0.0012)	(0.18 ± 0.01)
	2	2			1300-1530	2454	490	265	250	1.6×10^{-7}	0.54 ± 0.27	0.07 ± 0.02	0.0030 ± 0.0018	0.0004 ± 0.0001	0.023 ± 0.001	(3.4 ± 1.7)	(0.43 ± 0.12)	(0.019 ± 0.011)	(0.0025 ± 0.0006)	(0.14 ± 0.01)
	3	4			1310-1530	2860	540	300	290	1.4×10^{-7}	0.36 ± 0.21	0.05 ± 0.02	0.0014 ± 0.0009	0.0004 ± 0.0001	0.0010 ± 0.0001	(2.6 ± 1.5)	(0.38 ± 0.15)	(0.010 ± 0.007)	(0.0029 ± 0.0007)	(0.07 ± 0.01)
	4	21			1323-1530	4264	714	450	380	1.0×10^{-7}	0.87 ± 0.29	0.06 ± 0.02	0.0054 ± 0.0016	0.0004 ± 0.0001	0.0036 ± 0.0001	(8.7 ± 2.9)	(0.60 ± 0.20)	(0.054 ± 0.016)	(0.0040 ± 0.0010)	(0.36 ± 0.01)
8/11/72	5	4	335° ($\sigma_\theta=16^\circ$)	3.9	1120-1400	1788	192	265	200	1.2×10^{-6}	0.88 ± 0.44	0.10 ± 0.03	0.0013 ± 0.0013	0.0017 ± 0.0004	0.039 ± 0.002	(0.73 ± 0.36)	(0.08 ± 0.02)	(0.0011 ± 0.0011)	(0.0014 ± 0.0003)	(0.033 ± 0.001)
	6	18			1130-1420	2138	262	275	220	8.5×10^{-7}	0.52 ± 0.31	0.05 ± 0.01	0.0024 ± 0.0007	0.0006 ± 0.0001	0.019 ± 0.001	(0.61 ± 0.37)	(0.06 ± 0.01)	(0.0028 ± 0.0008)	(0.0007 ± 0.0001)	(0.022 ± 0.001)
	7	19			1140-1430	2540	285	280	280	5.4×10^{-7}	1.20 ± 0.48	0.06 ± 0.01	0.0029 ± 0.0010	0.0007 ± 0.0002	0.039 ± 0.001	(2.22 ± 0.89)	(0.11 ± 0.02)	(0.0053 ± 0.0018)	(0.0013 ± 0.0004)	(0.072 ± 0.001)
	8	20			1150-1440	2750	300	300	290	5.7×10^{-7}	0.61 ± 0.48	0.06 ± 0.01	0.0021 ± 0.0010	0.0008 ± 0.0001	0.020 ± 0.001	(1.07 ± 0.73)	(0.11 ± 0.02)	(0.0037 ± 0.001)	(0.0014 ± 0.0002)	(0.035 ± 0.001)

The generalized Gaussian plume formula is given by

$$\chi(x, y, 0) = \frac{Q}{\pi \sigma_y \sigma_z \bar{u}} \exp - \frac{1}{2} \left[\left(\frac{y}{\sigma_y} \right)^2 + \left(\frac{h_e}{\sigma_z} \right)^2 \right]$$

$$A = \frac{1}{\pi \sigma_y \sigma_z \bar{u}} \exp - \frac{1}{2} \left[\left(\frac{y}{\sigma_y} \right)^2 + \left(\frac{h_e}{\sigma_z} \right)^2 \right]$$

where χ = concentration of tracer ($\mu\text{g}/\text{m}^3$ of air)

Q = Emission rate of tracer ($\mu\text{g}/\text{sec}$)

$\bar{u}$ = averaged wind speed (meters/sec)

σ_y, σ_z = lateral and vertical dispersion coefficients (meters) (values taken from Smith, 1968)

x, y = downwind and crosswind distances of air sampler from stack (meters)

h_e = effective stack height (meters) (See Figure 18 for definition)

(1) Refer to Map 2

(2) Wind direction: northerly = 360° ; westerly = 270°

(3) σ_θ = Standard deviation of horizontal wind fluctuation

Table 12(b). Summary of Experimental Results for the Estimation of Emission Rates of V, Co, and Hg from Western Kraft Paper Company

Date of Experiment	Sample Number	Location of Air Samples (1)	Mean Wind Direction (2) and Fluctuation ($\sigma_{\theta}(3)$)	Mean Wind Speed (m/sec)	Time of Collection	With Reference to Western Kraft Co.					Measured Trace Element Concentration ($\mu\text{g/sec}$)			Calculated Emission Rates (gm/sec)		
						x	y	σ_y	σ_z	A_n	V	Co	Hg	V	Co	Hg
8/28/72	1	1	360° ($\sigma_{\theta}=9^\circ$)	5.3	1244-1500	2612	245	170	60	8.9×10^{-7}	0.0027 ± 0.0002	0.0063 ± 0.0006	0.239 ± 0.012	$(3.0 \pm 0.2) \times 10^{-3}$	$(7.1 \pm 0.5) \times 10^{-3}$	(0.27 ± 0.01)
	2	2			1300-1530	4260	18	260	80	1.8×10^{-6}	0.0008 ± 0.0001	0.0074 ± 0.0012	0.494 ± 0.015	$(4.5 \pm 0.6) \times 10^{-4}$	$(4.1 \pm 0.4) \times 10^{-3}$	(0.27 ± 0.01)
	3	4			1310-1530	4593	1016	280	82	2.3×10^{-9}	0.0083 ± 0.0002	0.0040 ± 0.0005	0.075 ± 0.007	(3.6 ± 0.9)	(17.4 ± 2.5)	(326 ± 30)
	4	21			1323-1530	6065	1402	360	100	6.0×10^{-10}	0.0102 ± 0.0003	0.0066 ± 0.0009	0.107 ± 0.010	(17.0 ± 0.5)	(110.0 ± 15.0)	(1783 ± 167)
8/11/72	5	4	335° ($\sigma_{\theta}=16^\circ$)	3.9	1120-1400	2910	1156	280	160	3.0×10^{-10}	0.0009 ± 0.0001	0.0025 ± 0.0005	0.081 ± 0.017	(3.0 ± 0.3)	(83.3 ± 8.5)	(2700 ± 567)
	6	18			1130-1420	3300	370	310	182	6.4×10^{-7}	0.0008 ± 0.0001	0.0019 ± 0.0003	0.191 ± 0.006	$(1.3 \pm 0.2) \times 10^{-3}$	$(3.0 \pm 0.2) \times 10^{-3}$	(0.30 ± 0.04)
	7	19			1140-1430	3218	251	305	178	9.7×10^{-7}	0.0003 ± 0.0001	0.0003 ± 0.0001	0.063 ± 0.007	$(3.1 \pm 1.0) \times 10^{-4}$	$(93.0 \pm 1.0) \times 10^{-4}$	(0.064 ± 0.007)
	8	20			1150-1440	3920	1438	360	215	3.0×10^{-10}	0.0007 ± 0.0001	0.0021 ± 0.0003	0.001 ± 0.007	(2.3 ± 0.3)	(70.0 ± 10.0)	(2866 ± 233)

The generalized Gaussian plume formula is given by

$$X(x, y, 0) = A Q = \frac{Q}{\pi \sigma_y \sigma_z \bar{u}} \exp - \frac{1}{2} \left[\left(\frac{y}{\sigma_y} \right)^2 + \left(\frac{h_e}{\sigma_z} \right)^2 \right]$$

$$A = \frac{1}{\pi \sigma_y \sigma_z \bar{u}} \exp - \frac{1}{2} \left[\left(\frac{y}{\sigma_y} \right)^2 + \left(\frac{h_e}{\sigma_z} \right)^2 \right]$$

where X = concentration of tracer ($\mu\text{g}/\text{m}^3$ of air)
 Q = emission rate of tracer ($\mu\text{g}/\text{sec}$)
 $\bar{u}$ = averaged wind speed (meters/sec)

σ_y, σ_z = lateral and vertical dispersion coefficients (meters) (values taken from Smith, 1968)
 x, y = downwind and crosswind distances of air sampler from stack (meters)
 h_e = effective stack height (meters) (See Figure 18 for definition)

- (1) Refer to Map 2
- (2) Wind direction: northerly = 360°; westerly = 270°
- (3) σ_{θ} = Standard deviation of horizontal wind fluctuation

emission rates are found to be about the same as the ratios calculated from the measurements of atmospheric trace elements in the Albany area. This clearly indicates that this group of trace elements comes from the same origin.

In the case of V, Co and Hg (see Table 12b), the calculated emission rates from the stack of Western Kraft vary greatly, possibly indicating that multiple sources of these elements exist in the area. This is consistent with the fact that there is another big paper company (Duraflake Paper Company) nearby, as shown in Map 2. Also the motor-vehicle exhaust along Highway 5 may contribute substantially to the concentration of these elements. The technique of calculating the proportional amount of tracers or pollutants emitted from several point-sources will be discussed in the succeeding section and the calculations for V, Co and Hg will not be given here since we do not exactly know what other sources could contribute to the concentration of these elements.

IV. THE DEVELOPMENT OF AN ARTIFICIAL TRACER TECHNIQUE FOR ATMOSPHERIC DIFFUSION STUDIES

The disadvantage of using the "naturally occurring" trace elements emitted from industrial stacks to trace the dispersal of pollutants quantitatively is that the emission rates of these tracers are not constant. They may vary greatly depending on the production schedule of the company. For meteorological model testing where accurate pollutant emission rates are needed, artificial tracers are preferred because their emission rates can be controlled.

Choice of Artificial Tracer

Many types of artificial tracers have been introduced for atmospheric studies. Oil fog had been introduced as early as 1958 by Barad and Shorr (1958). It has the advantage of permitting one to locate plume trajectories by visual means but suffers from its low detection sensitivity. Cramer et al. (1957, 1958) developed a tracer technique using sulfur dioxide. Because of the high background levels of SO_2 it is rather difficult to trace at longer distances from the source. Fluorescent pigment (a mixture of zinc and cadmium sulfide) was used as a tracer by Hewson et al. (1960), Braham et al. (1952) and Leighton (1955) for atmospheric diffusion studies over longer distances. It has high detection limit but suffers from the difficulties in defining source strengths in terms of particles per unit mass and

also requires the counting of the particles under a microscope. Robinson et al. (1959) introduced the use of uranine dye (di-sodium fluorescein) for atmospheric studies. It has the advantages of high sensitivity and convenience of dispersion and analysis; but it loses fluorescence in the presence of sunlight and cannot be injected in a hot-stack at a temperature greater than 100° C due to its decomposition at high temperatures. Radioactive argon has been chosen by Stewart et al. (1958) as a tracer for atmospheric studies. But the release of radioactive gas into the atmosphere and the attendant health hazard considerations make this an undesirable choice. Stable activable tracers, such as In and Co were introduced by Dahl et al. (1971) and Nakasa and Ohno (1967) as tracers to monitor stack effluent. The tracer can be neutron activated and its concentration can be determined using the principles of activation analysis. These elements chosen have high detection sensitivities in activation analysis. The only disadvantage is that the analysis procedures are expensive (requires a nuclear reactor and the associated equipment) and sometimes quite time-consuming.

In this study, I have chosen the rare-earth elements such as Dy, Sm, La and Ce. They have high detection sensitivity with neutron activation analysis and the amount of tracers (from 20 to 40 gm in an experiment) released are non-toxic to humans, animals and plants (Haley, 1965). The background of these elements in the atmosphere

is negligible. They were chosen to test meteorological diffusion models in the present study and were used to provide clear-cut source identification in the study of multiple sources of air pollution in the Albany area.

Method of Release

The rare-earth elements used were either in the form of their oxides or chlorides (Dy_2O_3 , SmCl_3 , La_2O_3 , and CeCl_3). They were first dissolved in 12 N nitric acid. The solution was then transferred to a one-gallon bottle to which distilled water was added to make up four liters of solution. The normality of the final solution was about 1 to 1.5 N. The bottle of solution with the spraying equipment as shown in Figure 13 was wrapped with plastic bags to avoid spilling and vaporization of the solution during transportation to the stack and the air samplers used in field work were not kept in the same car with the spraying system. This was to avoid contamination of equipment, clothes and personnel with tracer material and its subsequent transfer to the sample. We also used different tracers in successive experiments to eliminate any high background of the tracer still existing in the atmosphere. (The background of the tracer is usually negligible in about two days after emission of the tracer.) After the air samplers were turned on for about two hours to take a background sample, the spraying system was inserted into a hole drilled on the

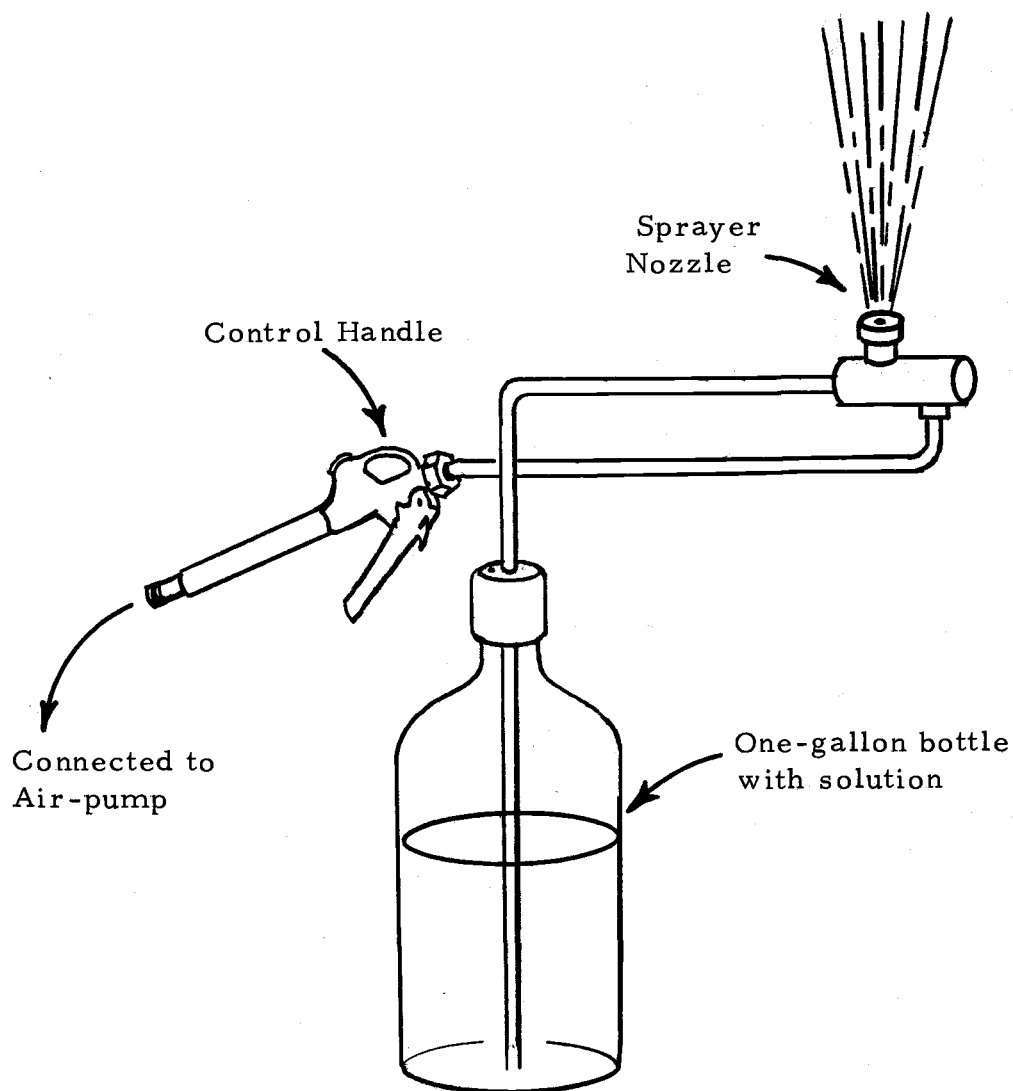


Figure 13. Set-up of spraying system for tracer study. (The solution containing the tracers is siphoned from the bottle to the pneumatic atomizing nozzles (orifice diameter = 0.028") by a stream of compressed air at about 30 p. s. i.)

side of the stack at Wah Chang and Western Kraft and turned on. (For the stack at Simpson Timber Company, since it was difficult to drill a hole in a cement stack, the spraying system was set at the top of a 13.5 meter high blower.) The solution containing the tracers was siphoned from the bottle to the atomizer by a stream of compressed air flowing through the sprayer nozzle. The pressure of the compressed air was controlled by a reduction valve connected to an air pump. Very fine aerosols in the form of mist were generated and they were totally vaporized at about four feet away from the sprayer. The tracers were carried along to the atmosphere with the effluent in the stack. Since the tracer was sprayed near the exit of the stack (about 10 to 20 feet below the exit), the loss of tracer on the wall of the stack was insignificant. The emission rate of the tracer can be calculated easily by measuring the volume of the solution used in a given time.

Particle Size Distribution

In order to insure that the tracer dispersion pattern will resemble the dispersal pattern of the pollutants, one must study the distribution of particle sizes for the tracer. Large spherical particles with diameter of 20 microns and specific gravity of 5gm/cm^3 have a settling speed of 6 cm/sec in still air (Meteorology and Atomic Energy, 1968), and particles with diameters greater than 20 microns

will tend to fall out significantly during transport processes in the atmosphere due to gravitational settling. This results in loss of particles during the transport process so that the dispersal pattern may not resemble that of the effluent, most of which is gaseous.

Leighton et al. (1965) compared the diffusion pattern of a fluorescent tracer (zinc-cadmium sulfide with mean particle diameter of 3 microns), and sulfur dioxide by emitting them from the same generator. They found that there was no significant difference in diffusion patterns up to a travel distance of 400 meters. However, Niemeyer and McCormick (1968) conducting the same test using zinc-cadmium fluorescent tracer and a gaseous tracer, SF_6 , found that there was significant loss of the fluorescent tracer as compared to the gaseous tracer if the travel distance was more than 35 km.

In this study, the distribution of particle sizes for the tracer (Dy) emitted from the stack at Wah Chang Company was measured with a cascade impactor which fractionated the particles according to their sizes. Air samples were taken at about 200 meters and 5 km away from the stack where the tracers were emitted. The results are summarized in Table 13. One notes from examining the data of Table 13 that the tracers with diameters greater than $11\mu\text{m}$ travelling about 5 km from the stack, do not fractionate significantly (from 17 to 13 %), indicating that no significant amounts of the tracers have fallen out. Therefore, we conclude that the loss

of aerosol caused by gravitational settling is negligible. (Also within the time scale of the experiment, any chemical and physical reactions between the tracers and the atmosphere to cause an increase of molecule size of the tracer are insignificant as the results in Table 13 indicate.) The data also shows a loss of about 20 percent of the particles greater than $5\text{ }\mu\text{m}$ and about 100 percent increase of particles less than $1\text{ }\mu\text{m}$, indicating that continuous evaporation of the tracer was taking place during the transport process.

Table 13. Particle Size Distribution of Artificial Tracers (Dy)
Emitted from Stack at the Wah Chang Company.

Stage Number	Range of Particle Sizes (microns)	Percent by Weight	
		Location 1 (200 m from stack)	Location 2 (5 km from stack)
0	>11	17	13
1	7-11	10	10
2	4.7-7	24	16
3	3.3-4.7	16	22
4	2.1-3.3	9	9
5	1.1-2.1	13	7
6	0.65-1.1	4	12
7	0.43-0.65	7	11

The Use of Artificial Tracers in Stack Effluent Tracing

The controllable emission rate of artificial tracers makes it possible to estimate pollutant concentrations accurately without reliance on meteorological models. Assuming that the diffusion pattern of an emitted artificial tracer is the same as the stack effluent, we have the following relationship

$$C_p = (Q_p/Q_t) \times C_t \quad (1)$$

where C_p is the estimated concentration of the pollutants in the stack effluent at any point, C_t is the measured concentration of the tracer at the same point, Q_p and Q_t are emission rates of the pollutant and tracer respectively. From equation (1), one can estimate the concentration of a particular pollutant at any location and under any meteorological conditions using the artificial tracer as a reference. This is very useful in the case of multiple sources of pollution. With the use of a different artificial tracer to label each individual source of pollution, one can estimate the proportional share of the same pollutant at any point due to each different pollution source without relying on the use of meteorological models. Suppose we have three sources of air pollution contributing substantial amounts of the same pollutant, SO_2 , to the atmosphere. We can use three different tracers, Dy, Sm and La, to label the sources individually. Then the proportional share of SO_2 at any location contributed by source

#1 is given by (P_1)

$$P_1 = C_{t,1}(Q_{s,1}/Q_{t,1}) / (C_{t,1} \cdot \frac{Q_{s,1}}{Q_{t,1}} + C_{t,2} \cdot \frac{Q_{s,2}}{Q_{t,2}} + C_{t,3} \cdot \frac{Q_{s,3}}{Q_{t,3}}) \quad (2)$$

where $C_{t,n}$ are concentrations of tracer with $n = 1, 2$ and 3

$Q_{t,n}$ are emission rates of tracers with $n = 1, 2$ and 3

$Q_{s,n}$ are emission rates of pollutant with $n = 1, 2$ and 3

This technique can be applied to monitor some of the potential toxic gases, such as H_2S , SO_2 , Cl_2 and the oxides of nitrogen emitted in the Albany area. Since the concentrations of these gases could not be measured using neutron activation analysis in our study of atmospheric trace element abundances in the Albany area, we used two tracers emitting from the same stack of known emission rates to test the relationship in equation 1. An example of this is shown in Table 16. In the "AA" experiment performed on 9/13/72, two tracers, Dy and Sm were used. The emission rates of Dy and Sm emitted from the same stack were equal, i. e., $Q_{Sm}/Q_{Dy} = 1$. The results from Table 16 show that the measured concentrations of Dy (C_{Dy}) are in general equal to the concentrations of Sm (C_{Sm}) measured.

V. THE APPLICATION OF ARTIFICIAL TRACERS TO TEST METEOROLOGICAL MODELS

One important aspect of the study of air pollution is to understand the role played by the atmosphere in affecting the dispersal of pollutants once they are released. Meteorological models provide us with ways of testing the relationship between meteorological parameters and air pollution. Due to the complexity of air pollution problems, a wide scope of meteorological models for pollutant dispersal have been developed. This study is confined to the meteorological models of industrial air pollution (defined as the pollution from a single plant or group of plants in a limited area).

In this study, I have attempted to test the applicability of various meteorological models to describe the dispersal pattern of the stack effluent discharged from certain industries in Albany, Oregon. To test the applicability of these meteorological models, artificial activable tracers such as Dy, Sm, La and Ce were used to label the stack effluent from each source and to provide a constant source emission rate. Ultimately, I hoped to develop models to treat situations involving multiple sources of air pollution as found in the Albany area. Three sources of air pollution representing different industries and locations in Albany were chosen for this study. They were Teledyne Wah Chang, Western Kraft and the Simpson Timber Company (see Map 2 for location).

Testing Meteorological Models Which Describe
the Dispersal Pattern of Stack Effluent

A test of a meteorological air pollution model consists of four essential components. The first component is the information describing the source. We must know what materials, how much, from what location and at what rate they are being injected into the atmosphere. The second component is the measurement of the pollutant concentrations at suitable locations sampled properly in time and space. The third component is the meteorological parameters, such as wind direction, wind speed, temperature lapse rate, etc. which describe the state of the atmosphere. The fourth component is the mathematical model itself which describes how the source input is transformed into observed values of pollutant concentrations.

The use of an activable tracer to label each source will provide accurate source information. (The tracer technique was described in the previous section.) The method of air sampling and the technique of sample handling was described in the "Methodology" section. Observations of pollutant concentrations were made in the daylight hours from 10:00 A.M. to 7:00 P.M. during the months of July to October, 1972. The necessary meteorological information such as wind speed and wind direction were obtained directly from the wind chart recorder (manufactured by the Esterline-Angus Instrument Co. and set up at a height of about 40 meters) at Western Kraft and also

compared with the results obtained from the wind chart recoder (manufactured by the Teledyne Geotech Co. and set up at a height of about 38 meters) from Wah Chang. Both instruments were calibrated with a wind cup anemometer and the wind records obtained from both companies were found to be very reliable. (The mean wind directions obtained from both companies were found to be the same or at most differing by 1 - 2 degrees. Also the difference between the mean wind speed was small, about 10% at most.) Since the stack heights do not differ very much from the heights at which the instruments were set up, the mean wind direction and speed were assumed to be the same at both heights. The temperature lapse-rate was obtained from data collected at the U.S. Weather Service station at Salem (about 25 miles north of Albany, Oregon). The meteorological models tested are discussed in detail in the following sections.

The Generalized Gaussian Plume Model

The mathematical equations in a meteorological model describe the processes by which air pollutants are diluted under given meteorological conditions. There are quite a number of mathematical formulations developed to describe the atmospheric diffusion processes of stack effluent (Stern, 1968), but the one which enjoys the widest use is a form of the Gaussian equation which is modified from the Sutton equation (1953). In its simplest form for a continuous elevated

level point source, the concentration of the pollutant, χ is described by

$$\chi(x, y, z) = \frac{Q}{2\pi\sigma_y\sigma_z u} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \left\{ \exp\left[-\frac{1}{2}\left(\frac{z-h_e}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{z+h_e}{\sigma_z}\right)^2\right] \right\} \quad (1)$$

where χ = concentration (g/m^3)
 Q = the emission rate (g/sec)
 u = mean wind speed at h_s , the height of the stack (m/sec)
 σ_y, σ_z = crosswind and vertical plume standard deviations (m)
 x, y, z = distances (m) with reference to the coordinate system as shown in Figure 14
 h_e = effective stack height (m) = $h_s + \Delta h$ (plume rise)
 (See Figure 18 for definition)

Equation 1 assumes that the spread of the plume has a Gaussian distribution in both the horizontal and vertical planes with standard deviation σ_y and σ_z . The equation also assumes that there is no significant deposition of particles, i. e., total reflection of the plume at the earth's surface. One must realize that these assumptions are only approximations. In the horizontal plane, the plume spread may be assumed to be Gaussian due to the random fluctuations of the plume in the horizontal directions; but in the vertical plane, due to the wind

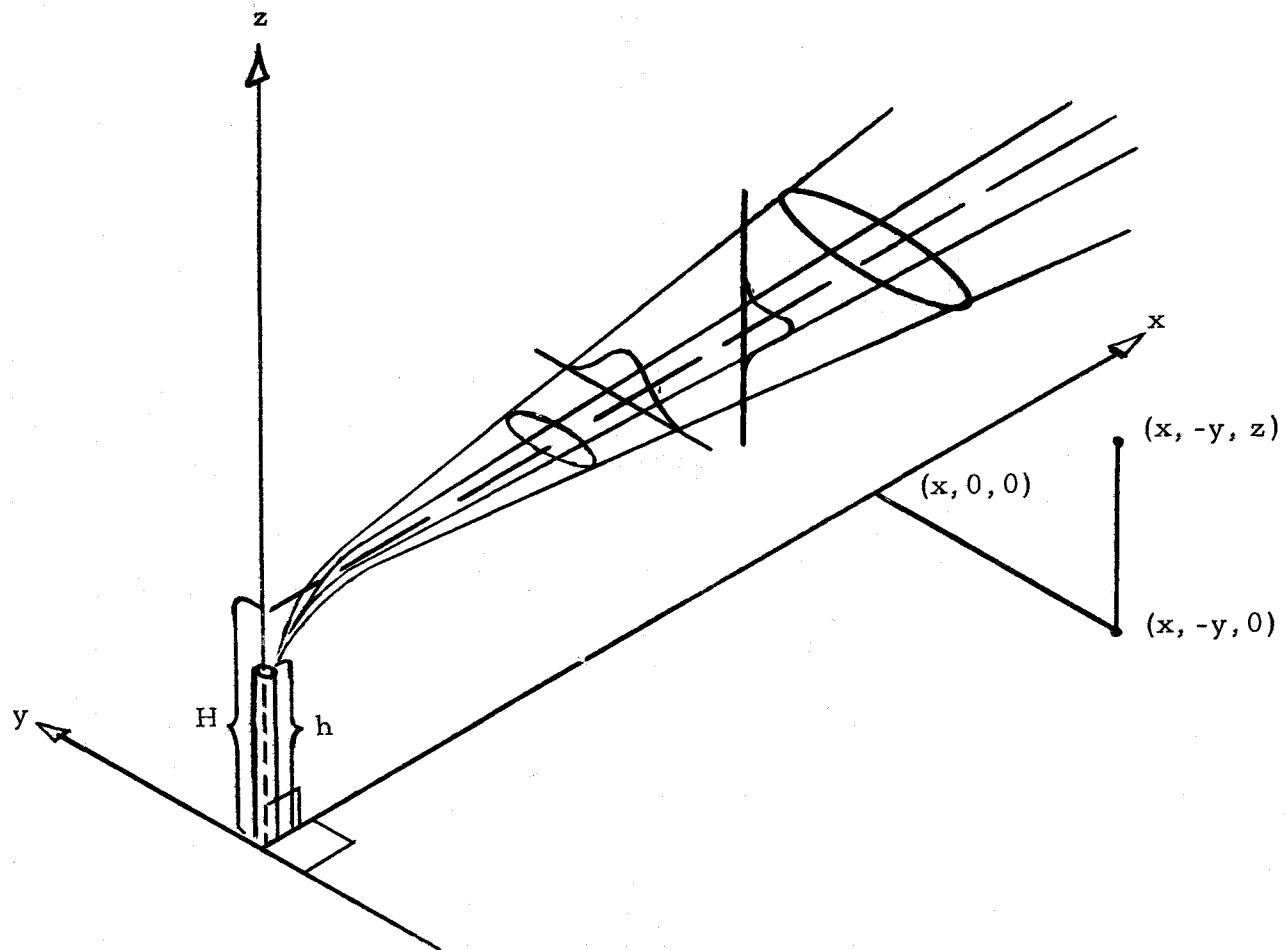


Figure 14. Coordinate system showing Gaussian distributions in the horizontal and vertical (from Turner, 1970).

structure as a function of height, one would expect a skewed Gaussian spread of the plume as shown in Figure 15 (from Smith, 1957). Also, there will be some loss of large particles in the transport process due to gravitational settling and the loss of small particles due to impaction on the earth's surface (Chamberlain, 1953).

For ground-level pollutant concentrations, equation (1) reduces to

$$\chi(x, y, 0) = \frac{Q}{\pi \sigma_y \sigma_z u} \exp \left[-\frac{1}{2} \left(\frac{y}{\sigma_y} \right)^2 - \frac{1}{2} \left(\frac{h_e}{\sigma_z} \right)^2 \right] \quad (2)$$

To use equation (2), the meteorological information required is the wind speed, u , and the wind direction which governs the coordinates of the receptor. The values of σ_y and σ_z depend on the atmospheric stability which in turn depends upon the variation of temperature with height, another meteorological parameter.

Pasquill (1961, 1962) has developed a weather classification scheme (Type A to F in Table 14) which employs only simple measurements of surface wind, sunshine and cloudiness to classify the atmospheric stability. He also estimated the values of vertical and angular spread of plumes based on existing experimental data for various classes of atmospheric stability. These estimates were converted by Gifford (1961) into horizontal and vertical dispersion coefficients as a function of distance from the source. A family of these curves is shown in Figures 16 and 17. Based on experimental results on

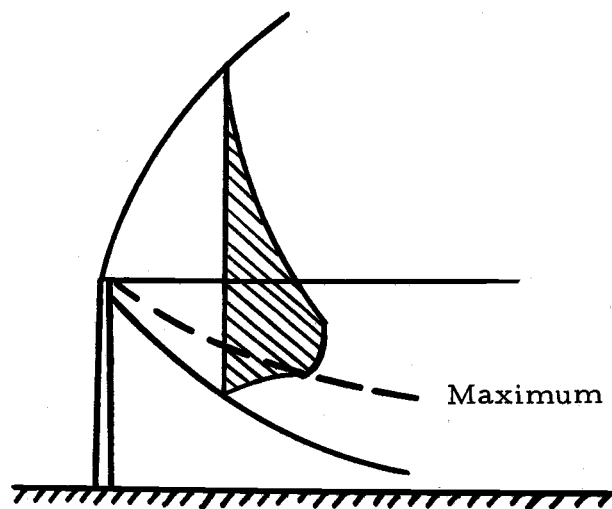


Figure 15. Sketch showing, in exaggerated form for emphasis, the influence of wind speed shear with increasing height in producing a skewed distribution of concentrations along the vertical near the source (after Smith, 1957).

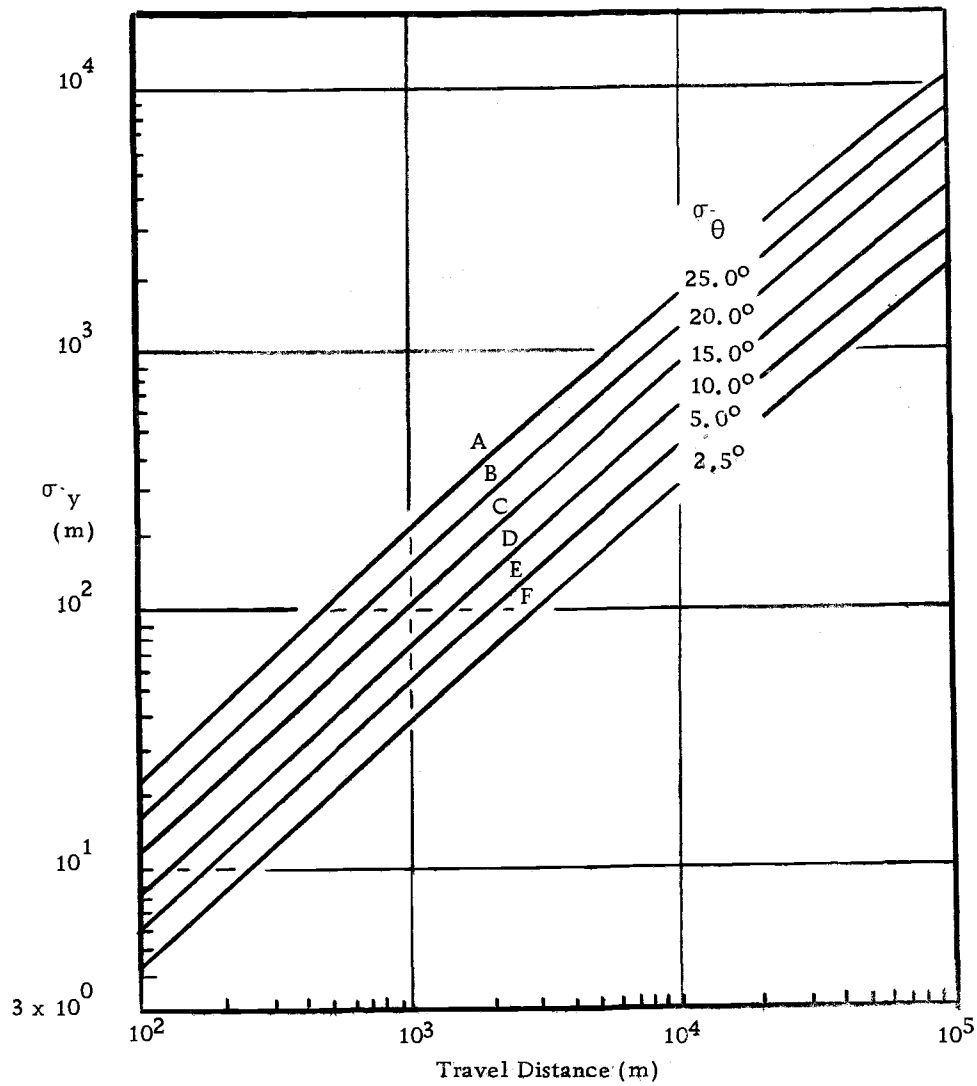


Figure 16. Standard deviation of the lateral concentration distribution, σ_y , as a function of travel distance from a continuous source. A - F are Pasquill's diffusion categories (from Gifford, 1961).

