Dispersion Modeling of Sulfur Dioxide in the Vicinity of Two Hawaiian Power Plants

by
Northrop Services, Inc.
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FOREWORD

Protection of the environment requires effective regulatory actions which are based on sound technical and scientific information. This information must include the quantitative description and linking of pollutant sources, transport mechanisms, interactions, and resulting effects on man and his environment. Because of the complexities involved, assessment of specific pollutants in the environment requires a total systems approach which transcends the media of air, water, and land. The Environmental Monitoring and Support Laboratory-Las Vegas contributes to the formation and enhancement of a sound monitoring data base for exposure assessment through programs designed to:

- develop and optimize systems and strategies for monitoring pollutants and their impact on the environment,
- demonstrate new monitoring systems and technologies by applying them to fulfill special monitoring needs of the Agency's operating programs.

This report is one of six reports published separately by the U.S. Environmental Protection Agency (EPA). The series of reports was prepared by Northrop Services, Incorporated, and the Environmental Monitoring and Support Laboratory-Las Vegas for EPA Region IX. The reports will serve as a Technical Support Document to be used in the development of a sulfur dioxide State Implementation Plan for the State of Hawaii. This document provides the factual basis for the development of regulations for the State of Hawaii to avoid exceeding National Ambient Air Quality Standards.

Two oil-fired power plants were identified as major sources of sulfur dioxide within the State. These souces were monitored to:

- determine if violations of air quality standards occurred in the vicinity of the plant,
- obtain data for incorporation into a mathematical dispersion model for the plants.

The data and findings presented in the Technical Support Document should interest a wide variety of parties. Regulatory agencies and electric utilities directly involved with the effects of a State Implementation Plan have an immediate and obvious interest in the data presented in this report. The public has an interest in how the data and findings contained in this report will be used to develop the State Implementation Plan. The implementation of the Plan will directly affect the electric companies and indirectly affect

the public. Scientists who are interested in the methods used to assess the impact of a power plant on the air quality in the area of that plant may be interested in the extensive data base presented in this report.

The 1-year study of both power plants was conducted by the Monitoring Operations Division of the Environmental Monitoring and Support Laboratory-Las Vegas.

George B. Morgan
Director
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ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

AFB	--Air Force Base
BEH072	--subroutine in PTMTP program
BTU	--British thermal units
C/M	--ratio of calculated to measured
COSPEC	--correlation spectrometer
EPA	--U.S. Environmental Protection Agency
FPC	--Federal Power Commission
km	--kilometer(s)
kw	--kilowatt(s)
LST	--Local Standard Time
m	--meter(s)
m/sec	--meter(s) per second
min	--minute(s)
MW	--megawatt(s)
$\mu g/m^3$ (μg/cu.m)	--microgram(s) per cubic meter
NE	--northeast
NOAA	--National Oceanic and Atmospheric Administration
NNW	--north-northwest
NRC	--Nuclear Regulatory Commission
P-G	--dispersion data collected by Pasquill and Gifford
PTMTP	--program in UNAMAP library; a Gaussian model
SE	--southeast
SSE	--south-southeast
Std. Dev.	--standard deviation
STL	--dispersion data collected in St. Louis, Missouri, by McElroy and Pooler
TECO	--Thermo Electron Company model 43 sulfur dioxide analyzer
UNAMAP	--User's Network for Applied Modeling of Air Pollution

SYMBOLS

A	--extremely unstable atmospheric conditions
a	--crosswind constant dependent on stability
B	--moderately unstable atmospheric conditions
b	--vertical constant dependent on stability
B_H	--building height, meters
B_W	--building width, meters
C	--slightly unstable atmospheric conditions
c	--regression coefficient relating σ_y to σ_θ
χ	--ground-level concentration, micrograms per cubic meter
D	--neutral atmospheric conditions

SYMBOLS (continued)

d	--regression coefficient relating σ_y to σ_θ
d_s	--inside stack diameter, meters
°	--degrees of temperature
E	--slightly stable atmospheric conditions
F	--moderately stable atmospheric conditions
f_1	--coefficient in plume rise equation
f_2	--coefficient in plume rise equation
$f(x)$	--coefficient relating σ_y to σ_θ
HE	--total plume height, meters
h_E	--contribution to plume height for downwash effects, meters
h_F	--plume height when B_H is greater than or equal to B_W, meters
h_s	--stack height
HX	--plume height at downwind distance of receptor, meters
K	--variable
l_B	--minimum value between B_H and B_W, meters
N	--integer value
p	--crosswind constant dependent on stability
%	--percent
π	--Pi = 3.14159
Q	--source emission rate, micrograms per second
q	--vertical constant dependent on stability
SO_2	--sulfur dioxide
σ_θ	--standard deviation of the horizontal wind angle, degrees
σ_y	--standard deviation of the concentration distribution in the horizontal direction, meters
σ_z	--standard deviation of the concentration distribution in the vertical direction, meters
u	--wind speed at stack height, meters per second
v_s	--stack gas exit velocity, meters per second
X	--relationship "$\sigma_y = x\sigma_\theta$"
x	--distance downwind of source, meters
x	--"times" (multiplied by)
x_o	--virtual distance, meters

