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ATMOSPHERIC MEASUREMENT OF PHOTOCHEMICAL SMOG REACTIONS - A PRELIMINARY ANALYSIS

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ATMOSPHERIC MEASUREMENT OF PHOTOCHEMICAL SMOG REACTIONS - A PRELIMINARY ANALYSIS

by

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ABSTRACT

This research study was a brief feasibility study and field measurement program to determine whether the San Francisco Bay Area might provide meteorological and photochemical smog patterns that were especially conducive to field research on smog reaction processes. It was concluded from both climatological and field oxidant sampling that this was the situation if atmospheric data could be gathered over the waters of the Bay, particularly east and south of San Francisco. A detailed program to carry out such research was designed.

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I INTRODUCTION

Photochemical smog results from photochemical reactions in the atmosphere that occur when nitrogen oxides and hydrocarbons are present. The reaction products include ozone, peroxyacyl nitrates (PAN), aldehydes, and a variety of secondary reaction products. To date, knowledge of the photochemical smog reaction process is largely based on controlled experiments in laboratory test chambers and on statistical correlation analyses using atmospheric data on photochemical smog. In the latter case, most of the data have come from observations in the Los Angeles Basin.

As yet not satisfactorily resolved in the smog-forming process is the question of the importance of specific types of hydrocarbons, i.e., the olefins and other highly reactive types as compared to the less reactive aromatics. Another question is the significance of the ratio of nitrogen oxides to hydrocarbons in the photochemical mixture. Chamber experiments are now being used to judge the significance of hydrocarbon and NO_x reactivity to HC ratios in order to postulate smog formation mechanisms. Ultimately, such studies could serve as a basis for air pollution control regulations and air quality standards on photochemical smog constituents such as NO_2, hydrocarbons, and oxidant or ozone. Chamber studies cannot simulate all the variabilities of the real atmosphere, and thus increased efforts have been made to carry out detailed aerometric analyses in Los Angeles. A goal is a simulation model of photochemical smog.

The interpretation of aerometric measurements from Los Angeles, however, presents major problems. One of the more important is the very great complexity of the area sources and their emissions. For example,

any sampling station in Los Angeles will be surrounded by sources of both hydrocarbons and NO_x at distances varying from the street just outside the door to the freeway 20 miles away. As a result, each sample will contain a wide mixture of emissions that have had various histories, times for reaction, and exposures to atmospheric influences. Although partial evaluations of the Los Angeles aerometric data have been published, because of these and other difficulties, the analyses leave unanswered many questions about the real photochemical smog system.

II OBJECTIVES AND CONCLUSIONS

In the research study reported here, the objectives were:

(1) To review air pollution and meteorological data pertaining to photochemical smog in the San Francisco Bay area

(2) To carry out preliminary air sampling analyses to verify the existence of relative maximum concentrations of photochemical smog over the water areas of San Francisco Bay

(3) To determine whether the patterns of photochemical smog are such that a detailed sampling program would provide a unique opportunity to investigate the progress of smog reactions, and, if so, to design a detailed program to study smog reaction processes in this area.

In general, the conclusions that we have drawn from this initial feasibility study are as follows:

(1) Weather patterns in the San Francisco Bay area are such that air pollutants are carried over the waters of the Bay during almost all typical weather conditions and there are indications in local pollutant measurements that photochemical smog continues to persist after the contaminated air mass moves over the water. (Appendix A describes the general weather and climate of the Bay area.)

(2) Air sampling -- especially that done using an airplane on a heavy smog day -- showed that high oxidant concentrations indicative of photochemical smog reactions persisted over the Bay waters; however, we were unable to show in our limited sampling that the Bay was an area of relative maximum concentrations.

(3) The expected weather patterns and our observed oxidant data all indicate that detailed analyses of photochemical processes occurring over the Bay should provide valuable data on the atmospheric conditions that take place in time sequence in the development of photochemical smog.

III RESULTS AND DISCUSSION

The general approach to determining the feasibility of using San Francisco Bay as a site to study photochemical smog reactions was as follows:

a. Collect the oxidant measurement data upon which Sandberg and Thuillier[1] based their presentation and additional unpublished data from the Bay Area Air Pollution Control District. In addition, collect significant meteorological data from other sources for the smog season of 1967. These data would then be analyzed to determine if additional conclusions or different conclusions than those presented by Sandberg could be developed as a result of a broader data base.

b. The general climatology of San Francisco was analyzed based on topographical and meteorological factors with special emphasis on the historical patterns and trends of oxidant concentrations.

c. An oxidant measurement program was undertaken, both ground based and airborne, to add spatial and temporal resolution to the oxidant measurement data available from the Control District during the 1971 smog season.

d. The feasibility of undertaking a more comprehensive study to define photochemical processes over San Francisco Bay was investigated based on all the information required during this research program.

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1. Sandberg, J. S., and R. H. Thuillier, "Oxidant Levels over San Francisco Bay and Adjacent Land Stations," Bay Area Air Pollution Control District, San Francisco, Calif. Presented to 10th Methods Conference of the State Department of Public Health, San Francisco, Calif., February 1969.

A. Discussion of Sandberg and Thuillier Data

The stationary oxidant maximum occurring in the center of the Bay is inferred from the concentration isopleth maps included within Sandberg and Thuillier's presentation. However, insufficient data were available to conclude that the oxidant maximum remained stationary in the vicinity of the San Mateo Bridge. Neither in the text of Sandberg's report nor in his conclusions does he state that a stable, stationary oxidant maximum is maintained while wind pattern moves air through this region of high oxidant content. Five conclusions are drawn by Sandberg and Thuillier concerning the data obtained as background to this publication.

(1) Although there is no significant Bay effect, positive or negative, in the mean data, analysis on a case basis shows that conditions favoring adverse oxidant development over the District favor even higher levels over the Bay itself.

(2) Time-sequence studies demonstrate that the Bay is an important avenue of transport to oxidant clouds, not a significant sink or diffusive mechanism.

(3) Models implying lower concentrations over the Bay are refuted, and those implying higher values are, for an important class of circumstances, confirmed.

(4) Patterns of oxidant concentration or dosage reinforced by the midbay data support a broadly distributed community air pollution level, whose general features are well established by the existing station network.

(5) These patterns further support the mixing of oxidant precursors from area-wide sources so that the Bay and the surrounding land are equally involved as sites for the photochemical process of oxidant formation.

Further evaluation of the data on which Sandberg based his conclusions tends to substantiate his findings. However, the interpretation of his data in constructing the isopleth maps may not show the true picture of the oxidant-forming processes over the Bay.

When the Sandberg measurements were made, May through October 1967, BAAPCD monitoring stations had not been established at Fremont or at Burlingame. Therefore, the data available for evaluation in 1967 are less complete than are available for this study. The data on which Sandberg's paper is based were available, with the exception of the San Leandro monitoring station, and were acquired by SRI for analysis and evaluation. The San Leandro data have not been transcribed from recorder charts and would be expensive and time consuming to recover. In addition, some unpublished data from 1967 were acquired from the BAAPCD to supplement the available data. Meetings were held between SRI personnel and Sandberg and Thuillier to discuss and evaluate the 1967 study.

In 1967 from May through October, peak oxidant concentrations exceeded 10 pphm at all three stations, San Mateo Bridge, Redwood City, and San Jose during 37 days. During the same period in 1971, using Fremont instead of San Mateo Bridge data, peak oxidant exceeded 10 pphm for the three stations during 13 days. Figure 1 shows the pollution-monitoring sites of BAAPCD, the SRI mobile laboratory, and a typical aircraft monitoring track.

The Sandberg data were first reviewed with respect to meteorological conditions as reported at San Francisco Airport. The correlation of oxidant to meteorological factors is shown in Table 1 for both those days of high oxidant (11 pphm up) and those of low oxidant (0 → 5 pphm) for the period May through October 1967.

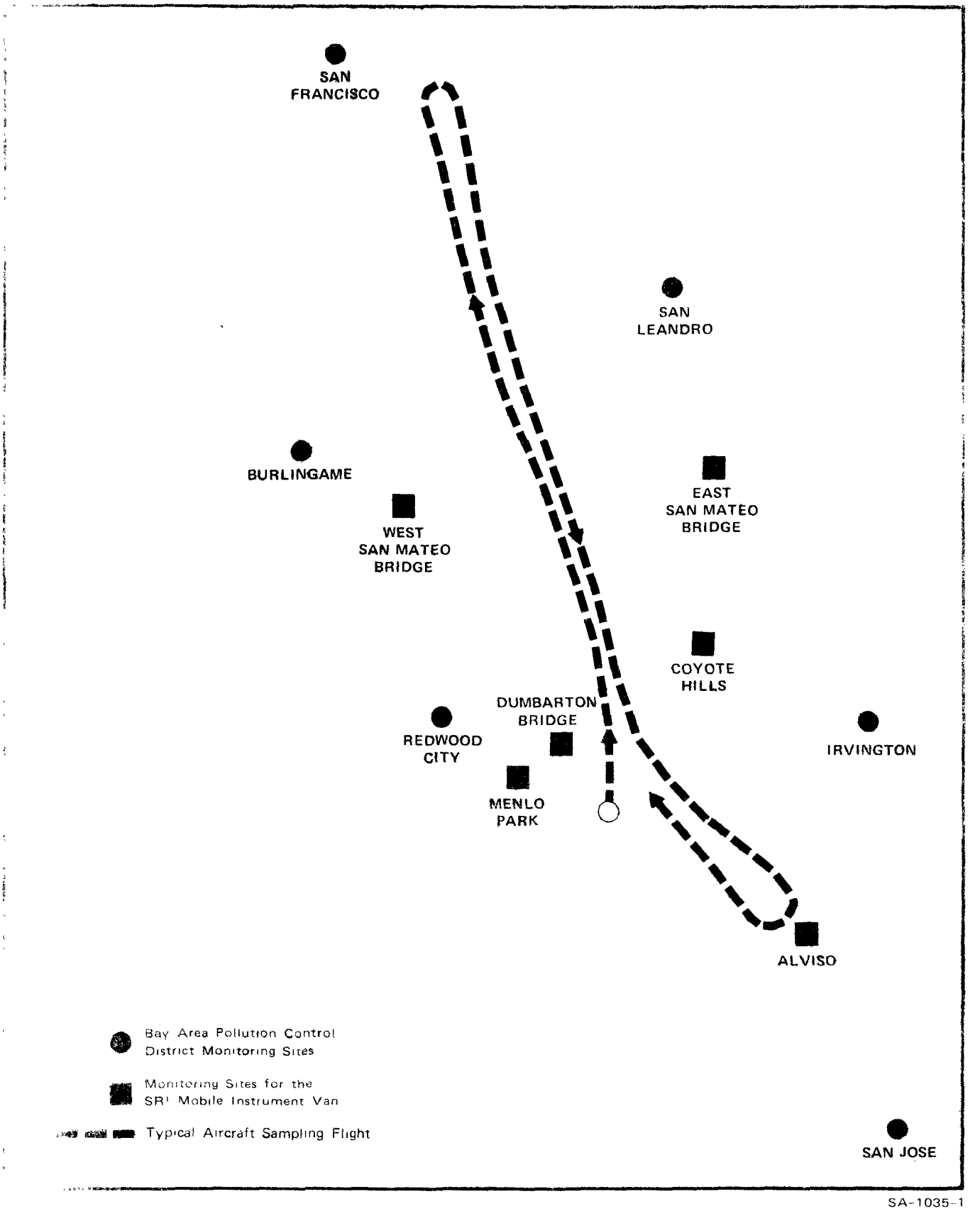

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FIGURE 1 POLLUTION MONITORING SITES