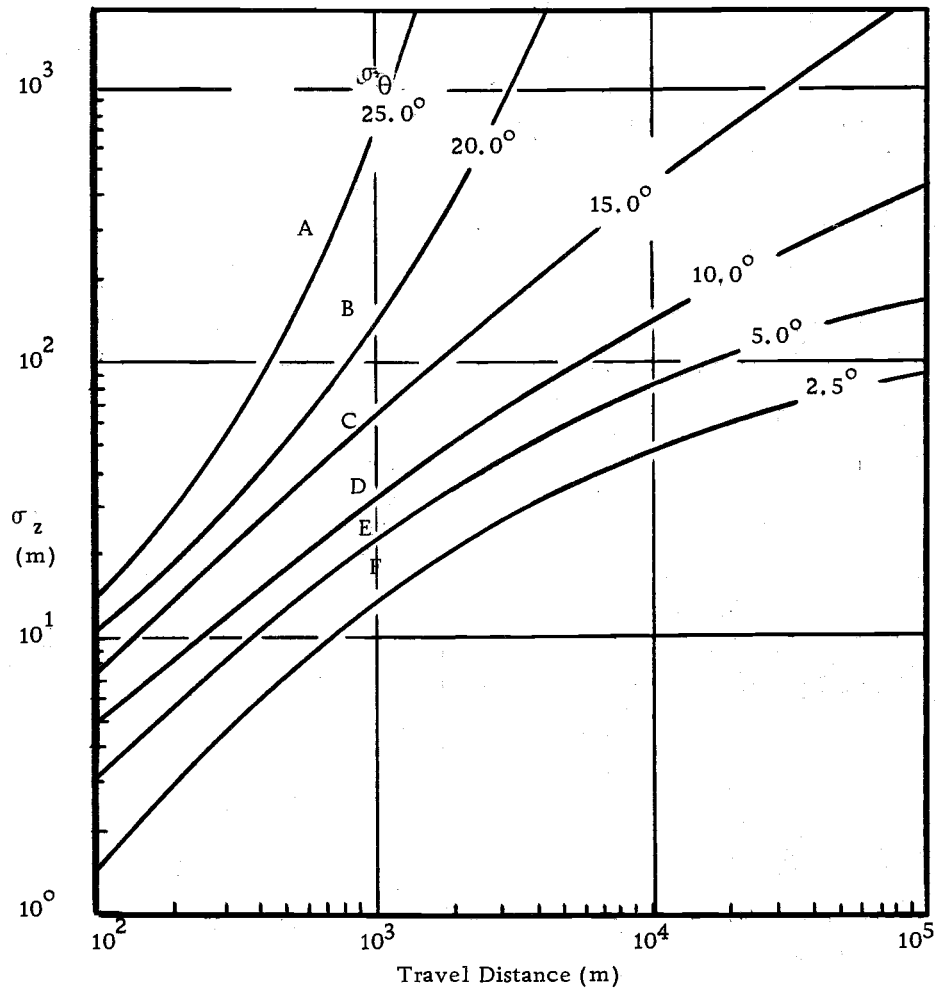


Figure 17. Standard deviation of the vertical concentration distribution σ_z , as a function of travel distance from a continuous source. A - F are Pasquill's diffusion categories (from Gifford, 1961).

diffusion studies performed by several groups (Cramer, 1957; Fuquay et al., 1964; Haugen and Fuquay, 1963(a), 1963(b); Islitzer and Dumbauld, 1963), it was demonstrated (Meteorology and Atomic Energy, 1968, Chapter 4) that the standard deviation of the horizontal wind direction, σ_{θ} for a short averaging time and for the sampling times used in these experiments (10 minutes to 60 minutes) can be related empirically to the measured values of plume width. On the basis of these data, therefore, Pasquill's stability categories can be relabeled in terms of σ_{θ} as shown in Figures 16 and 17.

Table 14. Key to Stability Categories (from Pasquill, 1961, 1962)

Surface Wind Speed (at 10 m), m sec ⁻¹	Day			Night		
	Incoming Solar Radiation			Thinly Overcast or ≤ 3/8		
	Strong	Moderate	Slight	≥4/8	Low Cloud	Cloud
< 2	A	A-B	B			
2-3	A-B	B	C	E		F
3-5	B	B-C	C	D		E
5-6	C	C-D	D	D		D
> 6	C	D	D	D		D

The neutral class, D, should be assumed for overcast conditions during day or night.

A: Extremely unstable conditions	D: Neutral conditions
B: Moderately unstable conditions	E: Slightly stable conditions
C: Slightly unstable conditions	F: Moderately stable conditions

In this study, the horizontal wind fluctuation σ_{θ} was measured for the classification of atmospheric stability. The mean wind speed was also used as a help in defining the atmospheric stability.

The values of σ_y and σ_z in Figures 16 and 17 are representative for a sampling time of about 10 minutes and applicable to open country and rural areas. For sampling times longer than 10 minutes, the pollutant concentration will decrease because of larger dispersions due to increased meander of wind direction. The power law proposed by Stewart, Gale and Crooks (1958) was used for this correction. It states that

$$X_s = X_k (t_k/t_s)^p \quad (3)$$

where X_s is the corrected concentration estimated for the sampling time t_s , X_k is the concentration estimated for the shorter sampling time t_k , i.e., 10 minutes and p is equal to 0.2. This formula applies for a sampling period up to 60 minutes.

The other variable to be evaluated in equation (2) is the effective stack height, h_e , which is the sum of the actual stack height (h_s) and the plume rise (Δh) as shown in Figure 18. The plume rise is affected by the exit velocity of the stack, temperature of the effluent at the top of the stack, the wind speed, the diameter of the stack, the temperature of the air, shear of the wind speed with height and the temperature lapse-rate. Even though many formulations have been developed in calculating the plume rise, none of them relate to all of the parameters mentioned since the measurements of all of these

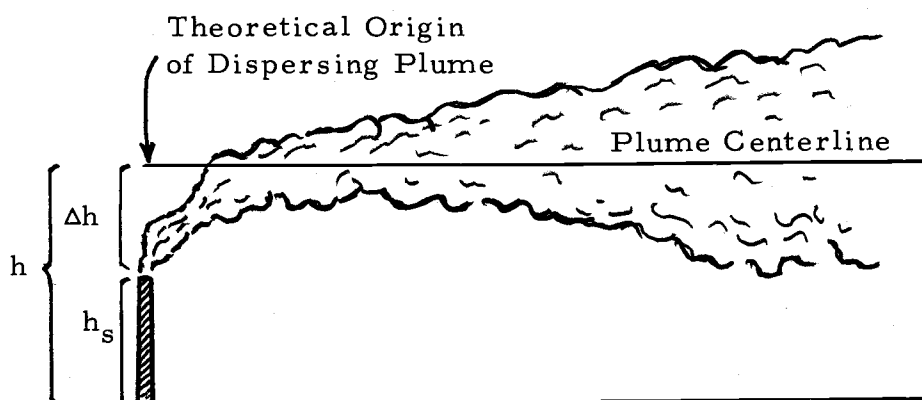


Figure 18. Effective stack height. In the mathematical representation used in this guide, it is assumed that dispersion begins at a theoretical point directly above the stack, whose height (h) is the sum of the actual stack height (h_s) and the plume rise (Δh) (from Smith, 1968).

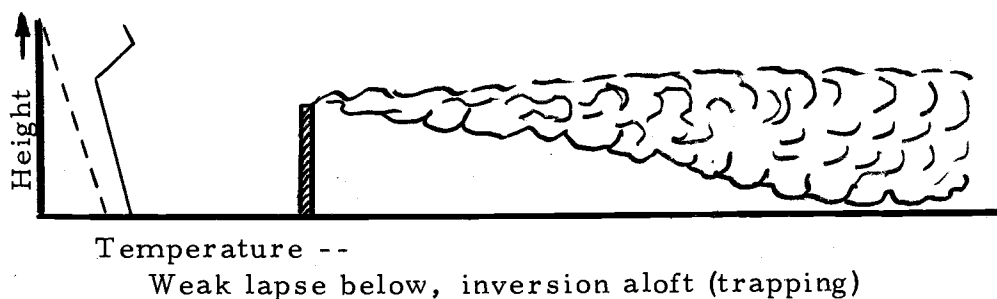


Figure 19. Trapping plume (from Hewson, 1964).

parameters are difficult. A summary of these formulas is discussed in Meteorology and Atomic Energy (1968).

The tall stack of the Western Kraft plant has a large plume with a stack diameter of 4 meters. The exit velocity ranged from 6 to 12 meters/sec and the temperature of the stack effluent was about 145°C. Holland's equation (1953) (developed with experimental data for large plumes with stack diameters from 1.7 to 4.3 meters and stack temperature from 82°C to 204°C) was applied to calculate the plume rise.

It is given by

$$\Delta H = \frac{V_s d}{u} \left[1.5 + 2.68 \times 10^{-3} p \frac{(T_s - T_a)}{T_s} d \right] \quad (5)$$

where ΔH = the rise of the plume above the stack

V_s = stack gas velocity (m/sec)

d = diameter of stack (m)

u = mean wind speed (m/sec)

p = atmospheric pressure (mb)

T_s = stack gas temperature (°K)

T_a = air temperature (°K)

The stack in Wah Chang has a small plume so that the plume rise is negligible as compared to the stack height. At the Simpson Timber Company, since the spraying system was set at the top of a blower, the plume rise is negligible.

Hewson's Trapping Plume Formula

Plume trapping occurs when there is an inversion layer present at some height above the stack. The inversion base serves as a reflecting boundary such that pollutants in the turbulent layer between the ground and the inversion layer are trapped. This situation leads to high concentrations of pollutant near the ground. The inversion may be a subsidence inversion which occurs quite frequently in western Oregon, particularly in late September when the Pacific anti-cyclone is dominant. A picture of the trapping plume is shown in Figure 19 (after Hewson, 1969).

This situation can be described by using the method of images for multiple reflections as indicated by Morse and Feshbach (1953). This is to establish an image source of equal strength at $z = -h$ where z is the vertical height and h is the stack height, and adding the solutions for both the real and image source together. By assuming that the ground and the inversion base act as reflecting barriers, Hewson, Gill and Bierly (1958) derived the following formula for trapping. (A detailed derivation of the formula is given by Strauss, 1971).

$$\chi(x, y, 0) = \frac{\exp\left[-\frac{1}{2}\left(\frac{y^2}{\sigma_y^2}\right)\right] Q}{2\pi\sigma_y\sigma_z u} \sum_{-j}^j \exp\left\{-\frac{1}{2}\left[\frac{(-h_e + 2jh_i)^2}{\sigma_z^2}\right]\right\} \\ + \exp\left\{-\frac{1}{2}\left[\frac{(h_e + 2jh_i)^2}{\sigma_z^2}\right]\right\} \quad (6)$$

where χ = concentration (g/m^3)

u = mean wind speed (m/sec)

Q = emission rate (g/sec)

σ_y, σ_z = crosswind and vertical dispersion coefficients (m)

h_e = effective stack height (m)

h_i = inversion height (m)

$j = 0, 1, 2, 3 \dots$

The first exponential term describes the Gaussian spread of the plume; the summation terms describe the multiple reflection of the particles between the inversion layer and the earth's surface. Since the series converges rapidly, only the first two terms need be considered. Then the formula is reduced to

$$\chi(x, y, 0) = \frac{Q}{\pi\sigma_y\sigma_z u} \left\{ \exp\left(-\frac{h_e^2}{2\sigma_z^2}\right) + \exp\left[-\frac{(2h_i - h_e)^2}{2\sigma_z^2}\right] \right. \\ \left. + \exp\left[-\frac{(-2h_i - h_e)^2}{2\sigma_z^2}\right] \right\} \quad (7)$$

The Use of Multiple Regression Analysis in Predicting the
Emission Rate from Multiple Sources of Air Pollution

In situations where multiple sources of air pollution are present, one would like to use meteorological models to predict the emission rates from the sources emitting the same pollutant. For multiple sources of air pollution, the following formula applies,

$$\chi = A_0 + A_1 Q_1 + A_2 Q_2 + A_3 Q_3 \cdots = A_0 + \sum_{i=1}^n A_i \times Q_i \quad (8)$$

where χ is the measured total concentration of the pollutant at a certain location, A_0 represents the background level of the pollutant, Q_i represents the emission rate of source i , and A_n is the coefficient representing the product of the terms of $1/(\pi u \sigma_y \sigma_z)$ and the exponential terms in the diffusion equation applied. A_n was calculated using the Gaussian plume formula (equation 2) and Hewson's trapping plume formula (equation 7). The values of the emission rates Q_i in equation (8) were determined by the use of a multiple linear regression analysis procedure in which the best fit to a series of measured pollutant concentrations, χ_i , and sampling parameters, A_i , was obtained. The independent variables in the analysis were taken to be the A_i terms, the dependent variable χ and the coefficients whose values were determined were the Q_i . The actual analyses was done using the *SIPS computer program from the Oregon State University statistical program library. Q_i values were determined for multiple sources of air pollution in Albany, Oregon

Experimental Results and Discussion in the Testing of Meteorological Models

The experimental results and theoretical calculations of the concentrations of the tracer are summarized in Tables 15-22. The theoretical calculations of the ground-level concentrations of the tracer were done using equation 2 (the Gaussian plume formula) and equation 7 (Hewson's trapping plume formula). The tables are categorized according to the meteorological model used, the atmospheric stability classification and the location of the stack. Fourteen experiments were conducted using artificial activable tracers to test the meteorological models. The wind records and temperature lapse-rate for each experiment are included in Appendix V.

From the values of the experimental results and theoretical calculations of the concentration of the tracer from each table, a scatter diagram with observed values vs. calculated values was made. Linear regression analysis was used to obtain the best fit line. The linear correlation coefficient was also calculated. An example of all these calculations is presented in Appendix IV. The results are summarized in Figures 20-26. By observing the degree of deviation of the best fit line from the 45° line, one can evaluate the effectiveness of the model. The intercept in the scatter diagram indicates the "background" concentration of the tracer.

In each experiment, the values of A_n from equation 8 were calculated for every sampling location and were summarized in the last column of the tables. From the experimental concentrations of the tracer and their corresponding coefficients, A_n , the best value

of Q , the predicted emission rate was calculated by the use of linear regression analysis. A comparison of the actual and predicted emission rate from each table gives an indication of the effectiveness of the model in predicting the emission rate.

In some experiments, two tracers were used at the same stack to test the difference among the elements. The concentrations measured for the different tracers were normalized to the same emission rate of one element for comparison purposes. The results show that in general, the four rare-earth elements, i. e., Dy, Sm, Ce and La, have the same diffusion pattern irrespective of the element used.

The release of the tracer at different stacks represents two categories of study. The stack at Western Kraft is a tall stack 61 meters high; the stacks at Wah Chang and Simpson Timber companies are short stacks 25 and 13.5 meters high respectively. They represent a high and two low sources. For the low sources, one has to evaluate the effect on dispersion when the plume travels through the neighboring city.

In general, for the high source the Gaussian plume model (equation 2) describes the dispersal of the tracer quite well under D, C and B stability. Tables 15, 16 and 17 are summaries of results from the stack at Western Kraft under D, C and B conditions respectively. Under D and C conditions, Tables 15 and 16 show that 72% of the experimental concentrations measured are within a factor of two of the values predicted by the model. Table 17 shows that 63% of the experimental concentrations measured are within a factor of two of

the values predicted under B conditions. The predicted emission rates with this model under D, C and B conditions are within 20-40% of the actual values. Figures 20-22 show that the observed concentrations and the calculated concentrations are linearly correlated at the 95% confidence level.

For the low level point sources, since the plume has to travel through the city, the effect of the neighboring urban area has to be taken into account. In studies of this effect, Pooler (1966) and McElroy (1969) found that the crosswind diffusion σ_y in an urban area is greater initially than in open country and converges to the latter value at large distances. The vertical diffusion σ_z also becomes significantly greater than in open country and the increase is most pronounced under stable meteorological conditions. Mitchell (1962) has indicated that the greater instability over an urban area may be due to an increase in mixing caused by roughness and to the persistence of instability due to high surface temperature caused by the interception of radiation from one building by another and the release of heat from pavements and buildings.

To study the effect of an urban area on the crosswind dispersion coefficient, we lined up the air samplers approximately in a straight line perpendicular to the wind and measured the concentrations of the tracer at each location. Assuming the concentrations of the tracer across the centerline of the plume to be Gaussian, a Gaussian fit to

the data (concentrations vs. crosswind distance) was performed with a computer program (CURFIT program by Bevington, 1969) to obtain the best value of σ_y . An example of this calculation is illustrated in Appendix IV. From this calculation of σ_y from experimental data, one should be able to evaluate the effect of an urban area on the crosswind dispersion coefficient. Our results show that σ_y increases from values corresponding to D to approximately C stability at a downwind distance of about 1000 to 2000 meters. This agrees with the results found by McElroy (1969). The calculated σ_z shows the same increase in stability (from values corresponding to D to approximately C conditions). The results in Table 18 support this conclusion. In Table 18, the atmospheric stability for all the experiments corresponds to neutral conditions, i. e., D classification, but the measured concentrations agree quite well with theory.

In Table 19, the atmospheric stability of the "MM" experiment corresponds to D stability, but the measured concentrations at a downwind distance of about 800 to 1000 meters are best fitted if one assumes B stability. This indicates that the stability increase due to the effect of an urban area is a function of downwind distance, i. e., from D to B stability for downwind distance of 800-1000 meters and from D to C stability for downwind distance of 1000-2000 meters. This also agrees with the results of McElroy (1969). Since we did not have enough data to test this effect for all the downwind distances,

the correction was only an approximation. With this correction to allow for urban effects, Table 18 shows that 53% of the measured concentrations are within a factor of two of the theoretical values. Table 19 shows that 85% of the measured concentrations are within a factor of two of the predicted values under B stability. Figures 23 and 24 demonstrate that the observed concentrations and the calculated concentrations are linearly correlated at the 95% confidence level. For extremely unstable conditions (type A stability), Table 20 and Figure 25 show that the measured concentrations are not in good agreement with the predicted values, with only 30% of the measured concentrations within a factor of two of the predicted values. This fact is also reflected by the poor correlation coefficient in Figure 25.

Hewson's trapping plume model (1958) applies when there is an inversion layer above the top of the stack and the plume is trapped between the ground surface and the stable layer. Tables 21 and 22 present data for such trapped plumes. Table 21 shows that under moderately unstable conditions (stability type B), 73% of the measured concentrations are within a factor of two of the predicted values, indicating that this model describes the dispersal of the tracer quite well under these conditions. Figure 26 shows that the observed concentrations and the calculated concentrations are linearly correlated at the 95% confidence level. But under extremely unstable conditions as summarized in Table 22, the measured concentrations do not agree

Table 15. Summary of Results in the Study of the Gaussian Plume Model under Neutral Conditions (Stability Type D) for the High Source

Date of Experiment	Location of Stack (1)	Location of Air Sampler (1)	Sample Number	Mean Wind Direction (2) and Fluctuation (σ_θ) (3)	Mean Wind Speed (m/sec)	Time of Collection	Tracer Used	Emission Rate ($\mu\text{g}/\text{sec}$)	Concentration		x (meter)	y (meter)	σ_y (meter)	σ_z (meter)	A_n (10^{-4})	
									Experimental Results ($10^{-10} \text{ g}/\text{m}^3$)	Theoretical Results ($10^{-10} \text{ g}/\text{m}^3$)						
8/28/72	Western Kraft	1	V-1	360°	5.6	1330-1400	Dy	988 (Actual) (1249±220) (Predicted)	30.0 ± 4.2	12.7	2612	157	170	64	0.01280	
		2	V-2	$(\sigma_\theta = 9^\circ)$					14.0 ± 2.2	11.1	4260	150	255	82	0.01120	
		4	V-3	↓		↓			0.4 ± 0.2	0.2	4593	876	300	84	0.00020	
		1	V-4	↓		1400-1430			20.0 ± 3.4	12.7	2612	157	170	64	0.01280	
		2	V-5	↓		↓			8.0 ± 2.0	11.1	4260	150	255	82	0.01120	
		4	V-6	↓		↓			1.2 ± 0.5	0.2	4593	876	300	84	0.00020	
		1	V-7	↓		1430-1500			11.0 ± 1.7	14.2	2612	157	170	64	0.01440	
		2	V-8	↓		↓			11.0 ± 2.1	12.7	4260	150	255	82	0.01280	
10/14/72	Western Kraft	7	QQ-1	377°	4.9	1700-1730	Dy	417 (Actual) (599±168) (Predicted)	8.5 ± 1.0	4.6	3990	175	245	76	0.01100	
		6	QQ-2	$(\sigma_\theta = 10^\circ)$		↓			0.7 ± 0.6	0.1	2833	550	180	60	0.00017	
		1	QQ-3	↓		↓			1.4 ± 1.3	0.1	2630	508	168	59	0.00024	
		7	QQ-4	372°		1730-1800			2.1 ± 1.8	0.5	3944	550	243	76	0.00120	
		6	QQ-5	$(\sigma_\theta = 9^\circ)$		↓			2.7 ± 2.2	2.2	2875	263	183	60	0.00530	
		1	QQ-6	↓		↓			1.5 ± 1.3	2.1	2682	252	169	59	0.00500	
		6	QQ-7	372°		1800-1830			2.1 ± 0.7	2.2	2875	263	183	60	0.00530	
		1	QQ-8	$(\sigma_\theta = 9^\circ)$		↓			2.1 ± 1.8	2.1	2682	252	169	59	0.00500	
		8	QQ-9	↓		1640-1715			2.1 ± 1.8	2.8	4120	280	254	79	0.00670	
		8	QQ-10	↓		1730-1815			5.5 ± 2.8	2.8	4120	280	254	79	0.00670	

(1) Referred to Map 2.

(2) Northerly = 360° ; westerly = 270° (3) σ_θ = Standard deviation of horizontal wind fluctuation

Table 16. Summary of Results in the Study of the Gaussian Plume Model under Slightly Unstable Conditions (Stability Type C) for the High Source

Date of Experiment	Location of Stack (1)	Location of Air Sampler (1)	Sample Number	Mean Wind Direction (2) and Fluctuation (σ_θ)(3)	Mean Wind Speed (m/sec)	Time of Collection	Tracer Used	Emission Rate ($\mu\text{g}/\text{sec}$)	Concentration		x (meter)	y (meter)	σ_y (meter)	σ_z (meter)	A_n (10^{-4})	
									Experimental Results ($10^{-10} \text{ g}/\text{m}^3$)	Theoretical Results ($10^{-10} \text{ g}/\text{m}^3$)						
8/11/72	Western Kraft	11	R-1	349° ($\sigma_\theta = 16^\circ$)	3.1	1230-1300	Dy	643 (Actual)	4.1 $\pm$ 2.5	3.5	3218	402	310	180	0.00720	
		10	R-2	↓		↓		(1004 $\pm$ 149)	2.3 $\pm$ 1.3	0.03	3568	1106	330	200	0.00001	
		11	R-3	326° ($\sigma_\theta = 16^\circ$)		1300-1330		(Predicted)	2.3 $\pm$ 1.3	1.6	3218	560	310	180	0.00330	
		19	R-4	↓		↓			4.6 $\pm$ 1.9	3.5	3620	402	331	203	0.00680	
		12	R-5	↓		↓			6.0 $\pm$ 3.0	1.8	3922	578	365	210	0.00360	
		11	R-6	↓		1300-1400			2.8 $\pm$ 1.1	1.6	3218	560	310	180	0.00330	
		18	R-7	↓		↓			6.0 $\pm$ 1.6	3.5	3620	402	331	203	0.00680	
		19	R-8	↓		↓			2.5 $\pm$ 1.9	1.8	3922	578	365	210	0.00360	
9/13/72	Western Kraft	5	AA-1	341° ($\sigma_\theta = 15^\circ$)	3.7	1130-1230	(1)Dy (2)Sm	(1)1538 (Actual)	10.0 $\pm$ 2.0	11.6 $\pm$ 2.0	8.2	3418	333	320	190	0.00530
		2	AA-2	↓		↓		(2)1538 (Actual)	1.2 $\pm$ 0.7	2.3	4197	648	380	228	0.00150	
		6	AA-3	↓		↓		(1)(2163 $\pm$ 231)	3.3 $\pm$ 1.4	0.4	2408	683	235	138	0.00026	
		14	AA-4	343° ($\sigma_\theta = 15^\circ$)		1200-1300		(Predicted)	15.0 $\pm$ 2.3	12.0 $\pm$ 2.0	9.1	3576	284	330	198	0.00590
		5	AA-5	↓		↓		(2)(1974 $\pm$ 201) (Predicted)	10.0 $\pm$ 1.8	7.6 $\pm$ 1.6	8.2	3420	330	320	190	0.00530
		2	AA-6	↓		↓			1.0 $\pm$ 0.6	2.3	4200	650	380	228	0.00150	
		6	AA-7	↓		↓			1.6 $\pm$ 0.8	2.1	2420	690	338	140	0.00140	
		5	AA-8	350° ($\sigma_\theta = 15^\circ$)		1100-1200			11.0 $\pm$ 1.6	9.5 $\pm$ 2.0	6.0	3418	420	320	190	0.00390
		2	AA-9	↓		↓			1.4 $\pm$ 0.7	1.5	4190	746	380	228	0.00100	
		6	AA-10	↓		↓			4.8 $\pm$ 1.9	0.3	2408	736	235	138	0.00019	

(1) Referred to Map 2

(2) Northerly = 360°; westerly = 270°

(3) σ_θ = Standard deviation of horizontal wind fluctuation

Table 17. Summary of Results in the Study of the Gaussian Plume Model under Moderately Unstable Conditions (Stability Type B) for the High Source

Date of Experiment	Location of Stack (1)	Location of Air Sampler (1)	Sample Number	Mean Wind Direction (2) and Fluctuation (σ_θ)(3)	Mean Wind Speed (m/sec)	Time of Collection	Tracer Used	Emission Rate ($\mu\text{g}/\text{sec}$)	Concentration		x (meter)	y (meter)	σ_y (meter)	σ_z (meter)	A_n (10^{-4})
									Experimental Results ($10^{-10} \text{ g}/\text{m}^3$)	Theoretical Results ($10^{-10} \text{ g}/\text{m}^3$)					
9/14/72	Western Kraft	14	CC-1	325, 5°	4.2	1700-1800	Dy	1531	2.9 ± 1.0	4.5	3471	350	460	410	0.00290
		5	CC-2	($\sigma_\theta = 18^\circ$)	↓	↓		(Actual)	3.9 ± 1.6	5.0	3408	298	450	400	0.00336
		2	CC-3	↓	↓	↓		(1466 ± 221)	2.0 ± 1.0	2.0	4207	652	570	520	0.00130
		1	CC-4	↓	↓	↓			9.4 ± 1.3	2.5	2612	613	370	310	0.00160
		14	CC-5	360, 3°	3.9	1730-1830		(Predicted)	2.4 ± 0.8	1.1	3418	869	455	404	0.00072
		5	CC-6	($\sigma_\theta = 18^\circ$)	↓	↓			3.7 ± 1.5	5.5	3443	228	460	408	0.00360
		2	CC-7	↓	↓	↓			2.0 ± 1.0	3.9	4242	70	580	525	0.00250
		1	CC-8	↓	↓	↓			10.0 ± 1.4	8.4	2700	227	380	315	0.00550
		16	CC-9	↓	↓	1730-1845			5.2 ± 1.3	4.5	3506	329	470	425	0.00290
		14	CC-10	367, 0°	3.2	1800-1900			0.3 ± 0.2	0.2	3295	1209	445	396	0.00013
		5	CC-11	($\sigma_\theta = 20^\circ$)	↓	↓			4.8 ± 1.8	2.9	3401	561	450	400	0.00190
		2	CC-12	↓	↓	↓			2.3 ± 1.1	2.6	4207	501	570	520	0.00170
		1	CC-13	↓	↓	↓			6.6 ± 1.1	9.0	2717	70	383	318	0.00590
9/25/72	Western Kraft	5	EE-1	353, 0°	3.1	1830-1900	Dy	1179	2.4 ± 0.4	5.2	3450	238	490	425	0.00440
		2	EE-2	($\sigma_\theta = 18^\circ$)	↓	↓		(Actual)	1.4 ± 0.6	2.5	4163	553	570	520	0.00211
		1	EE-3	↓	↓	↓		(519 ± 37)	0.8 ± 0.7	2.7	2564	603	370	310	0.00232
		17	EE-4	↓	↓	↓		(Predicted)	2.1 ± 0.8	6.0	2429	402	350	285	0.00510
		5	EE-5	353, 0°	3.1	1900-1930			2.8 ± 0.4	5.2	3450	238	490	415	0.00443
		2	EE-6	($\sigma_\theta = 18^\circ$)	↓	↓			1.3 ± 0.8	2.5	4163	553	570	520	0.00211
		1	EE-7	↓	↓	↓			1.5 ± 0.6	2.7	2564	603	370	285	0.00234
		17	EE-8	↓	↓	↓			2.4 ± 0.9	6.0	2429	402	350	390	0.00512
		17	EE-9	327, 5°	3.4	1800-1830			1.1 ± 0.4	1.4	2061	653	305	243	0.00123
9/26/72	Western Kraft	19	GG-1	335, 5°	3.6	1620-1700	(1)Sm	(1)2013	(Sm)	(Ce)(4)	3620	402	510	450	0.00280
		14	GG-2	341, 7°	4.9	1700-1730	(2)Ce	(Actual)	15.0 ± 5.0	11.0 ± 3.0	5.6				
		19	GG-3	($\sigma_\theta = 18^\circ$)	↓	↓		(2)2488	4.6 ± 0.8	5.6	3200	271	462	390	0.00280
		1	GG-4	↓	↓	↓		(Actual)	0.3 ± 0.2	0.6	3519	1055	485	430	0.00029
		5	GG-5	↓	↓	↓		(1)(2797 ± 621)	1.4 ± 0.9	0.3	2413	1005	355	290	0.00015
		5	GG-6	340, 8°	4.3	1630-1730		(Predicted)	0.9 ± 0.7	1.5	3117	804	458	385	0.00074
		18	GG-7	($\sigma_\theta = 18^\circ$)	↓	1635-1725		(2)(3944 ± 1225)	0.7 ± 0.4	1.5	3117	804	458	385	0.00074
		3	GG-8	↓	↓	1630-1720		(Predicted)	5.7 ± 2.2	3.4	3519	532	485	430	0.00170
									5.2 ± 1.1	6.0 ± 2.4	6.3	3419	100	475	420

(1) Referred to Map 2

(2) Northerly = 360°; westerly = 270°

(3) σ_θ = Standard deviation of horizontal wind fluctuation

(4) The concentrations of Ce are normalized to the emission rate of Sm; the actual measured concentrations are higher by a factor of 1.24.