SECTION 1

INTRODUCTION

Regulations for air quality in the State of Hawaii do not cite emission standards but rely on air quality monitoring data to determine that air quality standards are met. In order to develop an air quality control strategy for sulfur dioxide (SO_2) that is based on emission limitations, it is desirable to test how effectively alternative strategies will control present sources. A first step in making this assessment is to measure the present air quality around significant sources. The expense of maintaining an array of monitoring sites for a sufficiently long period of time to assure that air quality standards are being met can be significantly reduced by combining monitoring with mathematical modeling. Application of mathematical dispersion modeling was selected as a practical alternative to determine where and at what levels ambient concentrations of sulfur dioxide may be expected. More specifically, two electricity-generating stations were selected to be studied by both a short-term monitoring-data collection period and dispersion modeling. The two stations were Maui Electric Company power plant in Kahului, Maui, and the Hawaiian Electric Company power plant at Kahe Point, Oahu.

The Kahului plant is located very near the shoreline of Kahului Bay. The waters of the bay cover the area north of the plant (except for approximately 100 meters of land between the plant and the shoreline). Populated areas lie principally south and west of the plant.

The Kahe Point plant is located on the southwest shore of the island of Oahu. The shoreline in the vicinity of the power plant follows a line oriented approximately north-northwest to south-southeast. Consequently, most of the area to the west of the plant and downwind of the prevailing northeast (NE) trade winds (with the exception of a narrow strip of land approximately 200 meters wide) is the Pacific Ocean. Along that land strip between the plant and the ocean there are a highway and public beach. The terrain rises very steeply in all directions around the plant except on the shore side. The 244-meter (m) elevation contour is generally within 1.3 kilometers (km) of the plant in the NE quadrant, while ridges in the southeast quadrant are generally about 90 m within 0.7 km of the plant.

The monitoring stations were set up in the vicinity of each plant to monitor air quality and meteorological conditions. Near the Kahului plant location the three stations were placed downwind of the power plant along a line oriented with the prevailing onshore winds. Station 1 was located approximately 0.4 km from the power plant; Station 2 was approximately 1.0 km, and Station 3 was approximately 1.8 km from the power plant. The azimuth

angles from the power plant to Stations, 1, 2, and 3 were approximately 228 degrees, 209 degrees, and 215 degrees, respectively. Ground elevations from the power plant to the monitoring stations change less than 10 meters. The stations were operated for a period of 6 months, from February to July 1977.

Near the Kahe Point plant site the three air quality monitoring stations were set up and operated for a 4-month period, from October 1977 to January 1978. The monitoring stations were located along the shore as follows: Site 1, 0.5 km on a bearing of 185 degrees from the plant; Site 2, approximately 0.15 km on a bearing of 240 degrees from the plant; Site 3, approximately 1.6 km on a bearing of 315 degrees from the plant.

The Kahului power plant operates using four separate oil-fired boilers each served by a separate stack to generate a maximum nameplate capacity of 34.93 megawatts (MW). The Kahe Point plant operates five oil-fired boilers, each with a separate stack, which combine to give a total nameplate generating capacity of 474.93 MW, according to Federal Power Commissions (FPC) figures.

Utilizing an existing dispersion model, Geomet developed parameters for each plant location which could be used to represent the atmospheric transport and diffusion process at each site. For a number of reasons, including the simple terrain influences and the ability to access a satisfactory number of desirable observation locations, the observations and the model treatment of the Kahului plant plume are more complete and more satisfactory than the treatment of the Kahe Point plant plume. For use in the vicinity of both plants, the model was modified by systematically introducing changes based on plume characteristics observed during a brief intensive monitoring period of 1 week at Kahului and 2 weeks at Kahe Point. However, the final agreement between model estimates and observations at the three monitoring stations was better at the Kahului location. More extensive model development work based on more detailed modeling of the complex terrain features at the Kahe Point location may produce better modeling results in the future. Only very simple modeling concepts have been applied in this study. The data collected may be useful in testing new and more complex modeling concepts which have not yet become accepted techniques.