Table 1

SOUTH SAN FRANCISCO BAY
SMOG OXIDANT CORRELATIONS FOR 1967

Days When Oxidant Exceeded 11 pphm		Days When Oxidant Was Less Than 6 pphm	
Factors	Percent of Occurrences	Factors	Percent of Occurrences
Skycover		Skycover	
0	45	0	24
<2	65	<2	29.7
Wind speed		Wind speed	
<5 knots	30	<5 knots	0
<10 knots	75	<10 knots	12
<15 knots	100	<15 knots	74.5
Wind direction			
300 to 310°	80		
Days of week		Days of week	
Sunday	7.5	Sunday	19
Monday	17.5	Monday	17.5
Tuesday	20	Tuesday	11
Wednesday	15	Wednesday	11
Thursday	17.5	Thursday	14.3
Friday	10	Friday	11
Saturday	15	Saturday	15.9
Weekends	22.5	Weekends	34.9
Av Max Temp	79.2°F	Av Max Temp	67.7°F
Av ΔT (max-min)	24.4°F	Av ΔT (max-min)	14.5°F

The data clearly indicate relationships with specific meteorological conditions. The relationships between oxidant concentration and wind speed, wind direction, maximum temperature inversion height, sky cover, and temperature difference between daily maximum and minimum temperature were examined. The daily temperature differential and the wind speed relate particularly well with oxidant concentration. Inversion height should also be related well, but complete data were not available. Also included in Table 1 are data on frequency of occurrence for both high and low oxidant days with respect to days of the week and weekends. The only definite trend shows Sunday to be least frequently associated with high oxidant and most frequently associated with low oxidant.

Insufficient data are available from 1967 oxidant measurements to draw any conclusions concerning the formations of oxidant over the Bay other than the general ones drawn by Sandberg. However, analysis of the oxidant data from the three available stations does indicate certain trends that are not described by Sandberg.

Figure 2 shows the peak-hour of oxidant versus the number of occurrences during the 37 days of high oxidant at San Mateo Bridge, Redwood City, and San Jose. This figure indicates that the peak oxidant hours occur sequentially from north to south on the Bay. During the 37 days, nearly 70 percent of the peak hour concentrations occurred later in San Jose than at the San Mateo Bridge. The peak hour concentration at Redwood City occurred later than those of the San Mateo Bridge on about 60 percent of the days. Wind speed data obtained at San Francisco Airport cannot exactly represent wind speeds over the Bay. Sandberg believes topographical factors on the San Francisco Peninsula produce higher winds at San Francisco Airport than will occur a few miles south and west over the Bay. An examination of wind speeds observed at Moffett Field (located at the southern perimeter of the Bay) indicates that during

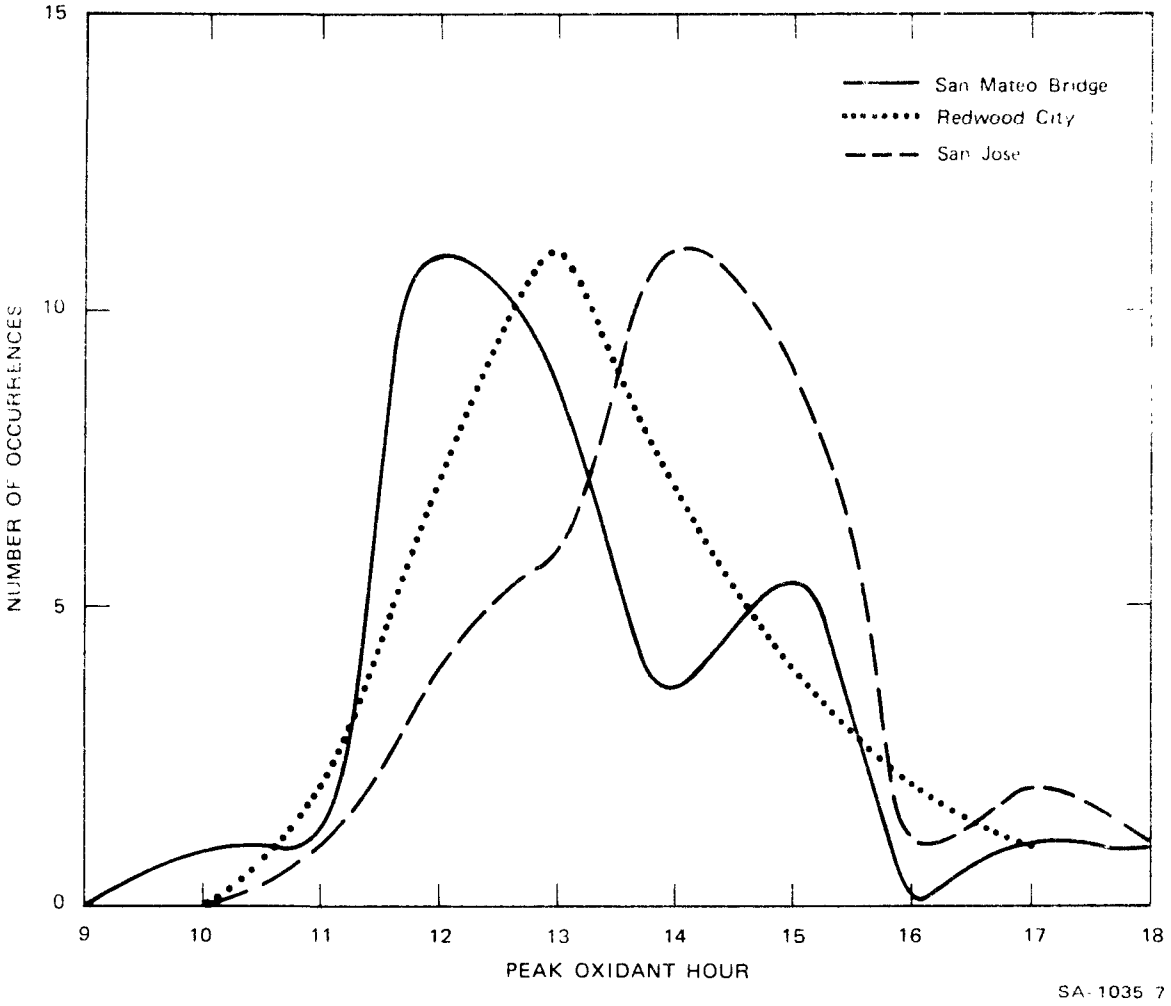

FIGURE 2 OXIDANT PEAK HOUR—OCCURRENCES DURING HIGH OXIDANT DAYS IN 1967

the 37 days of 1967, average observed wind speeds at Moffett Field were only 60 percent of the wind speeds observed at San Francisco Airport. The data from 1971 also show lower wind speeds over the South Bay; during the interval from May through October 1971, the average observed wind speeds at San Jose are only 39 percent of the wind speed averaged at San Francisco Airport and Oakland Airport.

The peak oxidant concentrations and the clock hours when peak concentration was observed for the three BAAPCD stations during the 37 days in 1967 when the concentration exceeded 10 pphm oxidant at all three stations are summarized in Table 2. In addition, Table 2 gives meteorological factors including inversion base height for this interval. The wind speeds are obtained from observations at San Francisco Airport, while the inversion base heights are obtained from Oakland Airport observations.

In spite of the obviously inadequate wind speed information, an attempt was made to correlate the peak-hour times differential between the San Mateo Bridge and San Jose during the days of interest in 1967 with wind speeds. The airline distance from San Mateo Bridge to San Jose is approximately 24 miles. Although there was a wide daily variation for individual days, the San Francisco wind data and the average difference between the times at which peak concentrations were observed at the San Mateo Bridge and at San Jose indicates an average travel distance of 25 miles. These averaged data thus indicate that the oxidant maxima moved down the Bay at velocities generally consistent with the velocities of the air parcels.

Discussion of 1971 Smog Season

The measurement objectives of this study were to obtain data during intervals of varied oxidant concentrations at locations both over and upwind to San Francisco Bay. Due to the limited time frame of this study, it was highly desirable to obtain the measurement data as soon as possible.

Table 2

OXIDANT AND METEOROLOGICAL FACTORS FOR DAYS THAT EXCEEDED 10 pphm OXIDANT AT SOUTH BAY BAAPCD STATIONS DURING 1967

Date	San Mateo Bridge		Redwood City		San Jose		San Francisco		ΔT[3,4]	Max[4] Temp	Sky[4] Cover	Res Wind Speed	Inversion Height (meters)
	Peak Conc	Time (PST)	Peak Conc	Time (PST)	Peak Conc	Time (PST)	Peak Conc	Time (PST)					
May 7	12	1510	15	1350	19	1705	7	1110	32	82	8	4.7	none
14	14	1450	13	1550	15	1720	12	1400	31	81	0	4.4	1390
15	20	1635	24	1635	19	1820	24	1610	32	85	0	5.7	1090
16	18	1350	20	1430	29	1620	14	1200	32	86	0	8.3	none
June 24	10	1320	13	1455	10	1335	3	1340	19	71	0	10.2	190
27	12	1310	12	1340	17	1435	3	945	19	71	1	8.9	260
28	21	1150	16	1155	25	1255	3	1340	25	77	0	12.2	260
29	16	1015	19	1120	19	1310	2	345	21	74	0	11.8	160
30	10	1145	20	1250	16	1530	2	1145	21	76	0	14.2	96
July 1	10	1225	13	1220	15	1340	2	1545	18	71	0	16.0	160
3	10	1155	12	1150	14	1430	5	930	17	70	8	14.4	170
11	30	1320	20	1255	22	1340	14	1030	31	85	0	11.7	210
12	10	1245	12	1410	13	1340	2	0345	16	70	1	18.9	140
26	17	1245	16	1315	18	1145	6	1030	31	84	0	12.3	300
27	17	1425	10	1320	20	1435	4	1430	31	86	9	8.8	200
28	38	1230	15	1320	20	1410	6	1030	29	87	5	12.7	220
Aug 1	16	1340	11	1335	16	1510	4	1310	22	76	2	7.4	320
3	10	1155	13	1230	16	1055[2]	4	1045	20	73	1	12.5	
8	15	1210	17	1240	12	1140	5	1040	17	72	8	8.3	200
12	25	1350	15	1410	16	1335	4	1040	23	74	0	14.4	200
13	10	1310	10	1440	15	1530	3	1230	21	74	0	15.7	
17	12	1250	15	1235	18	1400	2	1630	21	75	1	15.8	90
18	24	1320	11	1235	14	1345	3	1030	17	70	0	18.0	6
21	11	1215	12	1215	10	1445	3	1045	19	73	0	13.6	150
Sept 19	28	1535	18	1450	13	1430	21	1450	34	92	3	3.5	2330
20	35	1520	29	1545	21	1140	23	1120	31	92	7	5.0	none
25	12	1250	11	1250	13	1415	6	0210	14	71	2	9.9	190
26	19	1325	16	1255	14	1330	8	1115	18	74	2	10.8	90
Oct 6	11	1310	12	1345	10	1530	5	1200	21	73	0	7.6	1300
8	18	1450	16	1500	15	1455	9	1450	24	78	3	8.6	none
13	16	1220	12	1315	14	1430	6	1040	23	77	0	10.7	2680
16	34	1515	17	1420	13	1315			26	86	0	0.2	2100
17	17	1820[1]	19	1325	15	1200	10	1403	29	83	0	2.5	1720
18	16	1220	14	1130	19	1415	7	1130	19	72	2	15.3	2460
19	26	1425	19	1410	15	1615	8	1140	28	78	0	3.1	138
20	10	1510	14	1130	14	1325	5	1420	19	69	1	10.2	131
24	18	1125	16	1320	18	1220	9	1130	18	69	9	7.5	600

[1] A prior peak occurred at 1400.
[2] A secondary peak occurred at 1500.
[3] ΔT is daily maximum temp minus daily minimum temp.
[4] Meteorological factors from San Francisco Airport, Inversion heights from Oakland Airport.