Table 18. Summary of Results in the Study of the Gaussian Plume Model Under Slightly Unstable Conditions (Stability Type C) for the Low Source

Date of Experiment	Location of Stack (1)	Location of Air Sampler (1)	Sample Number	Mean Wind Direction (2) and Fluctuation (σ_0) (3)	Mean Wind Speed (m/sec)	Time of Collection	Tracer Used	Emission Rate ($\mu\text{g/sec}$)	Concentration			x (meter)	y (meter)	σ_y (meter)	σ_z (meter)	σ_y (meter)	σ_z (meter)	A_n (10^{-4})	
									Experimental Results (10^{-10} g/m^3)	Theoretical Results (10^{-10} g/m^3)									
										(C stability)	(D stability)								
10/5/72	Wah Chang	5	MM-1	355.0° ($\sigma_0=9^\circ$)	6.0	1630-1700	Dy	1168 (Actual) (983±61) (predicted)	1.3 ± 0.4	0.5	0.005	1689	490	168	95	110	45	0.00045	
		2	MM-2						9.0 ± 0.5	11.0	18.0	2482	246	240	137	160	58	0.00940	
		15	MM-3						2.3 ± 0.3	5.5	2.2	1999	350	197	115	130	50	0.00471	
		1	MM-4						32.0 ± 1.6	51.0	65.0	1052	105	108	64	74	36	0.04366	
		5	MM-5			1700-1730			1.4 ± 0.9	0.5	0.0	1689	490	168	95	110	45	0.00045	
		2	MM-6						6.4 ± 1.3	11.0	18.0	2482	246	240	137	160	58	0.00941	
		15	MM-7						4.1 ± 0.5	5.5	2.2	1999	350	197	115	130	50	0.00472	
		1	MM-8						40.0 ± 2.0	51.0	65.0	1052	105	108	64	74	36	0.04366	
		5	MM-9	351.0° ($\sigma_0=9^\circ$)	6.1	1730-1800			2.5 ± 0.8	3.6	0.6	1735	368	173	100	114	45	0.00308	
		2	MM-10						8.8 ± 1.3	17.0	55.0	2507	70	243	143	160	58	0.01460	
		15	MM-11						1.2 ± 0.2	1.2	0.1	1964	490	195	113	130	50	0.00103	
		1	MM-12						74.0 ± 3.7	78.0	158.0	1052	35	108	64	74	36	0.06681	
		5	MM-13	359.0° ($\sigma_0=10^\circ$)	6.0	1610-1630			1.4 ± 0.9	0.3	0.0	1630	631	165	93	105	43	0.00022	
		2	MM-14						8.0 ± 1.2	3.5	1.3	2471	438	238	135	158	57	0.00301	
		15	MM-15						8.8 ± 1.8	16.0	28.0	2033	192	199	117	132	51	0.01371	
		1	MM-16						30.0 ± 2.7	17.0	5.9	1051	193	108	64	74	36	0.01462	
		7	MM-17						0.5 ± 0.6	0.0	0.0	1945	830	198	111	129	47	0.00001	
		10/6/72	Wah Chang	5	NN-1	352.5° ($\sigma_0=10^\circ$)	6.3	1635-1700	Dy	1161 (Actual) (912±164) (Predicted)	1.1 ± 0.3	0.4	0.0	1717	508	171	100	113	46
2	NN-2								9.9 ± 3.6	10.0	17.6	2507	245	245	142	160	58	0.00961	
1	NN-3								20.8 ± 2.0	26.0	9.8	866	154	92	53	62	29	0.02242	
15	NN-4								21.7 ± 5.4	23.0	52.9	1830	122	183	106	120	47	0.01981	
5	NN-5			354.7° ($\sigma_0=10^\circ$)	5.6	1700-1730			1.7 ± 0.4	1.3	0.1	1780	455	178	103	119	41	0.00110	
2	NN-6								12.4 ± 3.8	14.7	36.9	2507	168	245	142	160	58	0.01270	
1	NN-7								43.4 ± 8.9	49.5	34.9	866	122	92	53	62	29	0.04260	
15	NN-8								20.0 ± 4.0	21.0	34.5	1830	175	183	106	120	47	0.01810	
5	NN-9			351.7° ($\sigma_0=10^\circ$)	6.0	1730-1800			1.8 ± 0.2	0.4	0.0	1717	508	171	100	115	46	0.00036	
2	NN-10								23.4 ± 2.3	14.0	34.0	2507	168	245	142	160	58	0.01200	
1	NN-11								6.3 ± 6.5	46.0	32.5	866	122	92	53	62	29	0.03960	
15	NN-12								42.0 ± 4.2	19.5	32.0	1830	175	183	106	120	47	0.01680	
8	NN-13								1.9 ± 1.1	0.0	0.0	2086	841	207	120	135	52	0.00001	
9	NN-14			351.1°		1700-1840			13.8 ± 1.2	5.8	1.8	1753	333	178	101	118	46	0.00500	
10	NN-15			351.1°		1710-1845			31.0 ± 1.9	11.0	6.9	1683	262	168	98	113	45	0.00950	
2	NN-16			345.0°	4.8	1800-1830			10.0 ± 3.6	17.0	41.0	2496	175	244	140	159	58	0.01460	
15	NN-17			345.0°	4.8	1800-1830			4.4 ± 0.5	2.6	0.3	1788	420	179	104	120	46	0.00220	
10/4/72	Wah Chang	6	LL-1	362.5° ($\sigma_0=9^\circ$)	7.3	1600-1630	(1) Dy	(1) 1061 (Actual)	(5m) 19.1 ± 3.5	21.0 ± 1.5	5.2	0.5	1024	245	110	62	72	32	0.00490
		5	LL-2						1.9 ± 0.5	0.01	0.0	1613	764	162	94	107	47	0.00001	
		2	LL-3				(2) Sm	(2) 1061 (Actual)		2.5 ± 1.2	0.09	0.0	2447	561	240	140	157	56	0.00008
		7	LL-4						1.2 ± 1.2	0.02	0.0	1974	736	200	115	130	50	0.00002	
		6	LL-5	358.6° ($\sigma_0=10^\circ$)	6.7	1630-1700		(1) 1016 ± 123 (Predicted)	18.2 ± 3.5	18.0 ± 1.3	19.0	9.1	1069	175	111	64	74	33	0.01790
		5	LL-6						1.9 ± 0.5	0.03	0.0	1655	613	163	96	108	48	0.00003	
		2	LL-7						2.9 ± 1.1	3.6	2.0	2472	403	241	142	158	56	0.00340	
		7	LL-8					(2) 1050 ± 234 (Predicted)	24.0 ± 2.9	1.9 ± 1.8	0.01	0.0	1893	870	190	112	128	49	0.00001
		6	LL-9	356.7° ($\sigma_0=10^\circ$)		1700-1730			22.0 ± 1.5	30.0	25.0	1070	140	111	63	74	33	0.02830	
		5	LL-10						1.5 ± 0.7	0.08	0.0	1683	561	163	97	109	48	0.00008	
		2	LL-11						4.0 ± 1.4	6.1	6.8	2482	316	242	142	158	57	0.00570	
		7	LL-12						0.4 ± 0.4	0.01	0.0	1847	946	188	110	122	49	0.00001	
		8	LL-13						2.6 ± 0.6	0.09	0.0	2103	690	210	120	135	52	0.00008	
		6	LL-14	358.5° ($\sigma_0=10^\circ$)	6.0	1730-1750			26.5 ± 3.4	21.5	10.0	1069	175	111	64	74	33	0.02020	
		5	LL-15						3.1 ± 0.8	0.03	0.0	1655	613	163	96	108	48	0.00003	
		2	LL-16						5.6 ± 1.7	4.0	2.2	2472	403	241	142	158	56	0.00380	
		7	LL-17						2.8 ± 1.8	0.01	0.0	1893	870	190	112	128	49	0.00001	

(1) Referred to Map 2

(2) Northerly = 360°, westerly = 270°

(3) σ_0 = Standard deviation of horizontal wind fluctuation

Table 19. Summary of Results in the Study of the Gaussian Plane Model under Moderately Unstable Conditions (Stability Type B) for the Low Source

Date of Experiment	Location of Stack (1)	Location of Air Sampler (1)	Sample Number	Mean Wind Direction (2) and Fluctuation (σ_θ) (3)	Mean Wind Speed (m/sec)	Time of Collection	Tracer Used	Emission Rate ($\mu\text{g/sec}$)	Concentration		x (meter)	y (meter)	σ_y (meter) (B stability)	σ_z (meter) (B stability)	σ_y (meter) (C stability)	σ_z (meter) (C stability)	A_n (B stability) (10^{-4})	
									Experimental Results (10^{-10} g/m^3)	Theoretical Results (10^{-10} g/m^3)								
																		(B stability)
10/5/72	Simpson Timber Co.	15	MM-18	354.3° ($\sigma_\theta = 9^\circ$)	6.0	1530-1600	La	960 (Actual)	8.1 ± 2.0	4.4	1.0	953	300	150	104	100	57	0.00458
		7	MM-19	359.3° ($\sigma_\theta = 9^\circ$)		1600-1630	(1605±262) (Predicted)	4.2 ± 0.8	4.8	0.8	841	280	135	90	89	52	0.00500	
		15	MM-20	↓		↓	1.9 ± 0.5	1.6	0.1	950	368	150	104	100	57	0.00167		
		15	MM-21	355.0° ($\sigma_\theta = 9^\circ$)		1630-1700	6.9 ± 0.8	3.9	0.8	953	308	150	104	100	57	0.00406		
		7	MM-22	355.0° ($\sigma_\theta = 10^\circ$)		1700-1730	1.7 ± 0.2	1.5	0.06	806	333	130	98	86	50	0.00156		
		15	MM-23	↓		↓	5.8 ± 0.7	3.9	0.8	953	308	150	104	100	57	0.00167		
		27	MM-24	355.0°	6.0	1637-1727		16.0 ± 1.6	6.5	3.2	1070	274	163	116	110	64	0.00677	
10/12/72	Simpson Timber Co.	8	00-1	347.6° ($\sigma_\theta = 10^\circ$)	4.5	1648-1718	Ce	2378 (Actual)	29.3 ± 7.1	26.2		1034	255	160	112			0.01102
		8	00-2	349.0°		1640-1647	(2852±454) (Predicted)	20.8 ± 7.4	33.7		1034	228	160	112			0.01417	
		8	00-3	342.6° ($\sigma_\theta = 10^\circ$)		3.4	1725-1750		12.2 ± 3.7	10.1		998	350	155	110			0.00420
		9	00-4	343.0°		↓	1720-1755		50.6 ± 15.0	23.9		789	262	126	84			0.01005
		9	00-5	349.0°		4.5	1605-1645		12.8 ± 3.8	2.8		789	357	126	84			0.00118
		30	00-6	346.6° ($\sigma_\theta = 10^\circ$)		4.0	1730-1800		66.7 ± 6.1	45.0		1458	20	220	168			0.01892
		30	00-7	342.0°	3.4	1658-1728		30.2 ± 4.2	35.0		1450	157	220	168			0.01472	

(1) Referred to Map 2.

(2) Northerly = 360°; westerly = 270°.

(3) σ_θ = Standard deviation for horizontal wind fluctuation.

Table 20. Summary of Results in the Study of the Gaussian Plume Model under Extreme Unstable Conditions (Stability Type A) for the Low Source

Date of Experiment	Location of Stack (1)	Location of Air Sampler (1)	Sample Number	Mean Wind Direction (2) and Fluctuation (σ_θ) (3)	Mean Wind Speed (m/sec)	Time of Collection	Tracer Used	Emission Rate ($\mu\text{g/sec}$)	Concentration				x (meter)	y (meter)	σ_y		σ_z		A_n (A stability) (10^{-4})
									Experimental Results		Theoretical Results				σ_y		σ_z		
									(10^{-10} g/m^3) (Dy)	(10^{-10} g/m^3) (La) (4)	(10^{-10} g/m^3) (A stability)	(10^{-10} g/m^3) (B stability)			(meter) (A stability)	(meter) (B stability)	(meter) (A stability)	(meter) (B stability)	
9/29/72	Wah Chang	14	II-1	358.3 $^\circ$ ($\sigma_\theta=20^\circ$)	3.8	1630-1700	(1) Dy	(1) 1000	1.5 $\pm$ 0.7		0.0	0.0	1655	1183	330	1030	250	190	0.000004
		5	II-2	353.3 $^\circ$ ($\sigma_\theta=18^\circ$)	3.4	1700-1730	(2) La	(2) 1250	8.9 $\pm$ 2.0	9.4 $\pm$ 1.0	0.6	1.2	1683	589	355	1035	255	195	0.000600
		2	II-3					(1)(1151 $\pm$ 347) (Predicted)	1.6 $\pm$ 1.0		0.4	4.6	2478	368	460	3000	355	300	0.000400
		1	II-4					(2)(1493 $\pm$ 604) (Predicted)	3.3 $\pm$ 1.6		5.7	26.0	1065	158	220	520	165	120	0.005700
		14	II-5					(Predicted)	1.3 $\pm$ 0.7		0.0	0.0	1744	1069	340	1040	260	200	0.000100
		5	II-6						6.3 $\pm$ 2.2	3.5 $\pm$ 1.1	1.1	3.8	1739	456	340	1040	260	200	0.001100
		2	II-7						2.0 $\pm$ 0.8		0.6	7.5	2524	175	470	3100	340	320	0.000600
		1	II-8						4.3 $\pm$ 2.4		7.6	40.0	1070	77	220	525	167	122	0.007600
		20	II-9						7.0 $\pm$ 2.0	6.0 $\pm$ 2.0	0.1	0.2	1840	806	360	1700	270	215	0.000130
		21	II-10						22.0 $\pm$ 4.0	25.0 $\pm$ 2.1	2.9	1.5	684	326	150	200	113	82	0.002900
		14	II-11	346.6 $^\circ$ ($\sigma_\theta=17^\circ$)	3.4	1730-1800			1.3 $\pm$ 0.8		0.1	0.1	1893	841	370	1750	275	220	0.000100
		5	II-12	340.0 $^\circ$ ($\sigma_\theta=18^\circ$)	3.4	1800-1830			9.1 $\pm$ 1.1	7.4 $\pm$ 1.1	2.1	11.7	1739	238	340	1040	260	200	0.002100
		2	II-13						2.0 $\pm$ 0.8		0.6	7.9	2489	140	465	3050	357	305	0.000630
		1	II-14						8.9 $\pm$ 3.2	4.1 $\pm$ 1.1	7.8	42.0	1070	60	220	525	167	122	0.007800
		20	II-15						2.1 $\pm$ 2.1		0.4	2.1	1928	566	380	1800	285	220	0.000450
		21	II-16						7.2 $\pm$ 2.5	12.0 $\pm$ 2.0	8.8	9.5	704	245	160	205	115	84	0.008800
		14	II-17						1.7 $\pm$ 0.5		0.3	1.2	1963	638	390	1900	287	225	0.000330
		5	II-18						5.3 $\pm$ 0.6	7.1 $\pm$ 1.1	2.6	17.0	1745	56	345	1040	260	200	0.002600
		2	II-19						4.7 $\pm$ 0.8	4.0 $\pm$ 1.1	0.5	4.6	2461	403	455	3000	350	300	0.000460
		1	II-20						7.5 $\pm$ 3.0	6.0 $\pm$ 2.5	6.0	26.0	1051	175	210	520	165	120	0.006000

(1) Referred to Map 2

(2) Northerly = 360° ; westerly = 270° .(3) σ_θ = Standard deviation of horizontal wind fluctuation

(4) The concentrations of La are normalized to the emission rate of Dy; the actual measured concentrations are higher by a factor of 1.25.

Table 21. Summary of Results in the Study of the Hewson's Trapping Plume Model under Moderately Unstable Conditions (Stability Type B) for the High Source

Date of Experiment	Location of Stack (1)	Location of Air Sampler (1)	Sample Number	Mean Wind Direction (2) and Fluctuation (σ_θ)(3)	Mean Wind Speed (m/sec)	Time of Collection	Tracer Used	Emission Rate ($\mu\text{g/sec}$)	Concentration		x (meter)	y (meter)	σ_y (meter)	σ_z (meter)	A_h (10^{-4})
									Experimental Results (10^{-10}g/m^3)	Theoretical Results (10^{-10}g/m^3)					
									(Sm)	(Ce)(4)					
9/29/72	Western Kraft	14	II-21	358.3° ($\sigma_\theta=20^\circ$)	3.8	1630-1700	(1) Sm	(1) 1750 (Actual)	4.8 ± 3.0	3.2	3371	701	470	410	0.00180
		5	II-22	↓			(2) Ce	(2) 2162 (Actual)	6.8 ± 2.8	5.3 ± 2.0	3435	91	380	420	0.00685
		2	II-23	↓				(1) 1689 ± 229 (Predicted)	11.0 ± 3.8	4.6 ± 3.0	4241	122	570	520	0.00445
		1	II-24	↓	3.4	1700-1730			12.4 ± 5.2	6.5 ± 3.5	2838	350	405	340	0.00520
		14	II-25	353.3° ($\sigma_\theta=18^\circ$)			(2) (1835 ± 415) (Predicted)		3.6 ± 1.2	7.4	3471	420	383	420	0.00420
		5	II-26	↓					6.4 ± 1.6	4.6 ± 3.0	3436	210	380	415	0.00685
		2	II-27	↓					4.3 ± 0.9	6.3	4207	473	565	515	0.00360
		1	II-28	↓					1.7 ± 1.5	4.4	2805	600	400	338	0.00250
		20	II-29	↓					18.0 ± 2.3	13.0 ± 2.0	3534	175	390	445	0.00685
		21	II-30	↓					8.6 ± 1.8	7.8 ± 4.0	2419	330	350	285	0.00628
		14	II-31	346.6° ($\sigma_\theta=18^\circ$)	3.4	1730-1800			18.0 ± 5.0	16.3 ± 4.8	3506	35	385	425	0.00743
		5	II-32	↓					2.4 ± 0.9	4.0	3422	596	380	420	0.00228
		2	II-33	↓					4.3 ± 1.0	2.0	4119	964	565	510	0.00114
		20	II-34	↓					8.9 ± 2.7	10.8 ± 2.1	3528	245	388	445	0.00628
		21	II-35	↓					11.0 ± 2.9	17.0 ± 4.0	2349	607	345	280	0.00205

(1) Referred to Map 2

(2) Northerly = 360°; westerly = 270°

(3) σ_θ = Standard deviation of horizontal wind fluctuation

(4) The concentrations of Ce are normalized to the emission rate of Sm; the actual measured concentrations are higher by a factor of 1.24.

Table 22. Summary of Results in the Study of the Hewson's Trapping Plume Model Under Extremely Unstable Conditions (Stability Type A) for the High Source

Date of Experiment	Location of Stack (1)	Location of Air Sampler (1)	Sample Number	Mean Wind Direction (2) and Fluctuation (σ_θ) (3)	Mean Wind Speed (m/sec)	Time of Collection	Tracer Used	Emission Rate ($\mu\text{g}/\text{sec}$)	Concentration		x (meter)	y (meter)	σ_y (meter)	σ_z (meter)
									Experimental Results ($10^{-10} \text{ g}/\text{m}^3$)	Theoretical Results ($10^{-10} \text{ g}/\text{m}^3$)				
8/7/72	Western Kraft	1	P-1	330.0° ($\sigma_\theta = 25^\circ$)	4.0	1230-1300	Dy	618	0.6 ± 0.6	0.01	2209	1473	420	410
		2	P-2	↓	↓	↓			5.4 ± 1.7	0.01	3647	1998	660	800
		3	P-3	338.0° ($\sigma_\theta = 25^\circ$)	4.0	1300-1330			4.0 ± 2.0	1.10	3576	281	640	750
		20	P-4	↓	↓	↓			3.7 ± 2.2	0.70	3366	701	610	650
		2	P-5	↓	↓	↓			4.1 ± 1.6	0.10	3927	1473	700	800
		1	P-6	↓	↓	↓			4.0 ± 2.0	0.09	2349	1150	450	450
		4	P-7	↓	↓	↓			0.7 ± 0.7	0.00	3647	2524	660	800
		21	P-8	↓	↓	↓			0.8 ± 0.7	0.00	5259	3422	900	800
		22	P-9	338.0° ($\sigma_\theta = 25^\circ$)	4.7	1330-1400			6.9 ± 1.6	0.40	3927	876	700	800
		23	P-10	↓	↓	↓			8.4 ± 2.1	0.40	4102	981	720	800
		2	P-11	↓	↓	↓			2.8 ± 1.4	0.20	3927	1473	700	800
		2	P-12	360.0°	↓	1400-1430			4.8 ± 1.0	0.70	4207	70	730	800
8/9/72	Western Kraft	25	Q-1	315.0° ($\sigma_\theta = 31^\circ$)	4.5	1200-1230	Dy	685	4.2 ± 1.1	0.00	4424	5249	800	860
		26	Q-2	↓	↓	↓			2.7 ± 1.1	0.15	7039	2115	1300	860
		23	Q-3	↓	↓	↓			1.6 ± 0.8	0.00	3590	5430	640	860
		24	Q-4	↓	↓	↓			7.5 ± 2.7	0.00	2940	3474	540	860
		25	Q-5	337.5° ($\sigma_\theta = 31^\circ$)	5.3	1230-1300			2.7 ± 1.1	0.02	6637	2584	1100	860
		26	Q-6	↓	↓	↓			1.8 ± 0.6	0.10	7039	2162	1300	860
		23	Q-7	↓	↓	↓			1.0 ± 0.8	0.00	5783	3419	1000	860

(1) Referred to Map 2

(2) Northerly = 360°; westerly = 270°.

(3) σ_θ = Standard deviation of horizontal wind fluctuation.

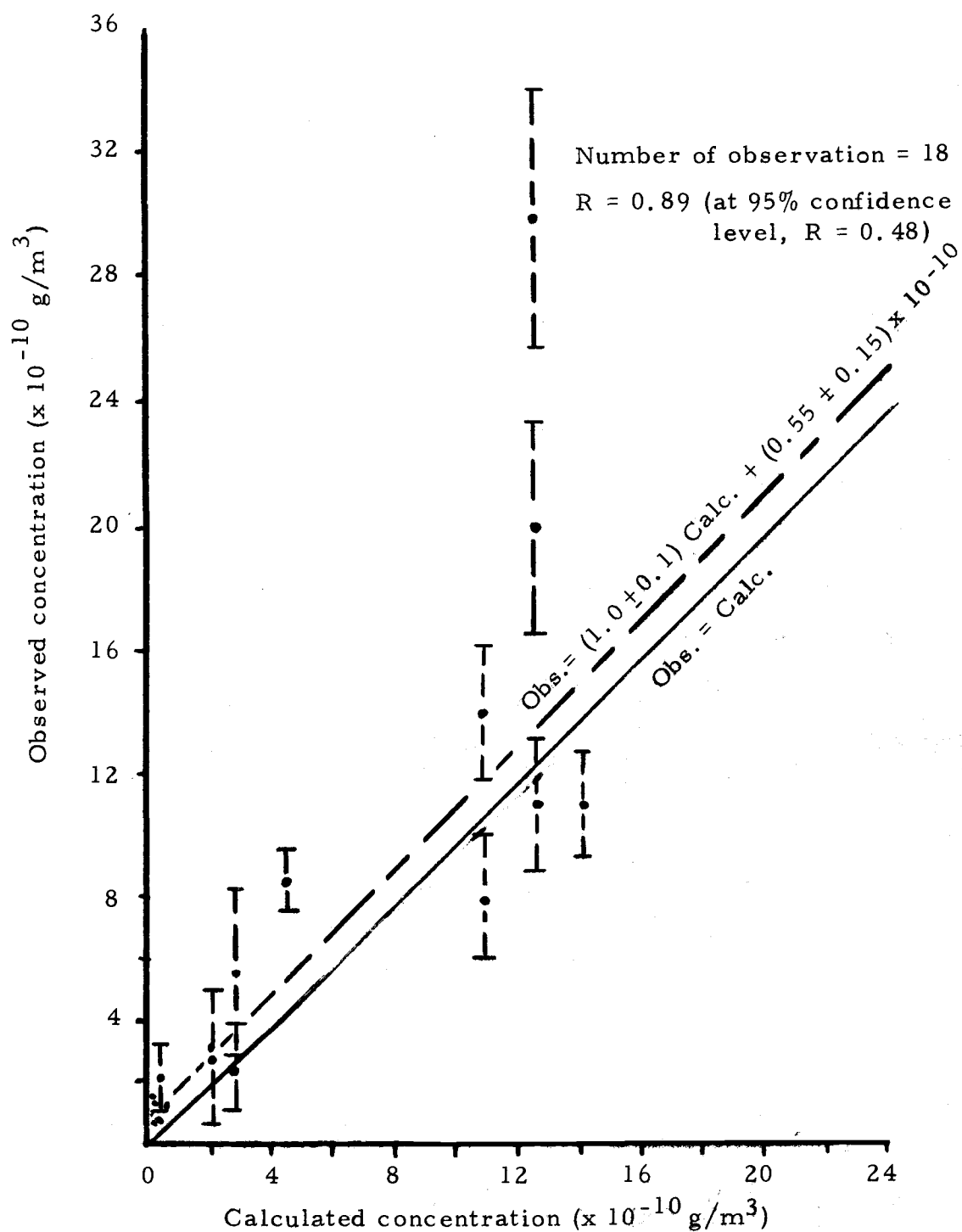


Figure 20. Scatter diagram in the study of the Gaussian plume model under neutral conditions (stability type D) for the high source at the Western Kraft Corporation.

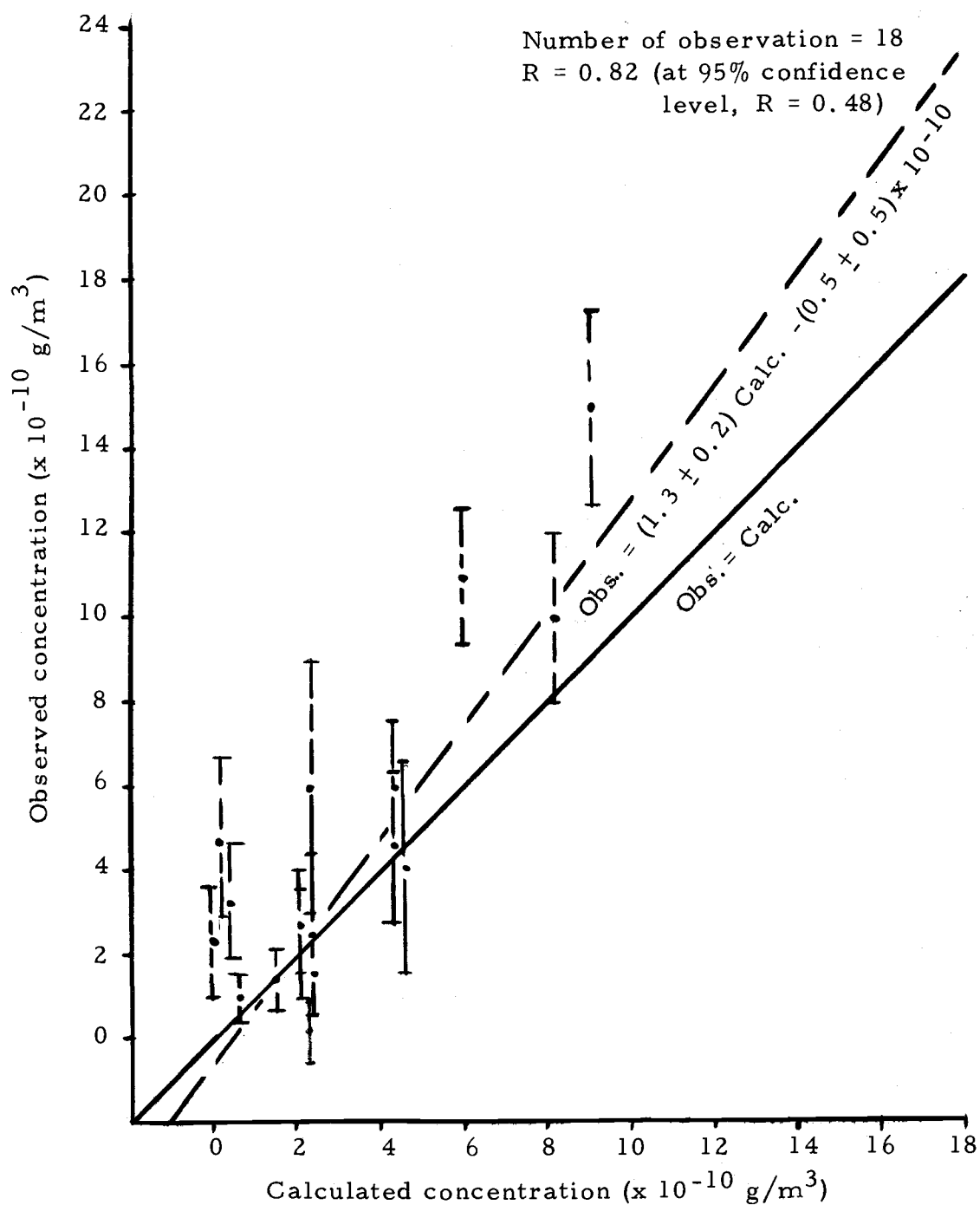


Figure 21. Scatter diagram in the study of the Gaussian plume model under slightly unstable conditions (stability type C) for the high source at the Western Kraft Corporation.

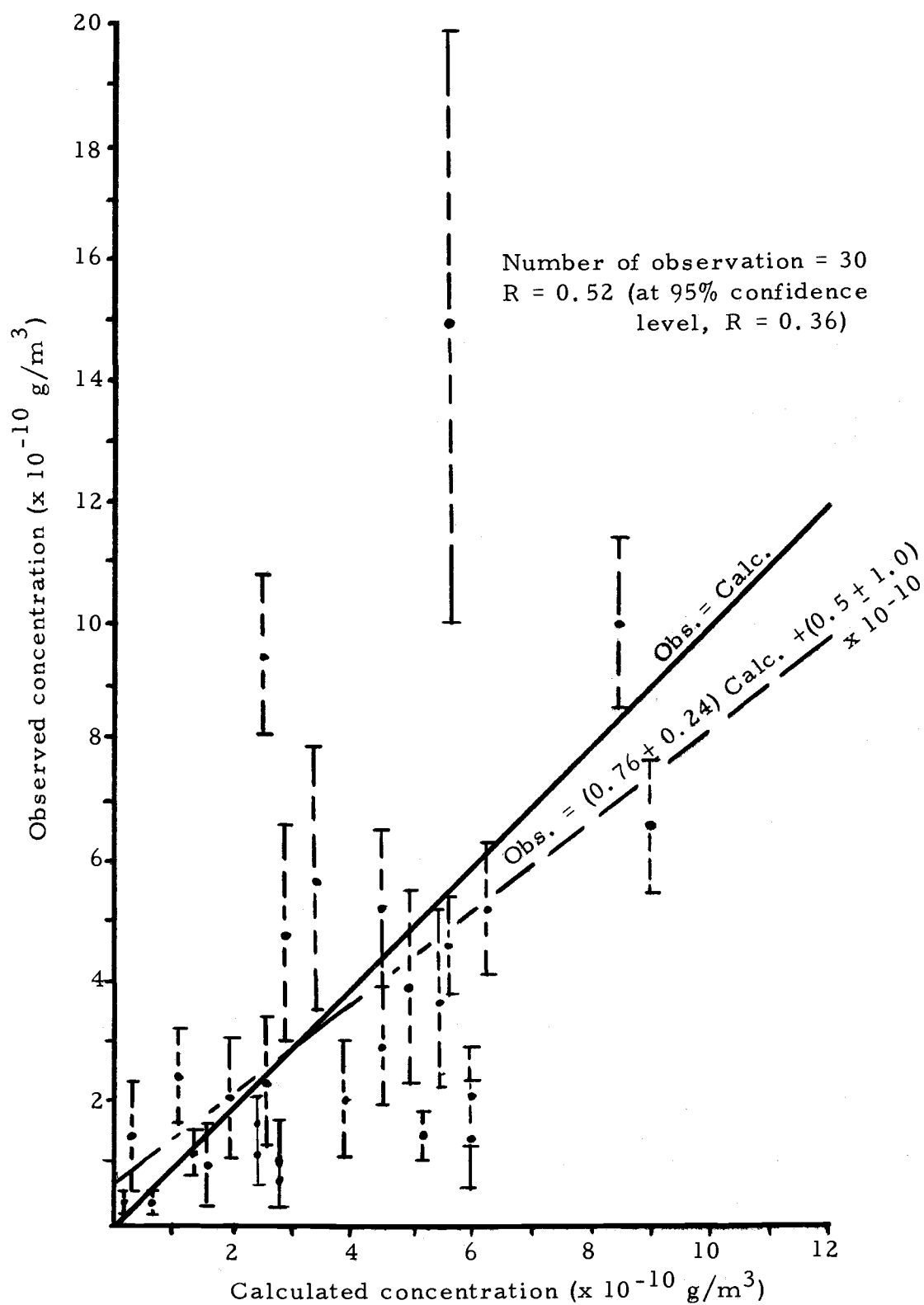


Figure 22. Scatter diagram in the study of the Gaussian plume model under moderately unstable conditions (stability type B) for the high source at the Western Kraft Corporation.

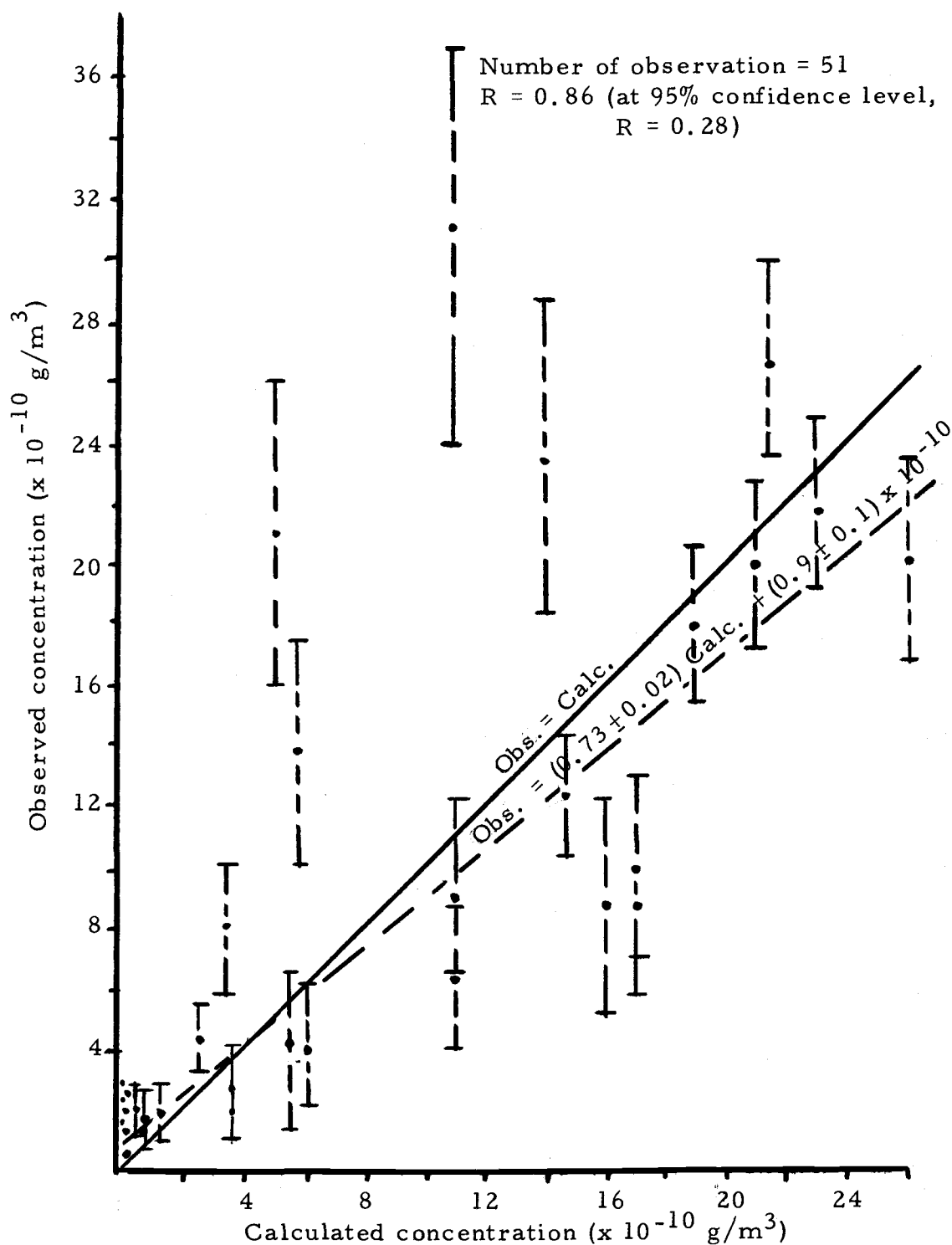


Figure 23. Scatter diagram in the study of the Gaussian plume model under slightly unstable conditions (stability type C) for the low source at the Wah Chang metallurgical processing company.

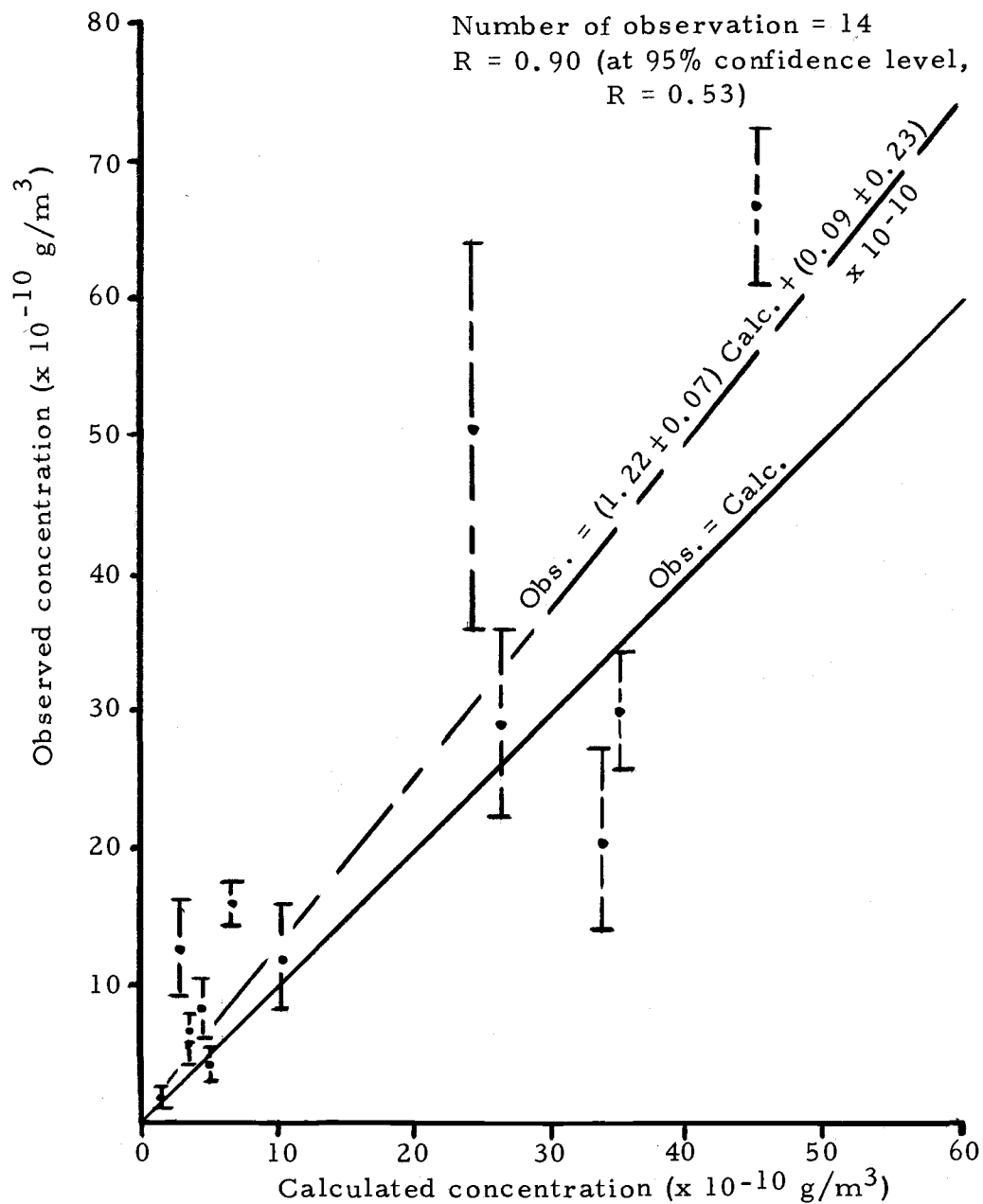


Figure 24. Scatter diagram in the study of the Gaussian plume model under moderately unstable conditions (stability type B) for the low source at the Simpson Timber Company.