The selected model as modified for each location was used to estimate the air quality effects which could be expected if any of several emissions control strategies for sulfur dioxide was adopted. The strategies evaluated included reduction of fuel sulfur content and utilization of an SO_2 scrubber, increasing the stack height to 2.5 times the building height or higher, and using a supplementary control system by which the plant load would be reduced during selected unfavorable meteorological conditions.

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

Site-specific parameters for use in a Gaussian plume model were developed to represent the transport and dispersion of the exhaust gases from the power plants located at Kahului and at Kahe Point. The model parameters were developed using wind observations from 10-meter towers (including direction, speed, and standard deviation of wind direction), temperatures from a nearby monitoring site, either solar radiation measurements or airport cloud observations, and mixing heights derived from twice-daily radiosonde observations. The relationship of meteorological parameters to the model dispersion parameter σ_y was determined from a combination of mobile van measurements of the plume (either from ground measurements in the plume or indirect overhead measurements using a correlation spectrometer) and comparisons of model calculations (using the hypothesized σ_y parameter) with fixed station SO_2 measurements. Previously published σ_z values were adjusted for site specificity by comparisons of model calculations with fixed-station SO_2 measurements.

The model as modified for application to the Kahului power plant location showed good agreement with concentrations measured at three sites over a 6-month monitoring period. The mean values and the characteristics of the frequency distribution of calculated and measured hourly and 24-hour SO_2 concentrations were compared. The mean ratio of calculated values to measured values averaged over the three sites was close to unity for all comparison statistics. The mean ratios of calculated-to-measured values were 1.0 and 0.8 for the highest hourly and 24-hour concentrations; 1.3 and 1.1 for the 90th percentile hourly and 24-hour concentrations; and 1.4 for the mean concentrations. The ratios at individual monitoring sites varied from 0.6 to 2.1 for these same statistics.

Model results for alternative control strategies applied to the Kahului power plant showed that controlling the sulfur content of fuel not to exceed 0.5 percent and raising stack heights to 2.5 times the building height are not adequate control strategies. However, the model results showed that requiring the use of a 90 percent efficient SO_2 scrubber, raising the stacks to a height of 91 meters, or raising the stacks to 2.5 times the building height and limiting the sulfur content of fuel to 0.5 percent or less are adequate control strategies which meet Federal ambient air quality standards for SO_2 in the vicinity of the plant.

The model as applied to the Kahe Point power plant location showed less agreement with concentrations measured at three sites over a 4-month monitoring period than were obtained for the Kahului location. The mean ratios of

the calculated values to measured values averaged over the three sites were 1.5, 1.4, and 2.0 for the mean, second high 24-hour, and second high 3-hour values. The ratios at individual monitoring sites for these same statistics varied from 0.8 to 3.0. The model, in general, overestimates the measured concentrations. One of the major sources of uncertainty in the model estimates is the highly turbulent flow which occurs on the lee side of the Waianae Mountain Range during prevailing northeasterly trade wind flow. The plant plume is influenced by the enhanced turbulence and wind deflection caused by the nearly rugged terrain with both onshore and offshore flow.

Model results for alternative control strategies applied to the Kahe Point power plant showed that requiring the sulfur content of fuel to be limited to 0.5 percent, reducing emissions by 70 percent, and raising the stack heights to 115 meters are not by themselves adequate control strategies. The model estimates of SO_2 air quality levels are above Federal levels. Because of the uncertainty of the model results and the demonstrated tendency to overestimate, this conclusion might be altered by more detailed study. Control strategies based on 90 percent reduction of present emissions <u>or</u> based on limiting the sulfur content of fuel to 1.0 percent and requiring the stack to be 2.5 times the building height are shown by the model results to be adequate to meet Federal standards for SO_2.

It is recommended that the influence of complex terrain on the dispersion of plumes from sources on the lee side of major terrain obstacles be studied in more detail. The results presented in this report for the Kahe Point plant reflect a relatively large degree of uncertainty regarding the model estimates. There are many potential plant sites in Hawaii which are on the lee side of major terrain obstacles during the prevailing trade wind influence. The nature of this effect on plume dispersion needs to be more carefully delineated by observation and modeling studies. Data obtained at the Kahe Point site provide a useful starting point for such a study.