On the other hand, oxidant measurements on days when conditions were not favorable would expend our resources with little benefit. The spring through midsummer of 1971 was remarkably free of smog in the San Francisco Bay area. The general trend through the summer indicated that if sampling was initiated only on smoggy days, there was a distinct possibility that insufficient data could be obtained during the 1971 season to form conclusions about the feasibility of an extended measurement program on San Francisco Bay.

Even when moderate concentrations of oxidant were present early in the day, strong afternoon winds often caused rapid dilution and short residence times, distorting the oxidant pattern over the Bay. These factors delayed the program; our oxidant measurements were often made on days of low photochemical activity.

1. Mobile Surface Oxidant Monitoring

In the first phase of the research, a Mast oxidant analyzer was mounted in a van and oxidant concentrations were measured at points along the perimeter of San Francisco Bay south of the San Mateo Bridge. The plan had been to measure the oxidant continuously while driving, and also at selected sites along the Bay perimeter. However, continuous mobile measurements were not practical, as heavy traffic concentrations and high local concentrations of NO resulted in negative interferences with the oxidant measurements. Ozone reacts rapidly with NO and, on heavily traveled freeways, there is a large excess of NO that reduces ambient ozone levels by as much as 80 percent. Thus the mobile van system was practically limited to making oxidant measurements at selected sites within the area of interest, but somewhat removed from major traffic streams.

The Bay Area Air Pollution Control District (BAAPCD) has several oxidant measuring stations located on the east and west sides of San Francisco Bay. The East Bay stations are located in San Leandro and Fremont. The West Bay sites are located in San Francisco, Burlingame, and Redwood City. The South Bay station is located inland at San Jose. The sites selected for measurement by the SRI van were located at the west end of the San Mateo Bridge, the east end of the San Mateo Bridge, the west end of the Dumbarton Bridge, Coyote Hills near the east end of Dumbarton Bridge, and Alviso on the south shore. The above locations are shown in Fig. 1.

The summer and fall of 1971 were remarkably free of days where observed concentrations exceeded 10 pphm of oxidant. The actual occurrence of oxidant days above the 10 pphm level decreased 39 percent from 1970 to 1971, with at least 23 percent of the decrease attributed to meteorological factors.[2] During the interval from May through October 1971 there were only 13 days where the peak oxidant concentration exceeded 10 pphm at all four South Bay BAAPCD stations; Redwood City, San Leandro, Fremont, and San Jose. On only 5 of the 13 high oxidant days did the peak concentrations exceed 15 pphm at all four stations. The presence of high oxidant concentrations at these four stations was presumed to indicate high oxidant concentrations throughout the South Bay area and hence, days suitable for data analysis.

The peak oxidant concentration and peak hour data are given in Table 3, and the pertinent meteorological data in Table 4 for the days in 1971 in which the odixant concentration exceeded 10 pphm at all four South Bay BAAPCD monitoring stations. The peak concentrations and peak hours are given for the Burlingame and San Francisco BAAPCD stations as well. The mean wind speed designated central is an average of the winds observed at

2. Bay Area Air Pollution Control District Information Bulletin, San Francisco, California, January 7, 1972.

Table 3

OXIDANT CONCENTRATIONS ON PEAK HOUR FOR THE 13 DAYS IN 1971 WHEN OXIDANT EXCEEDED 10 pphm
AT FOUR SOUTH BAY BAAPCD SITES

Date	San Francisco		Burlingame		Second Peak	San Leandro		Redwood City		Second Peak	Fremont		San Jose		Second Peak
	Peak Oxid	Time (PST)	Peak Oxid	Time (PST)		Peak Oxid	Time (PST)	Peak Oxid	Time (PST)		Peak Oxid	Time (PST)	Peak Oxid	Time (PST)	
June 16	2	0850	6	1015		12	1155	11	1150		19	1205	12	1310	
Sept 3	4	1420	4	1235		14	1415	11	1410		15	1410	12	1625	
4	5	1055	8	1150		18	1345	13	1450		21	1450	10	1620	
8	6	1330	6	1120		24	1340	13	1315		20	1435	16	1425	
13	24	1210	20	1410		39	1530	32	1410		37	1610	19	1210	(1700)
14	26	1250	15	1425		18	1655	19	1330	1500, 1600	29	1540	15	1335	1500, 1700
15	5	1015	14	1115		22	1315	19	1335		29	1450	19	1550	
19	3	1400	4	1425		12	1335	12	1410		18	1435	12	1610	
Oct 3	3	1120	4	1320		15	1250	13	1515		18	1420	11	1645	
4	7	1400	8	1450		20	1430	14	1545		21	1550	12	1710	
5	8	1120	11	1245		27	1430	22	1550		32	1550	19	1710	
12	15	1245	13	1405		26	1510	15	1545		23	1550	13	1450	
13	1	1130	3	1450	(1300)	13	1220	12	1350		22	1400	15	1415	

Table 4

METEOROLOGICAL FACTORS FOR THE 13 DAYS IN 1971 WHEN OXIDANT EXCEEDED 10 pphm AT FOUR SOUTH BAY BAAPCD SITES

Date	Mean Wind Speed (mph)		Maximum Temperature		ΔT San Francisco	Skycover San Francisco	Stability Factor	
	Central	San Jose	Central	San Jose			Oakland	San Jose
June 16	8.2	3.7	80	95	19	0	15	11
September 3	7.2	3.2	80	88	29	0	2	2
4	8.2	3.3	86	96	31	1	8	7
8	8.7	3.4	83	93	31	0	12	12
13	6.4	1.9	98	106	42	0	20	19
14	6.7	2.5	100	108	38	0	19	17
15	8.4	2.3	94	106	33	0	17	15
19	9.2	2.6	75	89	28	0	14	13
October 3	7.8	2.1	74	82	28	0	9	12
4	5.9	1.8	81	89	35	0	16	14
5	7.4	1.9	82	92	28	0	15	14
12	6.0	1.5	88	90	31	5	25	26
13	9.6	1.8	71	87	17	0	27	19
Oxidant Day Average	7.7	2.5	84	94	30			
Non-oxidant Day Average	10.8	4.1	68	78				

Bay Area Weather Factors in table include: Mean wind speed in mph for Central (C) averaged from SFO and OAK airports, Mean max temperature in °F for C averaged from SFO, OAK, and San Rafael. Stability factor is temperature (°F) at 2500 feet minus that at surface, representing low-level inversion strength at OAK, San Rafael, and SJ. Vertical mixing decreases with algebraic value of stability factor.

San Francisco and Oakland Airports. Likewise, the central maximum temperature is an average of the maximum temperatures observed at both San Francisco and Oakland Airports. The stability factor is determined from soundings at Oakland and San Jose and represents the temperature at 2500 feet minus the surface temperature. This stability factor should represent the inversion strength where positive numbers indicate the stable conditions of an inversion and negative numbers lapse conditions.

The 13 days tend to be classic examples of conditions conducive to the formation of high concentrations of oxidants. The unusual aspect is that the oxidant concentrations were not higher, as would be inferred from historical oxidant and meteorological data. During the 13 days, the wind speeds for the central region were 71 percent of the average wind speed for the 6 months' interval from May through October. The San Jose wind speeds were only 61 percent of the 6-month average. The average oxidant day temperatures for the Central bay and for San Jose were each 16 degrees F higher than the average temperatures for all the days of the interval. The factor ΔT (difference between daily maximum and minimum temperatures) indicates that insolation values were high. The stability factor indicates the presence of an inversion with stable conditions and reduced mixing. All of these conditions are conducive to the formation and entrapment of oxidant within the lower level of the atmosphere.

The peak oxidant concentrations and the clock hour when these concentrations were reached at the BAAPCD monitoring stations (shown in Table 3) definitely indicate the trend of an oxidant maximum moving down the Bay. In general, the peak hour occurred somewhat earlier at the sites on the western side of the Bay than at complementary locations on the East Bay side. San Francisco peak hours were often anomalous and cannot be related to the peak hours of the more southern station. The peak hour of oxidant at Burlingame usually preceded the peak hour

observed at Redwood City. The peak hour observed at Redwood City usually preceded that observed at San Jose. Similarly, on the East Bay sites, the oxidant peak hour occurred first at San Leandro, followed by Fremont, then finally at San Jose. In three instances, noted in Table 3, a secondary peak was observed at a time that tended to support the concept of a moving oxidant maximum. The peak hour time differential with respect to observed wind speeds tends to indicate that the rate of travel of the oxidant maximum is somewhat less than could be attributed to advection by wind. However, the wind speed varies considerably through the South Bay, and quite possibly the observed wind speeds are not representative of the area of interest.

Two types of sampling patterns were used to obtain the oxidant data with the SRI van. First, measurements were obtained sequentially in a circular pattern at sites as follows: Menlo Park, West and East San Mateo Bridge, Hayward, Coyote Hills, Alviso, Dumbarton Bridge, Coyote Hills, Alviso, and Menlo Park. This sampling pattern was designed to obtain data during the anticipated peak oxidant hours at the San Mateo Bridge, and then to proceed southward for measurements at the southern sites prior to peak oxidant hour. The SRI van was located at each sample site about one-half hour.

A variation of this circular pattern, but only encompassing the southernmost end of the Bay, was also used for oxidant sampling. In another pattern, the van was located at a sampling site for longer intervals to observe the passage of the oxidant peak. The van was then moved and relocated at a more southerly site to observe the peak oxidant passage. Obviously the second technique limits the number of sample sites at which measurements can be made during a single sampling day. However, a more accurate determination of peak oxidant hour can be obtained through the use of the second sampling pattern with longer sampling intervals at a few selected sites.

Table 5 shows the oxidant concentration data along the pertinent meteorological factors on the days during May through October when oxidant measurements, both surface and airborne, were made by SRI. In addition, the measurements from the BAAPCD monitoring stations are included. SRI made measurements on 16 days, 6 of which coincided with the 13 days when oxidant levels exceeded 10 pphm at Redwood City, San Leandro, Fremont, and San Jose. The oxidant concentration values obtained by the SRI mobile van are seldom inconsistent with the moving oxidant peak hypothesis. The sampling rationale of the mobile van, as described previously, does not lend itself to locating the peak oxidant hours at a number of sites during any one day. However, the measurement of oxidant concentrations at times other than the peak hours can provide useful information concerning trends of oxidant concentrations and oxidant transport within the South Bay. On only one sampling day, May 19, 1971, were the observed concentrations inconsistent with the moving oxidant maximum hypothesis. On two days, June 18 and September 14, 1971, the data are not definitive because they were not in the right location at an appropriate time for observation of the peak concentration. The remainder of the days definitely indicate a southward transport of the oxidant maximum.