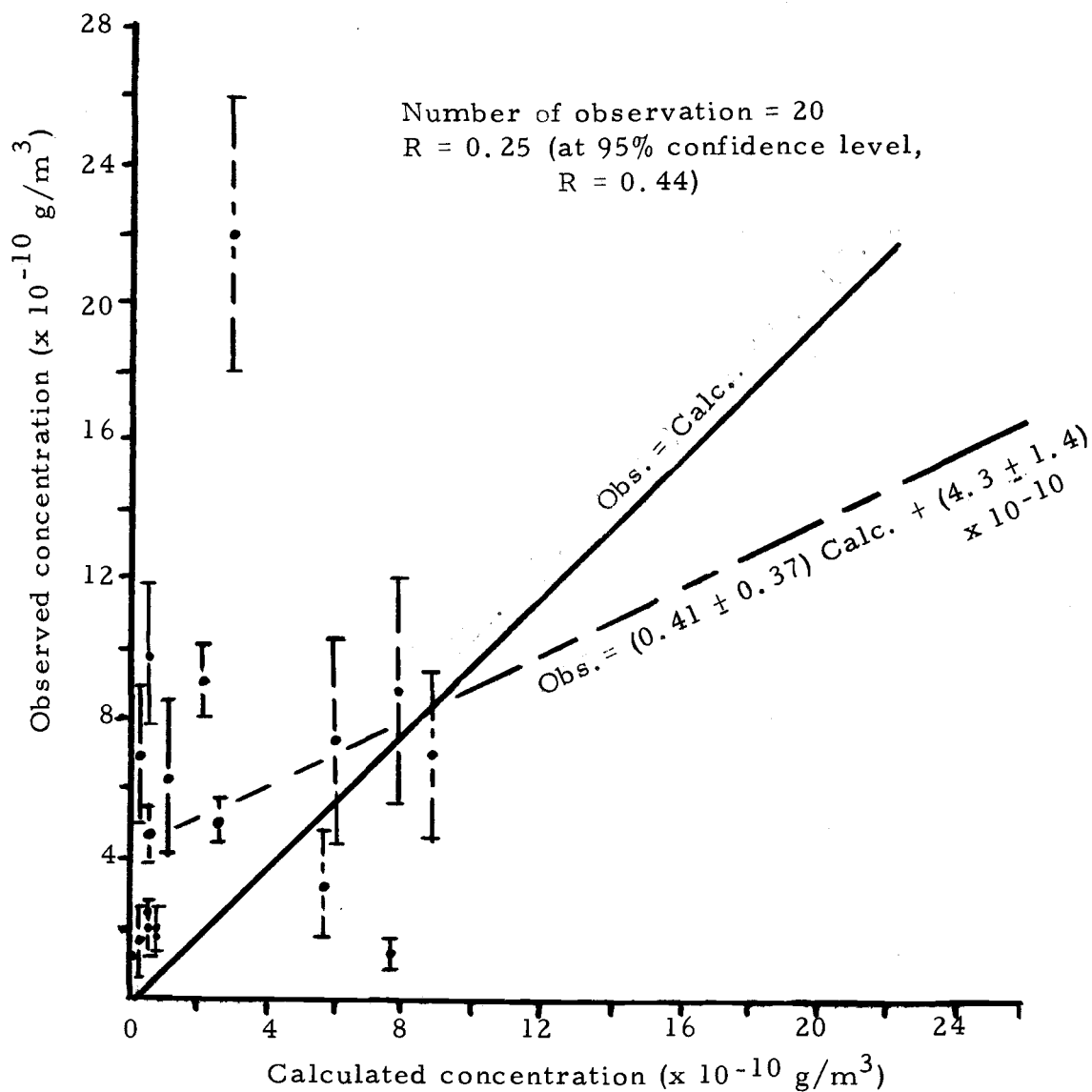


Figure 25. Scatter diagram in the study of the Gaussian plume model under extremely unstable conditions (stability type A) for the low source at the Wah Chang metallurgical

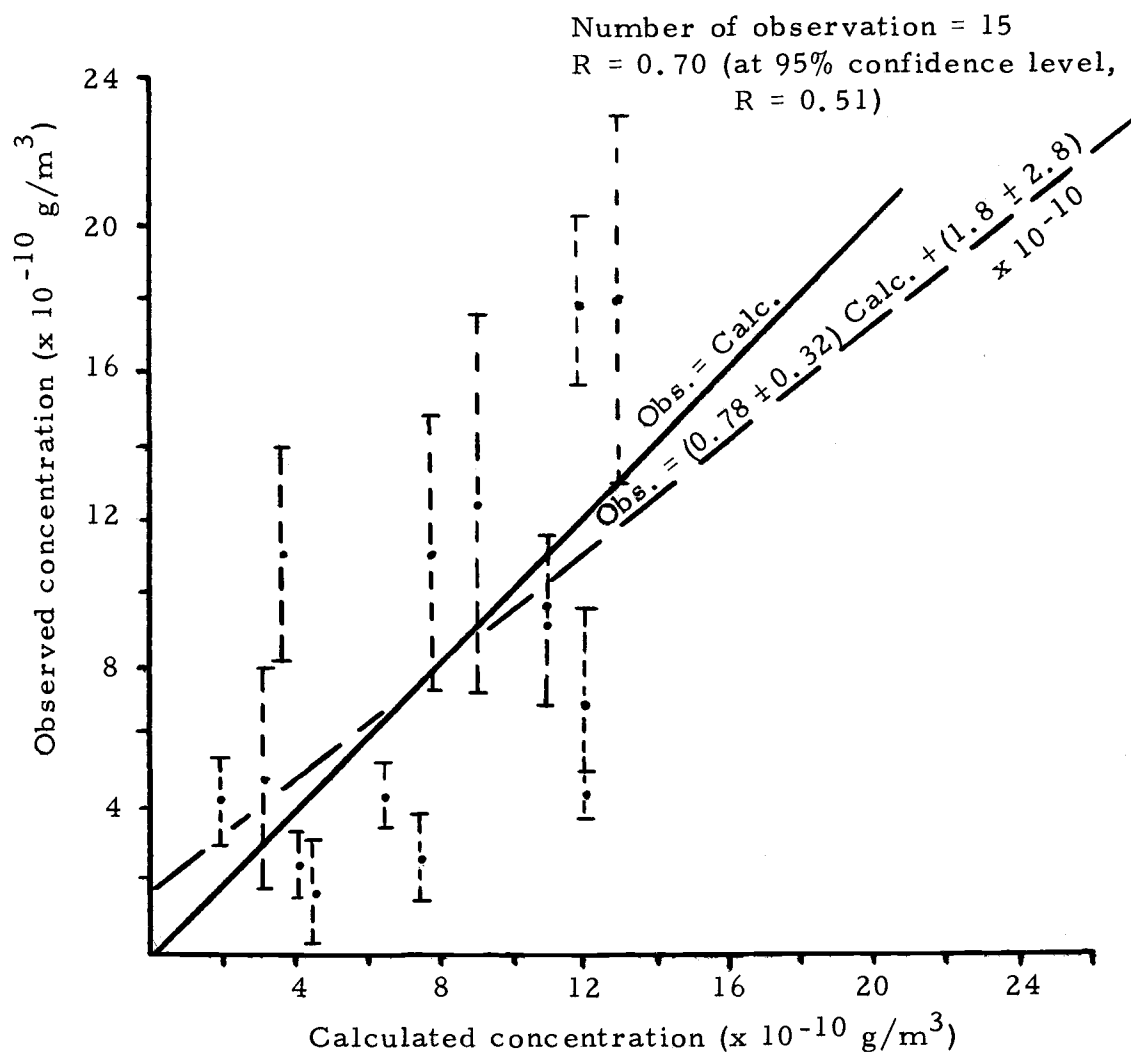


Figure 26. Scatter diagram in the study of the Hewson's trapping plume model under moderately unstable conditions (stability type B) for the high source at the Western Kraft Corporation.

with the values predicted under A stability. From these measured concentrations, one may conclude that the crosswind dispersion coefficients should be much higher than those for A stability under this trapping condition. This may be due to the large fluctuations of wind direction, with σ_{θ} (standard deviation of the horizontal wind fluctuation) equal to 25° and 31.5° in the "P" and "Q" experiments, respectively. The surface temperature at noon time was 36° C suggesting a pronounced superadiabatic lapse rate near the surface and, therefore, indicating a very turbulent air flow below the inversion layer. Under this condition, we found that no Gaussian plume type formulas could be used to describe this situation adequately. Therefore, we resorted to a simple box-model in which we assumed uniform mixing in all directions under this very turbulent condition. An example of this calculation is shown as follows for the "P" experiment.

Assume the mixing of the tracer is uniform in the x, y and z directions at a distance of 3000 meters downwind from the stack and the plume subtends an angle horizontally of one standard deviation, i. e., 25 degrees, a reasonable claim for this condition. Figure 27 shows the shape of the plume in two dimensions with the shaded area being the area where most of the air samplers were located. If the inversion height is estimated to be 800 meters (see Appendix V), then the mixing volume above the shaded area is given by

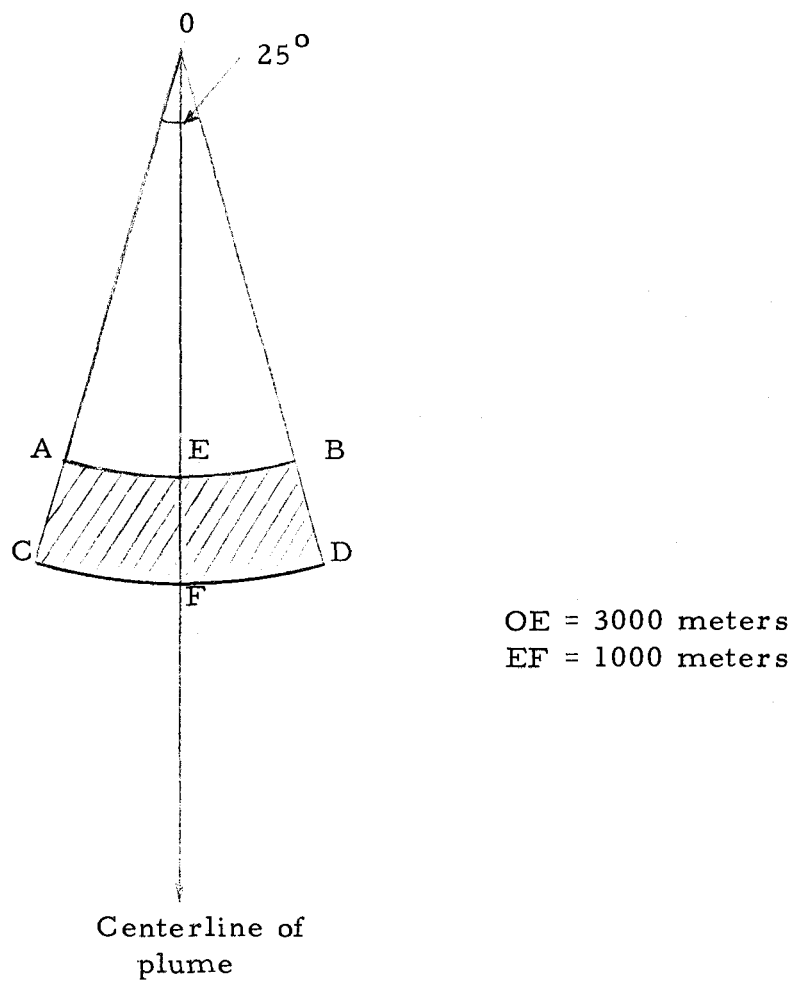


Figure 27. Projection of plume shape on horizontal plane.

$$V = 800 \times \left(\frac{25^\circ}{360^\circ}\right) (\pi) (4000^2 - 3000^2) = 1.2 \times 10^9 \text{ m}^3$$

Assuming the mean wind speed to be 4.0 m/sec and the emission rate of the tracer to be 618 $\mu\text{g}/\text{sec}$, then the amount of tracer input into the mixing volume is given by

$$W = 618 \left(\frac{\mu\text{g}}{\text{sec}}\right) \times \frac{1}{4} \left(\frac{\text{sec}}{\text{m}}\right) \times 1000(\text{m}) = 1.6 \times 10^5 \mu\text{g}$$

Therefore, for uniform mixing, the mean concentration of the tracer above the shaded area is given by

$$\bar{C} = \frac{W}{V} = \frac{1.6 \times 10^5 \mu\text{g}}{1.2 \times 10^9 \text{ m}^3} = 1.3 \times 10^{-4} \mu\text{g}/\text{m}^3 = 1.3 \times 10^{-10} \text{ g}/\text{m}^3$$

This mean value is of the same order of magnitude as the measured concentrations.

In conclusion, the Gaussian plume model and Hewson's trapping plume model work quite well under D, C and B conditions. Under turbulent situations (type A stability) these models start to break down. At very turbulent conditions (above A stability), no Gaussian plume formula applies, and a box model may be used to describe the diffusion pattern of the pollutants. Except under very turbulent conditions (type A stability or above), these models can be used to predict the emission rates of the stack effluent to within 20-60 percent accuracy.

The Prediction of Emission Rates of Trace Elements
from Multiple Sources of Air Pollution

Experimental

After evaluating the effectiveness of the diffusion models applied in the Albany area, the next step is to apply these models to predict the emission rates of the stack effluent for several sources of air pollution in the area emitting the same tracer.

Three "controlled" experiments were conducted to test the usefulness of the diffusion models in predicting the emission rates of trace pollutants from multiple sources. This was done by using the same tracer in different stacks and by taking air samples at locations where mixing of effluent from different stacks occurred. In the "controlled" tests, only two stacks were employed instead of three because the wind direction during the experiments made it impossible to cover the whole area with the limited number of air samplers used. Two "blind" tests were also conducted. In the "blind" tests, one or more of the rare-earth tracers Dy, Sm, La, or Ce was sprayed into the three stacks concerned. The experimenter had no knowledge as to which tracer, if any, was sprayed from each stack. The meteorological conditions were carefully chosen so that in some areas where the air samplers were located, the effluent from the three stacks mixed together and the air samplers used would cover the area of interest.

The air samples collected were analysed to determine the concentrations of Dy, Sm, La, and Ce. The procedure of analysis is referred to in the "Methodology" section. The concentrations of the rare-earth elements in the tracers were determined by the experimenter in a post-experiment determination.

Results and Discussion

The results for the three "controlled" tests are summarized in Tables 23-25. All the "controlled" tests were conducted under neutral conditions (stability type D). The generalized Gaussian plume model was used to predict the emission rates of the tracers from each stack. Corrections to σ_y and σ_z were made with the low sources to allow for urban influences as discussed in the last section. The predicted emission rates with the use of multiple regression analysis are included in Tables 23-25 for comparison. One observes from Tables 23-25 that the emission rates predicted are within 10-80 percent of the actual values. Due to the mixing of the effluent from the stacks, this prediction is in general not as accurate as in the prediction of emission rate from single source (see Tables 15-21 for comparison).

For the two "blind" tests, the results are summarized in Tables 26 and 27. The atmospheric stability prevailing at the time of the two tests were of type B and C (with $\sigma_\theta = 17^\circ$ and mean wind speed = 3.1 m/sec) and B (with $\sigma_\theta = 19^\circ$ and mean wind speed = 2.0 m/sec)

respectively. In both experiments, temperature inversion was very pronounced in the morning at ground-level and the inversion height at 4 P.M. was about 550 meters. In this case, Hewson's trapping plume formula (1958) was used to calculate the coefficients A_n for the high sources and the generalized Gaussian plume formula was used for low sources since the plume from the low level source did not reach the inversion base at the distances where the air samplers were located. Corrections were made for σ_y and σ_z for the low sources based on the results obtained by McElroy (1969) as shown in Figure 28. The correction was an approximation since σ_y could not be determined experimentally from the two "blind" tests. With the use of these models, the emission rates of the tracers emitted from each stack were calculated by the use of multiple regression analysis. From the predicted emission rates and the amount of solution used for spraying at a given time, the weights of the tracer inserted at each stack were calculated. The predicted weight and the actual weight of the tracer emitted from each stack are summarized in Table 28 for the two "blind" tests. From Table 28, a scatter diagram was made with predicted weight of tracer vs. actual weight. The predicted and actual weight are linearly correlated at the 95 percent confidence level ($R = 0.64$ for 24 observations). Figure 29a and 29b show plots of actual and predicted weight vs. predicted number.

From Table 28, one observes that the models in general can be used to predict the emission rate within a factor of two in multiple

sources of air pollution involving three stacks. The models can also predict accurately in cases where no tracer was actually inserted into the stack. But the models are rather insensitive in predicting accurately the ratio of the emission rates from stacks if their emission rates do not differ significantly (i. e., the difference is only within a factor of two or three from each other).

Table 23. Summary of Results in the Prediction of the Emission Rate of the Tracer Emitted from Western Kraft and Wah Chang Companies

Date of Experiment	Location of Stack (1)	Location of Air Sampler (1)	Sample Number	Mean Wind Direction (2) and Fluctuation (σ_θ) (3)	Mean Wind Speed (m/sec)	Time of Collection	Tracer Used	Emission Rate ($\mu\text{g/sec}$)	Measured Concentration (10^{-10} g/m^3)	(With Reference to Western Kraft)					(With Reference to Wah Chang)				
										x	y	σ_y	σ_z	A_n	x	y	σ_y	σ_z	A_n
										----- (in meters) ----- (10^{-4})					----- (in meters) ----- (10^{-4})				
10/14/72	Western Kraft and Wah Chang	7	QQ-1	377° ($\sigma_\theta=10^\circ$)	4.9	1700-1730	La	Wah Chang = 1300	17.0 $\pm$ 1.8	3990	175	245	76	0.01281	2121	231	240	170	0.00792
		6	QQ-2	↓	↓	↓		Predicted = (2244 $\pm$ 794)	8.9 $\pm$ 1.8	2833	550	180	60	0.00019	994	429	155	100	0.00021
		1	QQ-3	↓	↓	↓		Western Kraft = 862	0	2630	508	168	59	0.00023	771	447	125	86	0.00008
		7	QQ-4	372° ($\sigma_\theta=9^\circ$)	5.3	1730-1800			6.1 $\pm$ 1.5	3944	550	243	76	0.00119	2013	420	230	165	0.00236
		6	QQ-5	↓	↓	↓		Predicted = (1371 $\pm$ 505)	10.3 $\pm$ 1.7	2875	263	183	60	0.00669	994	447	155	100	0.00047
		1	QQ-6	↓	↓	↓			6.0 $\pm$ 1.5	2682	252	169	59	0.00662	771	435	125	86	0.00010
		7	QQ-7	372° ($\sigma_\theta=9^\circ$)	5.3	1800-1830			6.9 $\pm$ 1.2	3944	550	243	76	0.00119	2013	420	230	165	0.00236
		6	QQ-8	↓	↓	↓			13.0 $\pm$ 1.8	2875	263	183	60	0.00669	994	447	155	100	0.00049
		1	QQ-9	↓	↓	↓			6.1 $\pm$ 1.5	2682	252	169	59	0.00662	771	435	125	86	0.00010
		8	QQ-10	372°	5.1	1640-1715			27.3 $\pm$ 2.5	4102	280	254	79	0.00832	2244	140	250	175	0.00964
		8	QQ-11	372° ($\sigma_\theta=9^\circ$)	5.3	1730-1815			41.5 $\pm$ 4.2	4102	280	254	79	0.00801	2244	140	250	175	0.00928
		9	QQ-12	↓	↓	1721-1817			39.5 $\pm$ 3.5	3611	145	230	72	0.01323	1705	280	210	145	0.00638
		9	QQ-13	↓	↓	1635-1720			42.7 $\pm$ 4.5	3611	145	230	72	0.01323	1705	280	210	145	0.00638

(1) Referred to Map 2

(2) Northerly = 360°; westerly = 270°

(3) σ_θ = Standard deviation of horizontal wind fluctuation

Table 24. Summary of Results in the Prediction of the Emission Rate of the Tracer Emitted from Wah Chang and Simpson Timber Companies

Date of Experiment and Location of Stack	Location of Air Samplers (1)	Sample Number	Mean Wind Direction (2) and Fluctuation (σ_θ) (3)	Mean Wind Speed (m/sec)	Time of Collection	Tracer Used and Emission Rate ($\mu\text{g/sec}$)	Measured Concentration (10^{-10} g/m^3)	With Reference to Wah Chang					With Reference to Simpson Timber Co.				
								x	y	σ_y	σ_z	A_n	x	y	σ_y	σ_z	A_n
								(in meters)-----					(in meters)-----				
10/12/72	5	00-1	347.6° ($\sigma_\theta = 10^\circ$)	4.5	1600-1630	Ia	16.0 ± 3.0	1736	282	250	200	0.00594	806	1069	130	105	0.00000
Wah Chang and Simpson Timber Co.	2	00-2	↓	↓	↓	Wah Chang = 1219	6.2 ± 1.4	2489	73	355	275	0.00565	1560	701	235	185	0.00015
	7	00-3	↓	↓	↓	Predicted = (1361 ± 288)	2.1 ± 0.6	1788	1234	260	210	0.00000	806	455	130	105	0.00009
	5	00-4	349.0° ($\sigma_\theta = 10^\circ$)	4.5	1630-1700	Simpson Timber Co. = 1980	7.8 ± 1.8	1700	322	248	200	0.00486	806	1086	130	105	0.00000
	2	00-5	↓	↓	↓	Predicted = (2035 ± 232)	3.7 ± 0.9	2507	32	360	280	0.00539	1560	743	235	185	0.00009
	7	00-6	↓	↓	↓		1.7 ± 0.5	1788	1186	260	210	0.00000	806	437	130	105	0.00014
	5	00-7	346.6° ($\sigma_\theta = 10^\circ$)	4.0	1700-1730		12.9 ± 1.3	1736	245	250	200	0.00781	806	989	130	105	0.00000
	2	00-8	↓	↓	↓		2.2 ± 0.7	2489	140	355	275	0.00601	1560	715	235	185	0.00015
	7	00-9	↓	↓	↓		1.4 ± 0.4	1788	1262	260	210	0.00000	806	470	130	105	0.00007
	9	00-10	348.0°	4.5	1645-1720		7.0 ± 1.5	1742	340	250	200	0.00445	806	350	130	105	0.00110
	8	00-11	347.6°	4.5	1648-1718		25.7 ± 2.1	2016	984	300	235	0.00004	1034	255	160	120	0.00822
	8	00-12	349.0°	4.5	1620-1647		23.4 ± 2.2	2016	984	300	235	0.00004	1034	228	160	120	0.01061
	9	00-13	349.0°	4.5	1605-1645		11.3 ± 0.6	1742	340	250	200	0.00440	789	357	128	102	0.00086
	8	00-14	342.6°	3.4	1725-1750		6.8 ± 0.8	2016	984	300	235	0.00000	998	350	160	127	0.00256
	30	00-15	346.6° ($\sigma_\theta = 10^\circ$)	4.0	1730-1800		25.6 ± 3.1	2384	525	340	270	0.00186	1458	20	220	175	0.01459

(1) Referred to Map 2

(2) Northerly = 360°; westerly = 270°

(3) σ_θ = Standard deviation of horizontal wind fluctuation

Table 25. Summary of Results in the Prediction of the Emission Rate of the Tracer Emitted from Wah Chang and Simpson Timber Companies

Date of Experiment and Location of Stack	Location of Air Samplers (1)	Sample Number	Mean Wind Direction (2) and Fluctuation (σ_θ) (3)	Mean Wind Speed (m/sec)	Time of Collection	Tracer Used and Emission Rate ($\mu\text{g/sec}$)	Measured Concentration (10^{-10} g/m^3)	With Reference to Wah Chang					With Reference to Simpson Timber Co.				
								x	y	σ_y	σ_z	A_n	x	y	σ_y	σ_z	A_n
								----- (in meters) -----					----- (in meters) -----				
10/6/72 Wah Chang and Simpson Timber Co.	5	NN-1	352.5° ($\sigma_\theta = 10^\circ$)	6.3	1630-1700	Sm	1.1 ± 0.4	1717	508	210	150	0.00068	701	1086	120	80	0.00000
	2	NN-2	↓	↓	↓	Wah Chang = 1451	8.9 ± 1.3	2507	245	270	190	0.00517	1490	788	200	135	0.00002
	15	NN-3	↓	↓	↓	Predicted = (1518 ± 184)	11.0 ± 2.7	1830	122	220	153	0.01014	806	466	130	88	0.00006
	7	NN-4	↓	↓	↓	Simpson Timber Co. = 1602	6.5 ± 0.6	1823	999	220	153	0.00002	806	250	130	88	0.00550
	5	NN-5	354.7° ($\sigma_\theta = 10^\circ$)	5.6	1700-1730		1.9 ± 0.5	1780	455	218	156	0.00149	701	1122	120	80	0.00000
	2	NN-6	↓	↓	↓	Predicted = (1364 ± 624)	15.0 ± 1.5	2507	168	270	190	0.00723	1490	876	200	135	0.00030
	15	NN-7	↓	↓	↓		7.0 ± 0.8	1830	175	220	153	0.00970	806	508	130	88	0.00002
	5	NN-8	351.7° ($\sigma_\theta = 10^\circ$)	6.0	1730-1800		4.1 ± 1.3	1717	508	210	150	0.00071	701	1090	120	80	0.00000
	2	NN-9	↓	↓	↓		13.4 ± 1.1	2507	168	270	190	0.00675	1490	800	200	135	0.00002
	15	NN-10	↓	↓	↓		20.0 ± 2.1	1830	175	220	153	0.00905	806	480	130	88	0.00004
	8	NN-11	↓	↓	↓		4.6 ± 0.4	2086	841	240	170	0.00002	806	368	130	88	0.00067
	9	NN-12	351.1° ($\sigma_\theta = 10^\circ$)	6.0	1700-1740		11.0 ± 0.6	1753	333	214	154	0.00378	824	298	130	88	0.00309
	10	NN-13	↓	↓	↓		10.0 ± 1.0	1683	262	210	145	0.00629	701	911	120	80	0.00000

(1) Referred to Map 2

(2) Northerly = 360°; westerly = 270°

(3) σ_θ = Standard deviation of horizontal wind fluctuation

Table 26. Summary of Results in the Prediction of the Emission Rates of Tracer Emitted from Wah Chang, Western Kraft and Simpson Timber Companies

Date of Experiment	Location of Air Sampler (1)	Sample Number	Mean Wind Direction (2) and Fluctuation (σ_θ)(3)	Mean Wind Speed (m/sec)	Time of Collection	Tracer Used	Concentration Experimental Results (10^{-10} g/m ³)				With Reference to Western Kraft				
							Dy	Sm	La	Ce	x	y	σ_y	σ_z	A_n
											----- (in meters) ----- (10 ⁻⁴)				
10/16/72	14	SS-1	342°	2.0	1630-1700	Dy	3.5 ± 1.5	0	4.7 ± 0.4	2.2 ± 0.4	3478	175	480	430	0.00616
	2	SS-2	($\sigma_\theta=20^\circ$)	↓	↓	Sm	1.1 ± 1.1	1.6 ± 0.2	2.4 ± 0.3	6.7 ± 0.8	4112	1218	530	520	0.00040
	5	SS-3	↓	↓	↓	La	2.6 ± 1.0	3.5 ± 0.1	15.6 ± 0.2	4.4 ± 0.6	3419	804	475	420	0.00160
	6	SS-4	↓	↓	↓	Ce	10.1 ± 2.5	6.4 ± 0.2	17.2 ± 0.2	9.1 ± 0.9	2704	1072	385	320	0.00021
	7	SS-5	↓	↓	↓		0	3.7 ± 0.2	0	0	3307	2324	465	400	0
	14	SS-6	332°	2.0	1700-1730		3.2 ± 2.0	0.9 ± 0.1	9.7 ± 0.9	1.8 ± 0.4	3338	897	465	410	0.00108
	2	SS-7	($\sigma_\theta=18^\circ$)	↓	↓		3.6 ± 0.6	2.2 ± 0.1	6.0 ± 0.7	13.8 ± 1.0	3665	2045	500	450	0
	5	SS-8	↓	↓	↓		5.5 ± 1.6	2.3 ± 0.1	6.6 ± 0.8	2.1 ± 0.4	3151	1475	440	380	0
	6	SS-9	↓	↓	↓		7.3 ± 2.9	4.2 ± 0.2	5.3 ± 0.6	8.7 ± 0.9	2413	1598	350	285	0
	7	SS-10	↓	↓	↓		0	0	0	0	2704	2928	385	320	0
	14	SS-11	328.0°	2.0	1730-1800		2.7 ± 2.0	1.9 ± 0.1	3.0 ± 0.6	1.3 ± 0.5	3231	1122	460	395	0.00037
	2	SS-12	($\sigma_\theta=18^\circ$)	↓	↓		0.7 ± 0.7	6.2 ± 0.1	2.8 ± 0.3	13.6 ± 1.0	3620	2302	500	450	0
	5	SS-13	↓	↓	↓		4.5 ± 1.5	3.2 ± 0.1	3.7 ± 0.5	3.4 ± 0.5	3044	1699	425	370	0
	6	SS-14	↓	↓	↓		8.6 ± 3.0	4.5 ± 0.1	3.4 ± 0.4	7.6 ± 0.9	2324	1766	340	270	0
	7	SS-15	↓	↓	↓		0	0	0	0	2648	3196	380	315	0
	15	SS-16	323°	2.0	1730-1800		0	6.0 ± 0.3	3.7 ± 0.4	19.7 ± 1.2	3039	2570	425	365	0
	11	SS-17	339°	↓	1635-1712		7.8 ± 1.9	0	8.2 ± 0.6	5.6 ± 1.0	3589	371	495	440	0.00476
	11	SS-18	325°	↓	1714-1750		7.9 ± 2.0	4.2 ± 0.1	7.3 ± 0.6	4.4 ± 1.0	3525	544	490	435	0.00346
	11	SS-19	332°	↓	1752-1840		3.6 ± 1.4	1.0 ± 0.1	0	8.0 ± 0.6	3653	77	500	450	0.00611
	9	SS-20	341°	↓	1620-1703		0	7.5 ± 0.2	6.8 ± 0.7	11.2 ± 0.8	3218	1631	460	395	0
	9	SS-21	327°	↓	1704-1740		0	5.7 ± 0.1	5.5 ± 0.4	13.2 ± 1.0	2771	2458	395	330	0
	9	SS-22	332°	↓	1740-1830		0	8.3 ± 0.2	13.3 ± 1.0	19.2 ± 1.2	2860	2179	400	345	0
	10	SS-23	341°	↓	1625-1709		20.0 ± 2.0	16.7 ± 0.3	5.1 ± 0.6	24.5 ± 1.0	3308	961	465	400	0.00084
	10	SS-24	327°	↓	1709-1748		8.0 ± 1.5	5.1 ± 0.1	5.9 ± 0.6	10.3 ± 1.2	2961	1910	420	360	0
	10	SS-25	332°	↓	1748-1835		14.0 ± 2.9	3.9 ± 0.1	7.6 ± 0.8	11.6 ± 1.2	3062	1609	425	365	0

(1) Referred to Map 2

(2) Northerly = 360°; westerly = 270°

(3) σ_θ = Standard deviation of horizontal wind fluctuation

(4) Air samples upwind from plume

Table 26. (Continued)

Date of Experiment	Location of Air Sampler (1)	Sample Number	Mean Wind Direction (2) and Fluctuation (σ_θ) (3)	Mean Wind Speed (m/sec)	Time of Collection	Tracer Used	Concentration Experimental Results (10^{-10} g/m ³)				With Reference to Wah Chang				
							Dy	Sm	La	Ce	x	y	σ_y	σ_z	A_n
											(in meters)-----				(10^{-4})
10/16/72	14	SS-1	342°	2.0	1630-1700	Dy	3.5 ± 1.5	0	4.7 ± 0.4	2.2 ± 0.4	1910	782	390	620	0.00070
	2	SS-2	($\sigma_\theta=20^\circ$)	↓	↓	Sm	1.1 ± 1.1	1.6 ± 0.2	2.4 ± 0.3	6.7 ± 0.8	2525	279	490	880	0.00250
	5	SS-3	↓	↓	↓	La	2.6 ± 1.0	3.5 ± 0.1	15.6 ± 0.2	4.4 ± 0.6	1788	156	370	580	0.00542
	6	SS-4	↓	↓	↓	Ce	10.1 ± 2.5	6.4 ± 0.2	17.2 ± 0.2	9.1 ± 0.9	1084	116	250	310	0.01470
	7	SS-5	↓	↓	↓		0	3.7 ± 0.2	0	0	1564	1363	330	480	0
	14	SS-6	332°	2.0	1700-1730		3.2 ± 2.0	0.9 ± 0.1	9.7 ± 0.9	1.8 ± 0.4	1986	367	400	660	0.00316
	2	SS-7	($\sigma_\theta=18^\circ$)	↓	↓		3.6 ± 0.6	2.2 ± 0.1	6.0 ± 0.7	13.8 ± 1.0	2347	771	460	810	0.00084
	5	SS-8	↓	↓	↓		5.5 ± 1.6	2.3 ± 0.1	6.6 ± 0.8	2.1 ± 0.4	1765	212	368	575	0.00509
	6	SS-9	↓	↓	↓		7.3 ± 2.9	4.2 ± 0.2	5.3 ± 0.6	8.7 ± 0.9	1009	335	230	290	0.00658
	7	SS-10	↓	↓	↓		0	0	0	0	1341	1658	290	410	0
	14	SS-11	328.0°	2.0	1730-1800		2.7 ± 2.0	1.9 ± 0.1	3.0 ± 0.6	1.3 ± 0.5	1986	298	400	660	0.00365
	2	SS-12	($\sigma_\theta=18^\circ$)	↓	↓		0.7 ± 0.7	6.2 ± 0.1	2.8 ± 0.3	13.6 ± 1.0	2414	860	470	840	0.00060
	5	SS-13	↓	↓	↓		4.5 ± 1.5	3.2 ± 0.1	3.7 ± 0.5	3.4 ± 0.5	1765	272	368	575	0.00457
	6	SS-14	↓	↓	↓		8.6 ± 3.0	4.5 ± 0.1	3.4 ± 0.4	7.6 ± 0.9	1009	378	230	290	0.00492
	7	SS-15	↓	↓	↓		0	0	0	0	1274	1698	280	360	0
	15	SS-16	323°	2.0	1730-1800		0	6.0 ± 0.3	3.7 ± 0.4	19.7 ± 1.2	1631	1296	345	520	0
	11	SS-17	339°	↓	1635-1712		7.8 ± 1.9	0	8.2 ± 0.6	5.6 ± 1.0	2307	1346	455	800	0.00004
	11	SS-18	325°	↓	1714-1750		7.9 ± 2.0	4.2 ± 0.1	7.3 ± 0.6	4.4 ± 1.0	2564	730	500	890	0.00098
	11	SS-19	332°	↓	1752-1840		3.6 ± 1.4	1.0 ± 0.1	0	8.0 ± 0.6	2435	1153	472	850	0.00016
	9	SS-20	341°	↓	1620-1703		0	7.5 ± 0.2	6.8 ± 0.7	11.2 ± 0.8	1620	715	343	510	0.00082
	9	SS-21	327°	↓	1704-1740		0	5.7 ± 0.1	5.5 ± 0.4	13.2 ± 1.0	1452	1072	315	450	0.00003
	9	SS-22	332°	↓	1740-1830		0	8.3 ± 0.2	13.3 ± 1.0	19.2 ± 1.2	1518	916	330	470	0.00017
	10	SS-23	341°	↓	1625-1709		20.0 ± 2.0	16.7 ± 0.3	5.1 ± 0.6	24.5 ± 1.0	1720	35	360	540	0.00651
	10	SS-24	327°	↓	1709-1748		8.0 ± 1.5	5.1 ± 0.1	5.9 ± 0.6	10.3 ± 1.2	1653	413	347	520	0.00347
	10	SS-25	332°	↓	1748-1835		14.0 ± 2.9	3.9 ± 0.1	7.6 ± 0.8	11.6 ± 1.2	1683	357	350	530	0.00407