The data show a general trend of higher oxidant concentrations and a later peak hour sequentially from northwest to southeast during days conducive to oxidant formation. Since this sequence correlates well with wind direction and velocity, it substantiates the hypothesis that area of oxidant maximum moves down the Bay as a function of the wind.

2. Airborne Oxidant Monitoring

On October 4 and 5, 1971, aerial oxidant surveys were made over San Francisco Bay. These were days of high oxidant level with high temperatures, light winds, and well-developed inversion layers at about 2000 feet.

Table 5

GROUND-BASED OXIDANT MEASUREMENTS

Date	Location	Peak		Observed		Wind Speed	Average Wind Speed	Av Dir	Day Leng	I	Skycover	Stability Facto
		Oxid Conc	Time (PST)	Oxid Conc	Time (PST)							
May 11	SF	3	0930				13.2	270	67	18	0	
	Burl	3	1010									
	RC	5	1040									
	MP	5	1100	4	1030							
				4	1200							
				4	1500							
	Al	5	1330									
				4	1410	22						
	SJ	7	1320				4.6		79			1
	Oak						9.8	270	67	16	0	1
	SL	4	1300									
	CH	5	1300			15						
	Fre	5	1300									
May 17	SF	3	0510				13.2	290	68	22	3	
	Burl	5	1010									
	W San Mat Br	5	1330									
	RC	5	1355									
	MP	6	1300									
				5	0835							
	Al	6	1500	5	1000	9 5						
	SJ	6	1450				5.2		77			-8
	Oak						11.7	270	71	21	2	1
	SL	4	1115									
	CH			6	0915	4						
				5	1420	18						
	Fre	--	--									
May 19	SF	4	0210				15.7	270	67	17	5	
	Burl	4	2350									
	W San Mat Br			5	1252	15						
	E San Mat Br			5	1320	10						
	RC	7	1910									
	MP	5	1230									
				4	1540							
	Al	5	1410			9						
	SJ	5	1220				4.0		75			-2
	Oak						10.9	280	66	15	4	2
	SL	6	1235									
	CH			5	1410	10						
	Fre	8	1240									

Note: SF - San Francisco
Burl - Burlingame
RC - Redwood City
MP - Menlo Park
Al - Alviso
SJ - San Jose
Oak - Oakland
SL - San Leandro
CH - Coyote Hills
Fre - Fremont

W San Mat Br - West San Mateo Bridge
E San Mat Br - East San Mateo Bridge

Table 5 (Continued)

Date	Location	Peak		Observed		Wind Speed	Average Wind Speed	Av Dir	Max Temp	ΔT	Skycover	Stability Factor
		Oxid Conc	Time (PST)	Oxid Conc	Time (PST)							
May 16	SF	2	0850				11.2	290	83	27	2	
	Burl	6	1015									
	W San Mat Br			4	1250	10						
	E San Mat Br			3	1332	10						
	RC	11	1200									
	MP	11	1200									
				3	0800							
				4	1015							
				5	1100							
				8	1130							
				9	1230							
	Al			1	1500							
	SJ	6	1110				3.7		95			11
	Oak						5.2	290	81	24	3	15
	SL	5	1320									
	CH			3	1410							
	Fre	6	1230									
June 17	SF	3	0510				12.1	270	83	29	1	
	Burl	5	1010									
	W San Mat Br			6	1030							
	E San Mat Br			7	1100							
	RC	8	1215									
	MP			1	0900							
				2	1000							
				3	1100							
				4	1400	25						
	Al	9	1230									
				3	1442							
	SJ	6	1110				3.9		93			6
	Oak						7.3	260	77	21	1	11
	SL	10	1220									
	CH			8	1130	3						
				3	1345	20						
	Fre	15	1220									
June 18	SF	3	0215				12.8	290	70	16	5	
	Burl	2	0040									
	RC	3	1030									
	MP	3	1045	2	0900							
				2	1110							
				2	1310							
	SJ	4	1120				5.3		81			0
	Oak						9.8	270	70	13	5	5
	SL	4	1100									
	Fre	5	1100									

Table 5 (Continued)

Date	Location	Peak		Observed		Wind Speed	Average Wind Speed	Av Dir	Max Temp	[illegible]	Skycover	Stability Factor
		Oxid Conc	Time (PST)	Oxid Conc	Time (PST)							
July 9	SF	1	1200				15.5	270	67	13	3	
	Burl	1	2120									
	W San Mat Br			1	1020	15						
	E San Mat Br			1	1040	15						
				1	1325	20						
				1	1525	20						
	RC	3	1735									
	MP	2	1030									
				1	1452							
	SJ	3	1210				5.2		77			-9
	Oak						8.9	270	67	10	1	-2
	SL	2	1450									
	Fre	3	1055									
Aug 10	SF	3	0150				13.7	300	75	19	1	
	Burl	2	0420									
	RC	7	1320									
	MP			4	1225							
	AI			6	1540	14						
	SJ	17	1155				3.3		95			22
	Oak						7.5	280	71	14	1	26
	SL	7	1330									
	CH	6.5	1415	6	1330	8						
				6	1520							
	Fre	15	1415									
Aug 12	SF	2	0235				12.9	270	71	14	1	
	Burl	1	0105									
	W San Mat Br			3	1123							
	E San Mat Br			3	1200							
	RC	5	1210									
	MP			3	1025							
				2	1520							
	AI			1	1355							
				3	1425							
	SJ	7	1235				1.3		82			1
	Oak						13.2	270	68	9	5	0
	SL	1	1115									
	CH	4	1215	3	1235							
				3	1410							
	Fre	5	1246									
Aug 19	SF	3	0120				8.6	290	75	23	3	
	Burl	--	--									
	W San Mat Br			2	1215							
	E San Mat Br	6.0	1240									
	RC	5	1150									
	MP			1	1140							
				2	1550							
	AI			6	1425							
	SJ	7	1320				5.1		81			13
	Oak						10.9	280	66	15	4	12
	SL	7	1330									
	CH	6	1420									
	Fre	18	1435									

Table 5 (Continued)

Date	Location	Peak		Observed		Wind Speed	Average Wind Speed	Av Dir	Max Temp	ΔT	Skycover	Stability Factor
		Oxid Conc	Time (PST)	Oxid Conc	Time (PST)							
Sept 3	SF	4	1420				8.2	290	84	29	0	
	Burl	4	1235									
	RC	11	1410									
	MP	19	1420									
	Al			15	1530							
	SJ	12	1625				3.2		88			2
	Oak						6.2	310	79	22	1	2
	SL	14	1415									
	Fre	15	1440									
Sept 9	SL	3	0050				11.1	290	79	27	0	
	Burl	5	1120									
	W San Mat Br			2	1055							
	E San Mat Br			3	1130							
	RC	10	1255									
	MP			7	1425							
	Al			10	1330							
	SJ	6	1500				3.1		89			10
	Oak						6.6	300	76	19	2	11
	SL	11	1345									
	CH	8	1200									
	Fre	10	1245									
Sept 11	SF	28	1250				7.5	280	103	38	0	
	Burl	15	1425									
	W San Mat Br			4	1050							
				4	1430							
	E San Mat Br			2	1155							
				10	1500							
	RC	19	1330									
	MP			5	1035							
				10	1605							
	Al			10	1215							
				10	1248							
				9	1305							
				10	1526							
				10	1540							
	SJ	15	1335				2.5		108			17
	Oak						5.9	310	96	29	0	19
	SL	18	1655									
	CH			5	1010							
				10	1345							
	Fre	29	1540									

Table 5 (Concluded)

Date	Location	Peak		Observed		Wind Speed	Average Wind Speed	Av Dir	Max Temp	ΔT	Skycover	Stability Factor
		Oxid Conc	Time (PST)	Oxid Conc	Time (PST)							
Sept 15	SF	5	1015				8	300	98	[illegible]	0	
	Burl	14	1115									
	W San Mat Br			5	948							
				11	1410							
	E San Mat Br			10	1029							
				12	1425							
	RC	19	1335									
	MP			3	0855							
				8	1616							
	Al	19	1550									
				11	1145							
	SJ	19	1550				2.3		106			15
	Oak						8.2	320	91		0	17
	SL	22	1315									
	CH			11	1100							
				13	1230							
				19	1510							
	Fre	29	1450									
Oct 1	SF	7	1400				6.6	290	85	35	0	
	Burl	8	1450									
	Bay Ctr Alem	14	1420									
	San Mat Br			8	1436							
	Dunbarton Br			9	1440							
	Al			7	1446							
	RC	14	1545									
	SJ	12	1710				1.8		89			14
	Oak						6.6	290	85	35	0	16
	SL	20	1430									
	Fre	21	1550									
Oct 5	SF	8	1120				9.1	290	82	28	0	
	Burl (aircraft)	14	1245									
	2 mi N SM Br	14	1220									
	0.5 m S SM Br	17	1320									
	2.9 m S SM Br	19.5	1420									
	RC	22	1515									
	SJ	19	1710				1.9		92			14
	Oak						12	310	80	26	0	15
	SL	27	1430									
	Fre	32	1550									

The October 4 flight was of relatively short duration, from 1345 to 1445 PST, and there were some difficulties. One double profile was flown at 500 feet. The measured concentration of oxidant showed a peak just south of San Francisco, with the concentration nearly constant at 8 pphm over most of the South Bay. During the October 5 flight, four hours of oxidant data were accumulated over San Francisco Bay at 500-, 700-, and 1000-foot altitudes. Four double profiles were executed--first north, then south along the center line of the Bay. The first started from Palo Alto Airport, north to 10 miles north of the Hayward-San Mateo Bridge, then south to Alviso. The other three double profile started at Alviso at the southern end, to one mile south of the Bay Bridge at the northern end and return to Alviso. The first double profile was flown at an altitude of 500 feet, the second at 1000 feet, the third at 750 feet, and the fourth at 500 feet. After the fourth double profile, a rectangular flight path was made from Alviso at 500 feet, north up the east side of the Bay to the Hayward-San Mateo Bridge, then west over the Bridge to the west side of the Bay, then south to Palo Alto.

The data for October 4 and 5 are given in Table 6.