Table 26. (Continued)

Date of Experiment	Location of Air Sampler (1)	Sample Number	Mean Wind Direction (2) and Fluctuation (σ_θ)(3)	Mean Wind Speed (m/sec)	Time of Collection	Tracer Used	Concentration Experimental Results (10^{-10} g/m ³)				With Reference to Simpson Timber Co.				
							Dy	Sm	La	Ce	x	y	σ_y	σ_z	A_n
											----- (in meters)----- (10^{-4})				
10/16/72	14	SS-1	342°	2.0	1630-1700	Dy	3.5 ± 1.5	0	4.7 ± 0.4	2.2 ± 0.4	1039	1620	235	300	0
	2	SS-2	($\sigma_\theta=20^\circ$)	↓	↓	Sm	1.1 ± 1.1	1.6 ± 0.2	2.4 ± 0.3	6.7 ± 0.8	1631	561	345	510	0.00193
	5	SS-3	↓	↓	↓	La	2.6 ± 1.0	3.5 ± 0.1	15.6 ± 0.2	4.4 ± 0.6	905	972	215	250	0
	6	SS-4	↓	↓	↓	Ce	10.1 ± 2.5	6.4 ± 0.2	17.2 ± 0.2	9.1 ± 0.9	(4)	--	--	--	--
	7	SS-5	↓	↓	↓		0	3.7 ± 0.2	0	0	760	514	190	205	0.00084
	14	SS-6	332°	2.0	1700-1730		3.2 ± 2.0	0.9 ± 0.1	9.7 ± 0.9	1.8 ± 0.4	1341	1408	295	410	0
	2	SS-7	($\sigma_\theta=18^\circ$)	↓	↓		3.6 ± 0.6	2.2 ± 0.1	6.0 ± 0.7	13.8 ± 1.0	1720	245	360	520	0.00539
	5	SS-8	↓	↓	↓		5.5 ± 1.6	2.3 ± 0.1	6.6 ± 0.8	2.1 ± 0.4	1073	804	245	305	0.00008
	6	SS-9	↓	↓	↓		7.3 ± 2.9	4.2 ± 0.2	5.3 ± 0.6	8.7 ± 0.9	--	--	--	--	--
	7	SS-10	↓	↓	↓		0	0	0	0	670	636	170	175	0.00004
	14	SS-11	328.0°	2.0	1730-1800		2.7 ± 2.0	1.9 ± 0.1	3.0 ± 0.6	1.3 ± 0.5	1374	1341	300	420	0
	2	SS-12	($\sigma_\theta=18^\circ$)	↓	↓		0.7 ± 0.7	6.2 ± 0.1	2.8 ± 0.3	13.6 ± 1.0	1743	190	361	540	0.00568
	5	SS-13	↓	↓	↓		4.5 ± 1.5	3.2 ± 0.1	3.7 ± 0.5	3.4 ± 0.5	1084	760	250	310	0.00016
	6	SS-14	↓	↓	↓		8.6 ± 3.0	4.5 ± 0.1	3.4 ± 0.4	7.6 ± 0.9	--	--	--	--	--
	7	SS-15	↓	↓	↓		0	0	0	0	637	670	168	120	0
	15	SS-16	323°	2.0	1730-1800		0	6.0 ± 0.3	3.7 ± 0.4	19.7 ± 1.2	1005	190	230	290	0.01355
	11	SS-17	339°	↓	1635-1712		7.8 ± 1.9	0	8.2 ± 0.6	5.6 ± 1.0	1410	2179	305	265	0
	11	SS-18	325°	↓	1714-1750		7.9 ± 2.0	4.2 ± 0.1	7.3 ± 0.6	4.4 ± 1.0	1955	1826	400	640	0
	11	SS-19	332°	↓	1752-1840		3.6 ± 1.4	1.0 ± 0.1	0	8.0 ± 0.6	1763	2051	368	575	0
	9	SS-20	341°	↓	1620-1703		0	7.5 ± 0.2	6.8 ± 0.7	11.2 ± 0.8	815	245	200	220	0.01360
	9	SS-21	327°	↓	1704-1740		0	5.7 ± 0.1	5.5 ± 0.4	13.2 ± 1.0	826	45	200	220	0.02816
	9	SS-22	332°	↓	1740-1830		0	8.3 ± 0.2	13.3 ± 1.0	19.2 ± 1.2	826	111	200	220	0.02472
	10	SS-23	341°	↓	1625-1709		20.0 ± 2.0	16.7 ± 0.3	5.1 ± 0.6	24.5 ± 1.0	872	849	210	240	0
	10	SS-24	327°	↓	1709-1748		8.0 ± 1.5	5.1 ± 0.1	5.9 ± 0.6	10.3 ± 1.2	1073	561	245	310	0.00122
	10	SS-25	332°	↓	1748-1835		14.0 ± 2.9	3.9 ± 0.1	7.6 ± 0.8	11.6 ± 1.2	972	670	220	275	0.00020

Table 27. Summary of Results in the Prediction of the Emission Rates of Tracer Emitted from Wah Chang, Western Kraft and Simpson Timber Co.

Date of Experiment	Location of Air Sampler (1)	Sample Number	Mean Wind Direction (2) and Fluctuation (σ_θ) (3)	Mean Wind Speed (m/sec)	Time of Collection	Tracer Used	Concentration Experimental Results (10^{-10} g/m ³)				With Reference to Western Kraft				
							Dy	Sm	La	Ce	x	y	σ_y	σ_z	A_n
											(in meters)-----				(10^{-4})
10/18/72	14	RR-1	353.6°	3.1	1630-1700	Dy	0	2.4 ± 0.1	13.1 ± 1.5	9.3 ± 1.5	3508	350	390	295	0.00465
	5	RR-2	($\sigma_\theta=18^\circ$)	↓	↓	Sm	8.6 ± 0.9	3.6 ± 0.1	20.6 ± 1.6	25.3 ± 2.5	3436	224	370	290	0.00619
	2	RR-3	↓	↓	↓	La	0.9 ± 0.8	1.9 ± 0.1	10.5 ± 0.7	8.7 ± 1.0	4219	508	450	350	0.00280
	6	RR-4	↓	↓	↓	Ce	15.2 ± 2.4	1.6 ± 0.2	13.9 ± 1.3	17.2 ± 3.2	2805	610	315	232	0.00163
	1	RR-5	↓	↓	↓		25.2 ± 5.1	1.5 ± 0.1	33.8 ± 2.0	20.6 ± 3.1	2601	547	290	215	0.00208
	14	RR-6	360.0°	3.1	1700-1730		0.4 ± 0.4	2.4 ± 0.1	13.2 ± 1.6	6.9 ± 1.6	3447	806	385	285	0.00081
	5	RR-7	($\sigma_\theta=17^\circ$)	↓	↓		1.7 ± 1.0	3.2 ± 0.1	12.7 ± 0.9	8.4 ± 1.0	3456	182	385	285	0.00642
	2	RR-8	↓	↓	↓		0	2.5 ± 0.1	13.4 ± 1.0	0.3 ± 0.2	4260	18	455	355	0.00518
	6	RR-9	↓	↓	↓		3.8 ± 1.6	3.4 ± 0.2	20.3 ± 2.6	12.8 ± 2.4	2878	273	320	235	0.00719
	1	RR-10	↓	↓	↓		6.5 ± 2.2	6.2 ± 0.2	39.2 ± 2.3	7.4 ± 1.6	2594	245	290	215	0.00863
	14	RR-11	359.4°	3.1	1730-1800		0.4 ± 0.2	2.8 ± 0.1	15.3 ± 0.8	1.7 ± 0.2	3450	830	385	285	0.00071
	5	RR-12	($\sigma_\theta=17^\circ$)	↓	↓		1.7 ± 1.0	2.4 ± 0.1	12.5 ± 0.9	13.3 ± 1.5	3450	210	385	285	0.00625
	2	RR-13	↓	↓	↓		0	2.2 ± 0.1	19.5 ± 1.2	13.9 ± 1.5	4260	28	455	355	0.00518
	6	RR-14	↓	↓	↓		24.8 ± 2.0	4.8 ± 0.1	30.5 ± 2.8	27.2 ± 4.0	2878	259	320	235	0.00745
	1	RR-15	↓	↓	↓		19.0 ± 3.4	3.5 ± 0.1	36.0 ± 2.5	19.6 ± 2.7	2594	227	290	215	0.00908
	14	RR-16	357.5°	3.1	1800-1830		5.8 ± 1.3	3.0 ± 0.1	16.1 ± 1.3	0	3510	455	390	295	0.00352
	5	RR-17	($\sigma_\theta=18^\circ$)	↓	↓		1.8 ± 1.0	3.2 ± 0.1	14.3 ± 0.9	16.4 ± 1.8	3436	168	70	290	0.00671
	2	RR-18	↓	↓	↓		2.6 ± 0.8	1.8 ± 1.2	16.1 ± 1.6	15.2 ± 1.5	4219	445	450	350	0.00318
	6	RR-19	↓	↓	↓		9.3 ± 0.5	1.7 ± 0.2	15.0 ± 1.8	50.5 ± 5.0	2850	561	318	234	0.00220
	1	RR-20	↓	↓	↓		20.4 ± 0.8	2.0 ± 0.2	20.0 ± 2.2	11.1 ± 1.9	2620	508	292	217	0.00268
	15	RR-21	360°	3.1	1650-1732		13.9 ± 1.4	2.6 ± 0.7	11.5 ± 1.0	10.7 ± 1.5	3822	570	410	315	0.00239
	15	RR-22	358°	3.1	1732-1820		7.8 ± 0.3	3.2 ± 0.3	6.8 ± 0.9	3.3 ± 1.5	3821	701	410	315	0.00145
	15	RR-23	365°	3.1	1820-1855		5.1 ± 1.2	3.8 ± 0.6	19.4 ± 1.5	18.9 ± 4.0	3871	262	415	320	0.00502
	9	RR-24	360°	3.1	1658-1740		6.3 ± 1.3	3.8 ± 0.7	9.2 ± 1.8	22.4 ± 4.6	3593	561	390	295	0.00247
	9	RR-25	358°	3.1	1741-1825		7.0 ± 1.3	4.6 ± 0.8	9.2 ± 1.8	9.1 ± 3.6	3558	666	390	295	0.00162
	10	RR-26	360°	3.1	1655-1735		6.1 ± 1.5	4.4 ± 1.5	23.1 ± 1.2	23.6 ± 3.0	3436	35	370	290	0.00741
	10	RR-27	358°	3.1	1737-1823		1.5 ± 1.3	5.2 ± 1.3	25.1 ± 1.2	34.1 ± 4.0	3430	88	370	290	0.00723
	10	RR-28	365°	3.1	1824-1857		3.7 ± 1.8	3.4 ± 1.6	38.8 ± 2.0	19.6 ± 2.0	3422	315	370	290	0.00518
	8	RR-29	360°	3.1	1648-1727		1.3 ± 1.0	15.5 ± 2.0	22.2 ± 1.3	24.9 ± 5.2	3983	1051	430	325	0.00029
	8	RR-30	358°	3.1	1729-1815		2.0 ± 1.0	15.7 ± 0.7	24.0 ± 1.5	26.1 ± 3.0	3899	1189	420	320	0.00011
	8	RR-31	365°	3.1	1817-1851		2.0 ± 1.0	22.6 ± 0.5	24.0 ± 2.0	17.7 ± 2.0	4039	704	435	330	0.00154

(1) Referred to Map 2

(2) Northerly = 360°; westerly = 270°

(3) σ_θ = Standard deviation of horizontal wind fluctuation

(4) Air sampler up-wind from plume

Table 27. (Continued)

Date of Experiment	Location of Air Sampler (1)	Sample Number	Mean Wind Direction (2) and Fluctuation (σ_θ) (3)	Mean Wind Speed (m/sec)	Time of Collection	Tracer Used	Concentration Experimental Results (10^{-10} g/m ³)				With Reference to Wah Chang				
							Dy	Sm	La	Ce	x	y	σ_y	σ_z	A_n
											(in meters)-----				(10^{-4})
10/18/72	14	RR-1	353.6°	3.1	1630-1700	Dy	0	2.4 ± 0.1	13.1 ± 1.5	9.3 ± 1.5	1795	1077	330	340	0.00004
	5	RR-2	($\sigma_\theta=18^\circ$)	↓	↓	Sm	8.6 ± 0.9	3.6 ± 0.1	20.6 ± 1.6	25.3 ± 2.5	1718	473	310	320	0.00262
	2	RR-3	↓	↓	↓	La	0.9 ± 0.8	1.9 ± 0.1	10.5 ± 0.7	8.7 ± 1.0	2503	200	430	470	0.00364
	6	RR-4	↓	↓	↓	Ce	15.2 ± 2.4	1.6 ± 0.2	13.9 ± 1.3	17.2 ± 3.2	1086	84	218	210	0.01653
	1	RR-5	↓	↓	↓		25.2 ± 5.1	1.5 ± 0.1	33.8 ± 2.0	20.6 ± 3.1	866	140	180	165	0.02018
	14	RR-6	360.0°	3.1	1700-1730		0.4 ± 0.4	2.4 ± 0.1	13.2 ± 1.6	6.9 ± 1.6	1786	1263	330	340	0.00001
	5	RR-7	($\sigma_\theta=17^\circ$)	↓	↓		1.7 ± 1.0	3.2 ± 0.1	12.7 ± 0.9	8.4 ± 1.0	1647	666	305	305	0.00082
	2	RR-8	↓	↓	↓		0	2.5 ± 0.1	13.4 ± 1.0	0.3 ± 0.2	2472	473	430	470	0.00221
	6	RR-9	↓	↓	↓		3.8 ± 1.6	3.4 ± 0.2	20.3 ± 2.6	12.8 ± 2.4	1069	203	218	210	0.01154
	1	RR-10	↓	↓	↓		6.5 ± 2.2	6.2 ± 0.2	39.2 ± 2.3	7.4 ± 1.6	842	238	175	160	0.01148
	14	RR-11	359.4°	3.1	1730-1800		0.4 ± 0.2	2.8 ± 0.1	15.3 ± 0.8	1.7 ± 0.2	1739	1209	325	330	0.00001
	5	RR-12	($\sigma_\theta=17^\circ$)	↓	↓		1.7 ± 1.0	2.4 ± 0.1	12.5 ± 0.9	13.3 ± 1.5	1683	596	307	307	0.00134
	2	RR-13	↓	↓	↓		0	2.2 ± 0.1	19.5 ± 1.2	13.9 ± 1.5	2471	368	430	470	0.00281
	6	RR-14	↓	↓	↓		24.8 ± 2.0	4.8 ± 0.1	30.5 ± 2.8	27.2 ± 4.0	1069	158	218	210	0.01369
	1	RR-15	↓	↓	↓		19.0 ± 3.4	3.5 ± 0.1	36.0 ± 2.5	19.6 ± 2.7	850	203	177	160	0.01482
	14	RR-16	357.5°	3.1	1800-1830		5.8 ± 1.3	3.0 ± 0.1	16.1 ± 1.3	0	1786	1163	330	340	0.00002
	5	RR-17	($\sigma_\theta=18^\circ$)	↓	↓		1.8 ± 1.0	3.2 ± 0.1	14.3 ± 0.9	16.4 ± 1.8	1647	566	305	305	0.00159
	2	RR-18	↓	↓	↓		2.6 ± 0.8	1.8 ± 1.2	16.1 ± 1.6	15.2 ± 1.5	2472	340	430	470	0.00297
	6	RR-19	↓	↓	↓		9.3 ± 0.5	1.7 ± 0.2	15.0 ± 1.8	50.5 ± 5.0	1069	140	218	210	0.01448
	1	RR-20	↓	↓	↓		20.4 ± 0.8	2.0 ± 0.2	20.0 ± 2.2	11.1 ± 1.9	842	145	175	160	0.02053
	15	RR-21	360°	3.1	1650-1732		13.9 ± 1.4	2.6 ± 0.7	11.5 ± 1.0	10.7 ± 1.5	2033	119	360	380	0.00567
	15	RR-22	358°	3.1	1732-1820		7.8 ± 0.3	3.2 ± 0.3	6.8 ± 0.9	3.3 ± 1.5	2030	203	360	380	0.00509
	15	RR-23	365°	3.1	1820-1855		5.1 ± 1.2	3.8 ± 0.6	19.4 ± 1.5	18.9 ± 4.0	2033	70	360	380	0.00588
	9	RR-24	360°	3.1	1658-1740		6.3 ± 1.3	3.8 ± 0.7	9.2 ± 1.8	22.4 ± 4.6	2040	80	360	380	0.00583
	9	RR-25	358°	3.1	1741-1825		7.0 ± 1.3	4.6 ± 0.8	9.2 ± 1.8	9.1 ± 3.6	2040	157	360	380	0.00579
	10	RR-26	360°	3.1	1655-1735		6.1 ± 1.5	4.4 ± 1.5	23.1 ± 1.2	23.6 ± 3.0	1630	490	305	305	0.00244
	10	RR-27	358°	3.1	1737-1823		1.5 ± 1.3	5.2 ± 1.3	25.1 ± 1.2	34.1 ± 4.0	1620	420	303	305	0.00321
	10	RR-28	365°	3.1	1824-1857		3.7 ± 1.8	3.4 ± 1.6	38.8 ± 2.0	19.6 ± 2.0	1578	617	295	300	0.00104
	8	RR-29	360°	3.1	1648-1727		1.3 ± 1.0	15.5 ± 2.0	22.2 ± 1.3	24.9 ± 5.2	2139	611	365	400	0.00138
	8	RR-30	358°	3.1	1729-1815		2.0 ± 1.0	15.7 ± 0.7	24.0 ± 1.5	26.1 ± 3.0	2139	673	365	400	0.00112
	8	RR-31	365°	3.1	1817-1851		2.0 ± 1.0	22.6 ± 0.5	24.0 ± 2.0	17.7 ± 2.0	2188	413	380	410	0.00320

Table 27. (Continued)

Date of Experiment	Location of Air Sampler (1)	Sample Number	Mean Wind Direction (2) and Fluctuation (σ_θ) (3)	Mean Wind Speed (m/sec)	Time of Collection	Tracer Used	Concentration Experimental Results (10^{-10} g/m ³)				With Reference to Simpson Timber Co.				
							Dy	Sm	La	Ce	x	y	σ_y	σ_z	A_n
											----- (in meters) ----- (10 ⁻⁴)				
10/18/72	14	RR-1	353.6°	3.1	1630-1700	Dy	0	2.4 ± 0.1	13.1 ± 1.5	9.3 ± 1.5	771	1767	165	148	0
	5	RR-2	($\sigma_\theta=18^\circ$)	↓	↓	Sm	8.6 ± 0.9	3.6 ± 0.1	20.6 ± 1.6	25.3 ± 2.5	701	1157	150	132	0
	2	RR-3	↓	↓	↓	La	0.9 ± 0.8	1.9 ± 0.1	10.5 ± 0.7	8.7 ± 1.0	1479	841	175	280	0.00010
	6	RR-4	↓	↓	↓	Ce	15.2 ± 2.4	1.6 ± 0.2	13.9 ± 1.3	17.2 ± 3.2	(4)	--	--	--	--
	1	RR-5	↓	↓	↓		25.2 ± 5.1	1.5 ± 0.1	33.8 ± 2.0	20.6 ± 3.1	--	--	--	--	--
	14	RR-6	360.0°	3.1	1700-1730		0.4 ± 0.4	2.4 ± 0.1	13.2 ± 1.6	6.9 ± 1.6	550	1828	120	105	0
	5	RR-7	($\sigma_\theta=17^\circ$)	↓	↓		1.7 ± 1.0	3.2 ± 0.1	12.7 ± 0.9	8.4 ± 1.0	550	1227	120	105	0
	2	RR-8	↓	↓	↓		0	2.5 ± 0.1	13.4 ± 1.0	0.3 ± 0.2	1367	1034	260	260	0
	6	RR-9	↓	↓	↓		3.8 ± 1.6	3.4 ± 0.2	20.3 ± 2.6	12.8 ± 2.4	--	--	--	--	--
	1	RR-10	↓	↓	↓		6.5 ± 2.2	6.2 ± 0.2	39.2 ± 2.3	7.4 ± 1.6	--	--	--	--	--
	14	RR-11	359.4°	3.1	1730-1800		0.4 ± 0.2	2.8 ± 0.1	15.3 ± 0.8	1.7 ± 0.2	550	1823	120	105	0
	5	RR-12	($\sigma_\theta=17^\circ$)	↓	↓		1.7 ± 1.0	2.4 ± 0.1	12.5 ± 0.9	13.3 ± 1.5	550	1030	120	105	0
	2	RR-13	↓	↓	↓		0	2.2 ± 0.1	19.5 ± 1.2	13.9 ± 1.5	1402	980	270	270	0.00002
	6	RR-14	↓	↓	↓		24.8 ± 2.0	4.8 ± 0.1	30.5 ± 2.8	27.2 ± 4.0	--	--	--	--	--
	1	RR-15	↓	↓	↓		19.0 ± 3.4	3.5 ± 0.1	36.0 ± 2.5	19.6 ± 2.7	--	--	--	--	--
	14	RR-16	357.5°	3.1	1800-1830		5.8 ± 1.3	3.0 ± 0.1	16.1 ± 1.3	0	550	1800	120	105	0
	5	RR-17	($\sigma_\theta=18^\circ$)	↓	↓		1.8 ± 1.0	3.2 ± 0.1	14.3 ± 0.9	16.4 ± 1.8	550	1200	120	105	0
	2	RR-18	↓	↓	↓		2.6 ± 0.8	1.8 ± 1.2	16.1 ± 1.6	15.2 ± 1.5	1367	981	260	260	0.00001
	6	RR-19	↓	↓	↓		9.3 ± 0.5	1.7 ± 0.2	15.0 ± 1.8	50.5 ± 5.0	--	--	--	--	--
	1	RR-20	↓	↓	↓		20.4 ± 0.8	2.0 ± 0.2	20.0 ± 2.2	11.1 ± 1.9	--	--	--	--	--
	15	RR-21	360°	3.1	1650-1732		13.9 ± 1.4	2.6 ± 0.7	11.5 ± 1.0	10.7 ± 1.5	946	445	190	180	0.00145
	15	RR-22	358°	3.1	1732-1820		7.8 ± 0.3	3.2 ± 0.3	6.8 ± 0.9	3.3 ± 1.5	940	403	190	180	0.00227
	15	RR-23	365°	3.1	1820-1855		5.1 ± 1.2	3.8 ± 0.6	19.4 ± 1.5	18.9 ± 4.0	894	518	182	175	0.00045
	9	RR-24	360°	3.1	1658-1740		6.3 ± 1.3	3.8 ± 0.7	9.2 ± 1.8	22.4 ± 4.6	718	445	154	135	0.00057
	9	RR-25	358°	3.1	1741-1825		7.0 ± 1.3	4.6 ± 0.8	9.2 ± 1.8	9.1 ± 3.6	720	445	154	135	0.00057
	10	RR-26	360°	3.1	1655-1735		6.1 ± 1.5	4.4 ± 1.5	23.1 ± 1.2	23.6 ± 3.0	561	1051	122	107	0
	10	RR-27	358°	3.1	1737-1823		1.5 ± 1.3	5.2 ± 1.3	25.1 ± 1.2	34.1 ± 4.0	561	1034	122	107	0
	10	RR-28	365°	3.1	1824-1857		3.7 ± 1.8	3.4 ± 1.6	38.8 ± 2.0	19.6 ± 2.0	490	1065	112	95	0
	8	RR-29	360°	3.1	1648-1727		1.3 ± 1.0	15.5 ± 2.0	22.2 ± 1.3	24.9 ± 5.2	1069	35	210	202	0.01906
	8	RR-30	358°	3.1	1729-1815		2.0 ± 1.0	15.7 ± 0.7	24.0 ± 1.5	26.1 ± 3.0	1069	70	210	202	0.01828
	8	RR-31	365°	3.1	1817-1851		2.0 ± 1.0	22.6 ± 0.5	24.0 ± 2.0	17.7 ± 2.0	1069	70	210	202	0.01828

Table 28. A Summary of the Predicted and Actual Weight of Tracer Used for the "Blind" Tests.

Date of Expt.	Label of Unknown	Dy_2O_3		SmCl_3		La_2O_3		CeCl_3	
		Actual Weight* (g)	Predicted Weight (g)	Actual Weight (g)	Predicted Weight (g)	Actual Weight (g)	Predicted Weight (g)	Actual Weight (g)	Predicted Weight (g)
10/18/72	D(Simpson Timber Co.)	0 (0)	0	21 (17)	43 ± 2	24 (19)	34 ± 7	35	51 ± 15
	A(Western Kraft)	0 (0)	0	24 (19)	18 ± 2	74 (82)	62 ± 7	43	62 ± 16
	E(Wah Chang)	40 (51)	34 ± 3	0 (0)	0	18 (17)	24 ± 6	35	39 ± 14
10/16/72	E(Western Kraft)	40 (51)	35 ± 16	0 (0)	0	18 (17)	35 ± 13	35	55 ± 36
	B(Wah Chang)	34 (35)	23 ± 2	17 (15)	23 ± 5	18 (15)	24 ± 3	28	36 ± 10
	C(Simpson Timber Co.)	0 (0)	0	31 (39)	15 ± 3	18 (14)	11 ± 3	43	36 ± 7

*The concentrations of the rare-earth elements in the tracers were determined by the experimenter in a post-experiment determination. (The original solution was diluted to 1000 times and 2 ml of the diluted solution was used in the analysis.) The values in parenthesis were obtained by an independent analyst. (2 ml of the original solution was used without dilution for analysis.) The uncertainty in the analysis was about $\pm 20\%$.

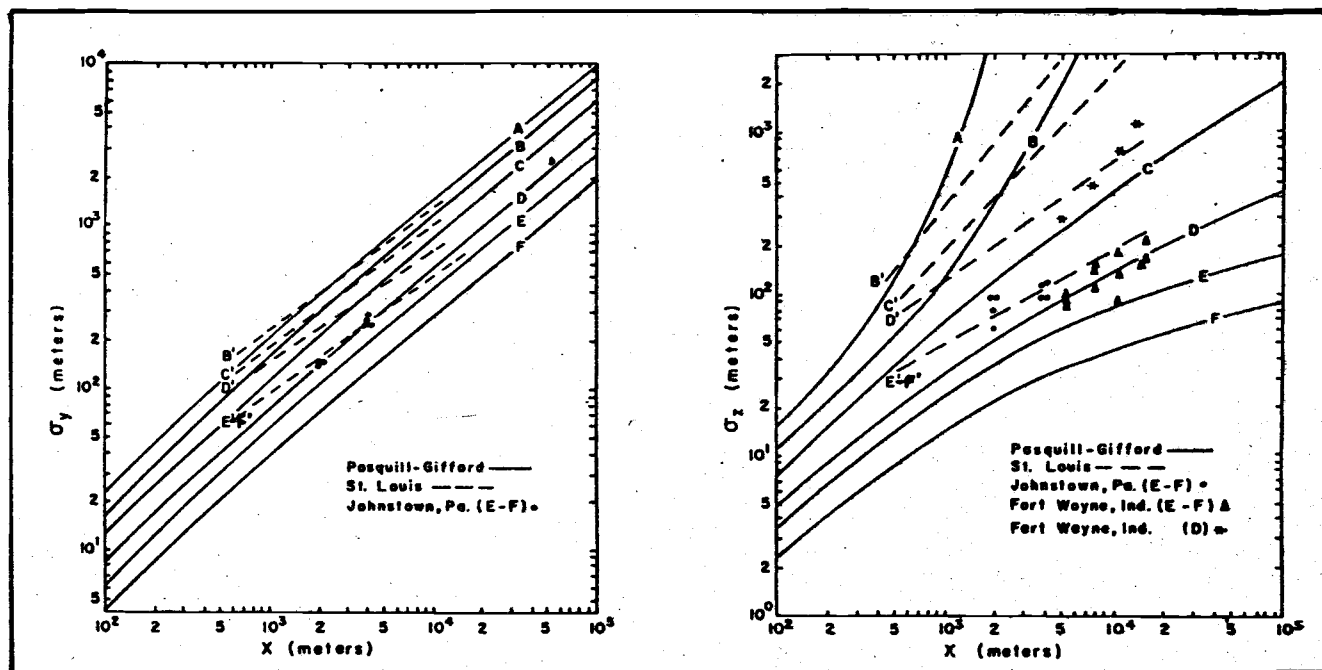


Figure 28. The horizontal and vertical coefficients of dispersion as a function of downwind distance from source in urban area (from McElroy, 1969).

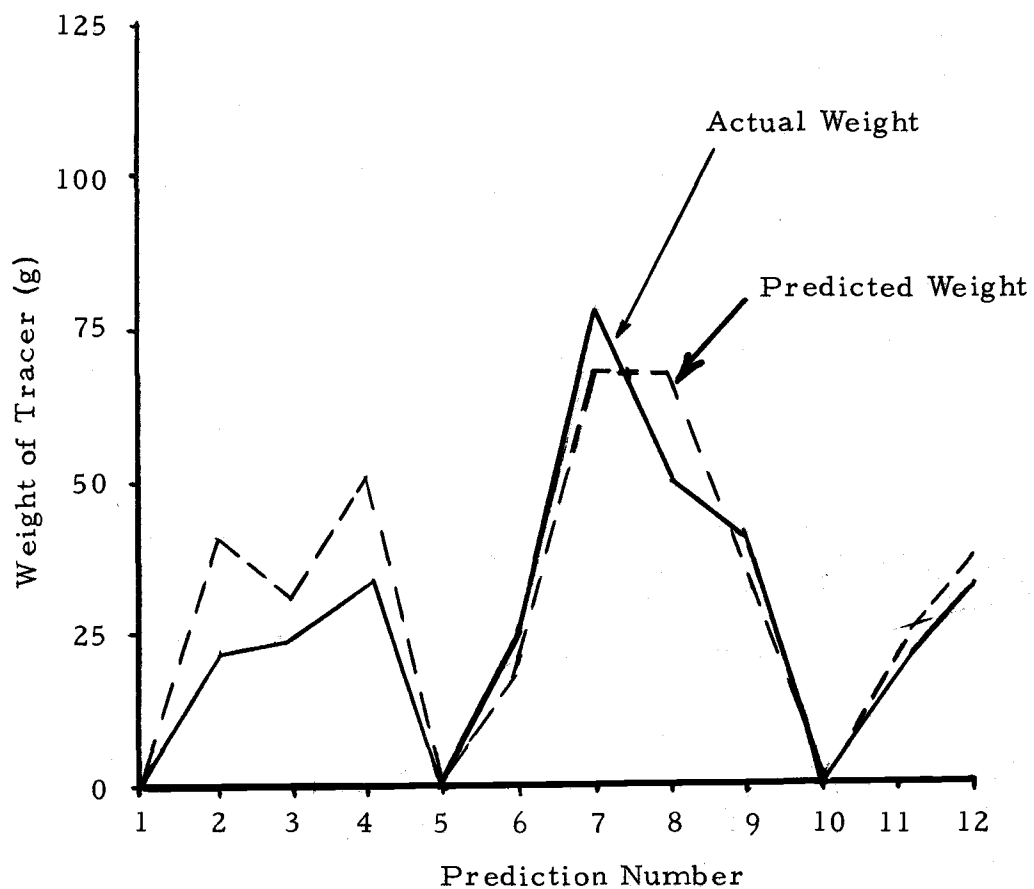


Figure 29a. Plot of actual and predicted weight of tracer vs. prediction number for "Blind" Test No. 1 (10/18/72).

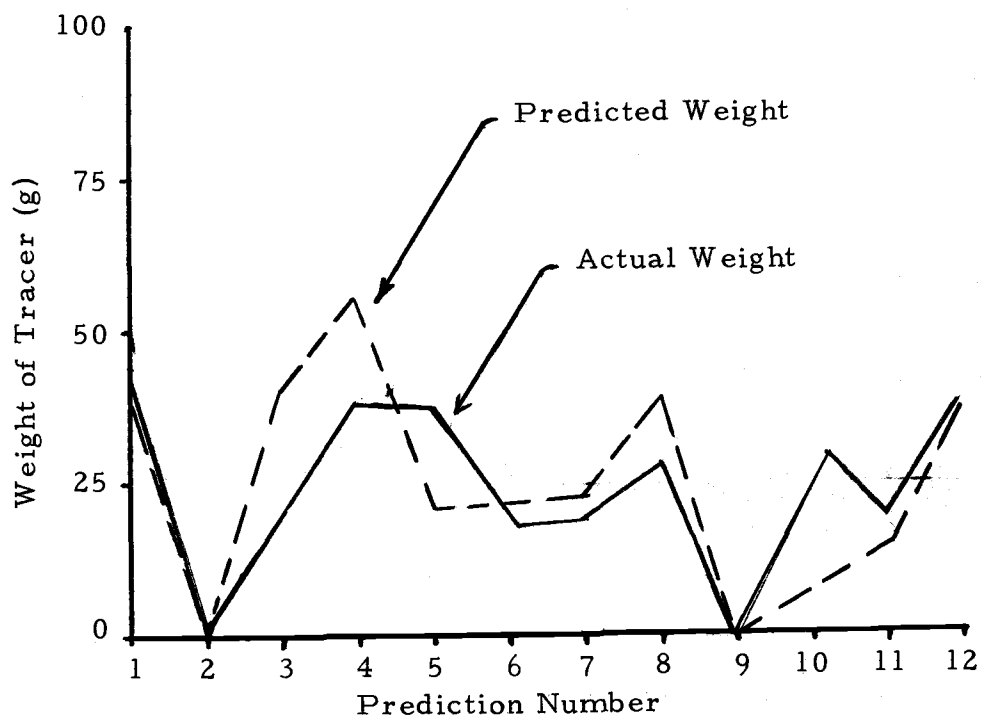


Figure 29b. Plot of actual and predicted weight of tracer vs. prediction number for "Blind" Test No. 2 (10/16/72).