An analysis of the data shows the movement of the oxidant profiles indicate the movement of the air down the Bay. The principal region of high oxidant concentrations that was observed at 500 feet was first located about 2-1/2 miles north of the Hayward-San Mateo Bridge at 1220 with a peak oxidant concentration of 14 pphm, as shown in Figure 3. At 1000 feet on the next traverse between about 1240 and 1315, the average profile was similar to that at 500 feet with concentrations averaging about 13 pphm north of the Bridge, and 11 pphm to the south. At 750 feet between about 1320 and 1400, the peak concentration shown by an average profile was 19 pphm and was located about

Table 6

AIRBORNE OXIDANT MEASUREMENTS
(October 4, 1971)

Time (PST)		Oxidant (pphm)
	500 feet	
1355	Leave Palo Alto Airport*	
1357	1 mile south Dumbarton Bridge	8
1405	Alviso-Turnaround	8
1408		8
1410	Dumbarton Bridge	8
1415	Hayward-San Mateo Bridge	8
1420		7
1425	Off NAS Alameda	14 (Peak)
1427	1 mile south Bay Bridge-Turnaround	8
1430		8
1434		9
1436	Hayward-San Mateo Bridge	8
1438		8
1440	Dumbarton Bridge	9
1442		8
1444		5
1446	Alviso-Turnaround	7
1448		7

* See Fig. 1 for track

Table 6 (Continued)

AIRBORNE OXIDANT MEASUREMENTS
(October 5, 1971)

Time (PST)		Oxidant (pphm)
1200	Leave Palo Alto Airport	
	500 Feet*	
1210	Dumbarton Bridge	12
1213		11
1215	Hayward-San Mateo Bridge	9
1216		13
1217		12
1219		14
1220		12
1221		11
1222	Turnaround	
1224		14
1225		16
1226		15
1227	Hayward-San Mateo Bridge	11
1228		11
1229		11
1230		11
1231	Dumbarton Bridge	12
1232		13
1234		14
1235		14
1237	Alviso	12
	1000 Feet	
1238		13
1239	High voltage transmission towers	12
1240		11
1241		11
1242	Dumbarton Bridge	10
1243		10
1244		10
1245		13
1246		11
1247	Hayward-San Mateo Bridge	10
1248		11
1250		14
1251		14
1252		12
1253		12
1254		12
1255	Hunters Point	12
1256		14
1257	Turnaround	13
1258		14
1259		15
1300		14
1301		14
1302		13
1303		13
1304		14
1305		14
1306	Hayward-San Mateo Bridge	13
1307		10
1308		11
1309		12
1310		13
1311	Dumbarton Bridge	15
1312		10
1313		10
1314		11
1315		12
1316	Alviso	14

* 500-foot data shown by Fig. 3

Table 6 (Continued)

Time (PST)		Oxidant (pphm)	Time (PST)		Oxidant (pphm)
	750 Feet			1 0 Feet	
1318		13	1400		16
1320		11	1401		14
1321		10	1402		12
1322		9	1403		14
1323	Dumbarton Bridge	9	1405		18
1324		11	1407		18
1325		12	1408	Hayward-San Mateo	18
1326		11		Bridge	
1327	Hayward-San Mateo	16	1410		15
	Bridge		1412		21
1328		18	1413		20
1329		17	1415		14
1330		16	1416	Hunters Point	18
1331		18	1418	Turnaround	20
1332		17	1420		16
1333		16	1421	Momentary Max.	24
1334		18	1422		13
1335	Hunters Point	18	1423		15
1336		12	1426		17
1337		18	1427	Hayward-San Mateo	20
1338	Turnaround			Bridge	
1339		10	1430		20
1340		20	1432	Dumbarton Bridge	13
1341		18	1435		9
1342		17	1437	Alviso Turnaround	20
1343		16	1440		14
1345		17	1442		13
1347	Hayward-San Mateo	20	1443	East end Dumbarton	12
	Bridge			Bridge	
1348		17	1445		20
1350		12	1447½	Turn to West at	20
1352	Dumbarton Bridge	12		Hayward-San Mateo	
1354		14		Bridge	
1357	Alviso Turn	12	1448		18

Table 6 (Concluded)

Time (PST)		Oxidant (pphm)
1449		15
1450	Minimum just east of high part of bridge	13
1451	South on western shore	19
1453		20
1455		14
1456	West end of Dumbarton Bridge	14
1459	Arrive Palo Alto Airport	

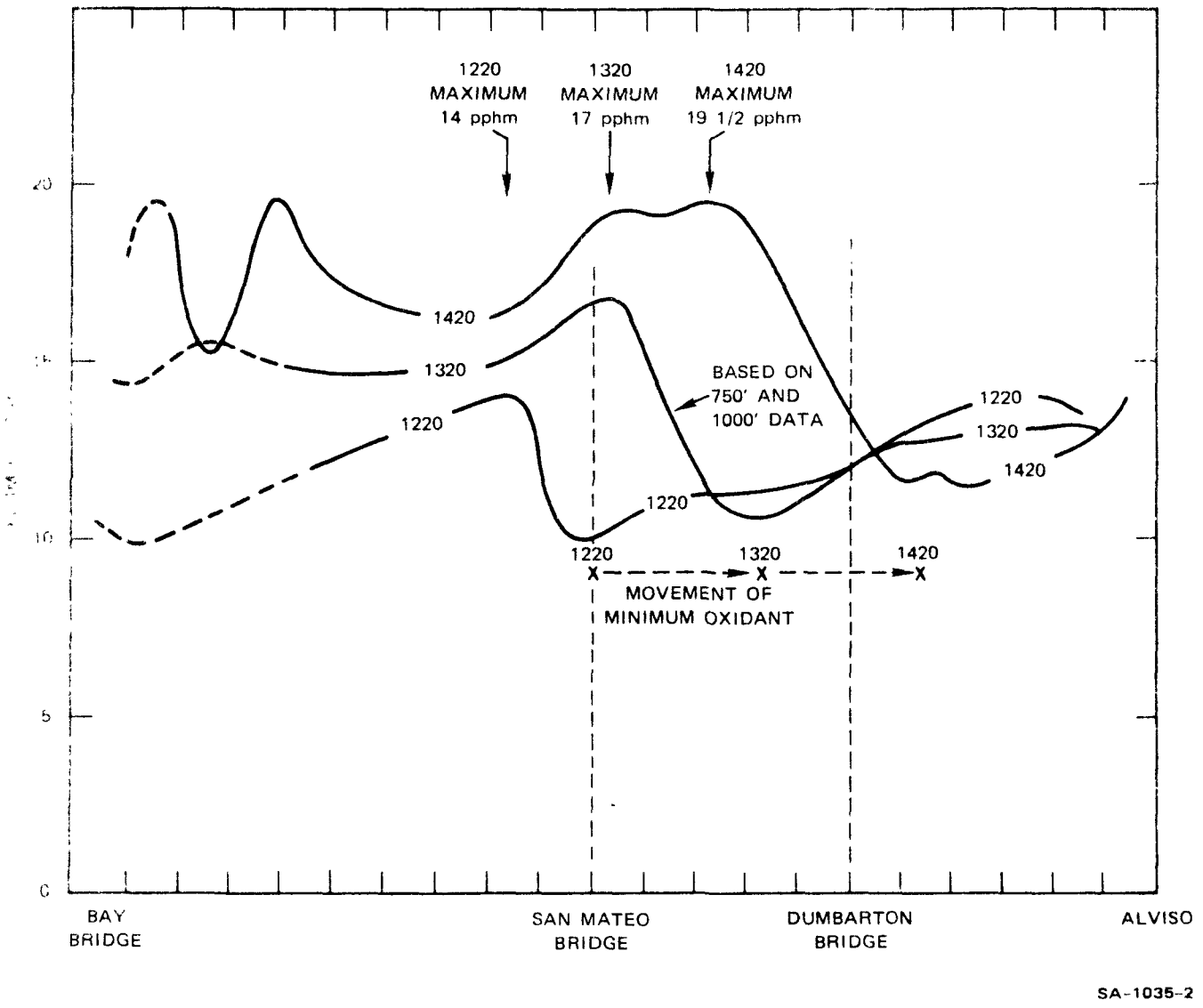

FIGURE 3 DISPLACEMENT OF 500 FOOT OXIDANT PROFILE WITH TIME (PST)

at the Bridge. The southward advection of the oxidant peak was clearly shown by the second 500-foot average profile taken between 1400 and 1500. The peak concentration was 19 pphm and was three miles south of the Bridge. Figure 3 shows three north-south profiles at 500 feet--the averages for the first or 1220 track, the fourth or 1420 track, and an estimated 1320 profile based on an analysis of the four available profiles. The combined data are consistent with wind advection of the oxidant peak at a speed of about 3 mph, which is comparable to the observed winds at Oakland Airport of 3.5 to 5 mph during the interval of interest. During this time the data indicate that an oxidant minimum was moving about two miles ahead of the maximum at 500 feet, with an oxidant level of 10 pphm at 1220, which increased to 11 pphm by 1420. The flight over land areas along the east and west sides of the Bay between about 1440 and 1500 did not detect significant differences in oxidant concentrations between the Bay and land areas.

A secondary oxidant maximum was observed developing 14 miles north of the principal maximum and about one hour later.

IV ANALYSIS AND SUMMARY

The original Sandberg data implied that oxidant production reactions predominate over diffusional dilution, [illegible], and other oxidant loss mechanisms within the air parcels transported downwind from San Francisco. Oxidant continues to increase until it reaches some arbitrary point in the Bay. Past this point in time and space, oxidant levels could have been interpreted as decreasing, resulting in a more or less stationary oxidant maximum somewhere in the Bay.

One mechanism that could account for this interpretation would be that the most reactive hydrocarbons present in the plume of San Francisco were consumed very rapidly (within about one hour) during transit to the Bay Center. After depletion of these very reactive hydrocarbons, the rate of reaction with the lesser reactive species decreased so abruptly that dilution became the dominant mechanism. The oxidant loss rate thus greatly exceeded the production rate and resulted in an apparent stationary area of oxidant maxima.

The van and airborne oxidant measurements made in the SRI survey added spatial resolution to the Sandberg study, and proved that the oxidant maximum is not stationary but moves at or near the speed of the air parcel for the time required to traverse the Bay.

The most important information developed is that oxidant maxima continue to increase in value during the entire Bay traverse. Analysis of the data shows that the rate of increase of oxidant with time reaches a maximum at about 2 hours after the peak hour occurs in San Francisco and that it remains positive for at least 3 hours. This 3-hour period with the usual 8- to 12-mph northwest winds is sufficient time for the air parcel to travel from San Francisco to the south end of the Bay.

This general trend of a continuing oxidant increase during advection to the southeast indicates that two mechanisms may be responsible for and quite likely do contribute to the observed phenomena. As stated previously, the highly reactive hydrocarbons react photochemically and result initially in a rapid increase in oxidant concentration during the early portion of the traverse down the Bay. The role of oxidant formation resultant from reactions of the lesser reactive hydrocarbons becomes more pronounced as the highly reactive species become depleted. The general Bay area meteorological factors of increasing wind speed in the late afternoon would tend to increase the contribution of dilution with an apparent decrease in the rate of oxidant formation.

Over the entire Bay, the oxidant formation reactions are dominant processes on days of photochemical smog. This trend of continuing oxidant increase during advection is shown in Figure 4.

Based on the above data interpretations, it appears that San Francisco Bay can provide simplified yet "real" conditions necessary to define photochemical processes. The net oxidant formations and, by inferred similarity, net changes in the other smog components may be utilized along with diffusion theory to model the San Francisco Bay smog system. A single area source and a continuously reacting system involving nitrogen oxides and a succession of hydrocarbon and organic reactants can be assumed.

No special or unusual transport mechanisms appear to be required to satisfy the observations as we interpreted them.

The proposed expanded Bay Area study should provide a basis for relating actual atmospheric observations with reaction chamber data. The concentration of primary reactants and secondary reactants will be measured, many in real time, within a single air parcel during transport

and aging. The measurements will include NO, NO_2, hydrocarbons, oxidant, aldehydes, organo-nitrates, and solar radiation intensity.