VI. CONCLUSION

Based on the results of several phases of studies in this thesis, the following conclusions can be drawn:

1. The technique of instrumental neutron activation analysis has been applied in the determination of atmospheric trace element concentrations in air particulate. For the collection of air particulate of low trace elemental abundances, Nucleopore filter paper and Handiwrap were found to be the best collection media because of their low trace element content. Most of the filter papers used for the collection of air particulate were found to be non-uniform in trace element content even though they were taken from the same batch.
2. The atmospheric trace element "abundances" associated with several major sources of air pollution in western Oregon were studied. The results show that some trace elements are highly correlated with a particular source of air pollution. The elements that are highly correlated with a particular source of air pollution are summarized as follows:

AGRICULTURAL FIELD BURNING: Ti, Na, Al, K, and Fe.

WAH CHANG METALLURGICAL PROCESSING PLANT: Zr, Cl, Br, As, Hf, and Ta.

WESTERN KRAFT CORPORATION: Na, Cl, Br, Cu, V, Co, Cr. and Hg.

SIMPSON TIMBER COMPANY: Na, K, Cl, Cr, Cu, Br, and Hg.

Of all these trace elements, only Zr, Hf, Ta, and As could be used as "naturally occurring" tracers representing a clearcut source identification for the tracing of the dispersal of air pollutants from the Wah Chang Company.

3. The potential toxic elements such as Hg, As, Se and V emitted from these sources of air pollution in western Oregon were also studied. The results show that the concentrations of these elements emitted into the atmosphere are too low to cause any health hazard.
4. The atmospheric trace element abundances in Albany (an industrial area) and in Corvallis (a rural area) were measured. The atmospheric trace element abundances in the Albany area are abnormally high; most of the trace element concentrations are highly correlated to the industries in the area. On the other hand, the rural air in Corvallis shows very low trace element concentrations and may serve as an indication of the "continental background" contribution to atmospheric abundances.

5. An artificial activable tracer technique using some of the rare-earth elements (Dy, Sm, La and Ce) was also developed to monitor industrial stack effluent in the Albany area. These tracers were used in testing the generalized Gaussian plume model and Hewson's trapping plume model applied to described the dispersal pattern of stack effluent in the Albany area under various meteorological conditions. Except under very turbulent conditions (stability type A or above), the models were found to work quite well under atmospheric stabilities types D, C, and B.
6. These meteorological models along with multiple regression analysis were applied to predict the emission rates of the stack effluent involving multiple sources of air pollution in the Albany area. The artificial activable tracers were used as source reference. It was found that these models in general, can be applied to predict the emission rate within a factor of two in multiple sources involving three stacks.

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APPENDICES

APPENDIX I

SAMPLING LOG ON THE TRACE ELEMENT CONCENTRATIONS
OF STACK EFFLUENT COLLECTED AT THE WAH CHANG,
WESTERN KRAFT AND SIMPSON TIMBER COMPANIES

Table 29. Concentration of Trace Elements of Stack Effluent at the Simpson Timber Company. Concentration of Elements ($\mu\text{g}/\text{m}^3$).

Date of Collection	11/22/72- 11/27/72	11/30/72- 12/4/72	1/8/73- 1/10/73	1/10/73- 1/12/73	1/12/73- 1/14/73	1/16/73- 1/19/73	1/19/73- 1/22/73	1/22/73- 1/26/73
Vol. of Air (at 25°C)* Collected (m^3)	0.13	0.10	0.05	0.05	0.05	0.08	0.08	0.10
Element								
Al	12.0	35.9	97.5	70.8	115.0	112.2	48.8	55.2
Fe	10.1	< 9.0	< 8.0	< 8.0	43.1	< 8.0	11.0	< 9.0
Na	73	248	194	580	546	238	304	206
K	58	211	< 131	101	106	77	182	121
Ti	< 2.0	< 4.5	5.6	< 6.2	< 6.8	< 4.6	< 4.2	< 5.7
Mn	5.8	2.2	8.6	19.6	12.9	12.1	3.5	5.1
Zr	< 42	< 42	< 100	< 102	< 65	< 68	< 107	< 42
V	0.18	0.58	0.21	0.80	0.60	0.56	0.37	0.27
Cl	89	291	262	369	241	139	215	123
Cr	< 0.4	0.6	< 0.4	< 0.4	7.2	< 0.4	< 0.4	1.8
Ni	< 2.4	< 3.2	< 2.6	< 2.4	< 3.2	< 2.2	< 2.4	< 1.5
Zn	< 1.4	< 2.5	< 5.6	< 5.6	< 5.6	< 3.3	< 5.1	< 1.4
Cu	< 2.5	< 3.0	12.2	21.5	4.6	7.6	4.1	< 3.1
La	< 0.02	< 0.04	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.01
Co	0.053	0.225	0.075	0.069	< 0.010	0.045	< 0.010	0.025
Sc	< 0.005	< 0.006	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
Sm	< 0.0021	0.079	0.014	0.020	0.034	< 0.003	0.014	< 0.002
Hf	< 0.06	< 0.06	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02
Br	32.1	35.9	< 0.7	11.7	1.8	47.6	12.8	9.0
Ta	< 0.05	< 0.05	< 0.04	< 0.06	< 0.04	< 0.06	< 0.04	< 0.06
As	< 0.4	< 0.4	< 0.9	< 0.6	< 1.7	< 0.6	< 1.7	< 0.4
Sb	< 0.02	< 0.02	< 0.04	< 0.04	< 0.03	< 0.02	< 0.02	< 0.07
Hg	< 0.20	0.59	2.09	3.21	< 0.20	1.29	< 0.20	0.62
Se	< 0.01	< 0.02	< 0.01	< 0.01	< 0.02	< 0.01	< 0.04	< 0.01
Au	< 0.0003	< 0.0002	< 0.0003	< 0.0002	< 0.0002	< 0.0002	< 0.0003	< 0.0001

* Temperature of stock effluent = 295° F

Table 30. Concentration of Trace Elements of Stack Effluent at the Wah Chang Metallurgical Processing Company.

<u>Date of Collection</u>	<u>Concentration of Elements ($\mu\text{g}/\text{m}^3$)</u>					
	10/18/72- 10/21/72	11/22/72- 11/27/72	11/30/72- 12/4/72	1/8/73- 1/10/73	1/10/73- 1/12/73	1/12/73- 1/16/73
<u>Vol. of Air (at 25°C)* Collected (m^3)</u>	0.46	0.68	0.76	0.30	0.31	0.59
<u>Element</u>						
Al	11.0	2.0	5.0	28.5	10.1	8.9
Fe	<2.8	<3.1	<2.6	16.0	5.3	<2.4
Na	46.7	26.4	19.7	41.3	43.2	15.5
K	9.2	2.8	2.6	1.7	3.9	2.0
Ti	<3.0	<4.1	<4.4	<2.4	<2.1	<1.1
Mn	0.81	0.33	0.28	1.23	0.53	0.17
Zr	1487	8067	6316	6239	1328	188
V	<0.02	<0.01	<0.02	<0.02	<0.02	<0.01
Cl	4967	3558	3542	4684	5172	2173
Cr	0.27	<0.14	0.41	1.53	0.84	<0.14
Ni	<2.2	<2.4	<2.2	<2.2	<2.4	<2.4
Zn	<0.5	<1.4	<1.1	<0.8	<0.6	<0.3
Cu	<4.9	<3.6	<3.7	<5.1	<3.6	<2.8
La	<0.04	<0.03	<0.04	<0.04	<0.08	<0.08
Co	0.11	0.08	0.10	0.012	0.013	0.017
Sc	0.022	0.009	0.014	0.16	0.055	0.005
Sm	<0.002	<0.001	<0.001	<0.004	<0.004	<0.002
Hf	1.58	1.16	2.63	4.20	4.32	0.60
Br	38.5	57.5	75.7	6.7	28.3	29.1
Ta	0.20	0.27	0.21	1.30	0.16	0.05
As	2.8	6.3	2.8	15.1	31.0	3.3
Sb	<0.04	<0.04	<0.03	<0.04	<0.02	<0.08
Hg	0.48	<0.02	<0.03	<0.03	<0.05	<0.10
Se	0.22	<0.009	0.40	0.42	0.12	0.05
Au	<0.0001	<0.0002	<0.0001	<0.0001	<0.0001	<0.0002

* Temperature of Stack Effluent = 198° F

Table 31. Concentration of Trace Elements of Stack Effluent at the Western Kraft Corporation.

<u>Date of Collection</u>	Concentration of Elements ($\mu\text{g}/\text{m}^3$)					
	11/22/72- 11/27/72	1/19/73- 1/22/73	1/26/73- 1/29/73	1/29/73- 2/1/73	2/21/73- 2/5/73	2/5/73- 2/6/73
<u>Vol. of Air (at 25°C)* Collected (m^3)</u>	0.11	0.40	0.40	0.40	0.13	0.14
Element						
Al	23.3	32.3	243.6	85.5	44.0	55.7
Fe	8.4	< 3.0	< 3.0	< 3.0	< 7.0	25.3
Na	1997	672	842	1410	1052	601
K	57.7	27.3	17.7	54.1	91.1	40.8
Ti	< 5.3	< 4.3	< 6.1	< 1.3	< 2.3	< 3.7
Mn	1.97	0.61	1.69	0.56	0.38	1.32
Zr	< 14	< 15	< 16	< 15	< 15	< 15
V	7.0	18.6	25.6	50.6	52.5	15.1
Cl	1039	560	415	344	600	414
Cr	< 0.15	1.0	1.38	1.48	1.70	1.63
Ni	< 2.4	< 2.0	< 3.0	< 1.0	< 2.2	< 2.6
Zn	< 1.3	< 0.9	< 0.7	< 0.3	< 1.0	< 1.0
Cu	< 2.9	9.6	11.2	12.2	43.0	11.1
La	< 0.03	< 0.007	< 0.009	< 0.009	< 0.026	< 0.021
Co	0.76	0.83	1.11	1.34	2.05	0.79
Sc	< 0.04	< 0.04	< 0.06	< 0.010	< 0.010	< 0.020
Sm	< 0.001	< 0.001	< 0.005	< 0.001	< 0.005	< 0.005
Hf	< 0.09	< 0.05	< 0.02	< 0.02	< 0.02	< 0.02
Br	16.6	11.3	9.0	9.6	22.2	6.8
Ta	< 0.02	< 0.01	< 0.01	< 0.01	< 0.02	< 0.01
As	< 0.8	< 0.2	< 0.5	< 0.2	< 0.9	< 0.7
Sb	< 0.01	< 0.05	< 0.06	< 0.02	< 0.02	< 0.02
Hg	< 0.1	< 0.1	0.25	0.87	0.56	< 0.1
Se	< 0.04	< 0.04	< 0.01	< 0.02	< 0.02	< 0.02
Au	< 0.0002	< 0.0002	< 0.0003	< 0.0001	< 0.0002	< 0.0002

* Temperature of Stack Effluent = 300° F

APPENDIX II

CALCULATION OF THE ENRICHMENT FACTORS OF THE
TRACE ELEMENTS FOR STACK EFFLUENT COLLECTED
AT THE WAH CHANG, WESTERN KRAFT AND
SIMPSON TIMBER COMPANIES

Table 32. Absolute and Normalized Concentrations of Trace Elements on Stack Effluent at the Wah Chang Metallurgical Processing Company.

Element	Ave. Conc. ($\mu\text{g}/\text{m}^3$)	Conc. Norm. to Al = 1.0 ($\mu\text{g}/\text{m}^3$)	Crustal Abundances ^a Norm. to Al = 1.0	Enrichment Factor, EF Col. 3/Col. 4
Al	11.0	1.00	1.00	1.00
Fe	10.6	0.96	0.68	1.4
Na	32.0	2.92	0.29	10.2
K	3.7	0.34	0.25	1.3
Ti	<2.8	<0.25	0.069	<3.6
Mn	0.56	0.05	0.012	4.2
Zr	3863	351.2	0.0020	$1.7 \times 10^{+5}$
V	<0.02	<0.0018	0.0016	<1.1
Cl	4016	365.1	0.0016	$2.3 \times 10^{+5}$
Cr	0.76	0.069	0.0012	57.5
Ni	<2.2	<0.2	0.00091	<219
En	<0.5	<0.045	0.00085	<53
Cu	<3.9	<0.35	0.00067	<522
La	<0.007	<0.00054	0.00036	<1.5
Co	0.054	0.0049	0.00030	16.3
Sc	0.044	0.0040	0.00027	14.8
Sm	<0.0023	<0.00018	7.3×10^{-5}	<2.4
Hf	2.5	0.22	3.6×10^{-5}	$6.1 \times 10^{+3}$
Br	39.2	3.6	3.0×10^{-5}	$1.2 \times 10^{+5}$
Ta	0.37	0.034	2.4×10^{-5}	$1.4 \times 10^{+3}$
As	10.2	0.93	2.2×10^{-5}	$4.2 \times 10^{+4}$
Sb	<0.05	0.0045	2.4×10^{-6}	<1875
Hg	<0.05	<0.0045	9.7×10^{-7}	< $5.0 \times 10^{+3}$
Se	0.25	0.022	6.1×10^{-7}	$3.7 \times 10^{+4}$
Au	<0.0001	< 9.0×10^{-1}	4.8×10^{-8}	<190

^a Values taken from Taylor (1964).

Table 33. Absolute and Normalized Concentrations of Trace Elements on Stack Effluents at the Western Kraft Corporation.

Element	Ave. Conc. ($\mu\text{g}/\text{m}^3$)	Conc. Norm. to Al = 1.0 ($\mu\text{g}/\text{m}^3$)	Crustal Abundances ^a Norm. to Al = 1.0	Enrichment Factor, EF Col. 3/Col. 4
Al	81.3	1.00	1.00	1.00
Fe	12.2	0.15	0.68	0.22 ^b
Na	1096	13.4	0.29	46.7
K	47.6	0.58	0.25	2.3
Ti	< 3.8	< 0.047	0.069	< 0.68
Mn	1.1	0.014	0.012	1.1
Zr	< 15	< 0.18	0.0020	< 90
V	28.1	0.35	0.0016	219
Cl	562	6.9	0.0016	4312
Cr	1.4	0.017	0.0012	14.2
Ni	< 2.2	< 0.027	0.00091	< 30
Zn	< 0.9	< 0.011	0.00085	< 13
Cu	17.3	0.21	6.7×10^{-4}	313
La	0.017	0.00021	0.00036	0.58
Co	1.25	0.015	3.0×10^{-4}	50.0
Sc	< 0.03	$< 3.6 \times 10^{-4}$	2.7×10^{-4}	< 1.3
Sm	< 0.003	$< 3.7 \times 10^{-5}$	7.3×10^{-5}	< 0.51
Hf	< 0.004	$< 4.9 \times 10^{-5}$	3.6×10^{-5}	< 1.4
Br	12.5	0.15	3.0×10^{-5}	5000
Ta	< 0.01	$< 1.2 \times 10^{-4}$	2.4×10^{-5}	< 5.0
As	< 0.5	$< 6.1 \times 10^{-3}$	2.2×10^{-5}	< 277
Sb	< 0.03	$< 3.7 \times 10^{-4}$	2.4×10^{-6}	< 154
Hg	0.6	7.4×10^{-3}	9.7×10^{-7}	8200
Se	< 0.02	$< 2.5 \times 10^{-4}$	6.1×10^{-7}	< 417
Au	< 0.0002	$< 2.4 \times 10^{-6}$	4.8×10^{-8}	< 50

^aValues taken from Taylor (1964).^bThe enrichment factor less than one indicates that the element is either depleted or some of the Al may be derived from sources other than the earth's crust.

Table 34. Absolute and Normalized Concentrations of Trace Elements on Stack Effluent at the Simpson Timber Company.

Element	Ave. Conc. ($\mu\text{g}/\text{m}^3$)	Conc. Norm. to Al = 1.0 ($\mu\text{g}/\text{m}^3$)	Crustal Abundances ^a Norm. to Al = 1.0	Enrichment Factor, EF Col. 3/Col. 4
Al	69.0	1.00	1.00	1.00
Fe	29.6	0.43	0.68	0.63
Na	299	43.3	0.29	149
K	123.3	1.8	0.25	7.2
Ti	<4.9	<0.071	0.069	<1.1
Mn	8.7	0.13	0.012	10.8
Zr	<95	<1.4	0.0020	<700
V	0.45	0.0065	0.0016	4.1
Cl	215.5	3.1	0.0016	1937
Cr	3.2	0.046	0.0012	38.3
Ni	<2.5	<0.036	0.00091	<39
Zn	<3.8	<0.055	0.00085	<65
Cu	11.5	0.17	0.00067	254
La	<0.02	<0.00029	0.00036	<0.8
Co	<0.051	<7.4 x 10 ⁻⁴	0.00030	<2.5
Sc	<0.009	<1.3 x 10 ⁻⁴	0.00027	<0.48
Sm	0.032	4.6 x 10 ⁻⁴	7.3 x 10 ⁻⁵	6.3
Hf	<0.03	<4.3 x 10 ⁻⁴	3.6 x 10 ⁻⁵	<11.9
Br	21.5	0.31	3.0 x 10 ⁻⁵	1.0 x 10 ⁴
Ta	<0.05	<7.2 x 10 ⁻⁴	2.4 x 10 ⁻⁵	<30
As	<1.1	<0.016	2.2 x 10 ⁻⁵	<727
Sb	<0.03	<4.3 x 10 ⁻⁴	2.4 x 10 ⁻⁶	<179
Hg	1.8	0.026	9.7 x 10 ⁻⁷	2.9 x 10 ⁴
Se	0.02	<2.9 x 10 ⁻⁴	6.1 x 10 ⁻⁷	<483
Au	<0.0002	<2.8 x 10 ⁻⁶	4.9 x 10 ⁻⁸	<5.7

^aValues taken from Taylor (1964).

APPENDIX III

SAMPLING LOG ON THE ATMOSPHERIC TRACE ELEMENTAL CONCENTRATIONS IN THE ALBANY AREA, OREGON AND THE CALCULATION OF THEIR ENRICHMENT FACTORS

Table 35. Absolute and Normalized Atmospheric Trace Element Abundances in Albany, Oregon.

Element	Ave. Conc. (ng/m ³)	Conc. Norm. to Al = 1.0 (ng/m ³)	Crustal Abundances ^a Norm. to Al = 1.0	Enrichment Factor, EF Col. 3/Col. 4
Al	11822	1.00	1.00	1.00
Fe	5105	0.43	0.68	0.63 ^b
Na	7172	0.61	0.29	2.1
K	1927	0.16	0.25	0.64
Ti	2150	0.18	0.069	2.6
Mn	122	0.010	0.012	0.8
Zr	1517	0.13	0.0020	65
V	8.9	0.00075	0.0016	0.47
Cl	6894	0.58	0.0016	362
Cr	168	0.014	0.0012	11.7
Ni	356	0.030	0.00091	33.0
Zn	595	0.050	0.00085	58.8
La	5.0	0.00042	0.00036	1.2
Co	3.4	0.00029	0.00030	1.0
Sc	0.7	6.0×10^{-5}	0.00027	0.22
Sm	1.2	0.00010	7.3×10^{-5}	1.4
Hf	4.4	0.00037	3.6×10^{-5}	10.3
Br	256	0.022	3.0×10^{-5}	733
Ta	82	0.0069	2.4×10^{-5}	288
As	20.4	0.0017	2.2×10^{-5}	77.3
Sb	20.4	0.0017	2.4×10^{-6}	708
Hg	323	0.027	9.7×10^{-7}	3×10^4
Se	7.8	0.00066	6.1×10^{-7}	1.1×10^3
Au	0.7	5.9×10^{-5}	4.9×10^{-8}	1.2×10^3

^aValues taken from Taylor (1964).^bThe enrichment factor less than one indicates that the element is either depleted or some of the Al may be derived from sources other than the earth's crust.

Table 36. Atmospheric Trace Element Abundances in the Albany Area, Oregon.

Date of Collection 8/11/72: Time of Collection 1130-1400

Meteorological Information: Wind Direction NNW; Wind Speed 3 m/sec

Weather Condition Clear Day

Location of Air Samplers (Refer to Map 2)	Concentration of Trace Elements (ng/m ³)			
	4	18	19	20
<u>Element</u>				
Al	6100	5500	3000	8400
Fe	1125	4232	3161	2571
Na	7700	4300	3300	3300
K	1625	1631	833	1036
Ti	1600	< 426	< 417	< 450
Mn	140	120	100	170
Zr	875	522	1204	614
V	0.9	0.8	0.3	0.7
Cl	4800	1800	< 400	1700
Cr	387	177	422	236
Ni	500	137	267	703
Zn	437	945	431	214
La	< 1.0	< 0.8	< 1.0	< 0.8
Co	2.5	1.9	0.3	2.1
Sc	0.3	0.2	0.1	0.3
Sm	< 0.1	< 0.1	0.3	0.8
Hf	1.3	2.4	2.9	2.1
Br	< 50	< 60	63	89
Ta	100	45	60	64
As	< 8	18	< 8	35
Sb	39	19	39	20
Hg	81	191	63	86
Se	5.4	6.6	4.9	3.3
Au	1.7	0.6	0.7	0.8

Table 36 continued.

Date of Collection 8/28/72: Time of Collection 1300-1500

Meteorological Information: Wind Direction N. and NNW wind;

Wind Speed 5-6 m/sec

Weather Condition Clear Day

Location of Air Samplers (Refer to Map 2)	Concentration of Trace Elements (ng/m ³)			
	1	2	4	21
<u>Element</u>				
Al	34700	5500	40900	57000
Fe	8868	627	5660	9556
Na	5000	3300	12600	16800
K	4968	1808	3046	2943
Ti	4500	600	1900	3100
Mn	460	90	120	90
Zr	2415	539	356	875
V	2.7	0.8	8.3	10.2
Cl	<300	10600	3000	3700
Cr	113	66	132	101
Ni	591	446	227	158
Zn	817	295	144	158
La	10.1	2.5	6.0	9.2
Co	6.3	7.4	4.0	6.6
Sc	1.9	0.4	1.7	3.3
Sm	1.3	0.3	1.1	3.5
Hf	9.4	3.0	1.4	5.4
Br	< 57	< 60	< 50	< 57
Ta	170	74	52	60
As	< 8	25	10	22
Sb	43	22	10	36
Hg	239	494	75	107
Se	5.7	3.2	2.7	2.0
Au	2.0	0.4	0.4	0.4

Table 36 continued.

Date of Collection 8/7/72: Time of Collection 1100-1430

Meteorological Information: Wind Direction NNW

Wind Speed 4-5 m/sec

Inversion Height 800 meters

Weather Condition Clear Day

Location of Air Samplers (Refer to Map 2)	Concentration of Trace Elements (ng/m ³)				
	1	2	3	4	5
<u>Element</u>					
Al	18100	8800	8400	2300	12700
Fe	2222	14827	8343	5981	6964
Na	11500	11500	6400	6700	9100
Ti	<600	1300	1500	700	3100
Mn	70	350	80	64	110
Zr	2202	1235	954	983	2625
V	14.0	22.0	9.0	6.0	1.0
Cl	24600	5500	<370	9600	15000
Cr	202	143	98	73	120
Ni	454	661	307	73	114
Zn	2323	547	306	236	334
Co	5.1	3.1	4.1	1.2	2.9
Sc	<0.2	0.6	0.3	<0.2	0.6
Hf	<0.9	3.0	<0.6	<0.7	7.6
Br	< 70	110	490	150	560
Ta	162	92	64	40	33
Hg	2858	109	89	369	55
Se	69	8	3	2	3

Table 36 continued.

Date of Collection 7/27/72: Time of Collection 1100-1430

Meteorological Information: Wind Direction N; Wind Speed 2-3 m/sec

Weather Condition Clear Day

Location of Air Samplers (Refer to Map 2)	Concentration of Trace Elements (ng/m ³)			
	1	3	16	4
<u>Element</u>				
Al	9200	3600	2900	2900
Fe	7190	3037	536	2252
Na	19800	13800	7300	7300
Ti	3000	1200	< 420	< 430
Mn	320	81	41	71
Zr	8750	358	2324	930
V	2.0	0.8	0.5	0.5
Cl	< 700	3000	< 800	< 800
Cr	382	165	86	102
Ni	< 89	< 90	< 89	< 89
Zn	1328	1288	965	590
Co	7.8	2.8	2.1	0.5
Sc	0.2	< 0.1	< 0.1	< 0.1
Hf	21.9	8.3	4.8	1.9
Br	< 57	< 60	< 58	< 60
Ta	211	52	38	46
Hg	203	74	206	118
Se	14.6	5.1	5.8	2.3

Table 36 continued.

Date of Collection 8/9/72: Time of Collection 1030-1330

Meteorological Information: Wind Direction NNW to NW

Wind Speed 4-5 m/sec

Inversion Height 860 meters

Weather Condition Clear Day

Location of Air Samplers (Refer to Map 2)	Concentration of Trace Elements (ng/m ³)			
	10	11	12	13
<u>Element</u>				
Al	25700	2800	1800	7400
Fe	315	2508	7426	<315
Na	8400	7000	6000	<500
Ti	1800	<600	<300	<300
Mn	240	60	940	48
Zr	414	1665	528	1973
V	27.0	15.0	10.0	17.0
Cl	< 400	< 400	10800	9300
Cr	101	80	62	276
Ni	334	445	284	< 96
Zn	31	635	375	69
Co	1.5	2.1	2.3	4.8
Sc	1.0	<0.2	<0.2	<0.2
Hf	2.5	2.0	2.1	<0.9
Br	< 70	< 70	220	370
Ta	55	94	80	124
Hg	135	87	804	345
Se	5	3	4	6

APPENDIX IV

AN EXAMPLE OF THE CALCULATION OF GROUND LEVEL
CONCENTRATION OF TRACER EMITTED FROM THE
STACK AND THE TREATMENT OF THE DATA

Data Log in Field Work

Date of Experiment	8/11/72 "R" experiment
Wind Direction	Approximately NNW
Wind Speed	About 3 meters per second
Cloud Cover	0/10 (clear sky)
Surface Temperature	About 90° F at noon time
Sprayer Location	Western Kraft
Tracer Used	Dy
Time of Tracer ON-OFF	1210 to 1350
Emission Rate of Tracer	643 µg/sec
Air Samplers Used	Gelman tape samplers (model No. 23000). High-volume air samplers (Shepherd and Associate. Model No. 8000)
Location of Air Samplers	As shown in Figure 32
Time of Sampling	Every half hour
Information of Stack	
Stack Temperature	149° C
Stack Height	61 meters
Exit Velocity	6.2 meters per second
Stack Diameter	4.0 meters

The detailed information of wind direction and speed and the temperature lapse-rate are shown in Appendix V.

Prediction of Atmospheric Stability

The standard deviation of the horizontal wind direction,

$$\sigma_{\theta} = \sqrt{\frac{\sum_{i=1}^N (\theta - \bar{\theta})^2}{N}} \quad \text{where}$$

$(\theta - \bar{\theta})$ is the wind fluctuation (in degrees) from the mean during the intervals N(10 minutes for each interval), was estimated to be about 16 degrees. This corresponds to C stability according to the Pasquill's categories. The assumption of this stability was also confirmed by experimental results as shown later.

Theoretical Calculations

Calculation of Plume Rise

The Western Kraft Paper Company has a large plume. To calculate the plume rise, Holland's formula was applied. It is given by

$$\Delta H = \frac{V_s d}{\mu} \left[1.5 + 2.68 \times 10^{-3} p \frac{T_s - T_a}{T_s} d \right]$$

$$= \frac{6.2(4)}{3.1} \left[1.5 + 2.68 \times 10^{-3} (970) \left(\frac{422 - 308}{422} \right) (4) \right] = 34 \text{ meters}$$

Calculation of the Downwind and Cross-wind Distance (x and y) of the Air Samplers from Stack

The mean wind directions with reference to the stack and the air samplers during the experiment are shown in Figure 32. Based on the scale in Figure 32 the downwind and cross-wind distances of the air samplers can be calculated. The results are summarized in Table 37.

Calculation of the Theoretical Concentration of the Tracer

Knowing the downwind distance and the atmospheric stability, one can look up the values of σ_y and σ_z in Figure 16 and 17. Once all the parameters in the Gaussian plume equation were known, the calculations of the theoretical concentration of the tracer were done with a computer and the results along with the concentrations determined

from experimental measurements are summarized in Table 37.

The values of σ_y and σ_z from Figure 16 and 17 are based on the sampling time of 10 minutes. Since half hour samples were taken, the theoretical concentrations of the tracer had to be corrected by the following formula,

$$X_s = X_k (t_k/t_s)^p$$

where X_s is the desired concentration estimate for the sampling time, t_s , X_k is the concentration estimate for the shorter sampling time, t_k , and $p = 0.2$. The difference is about 20% lower in concentration for half hour sampling than for 10 minutes.

Table 37. Summary of Results in the Study of the Gaussian Plume Model Under Slightly Unstable Conditions (Stability Type C)

Date of Experiment	Location of Stack (1)	Location of Air Sampler (1)	Sample Number	Mean Wind Direction (2) and Fluctuation (σ_θ) (3)	Time of Collection	Tracer Used	Emission Rate ($\mu\text{g/sec}$)	Concentration		x (meter)	y (meter)	σ_y (meter)	σ_z (meter)	A_n (10^{-4})
								Experimental Results (10^{-10} g/m^3)	Theoretical Results (10^{-10} g/m^3)					
8/11/72	Western Kraft	11	R-1	349° ($\sigma_\theta = 16^\circ$)	1230-1300	Dy	643 (Actual)	4.1 ± 2.5	3.5	3218	402	310	180	0.0054
		10	R-2	↓	↓		(1004 ± 149)	2.3 ± 1.3	0	3568	1106	330	200	0.0001
		5	R-3	↓	↓		(Predicted)	0	0	2715	2641	260	150	0
		5	R-4	326° ($\sigma_\theta = 15^\circ$)	1300-1330			0	0	2514	1508	245	143	0
		11	R-5	↓	↓			2.3 ± 1.3	1.6	3218	560	310	180	0.0025
		19	R-6	↓	↓			4.6 ± 1.9	3.5	3620	402	331	203	0.0054
		18	R-7	↓	↓			6.0 ± 3.0	1.8	3922	578	365	210	0.0028
		5	R-8	326° ($\sigma_\theta = 16^\circ$)	1330-1400			0	0	2514	1508	245	143	0
		11	R-9	↓	↓			2.8 ± 1.1	1.6	3218	560	310	180	0.0025
		18	R-10	↓	↓			6.0 ± 1.6	3.5	3620	402	331	203	0.0054
		19	R-11	↓	↓			2.5 ± 1.9	1.8	3922	578	365	210	0.0028

(1) Referred to Map 3

(2) Northerly = 360°; westerly = 270°.

(3) σ_θ = Standard deviation of horizontal wind fluctuation

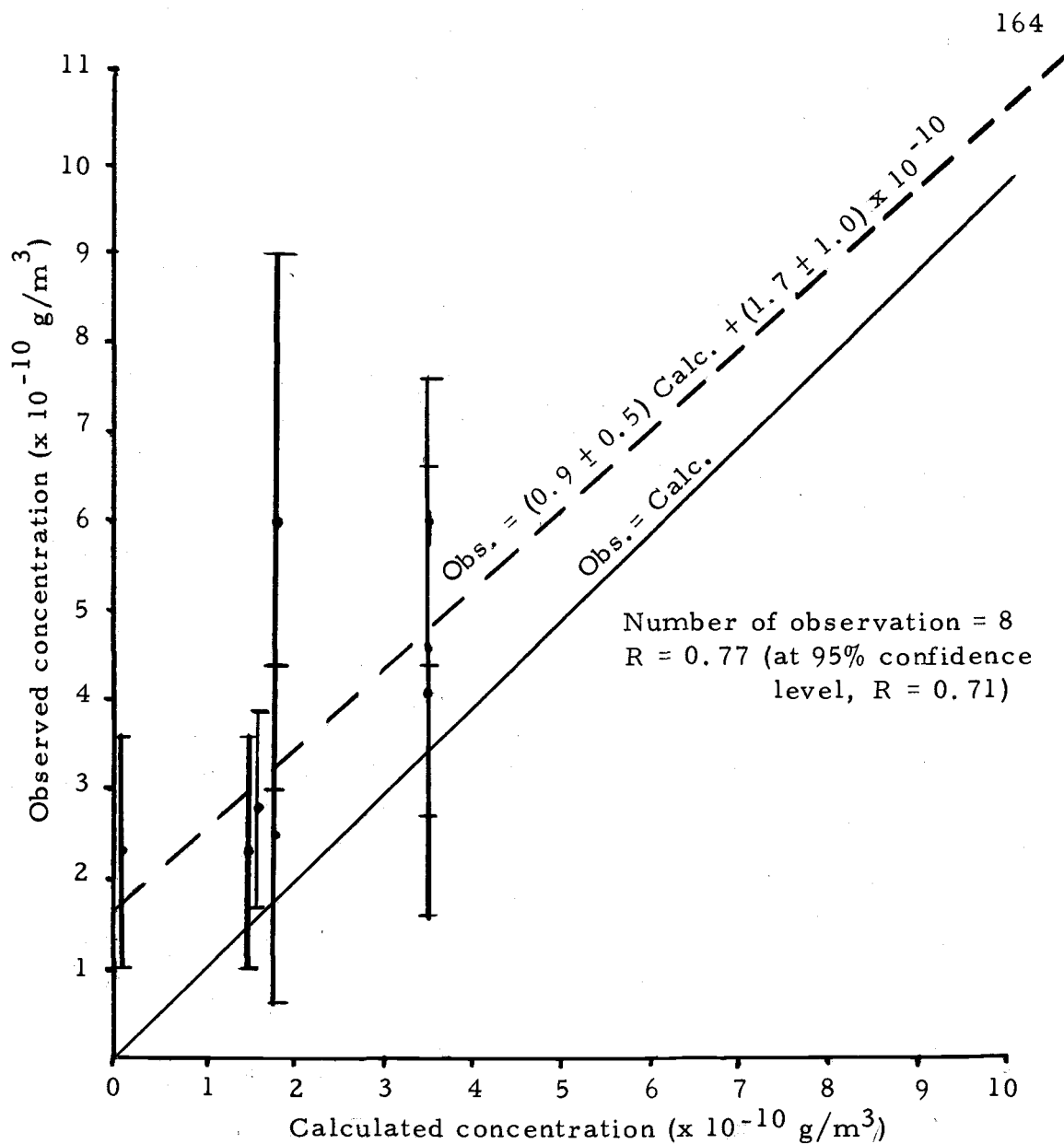


Figure 30. Scatter diagram in the study of the Gaussian plume model under slightly unstable conditions (stability type C) for the high source at Western Kraft Paper Company.

Treatment of Data

Figure 30 shows a plot of the observed values of the concentration of the tracer vs. the calculated values. Linear regression analysis (using the SIPS computer program from the O. S. U. statistical library revised on September 1972) was applied to obtain the best fit of the data. The dashed-line in Figure 30 represents the best fit line. The linear correlation coefficient R was calculated to be equal to 0.77 for eight observations showing that the values are highly correlated. (For eight observations, $R = 0.71$ at 95 percent confidence level.)

In order to test how accurate the model was for the prediction of the emission rate of the tracer, the following calculations were performed.

$$\text{Let } C_n = \frac{Q}{\pi \sigma_y \sigma_z u} \exp - 1/2 \left[\left(\frac{y}{\sigma_y} \right)^2 + \left(\frac{h_e}{\sigma_z} \right)^2 \right] = A_n Q$$

where C_n is the experimental value of the concentration of the tracer at a certain location and A_n can be evaluated by knowing the parameters y , h_e , u , σ_y and σ_z under a given meteorological condition. The values of A_n are summarized in Table 37. Linear regression analysis was performed to obtain the best value of Q . The calculation for the predicted emission rate was also included in Table 37 for comparison.