The proposed study should also provide unequivocal data to identify the important oxidant formation reaction and elucidate the mechanism of transport.

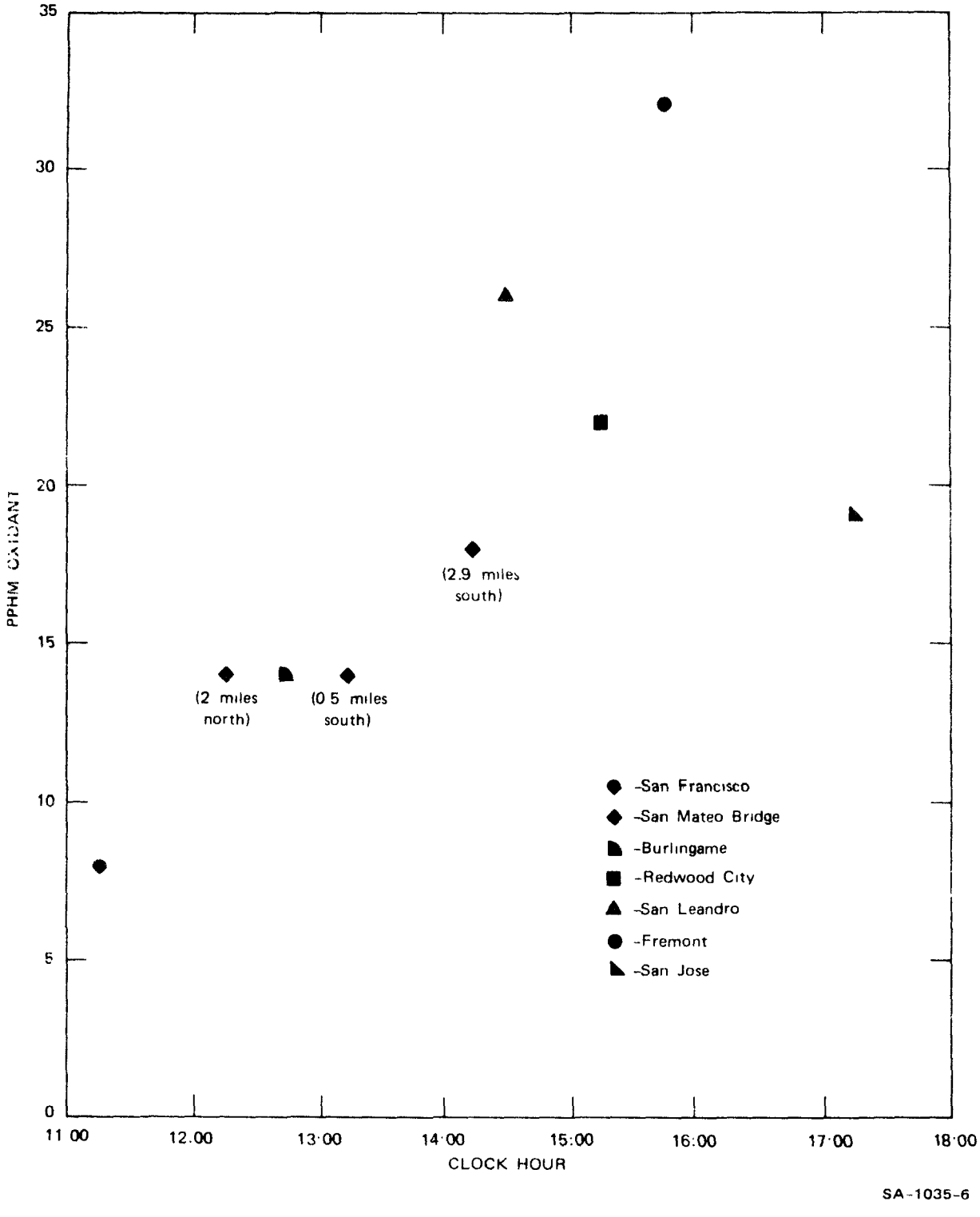

FIGURE 4 OXIDANT PEAK HOURS FOR OCTOBER 5, 1971

V RECOMMENDATIONS

The surface and airborne data obtained during this program indicate that a more comprehensive program--in which nitrogen oxides, hydrocarbons, formaldehyde, and carbon monoxide, as well as oxidants, are measured--would provide a means of analysis of real photochemical smog systems. Such a program would be possible because of the undisturbed course of photochemical reactions in air masses traveling across the water of San Francisco Bay where fresh reactants are not being introduced.

Appendix A

THE CLIMATOLOGY OF THE SAN FRANCISCO BAY AREA

1. Introduction

The pollution climate of an area is a summary of the meteorological factors pertinent to atmospheric transport and dispersion. These factors are wind, thermal stability, and precipitation. The meteorological factors are disrupted and modified by topographical and geographical features so that very important local effects are observed. In the San Francisco Bay area, a pollution climate is superimposed on a topographic situation with a large body of water and an encircling range of hills. Most of the air pollution sources are located in the low-lying areas surrounding the Bay. Prevailing surface air flow patterns indicate that very little pollution originating in the Bay area is transported out of the region over the surrounding hills. Limited sea-level flow to the east is accomplished through the narrow Carquinez Strait. Such a configuration approaches a closed system with a uniform base surface.

2. Topographic and Geographic Factors

The San Francisco Bay area centers about an elongated body of water enclosed by various mountains and hills that comprise the Coast Ranges. The Golden Gate is one sea-level entrance to the Bay; the other is at Carquinez Strait, where the Sacramento River empties into the northeast end of the Bay. The effect of the barrier of hills is to restrict air flow, giving rise to a multitude of mesoscale circulation patterns. Air flow is then tightly tied to the wind field gradient and thermal stability of the immediate area. The effectiveness of such topographic barriers is still dependent on the weather regime in effect. Figure A-1 shows a

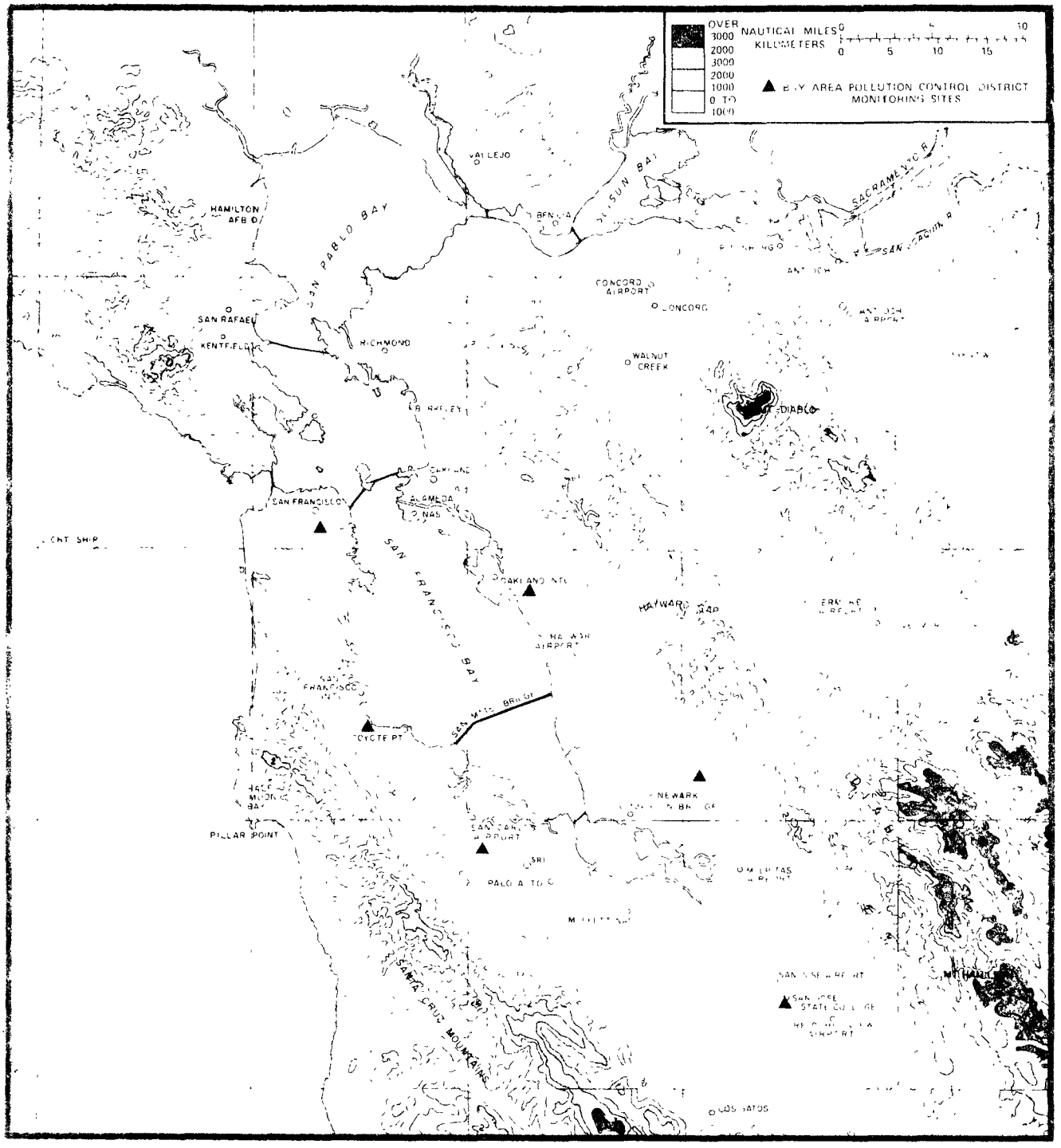

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FIGURE A-1 A CONTOUR MAP OF THE SAN FRANCISCO BAY AREA

contour map of the San Francisco Bay area. The "Bay" (San Pablo and San Francisco Bays) is the world's largest natural harbor, covering approximately 400 square miles. High densities of population and industrial activity have settled on the low lands surrounding the Bay. Modification of the natural surface is very extensive and is likely to continue or accelerate.

3. Meteorological Factors

a. Winds

The semipermanent Pacific high that dominates the Bay area summer climate reaches its maximum intensity in August. Characteristic features of the high are the persistent west-northwest flow and the strong subsidence inversions, both of which control the generation of a cold marine layer and its attendant stratus cloud system. Large scale temperature gradients are at their maximum because a thermal low pressure area develops over the great Central Valley north and south of Sacramento. During the fall, the Pacific high moves southeastward, merging occasionally with continental high cells to form large, stagnant blocking systems. Wind speeds decrease, become northerly or northeasterly, and in turn drastically reduce the on-shore movement of the cold marine layer. Shorter days, clear nights, and light winds contribute to the lessening of the large-scale thermal gradient between the ocean and Central California and bring about a strong seasonal influence on the wind patterns.

Within the Bay area, a certain amount of wind flow distortion is apparent when air is channeled by terrain features and forced to rise above or move around hills. Wind observations in the Bay area often show a pattern of opposing or converging and diverging directions that can be related back to physical features in the terrain. Differential heating plays a large role in determining wind patterns in the Bay area, where the total water surface is not much less than the total land surface.

The familiar pattern of land-sea breezes is strongest in the summer, but with decreasing solar radiation over the land area in the fall, the onshore sea breeze flow weakens accordingly. Light and variable wind conditions are prevalent favoring air pollution accumulation. Highest frequency of light and variable winds occurs during November, as evidenced by Smalley's findings[1] shown in Table A-1.

Table A-1

PERCENTAGE FREQUENCY OF LIGHT-VARIABLE WINDS IN THE SAN FRANCISCO BAY AREA (1952 to 1955)

	Time of Day (PST)				
Month	0400 (%)	1000 (%)	1600 (%)	2200 (%)	All Hours (%)
Jan	39	32	30	35	34
Feb	41	29	20	43	33
Mar	31	30	4	26	23
Apr	33	19	1	13	16
May	31	14	2	14	15
Jun	17	7	0	6	7
Jul	12	5	0	4	5
Aug	9	15	0	4	7
Sep	38	38	2	22	22
Oct	52	39	5	34	32
Nov	58	44	23	51	44
Dec	35	27	22	31	29
Annual	33	24	9	24	22

Smalley's study includes a summary of prevalent wind flow patterns that occurred over a four-year period. Figure A-2[1] is an October pattern showing a wind flow typical of the transition from summertime westerly flow to a wintertime north-northeasterly flow. Incidence of marine air intrusions over mountain tops and passes is restricted also by the lowering of the inversion. The implication of such a wind pattern for air pollution problems is obvious with pollutants generated in San Francisco and western parts of the area being carried to the east and especially southeast across San Francisco Bay.

b. Thermal Stability

Temperature inversions occur in the Bay area as two general types: the summer subsidence inversion and the winter radiation inversion. Fall appears to be a period of transition between the seasonal extremes of a high subsidence inversion and a low radiation inversion. Subsidence inversions are usually higher over the Bay area when accompanied by stratus clouds, whereas radiation inversions are surface based and best developed under cloudless skies. Often in the fall, both types of inversions can be found together or merged when conditions favor the simultaneous development of both types. During clear northwesterly and westerly wind conditions the inversion base averages 650 feet. When north to northeast winds prevail, the inversion base is less than 200 feet.[2] An SRI study found the most frequently occurring inversion base height during October to be less than 350 feet. The height of the inversion base is slightly lower over the South Bay than over the North Bay.[3] More recent observations by the Meteorology Department at San Jose State College show that, for any one instance, the height and the intensity of the subsidence inversion vary over the Bay area. Typically, the inversion is lowest over the Bay itself, increasing in height toward the hills and the sea.[4]

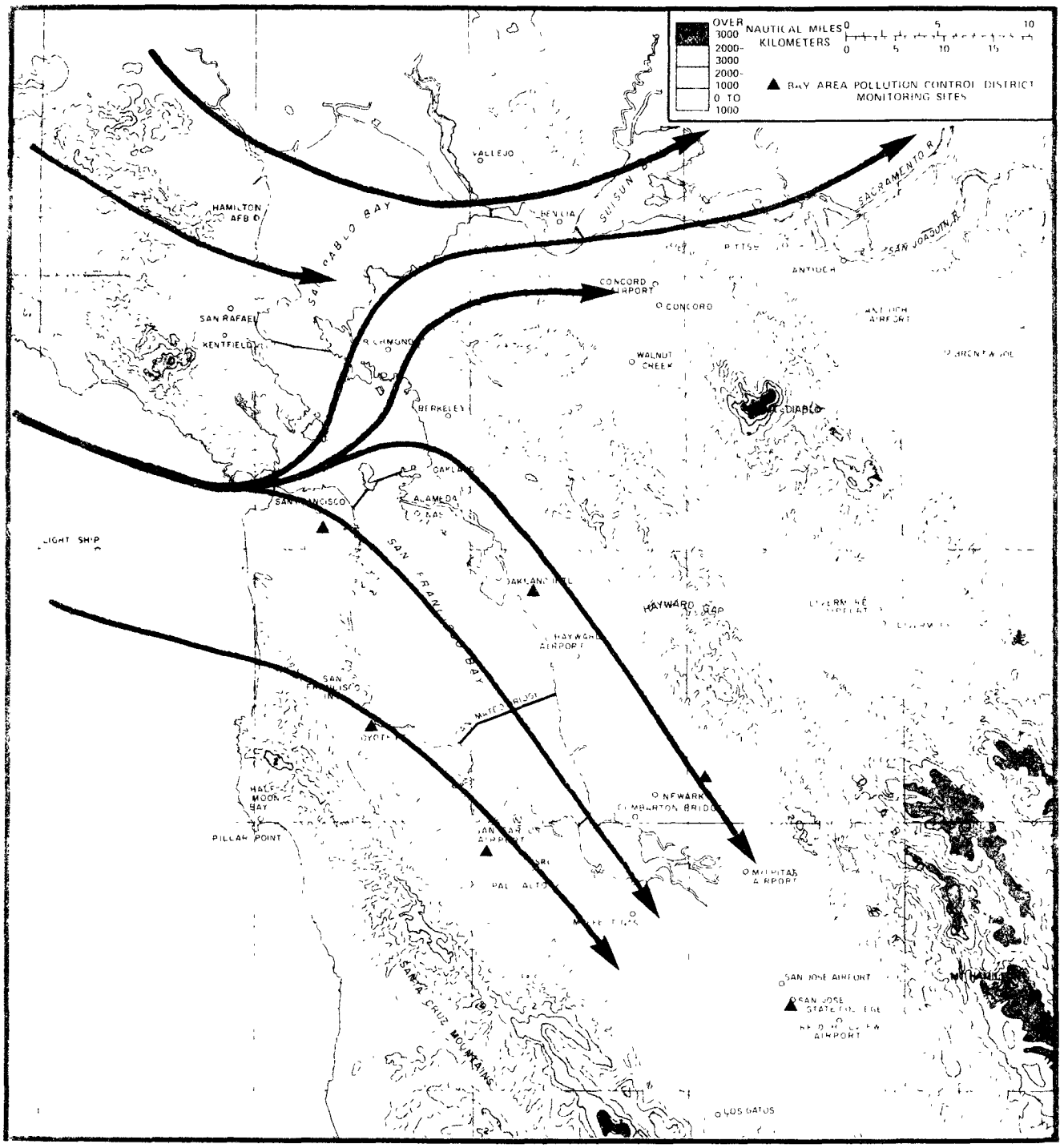

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FIGURE A-2 PREVALENT WIND FLOW PATTERN FOR OCTOBER. Mean Wind Speed at San Francisco - 9 mph; Oakland - 6 mph.

Diurnal variations are reflected in radiation inversions that are more closely linked to surface or local changes. Average inversion base heights for Oakland in the fall months are listed in Table A-2.[5] A lowering of the inversion base from September to November shows the transition from a summer subsidence to a winter radiation type. Two early morning and two early evening observations serve to point out that local effects have much more influence on radiation inversions than on subsidence inversions. Most radiation inversions have dissipated by 1600 PST, whereas subsidence inversions persist with only slight diurnal changes.

Surface temperatures of the Bay area in September are comparable to summer temperatures. Sites located near the Bay exhibit a much smaller diurnal range than inland sites. Some heating of the air is evident as it moves off the Pacific into the Bay.

c. Precipitation and Cloud Cover

Rainfall is greatly affected by local terrain. Heavier amounts are found at high elevations or on slopes that induce mechanical lifting. In the Bay area, precipitation amounts along the western ridges exceed amounts found to the east. The spatial pattern in Figure A-3[6] is probably reliable, although the rainfall totals may show variation from year to year. Precipitation producing mechanisms are synoptic in scale, with a trend in the fall toward a gradual increase in precipitation from a summer minimum to a winter maximum. A similar trend of increasing cloud cover is also evident from September to November. Table A-3[6] indicates that the number of clear days decreases from August through November.

Table A-2

FREQUENCY AND AVERAGE INVERSION BASE HEIGHTS BY MONTH FOR OAKLAND

Observation Time		0400 PST		0700 PST		1600 PST		1900 PST	
		% Frequency	Av Ht	% Frequency	Av Ht	% Frequency	Av Ht	% Frequency	Av Ht
Below 2501 feet	September	77	731	83	853	67	847	92	742
	October	76	396	74	506	47	790	79	579
	November	78	232	90	157	33	1125	85	187
Below 5001 feet	September	91	1100	97	1196	76	1164	97	912
	October	86	739	77	672	62	1481	87	905
	November	87	498	92	206	59	2155	85	187

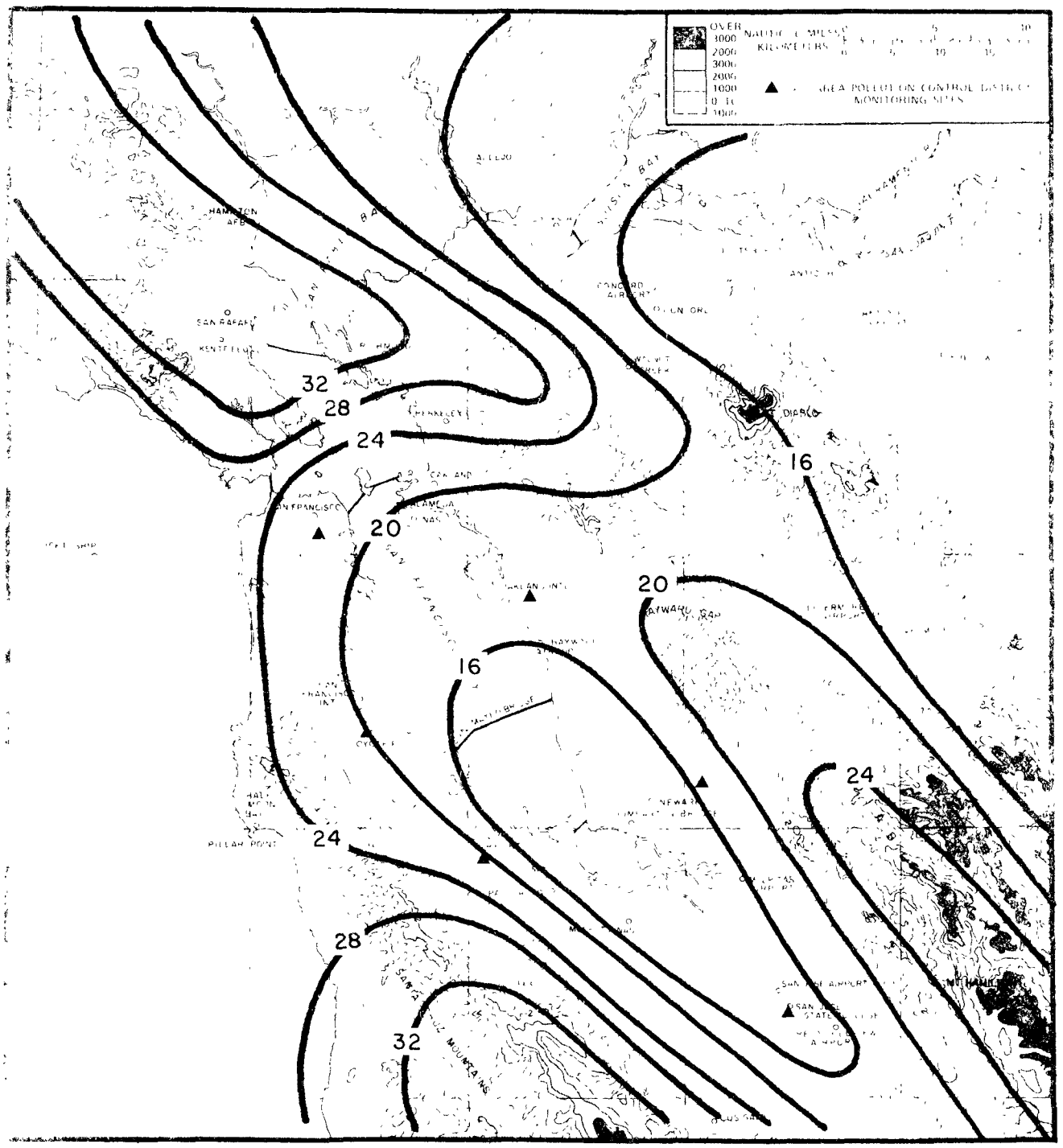

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FIGURE A-3 NORMAL ANNUAL TOTAL PRECIPITATION (Inches)