Experimental Test of the Gaussian Plume Model

The tracer concentrations measured at various distances from the center-line of the plume are expected to follow a Gaussian distribution. This was tested by lining up the air samplers in a straight line perpendicular to the center-line and measuring the tracer concentrations. Since the samplers were not exactly located in a straight line, small corrections were made with a $1/r^2$ law. The corrections were about 10-15 percent of the total concentration. An example of a plot of the concentrations of the tracer vs. the distances from the center-line of the plume is shown in Figure 31 (air samples No. 8, 9, 10, and 11).

A Gaussian fit to the data was performed with a computer program (the CURFIT program by Bevington, 1969), which also calculated the value of σ_y for the best fit. The result showed that at a distance of $x = 3620$, the best fit value of σ_y for the data (with air sample No. 8, 9, 10 and 11 in Table 37) was 320 meters. From Gifford's curves in Figure 16, this corresponds to the C stability. This confirms our prediction of the atmospheric stability.

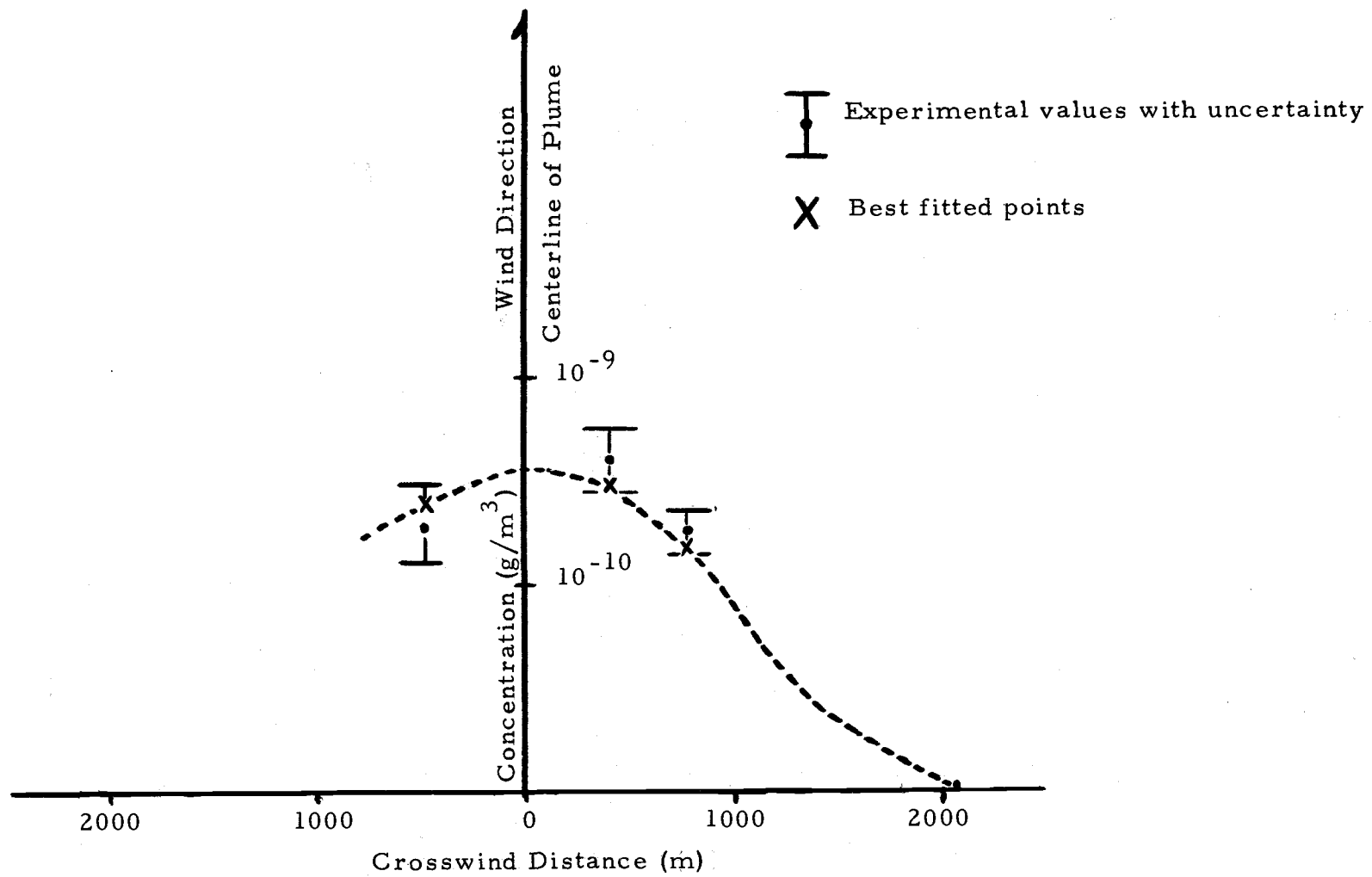


Figure 31. Plot of concentration of tracer vs. crosswind distance.

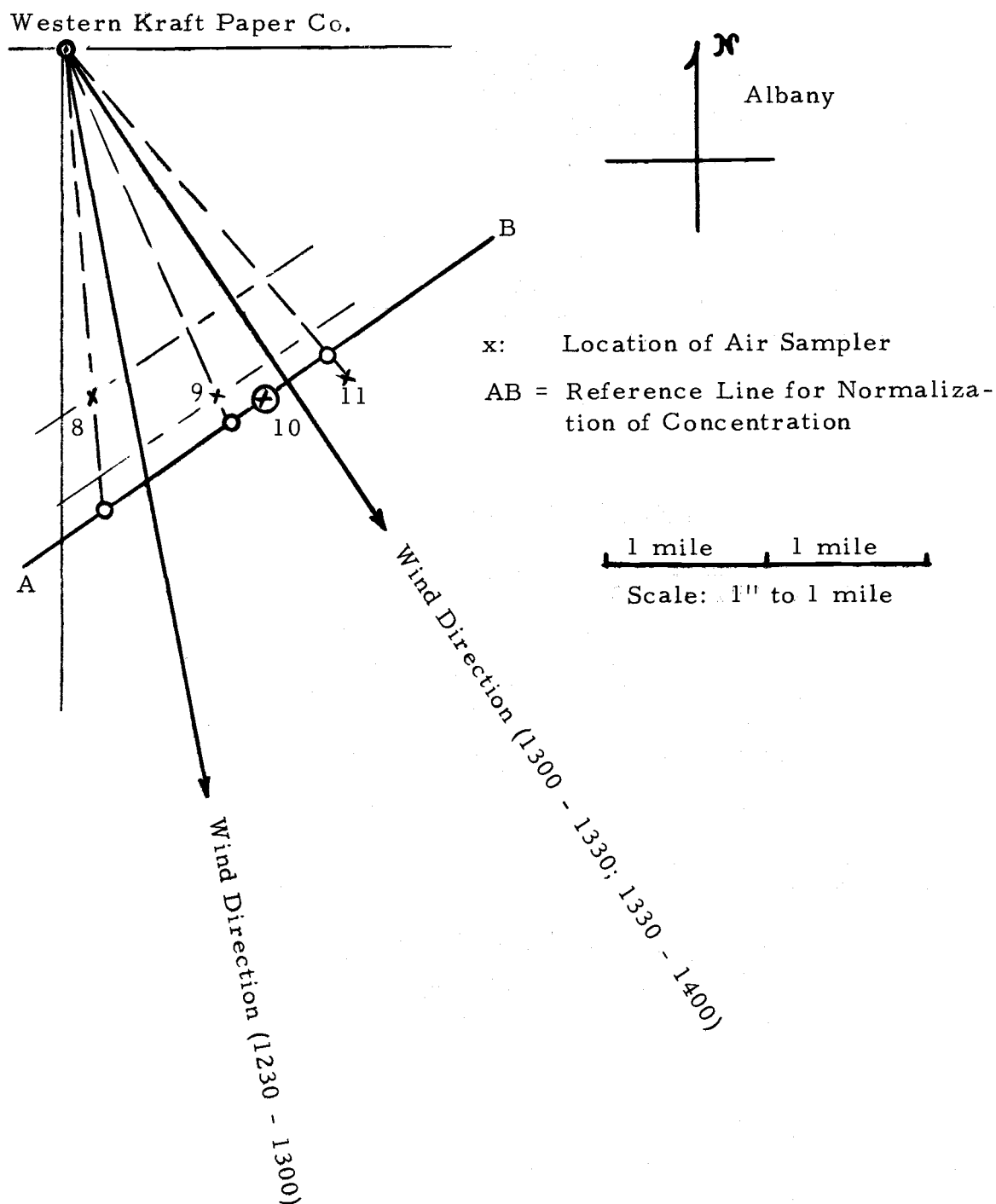
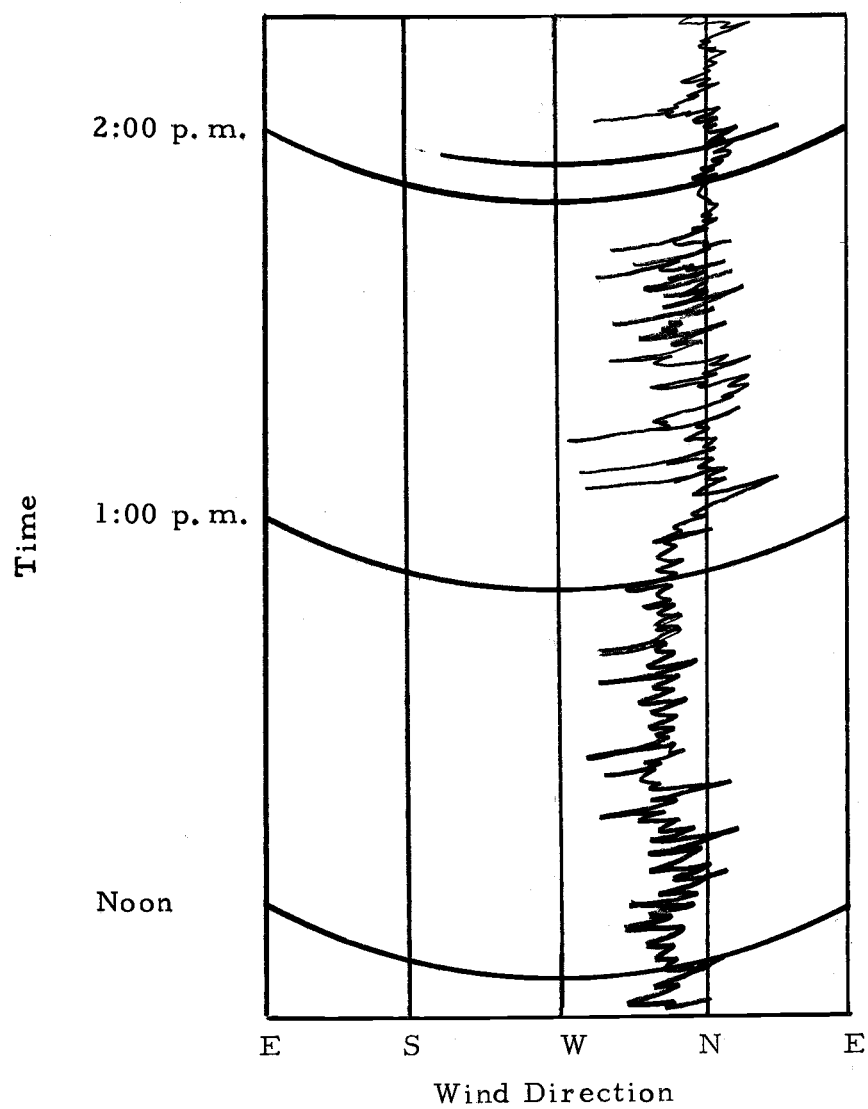


Figure 32. Location of air samplers with reference to the Western Kraft Corporation in Albany, Oregon.

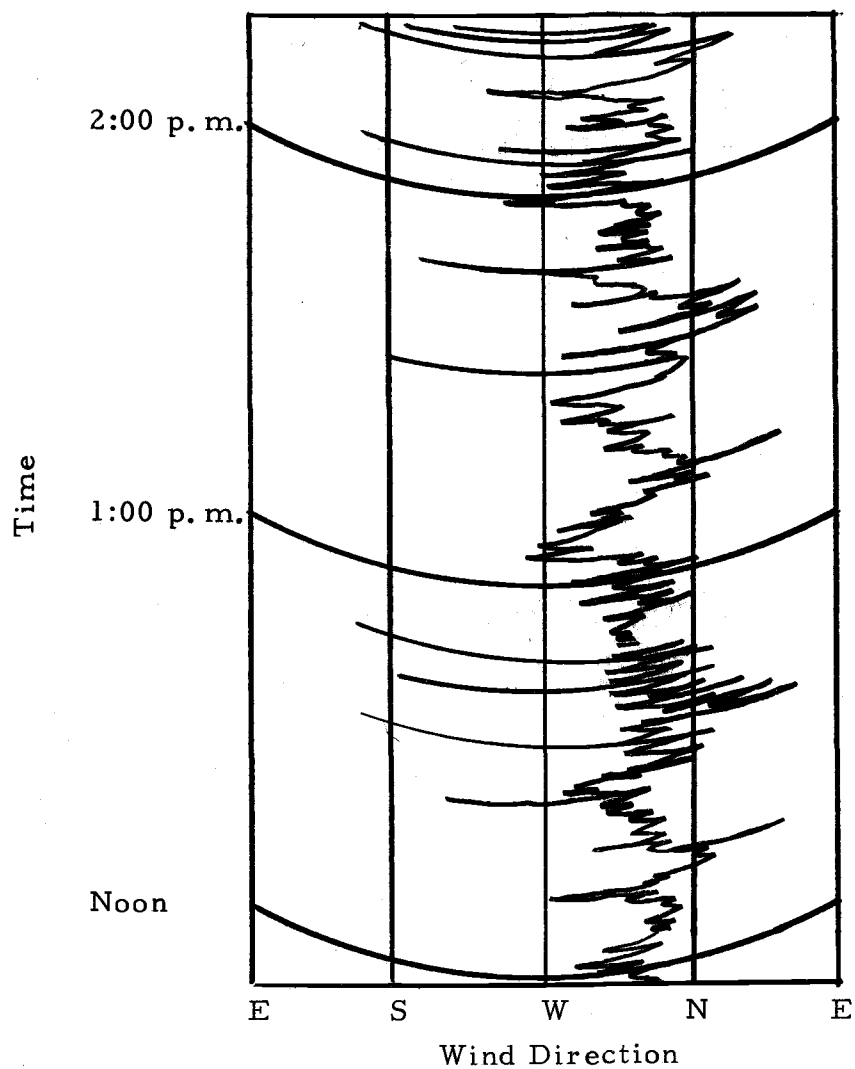
APPENDIX V

WIND DIRECTIONS AND TEMPERATURE
LAPSE-RATES

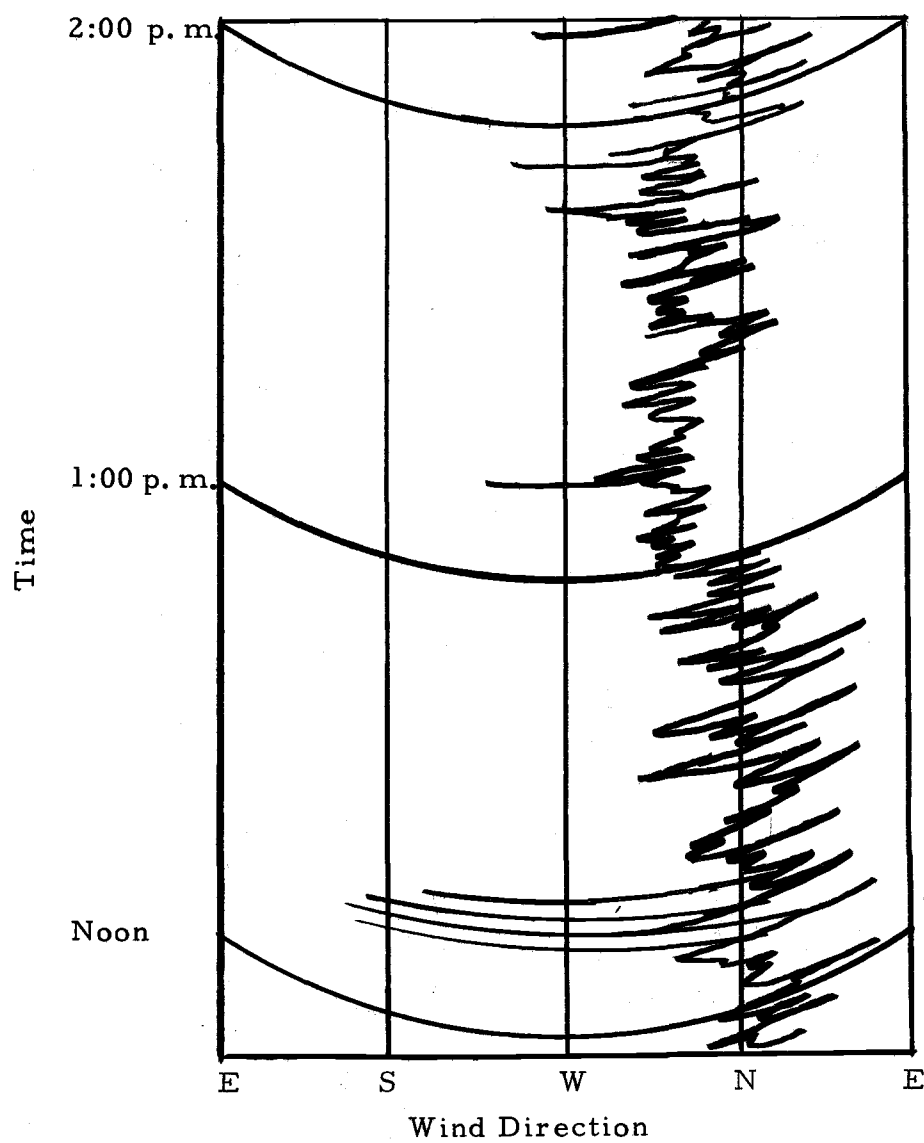
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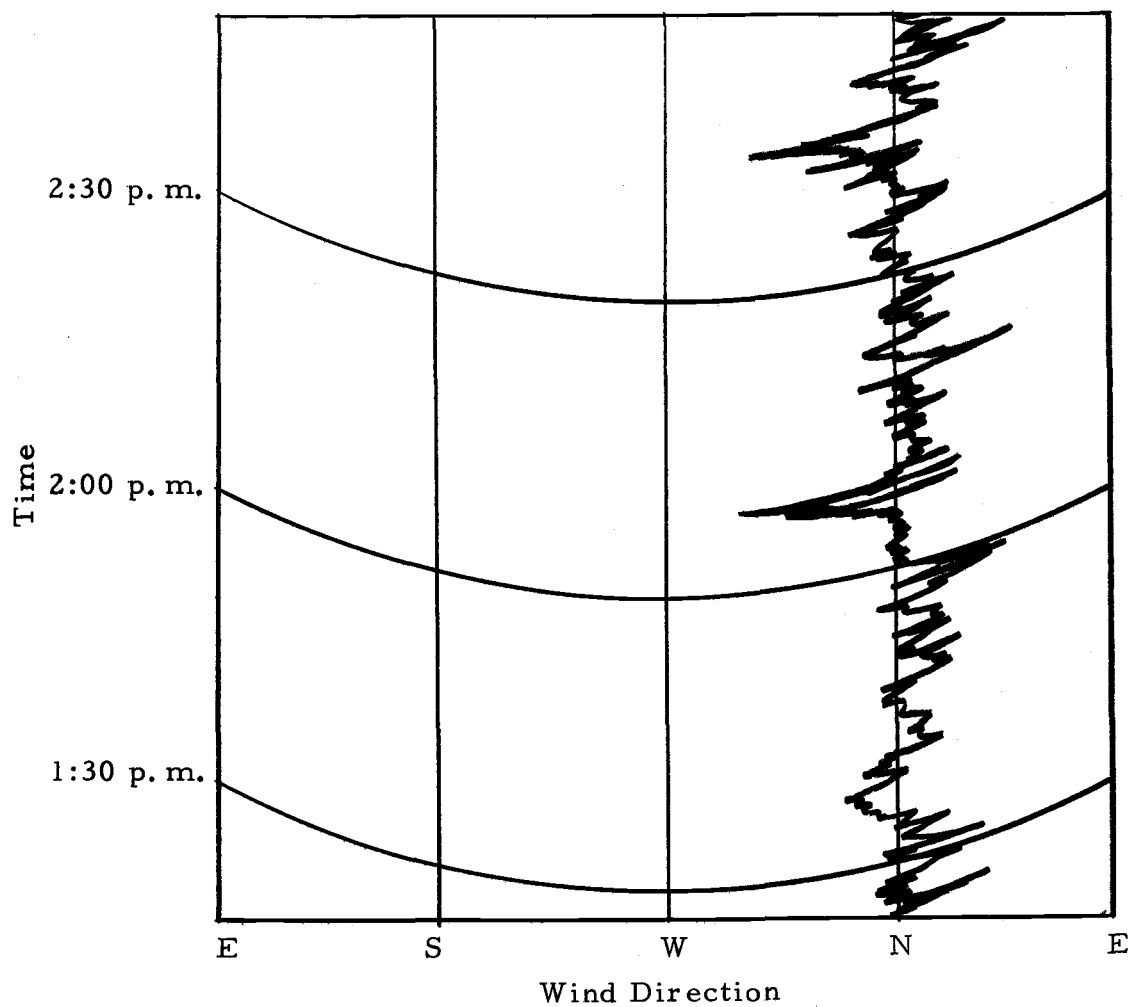
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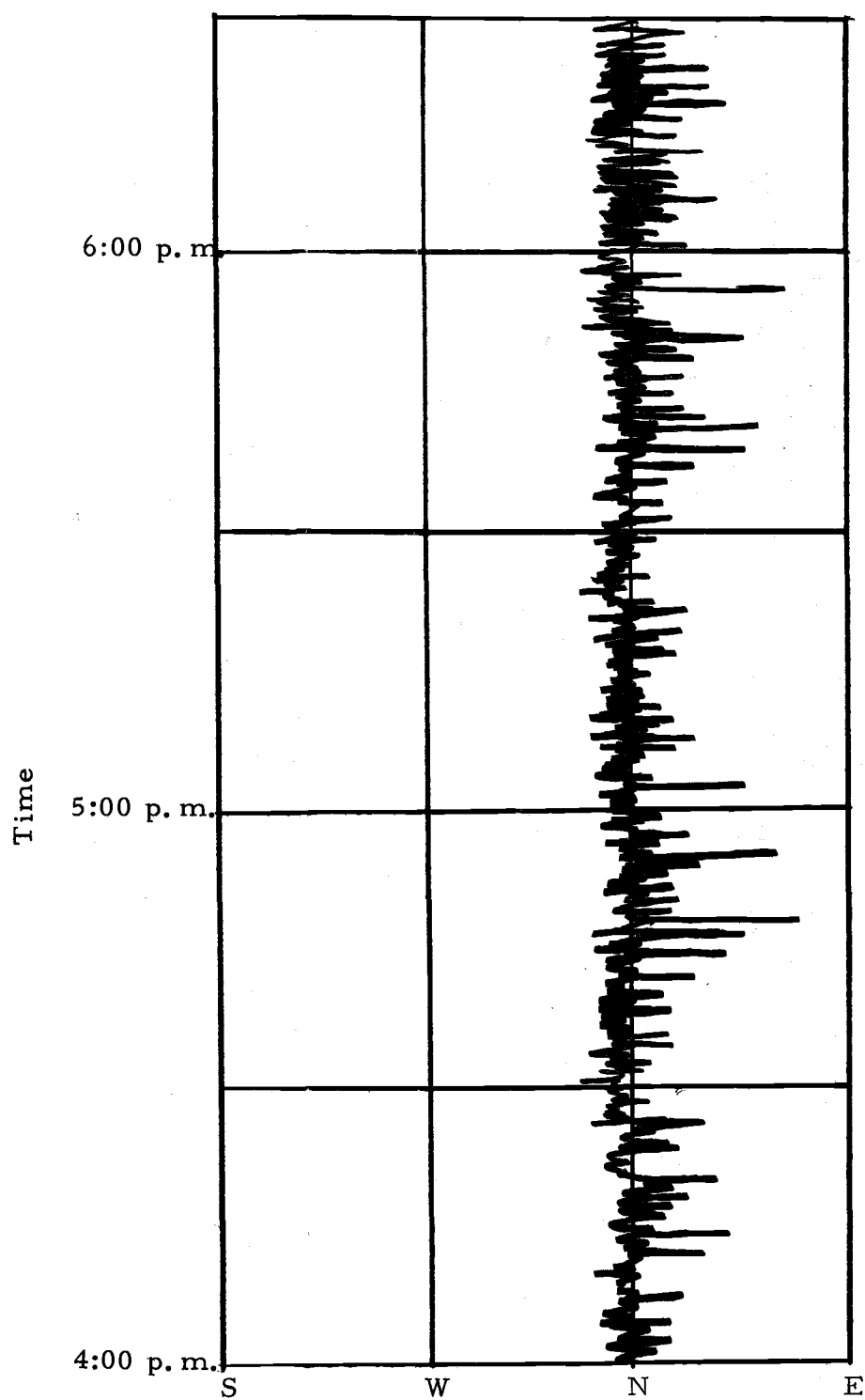


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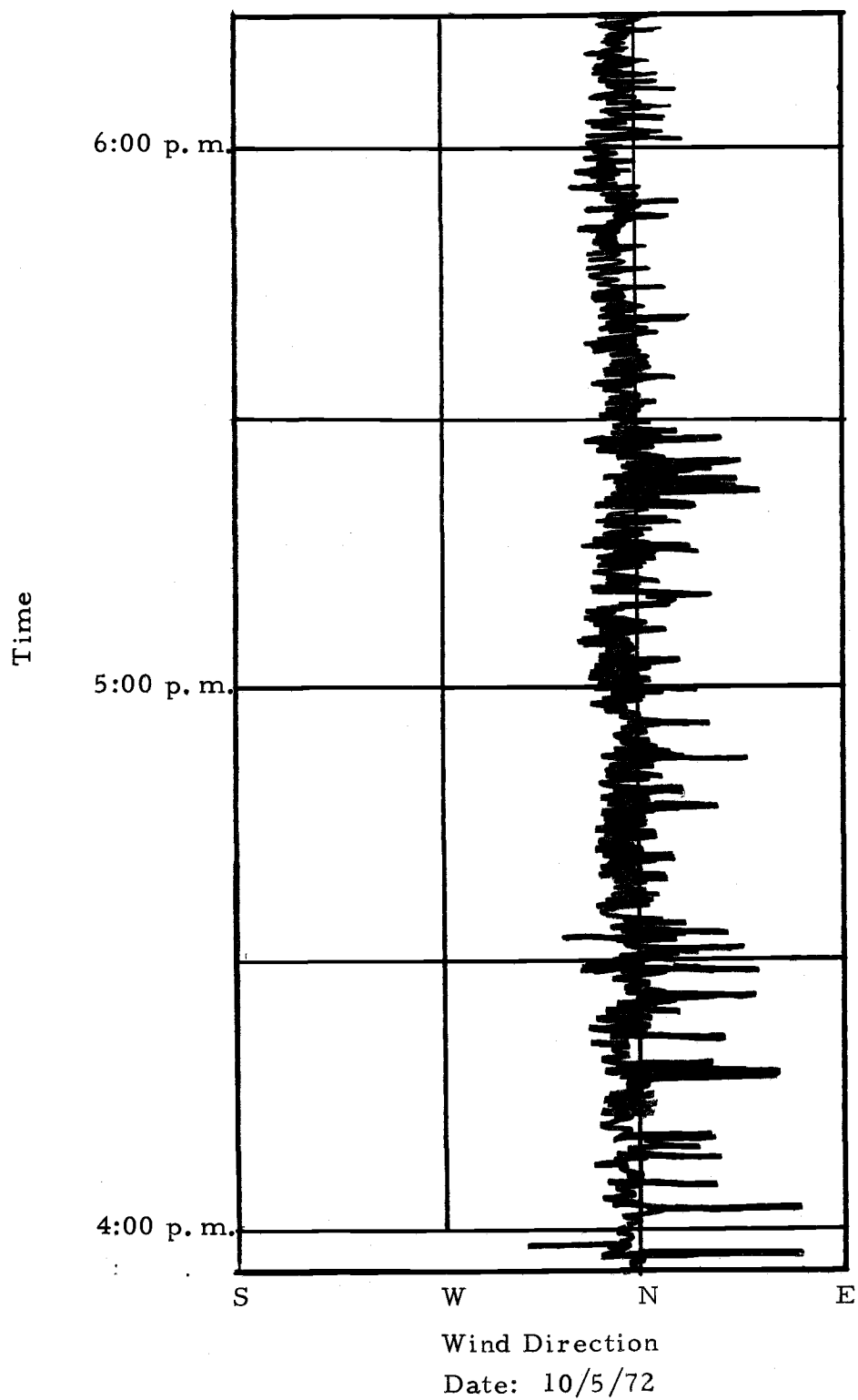
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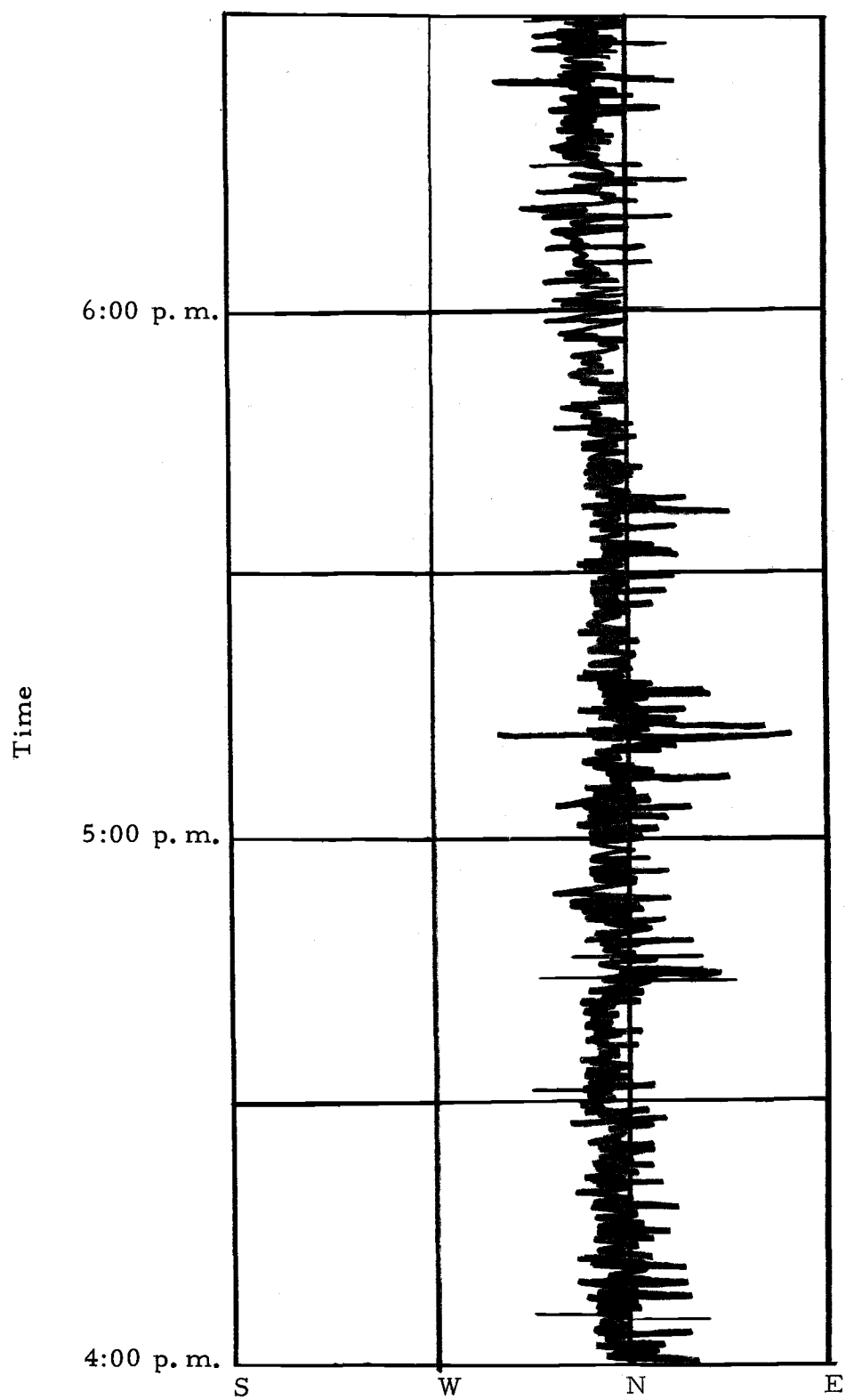




Wind Direction

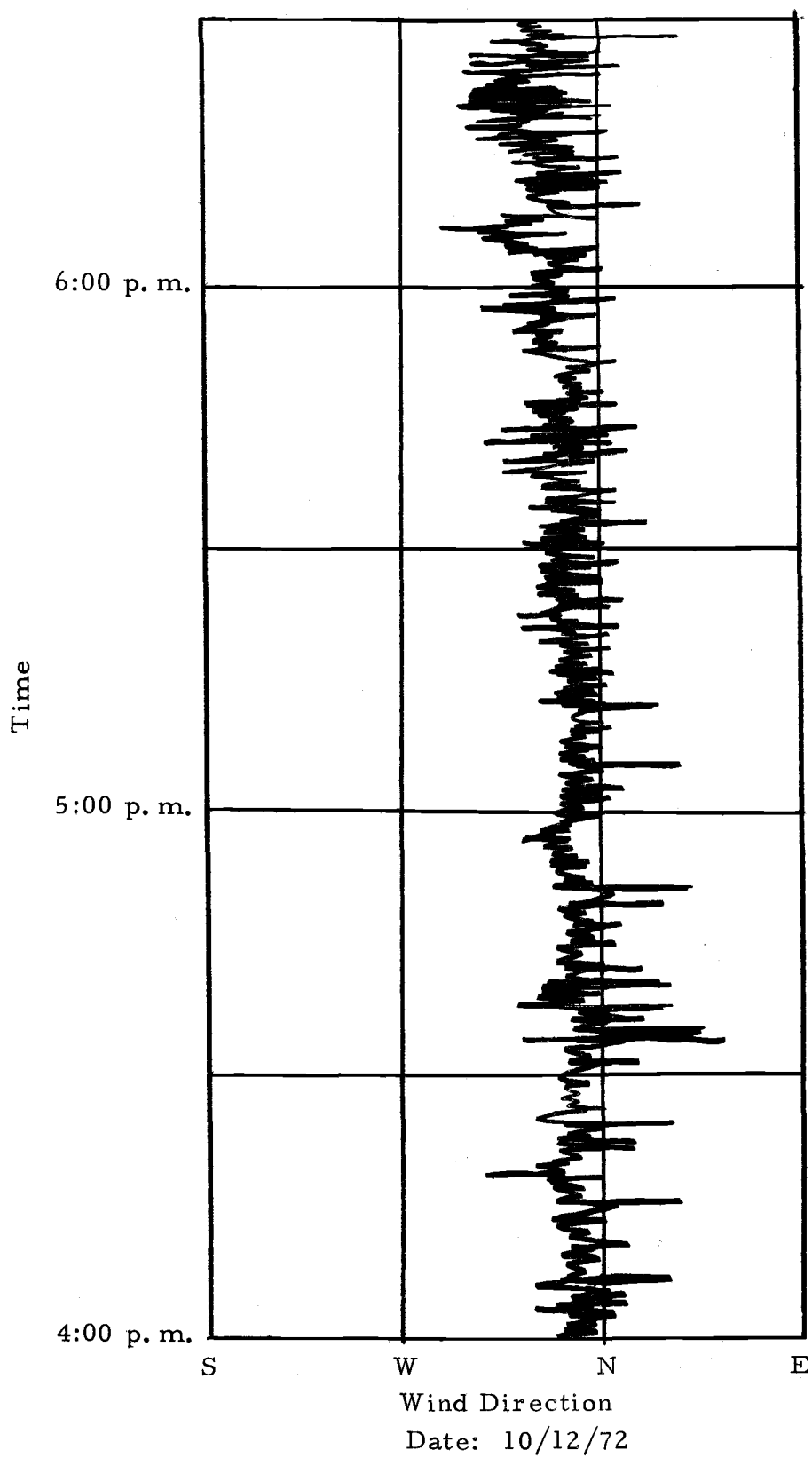
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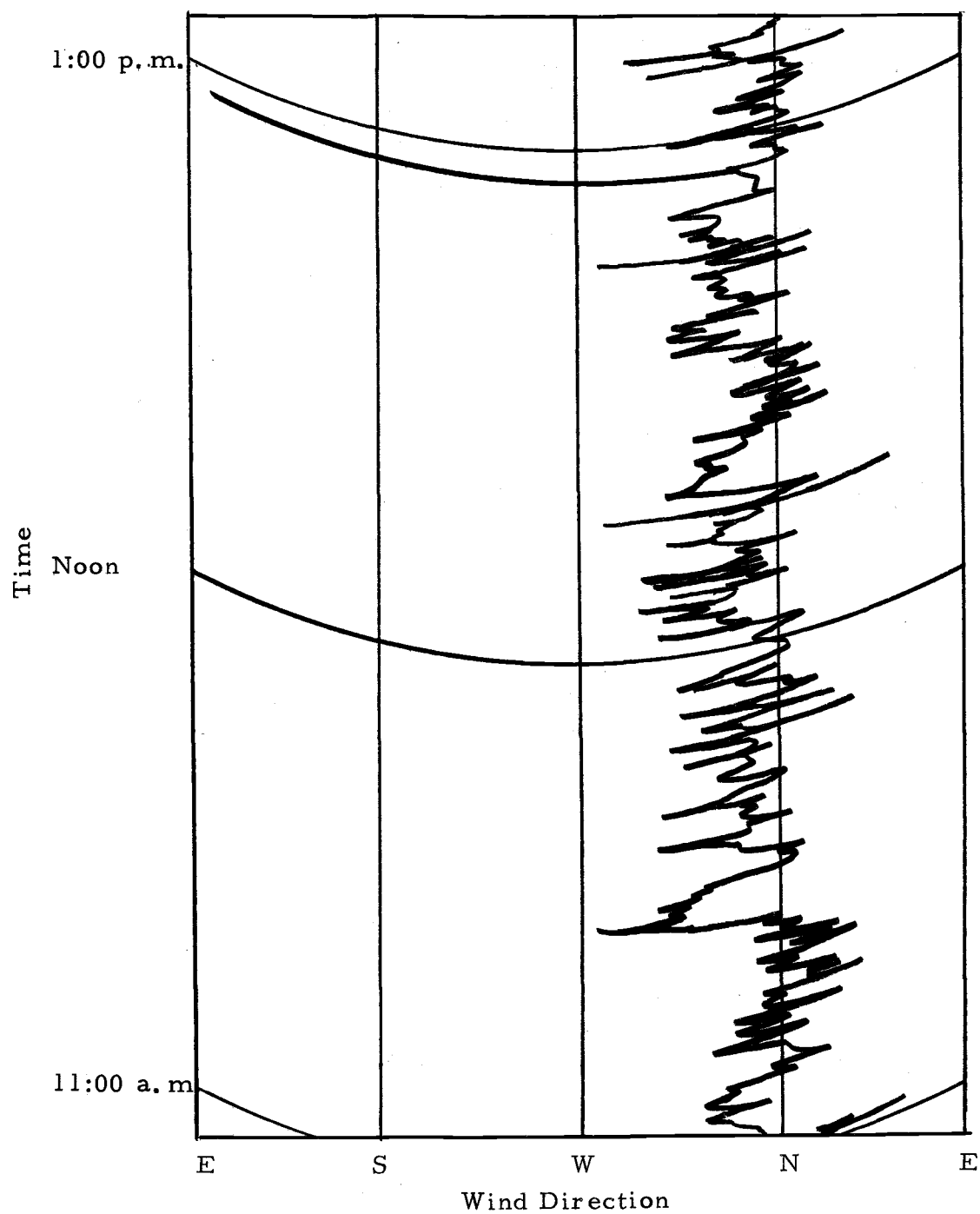


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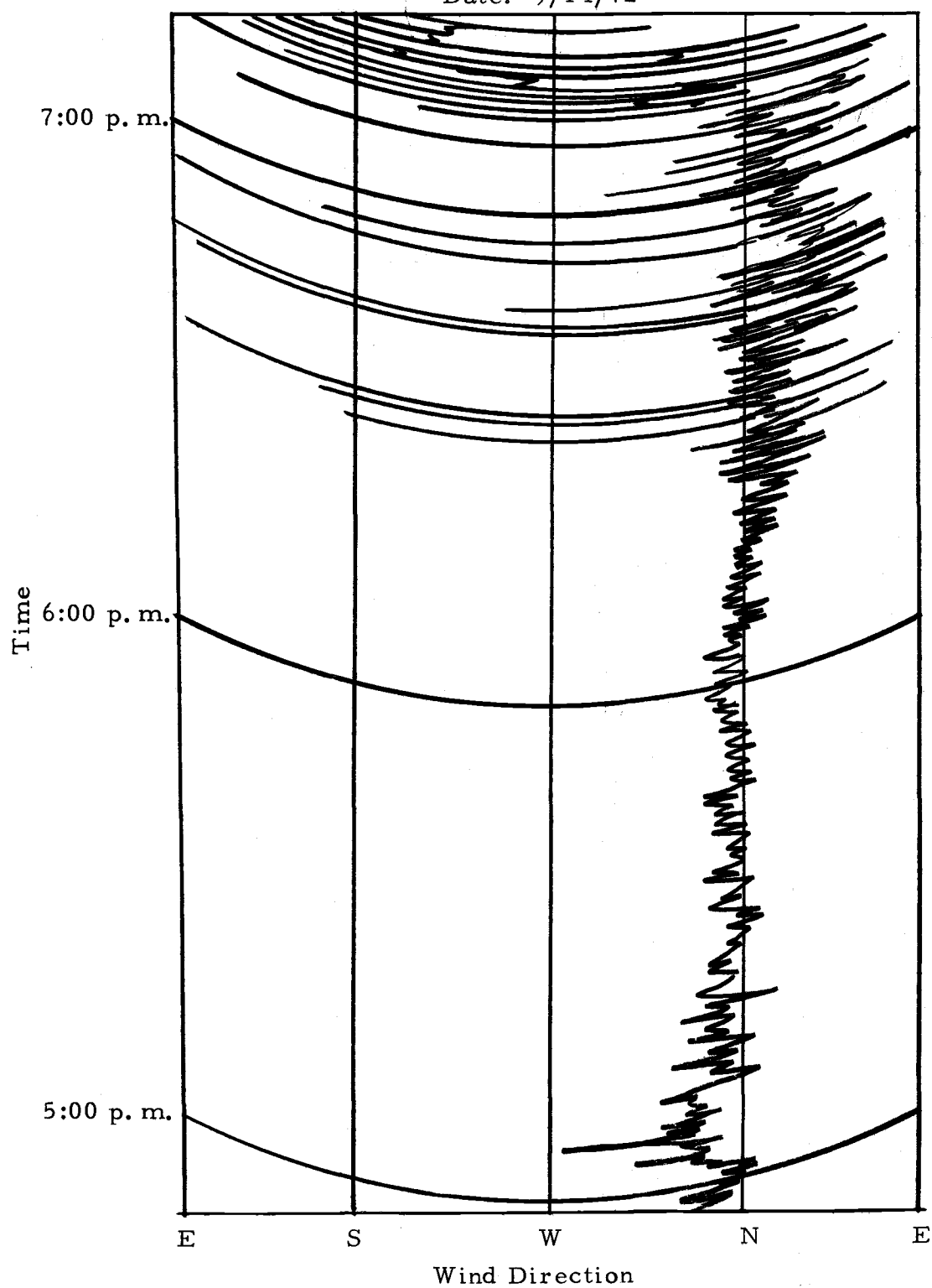
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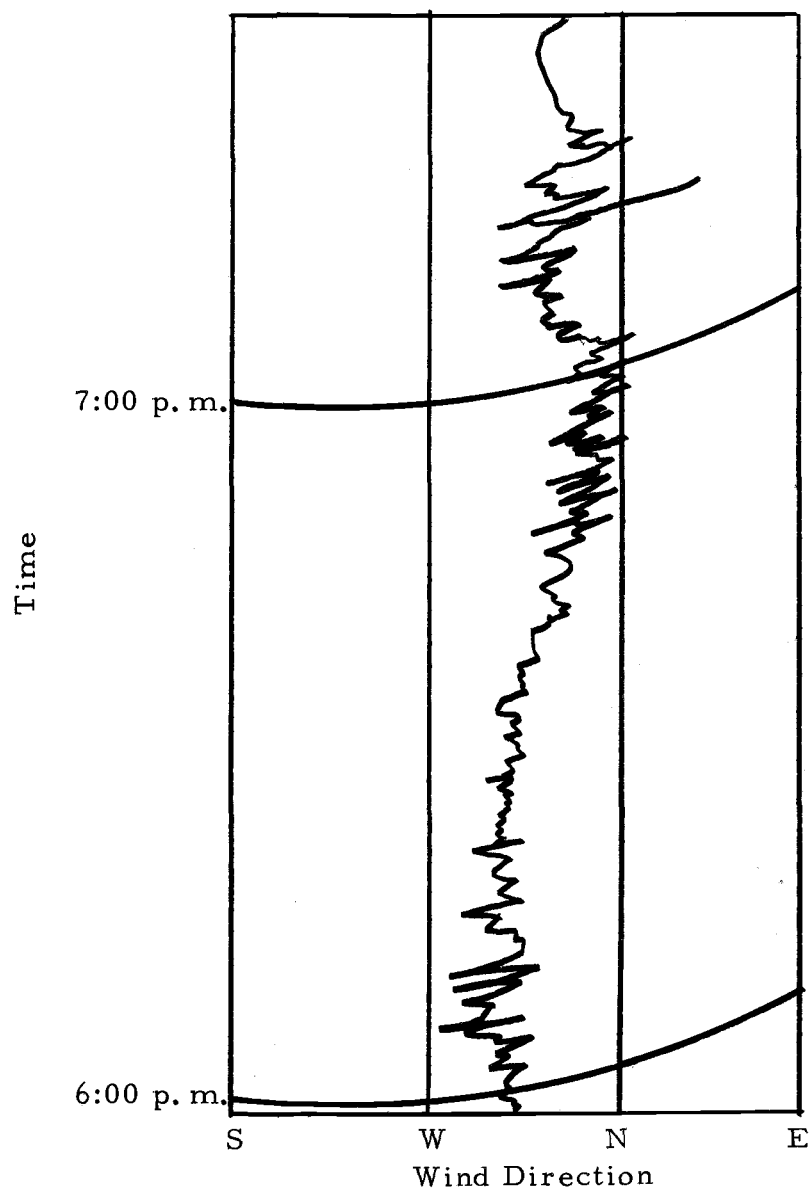
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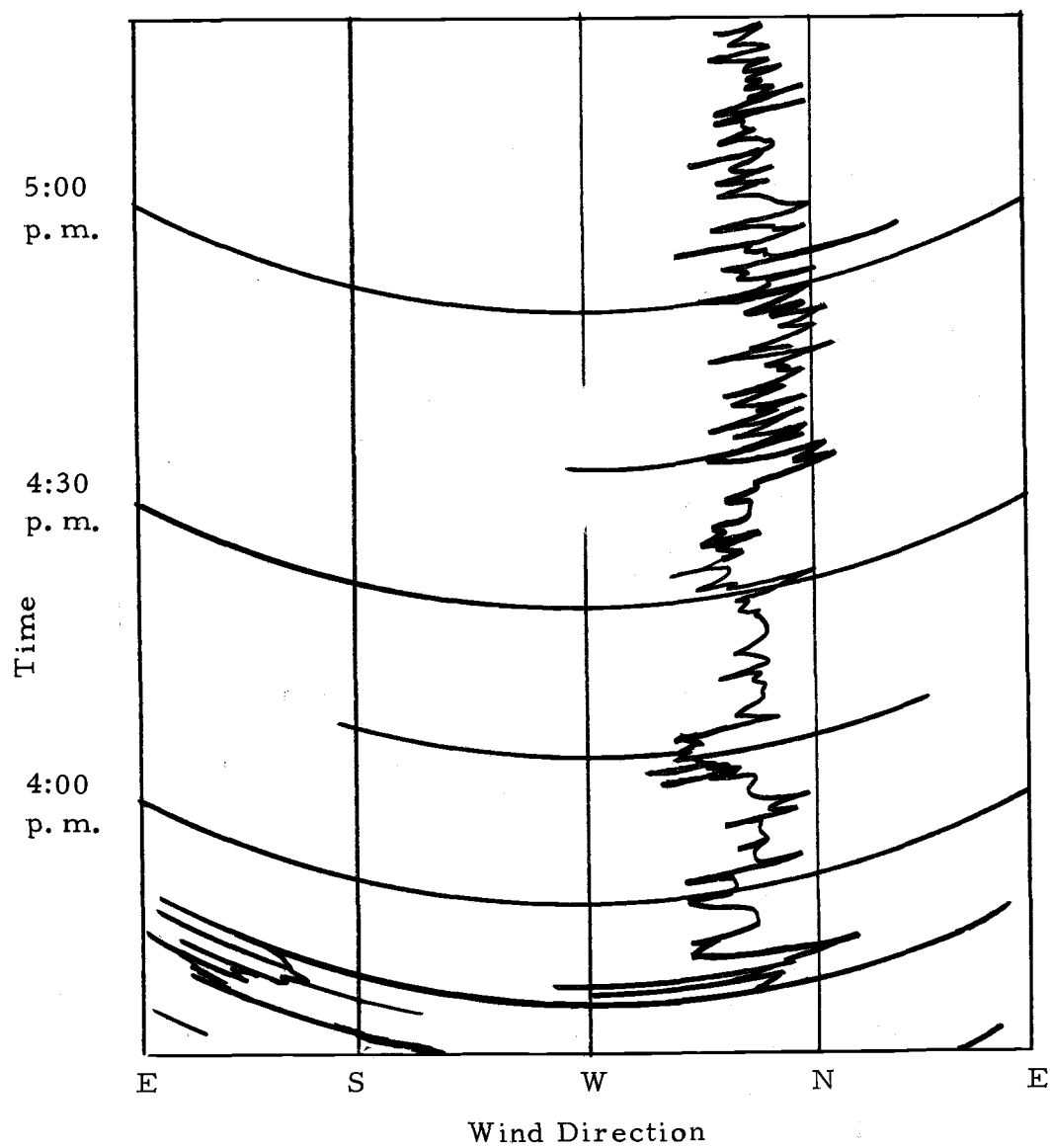
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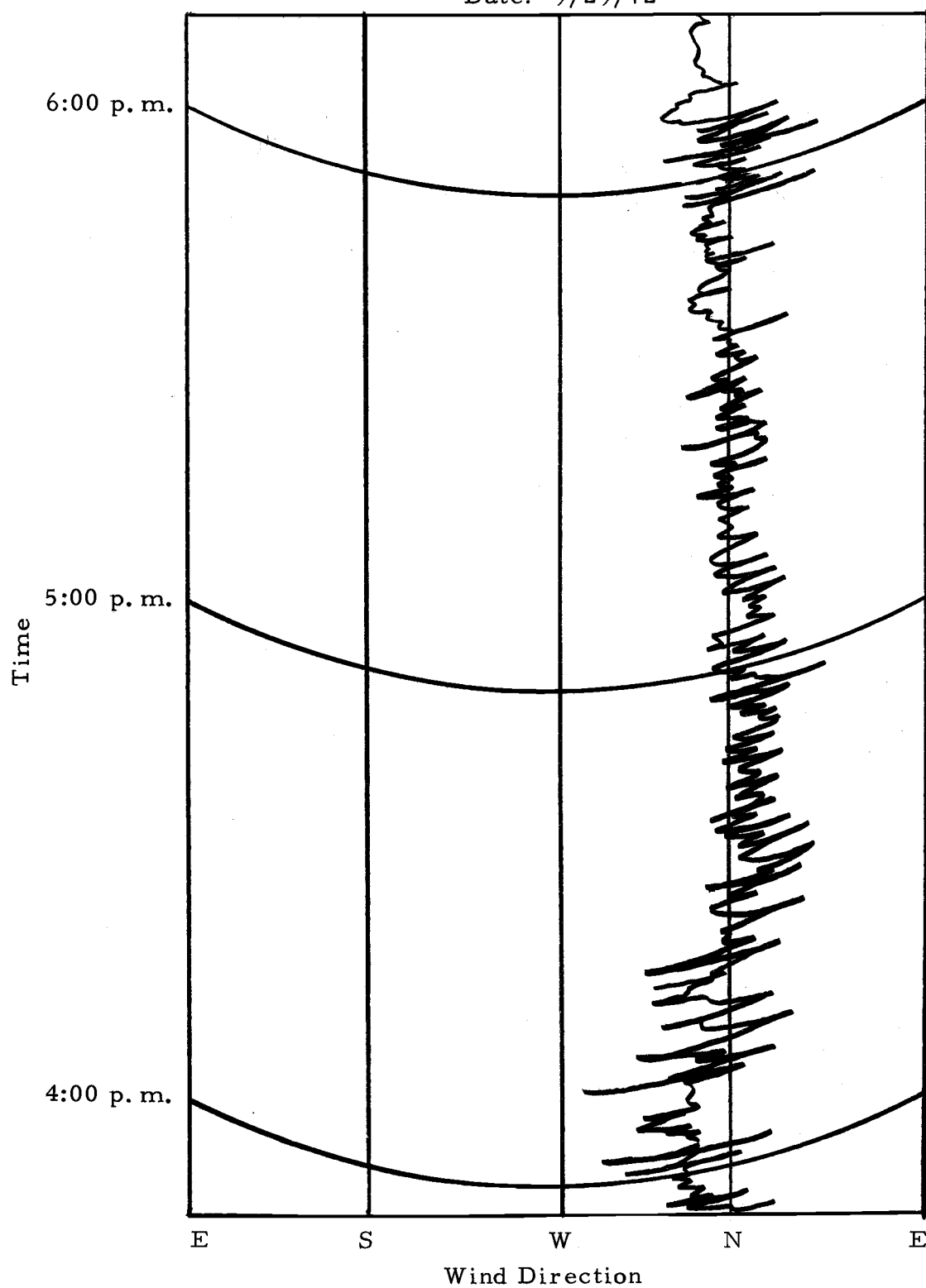
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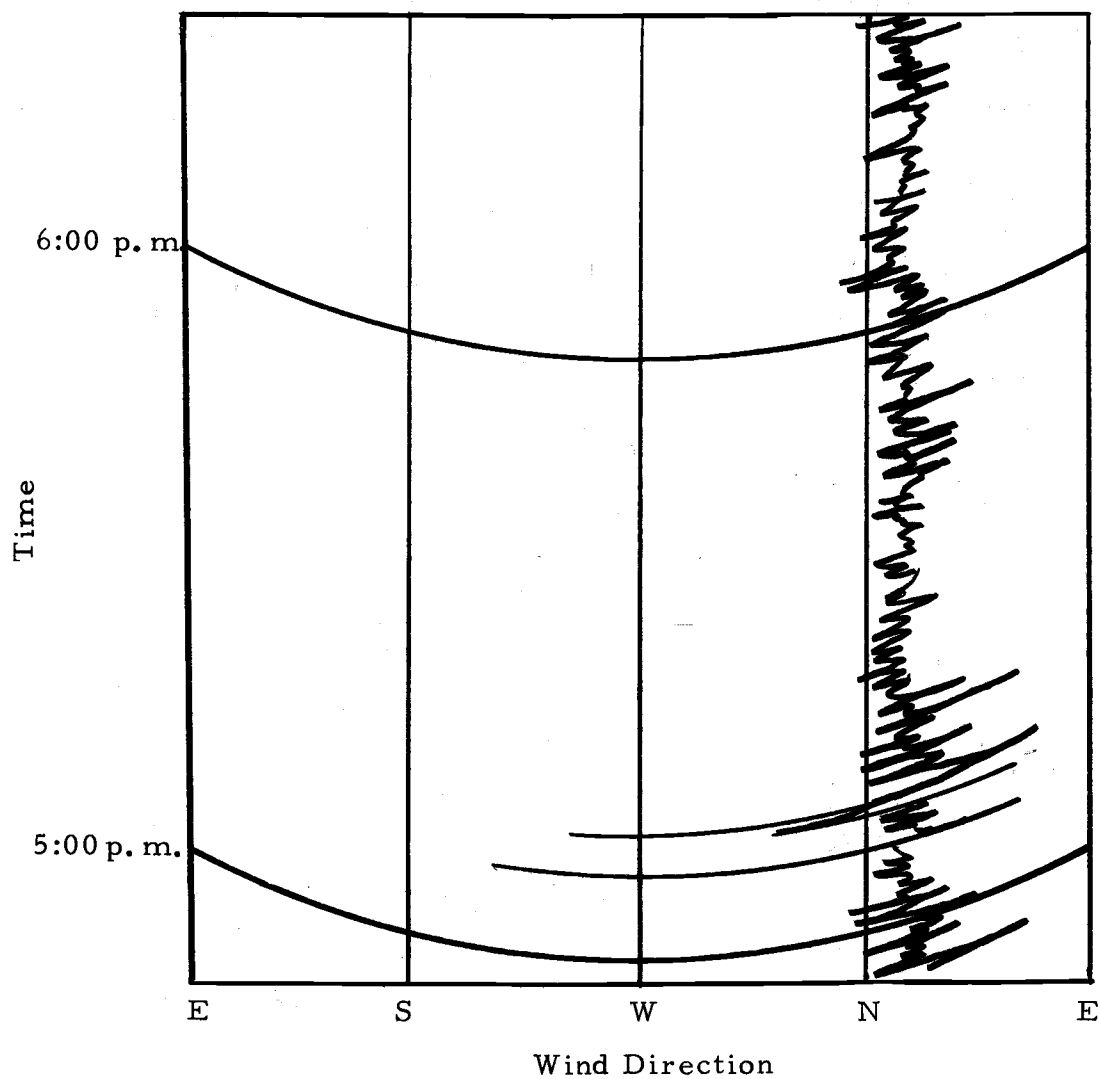
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Date: 9/29/72



Date: 10/14/72

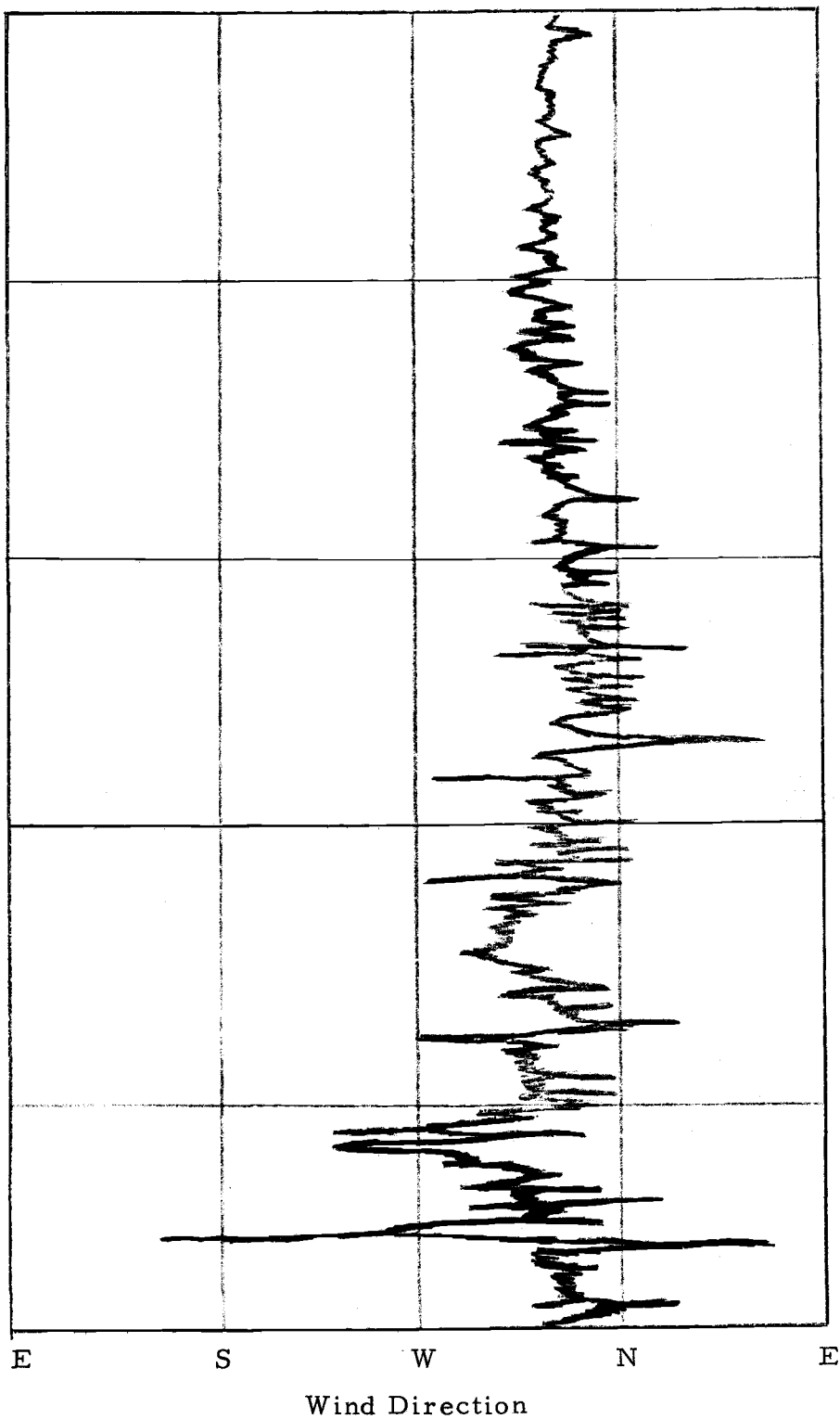


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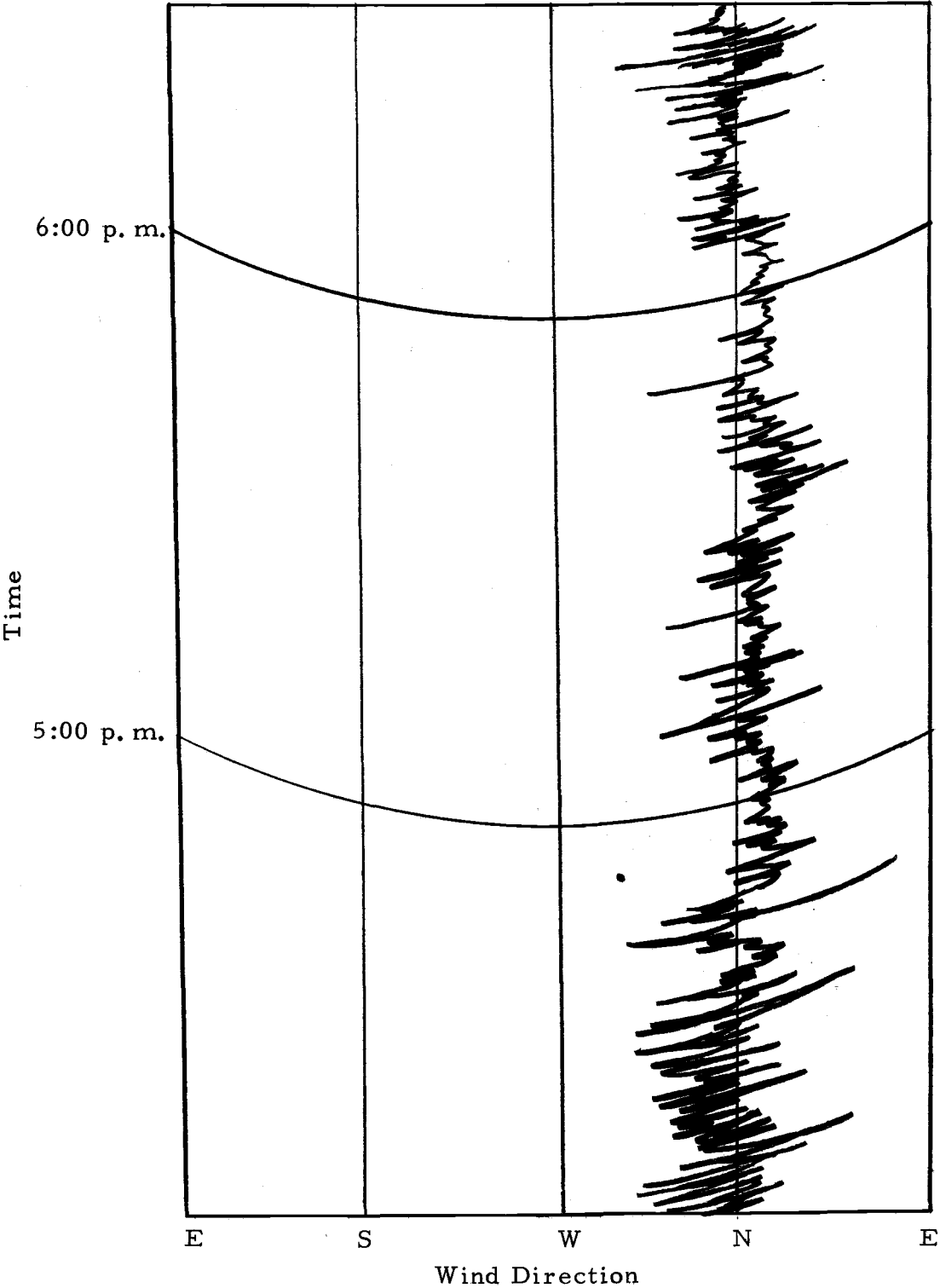
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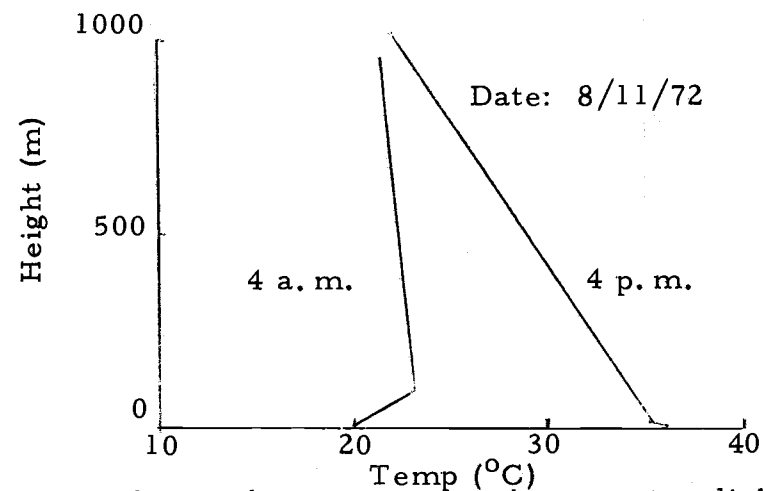
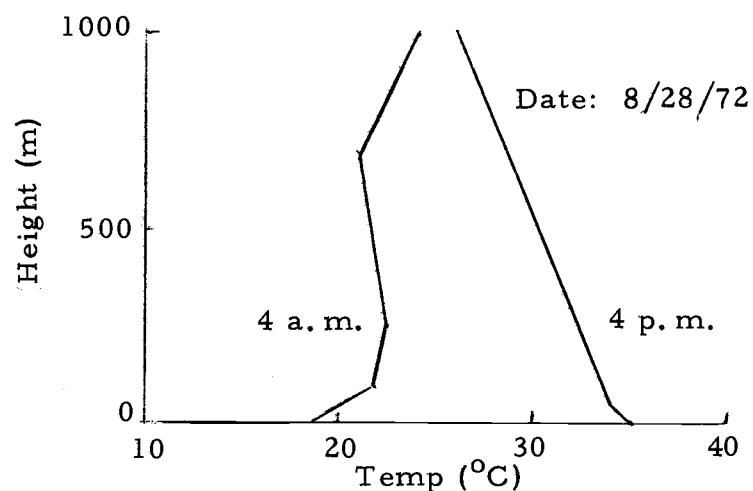
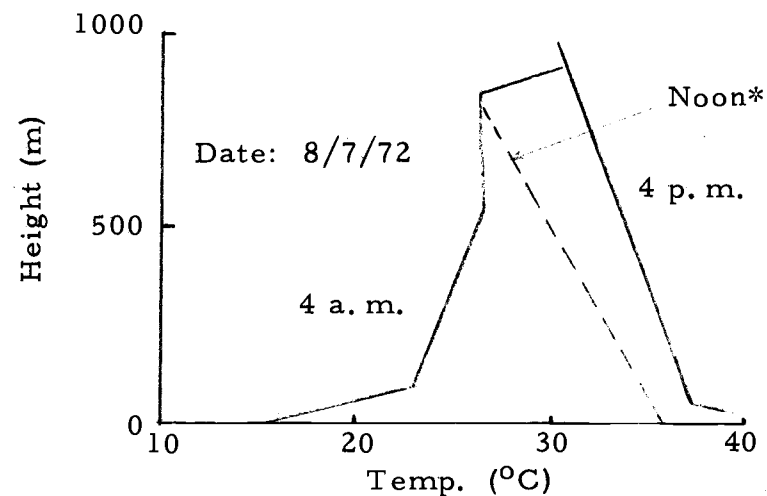
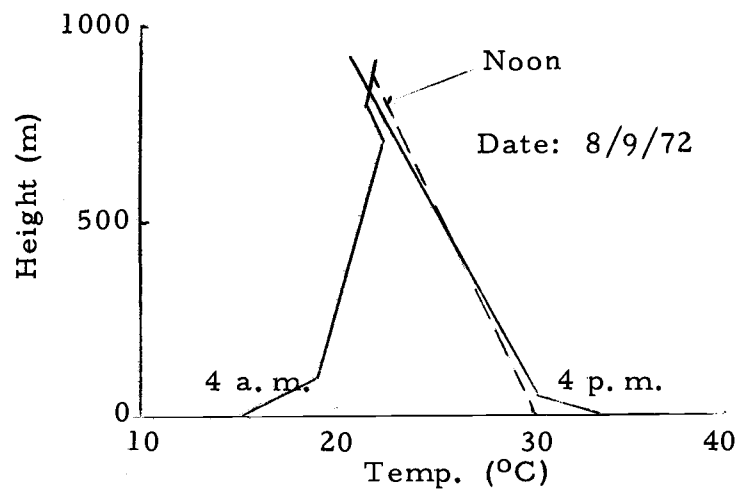
5:00 p. m.

4:00 p. m.



Date: 10/18/72





* The inversion height at noon was estimated by extrapolating the temperature lapse-rate adiabatically from the surface temperature at noon and was equal to 800 meters at the point of intersection of the lapse-rate curve at 4 a. m.