Table A-3

AVERAGE NUMBER OF CLEAR DAYS

Site	August	September	October	November	December
Oakland	14	16	14	11	9
San Francisco International Airport	19	18	16	12	9

Cloud cover and precipitation show clearly that the late summer and fall months typically have negligible rain and maximum sunshine. Thus this is the period most conducive to the occurrence of photochemical smog.

d. Oxidant

1. Trends in the Bay Area

The occurrence of high oxidant levels in the Bay Area varies considerably from year to year. The BAAPCD uses certain monitoring stations throughout the district where long-term historical oxidant concentration data are available to serve as benchmark stations for the district. These stations are San Francisco, San Leandro, San Jose, Redwood City, Walnut Creek, and San Rafael. The number of days where the high hourly average of 15 pphm or greater was reached at these benchmark stations was 57 in 1965, 28 in 1966, 44 in 1967, 36 in 1968, 44 in 1969, 31 in 1970, and 19 in 1971. The randomness or grouping of such days can be better correlated with meteorological factors than with the variation in anthropogenic emissions.

Several trend studies have been made by the BAAPCD[7,8] to determine the oxidant concentration trends throughout the district from 1954 through 1972. Both emissions, reactive organics and NO_x, and

meteorological factors must be considered in data analysis to provide information on oxidant concentration trend within the control district.

Three factors are associated with photochemical smog development:

(1) A supply of reactive organic compounds and nitrogen oxides

(2) Extensive solar radiation to initiate the photochemical reactions

(3) Poor ventilation to entrap the pollutants and prevent their dilution.

In the first two trend studies, 1954 through 1962 and 1962 through 1966, days with comparable meteorological conditions were compared with similar days through the interval of interest. The maximum daily temperature observed in the proximity of the measurement station was made the criterion for comparable days in these early trend studies. The results indicated that the general trend of annual oxidant concentration was increasing from 1954 through 1965. In 1966 there was a marked decrease in average oxidant concentration at all stations with an average decrease of 25 percent. Prior to 1971, 1966 was the cleanest year of the decade in terms of days when the oxidant exceeded 15 and 20 pphm levels.

In the later trend[9] studies, vertical dilution data based on inversion data from the NOAA radiosonde ascents at Oakland Airport were included with temperature data to identify meteorologically similar days.

For the next four years, 1967 through 1970, the oxidant levels stabilized at a lower level than had been observed in 1954 through 1965 for meteorologically similar days.

In 1971 another significant decrease, exceeding 16 percent, was observed. The actual decrease from 1970 to 1971 was 39 percent with 23 percent attributable to meteorological factors.

The broad climatological patterns of the Bay Area indicate that the most severe oxidant episodes will be encountered in the sheltered inland valleys, downwind of the urbanized central district. The oxidant season is usually regarded as April through October. However, in 1962 through 1967, over 16 percent of the days where oxidant concentrations exceeded 10 pphm occurred in October. Data analysis indicates that on days of high oxidant concentrations, the oxidant concentration peak hour generally occurs sequentially from northwest to southeast on both the west and east sides of the Bay. In general, oxidant concentration levels also occur in a similar pattern with the more southerly stations reporting higher concentrations on a given day. The monitoring stations on the East Bay perimeter generally report higher concentrations than those on the West Bay perimeter. Sandberg's data indicate that the oxidant concentrations at the Bay center often exceed those observed at the perimeter.

2. Discussion of San Jose State Ozone Soundings

Most studies of oxidants associated with air pollution have concentrated on the meteorological and photochemical processes that affect the production of ozone. Miller and Ahrens[10] report that the destruction rate of oxidant in polluted air may be a much more significant factor in determining the observed surface concentrations of oxidant. Miller made ozone soundings at half-hour intervals on August 29, 1968 at two points in the lower Santa Clara Valley with the following results:

(1) The ozone concentration increases sharply when the temperature inversion breaks down between 0900 and 1000 PST and decreases rapidly after about 1800 PST, as the inversion forms again.

(2) Between 1000 PST and 1500-1600 PST, the ozone concentration increases at all levels up to 2700 m.

These observations seem to indicate that ozone concentration is closely linked to the degree of vertical mixing but this is in a sense contrary to the idea of pollutant trapping. The mean destruction rate within the surface layer depends directly on the intensity of the eddy mixing and inversely on the depth of the mixing layer; thus, the existence of a temperature inversion does not necessarily lead to high concentration of oxidants. Miller also found that a stratified layer of higher concentration of ozone was formed just above the inversion, in air that has been cut off from surface contact.

The ozone in the stratified layer above the inversion is destroyed at a much lower rate than that below the inversion. Miller also concluded that vertical convergence within the descending air above the inversion may have helped to concentrate the ozone in this layer.

In the three hours after sunset on August 29, 1968, the average concentration decreased by 8 pphm in the relatively stable air below 650 m while little change was observed in the layer above 1250 m where lapse conditions persisted.

The relative importance of ozone destruction to mechanisms and the vertical distribution within an inversion proposed by Miller and Ahrens is academically interesting but cannot be integrated with the data obtained by Sandberg in 1967 or the 1971 oxidant data obtained in this feasibility study. The usefulness of Miller's finding in the proposed expanded Bay Study will be also limited as current reactive models (Seinfeld, Eschenroeder, and others) account for only oxidant produced as a result of photochemical activity and assume a uniform vertical distribution of oxidant within the volume of interest. The

Miller hypothesis may, however, help explain the frequently observed occurrence of the oxidant peak hour in San Francisco very early, often before sunrise.

4. Summary

Climatic characteristics that strongly favor the occurrence of air pollution situations are typical of the San Francisco Bay area during the fall months. Weather patterns are conducive to restricted transport and dispersion of pollutants. Winds are light and variable, often terrain channeled. Dispersion is limited by persistent and frequent inversions. Precipitation washout poses no real threat. For the investigation of oxidants, the typical long over-water trajectory minimizes changes of contamination from other route sources. The prevalence of clear, warm days indicates the availability of a radiation climate necessary for the production of oxidants and photochemical smog. A maximum in air stagnation is paralled by a maximum of air pollutants, as shown in Figure A-4 where Oakland visibility and wind circulation are shown.

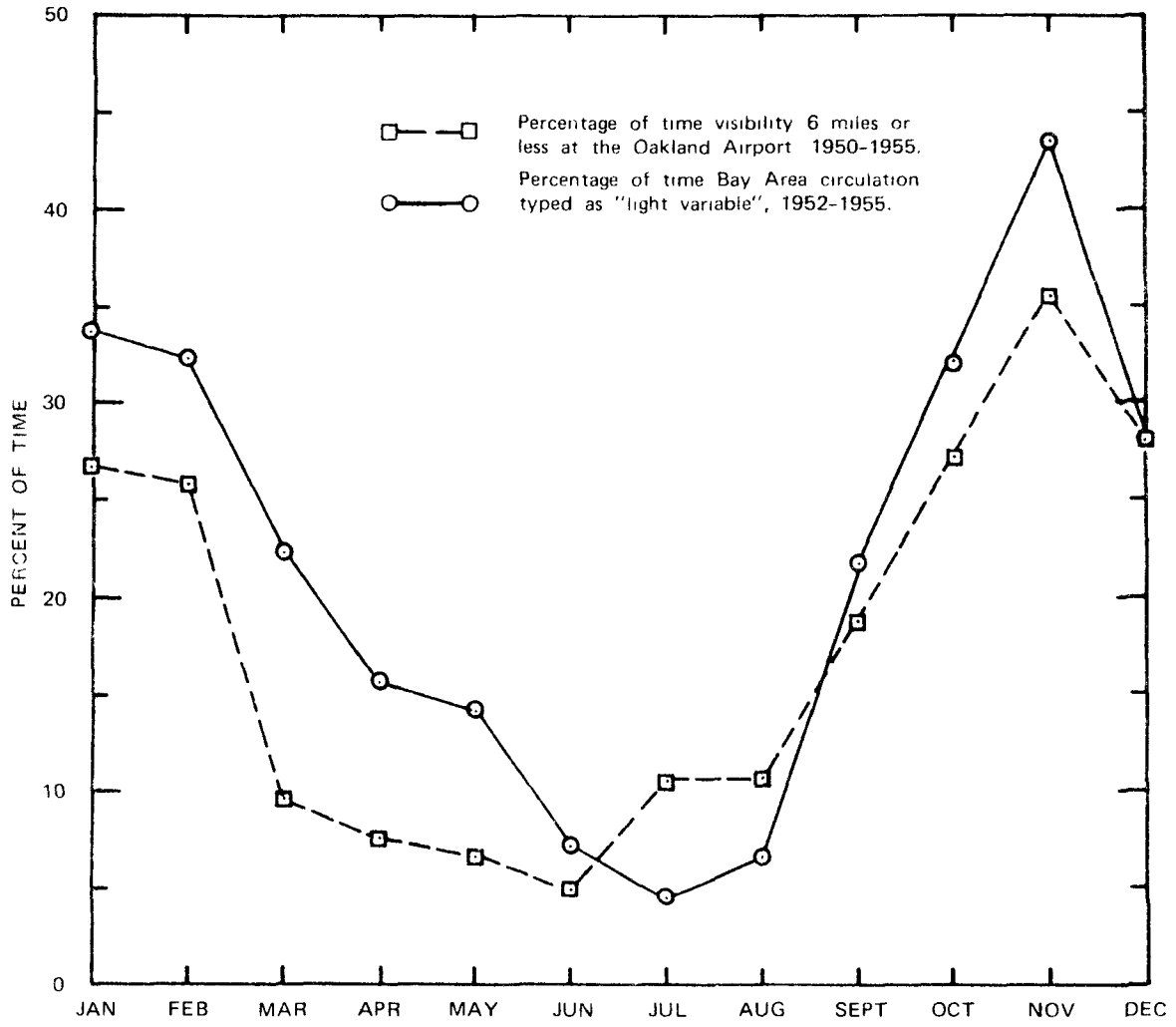

FIGURE A-4 VISIBILITY AT THE OAKLAND AIRPORT COMPARED WITH LIGHT WIND PATTERNS IN THE SAN FRANCISCO BAY AREA

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16. ABSTRACT

This research study was a brief feasibility study and field measurement program to determine whether the San Francisco Bay Area might provide meteorological and photochemical smog patterns that were especially conducive to field research on smog reaction processes. It was concluded from both climatological and field oxidant sampling that this was the situation if atmospheric data could be gathered over the waters of the Bay, particularly east and south of San Francisco.

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