SECTION 3

MODEL INPUT DATA

Meteorological and SO_2 emission data were obtained for each plant site. The emission data obtained for each plant are broken down by stack and include hourly variations. The meteorological data vary in detail and duration of observation at each site.

The Kahului plant is within 3 km of an airport where a record of meteorological observations, representative of winds in the vicinity of the plant location over several years, is available. At Kahe Point, the plant is in a bowl-shaped canyon which faces west and backs up against the southern end of the Waianae Mountain Range. The only meteorological data which can be considered reliable and representative of wind flow at the plant location were collected during the 4-month U.S. Environmental Protection Agency (EPA) monitoring study. Although there also is a strip chart record of wind observations made at the plant site covering an additional 3-year period, these data were not adequately maintained and annotated. A careful and detailed review by McElroy (1977) has developed some useful climatological estimates of seasonal variations in the frequency of occurrence of weather regimes (i.e., trade, sea breeze, and Kona winds). However, these data were judged by us in a conference with McElroy to be unsatisfactory for hour-to-hour simulation of plume transport.

KAHULUI

Meteorological Data

Meteorological data were available in two distinct forms: that from the monitoring stations operated by an EPA contractor and that obtained from the National Oceanic and Atmospheric Administration (NOAA) weather station at the Kahului Airport. The Kahului Airport data provide surface observations at 3-hour intervals from which sky condition, temperature, wind direction, and wind speed data were coded and stored in a computer file. The meteorological data from three monitoring stations included temperature, wind speed, wind direction, the standard deviation of wind direction, and, at one station, solar intensity. The meteorological data from the monitoring stations were available for each hour during the 6-month monitoring period, February through July 1977. To demonstrate the validity of the air quality model, the hourly data from the monitoring stations were carefully reviewed and the most appropriate measurements selected for use in the model. The wind direction and speed from Station 2 and the standard deviation of wind direction from Station 3 were found to be the most useful meteorological measurements.

Stability class was determined using sky condition information from the Kahului Airport and the method described by Turner (1964). Mixing height input to the model was determined using the radiosonde data obtained from the soundings made at Hilo, Hawaii. Upper air data for Hilo were obtained from the National Climatic Center.

Mixing depth information was determined from the radiosonde data at two times each day corresponding to the soundings made at 0000 and 1200 hours Greenwich time (1400 and 0200 Alaska-Hawaii time zones respectively). Hourly values of the mixing depth were approximated by a scheme which utilized the 0200 Local Standard Time (LST) sounding in the interval from 0200 to 0600 hours and then made a linear interpolation of the 0200 and 1400 mixing heights for the hours between 0600 and 1400 LST. The mixing depth from the 1400 LST sounding was used as a constant until the subsequent 0200 LST sounding.

This interpolation scheme is based on the fact that the mixing height rises gradually in the morning due to solar heating of the ground after sunrise and mechanical turbulence induced by surface friction. Linear interpolation with time has been found to give as good an estimate of the rate of rise as more sophisticated techniques. Therefore, linear interpolation is most frequently used because it is computationally convenient. In the evening a different process occurs. The boundary layer slowly stabilizes with the afternoon mixing height gradually weakening, and the temperature discontinuity which marks the mixing height at the top of the boundary layer gradually weakens but remains at the same height. A new layer forms underneath the old one due to a combination of radiative cooling and mechanically induced turbulent mixing from surface friction. A new mixing height is established by the time of the 0200 sounding. An alternative assumption frequently applied is that the mixing height decreases linearly in time between the two observations. Under most conditions the mixing height is high enough even at night to have little impact on the ground-level concentrations estimated by the model. If the 0200 mixing height is very low, there may be a period of 2 to 3 hours preceding 0200 when the two assumptions produce differing results.

Mixing height data were obtained from the Hilo and Lihue stations. However, the Hilo data were used because (1) the data record on magnetic tape from the Lihue station contained several significant sections from which data were missing or garbled, (2) the Hilo data approximated the radiosonde data for Kahului quite well, and (3) the Hilo data provided a record for the entire Kahului modeling period whereas the special Kahului radiosonde information was available for a 6-day period only. Figure 1 shows the mixing height as determined from the special soundings made during the Kahului intensive period compared to the mixing height derived from the Hilo data for corresponding times. In plotting the data in Figure 1, an arbitrary height of 1,500 m was assigned to the Kahului soundings when no mixing height was apparent from the soundings. Except for two cases when very low mixing height was indicated on Hilo soundings in comparison to Kahului soundings, the agreement between the two estimates is good and very satisfactory for dispersion modeling purposes.

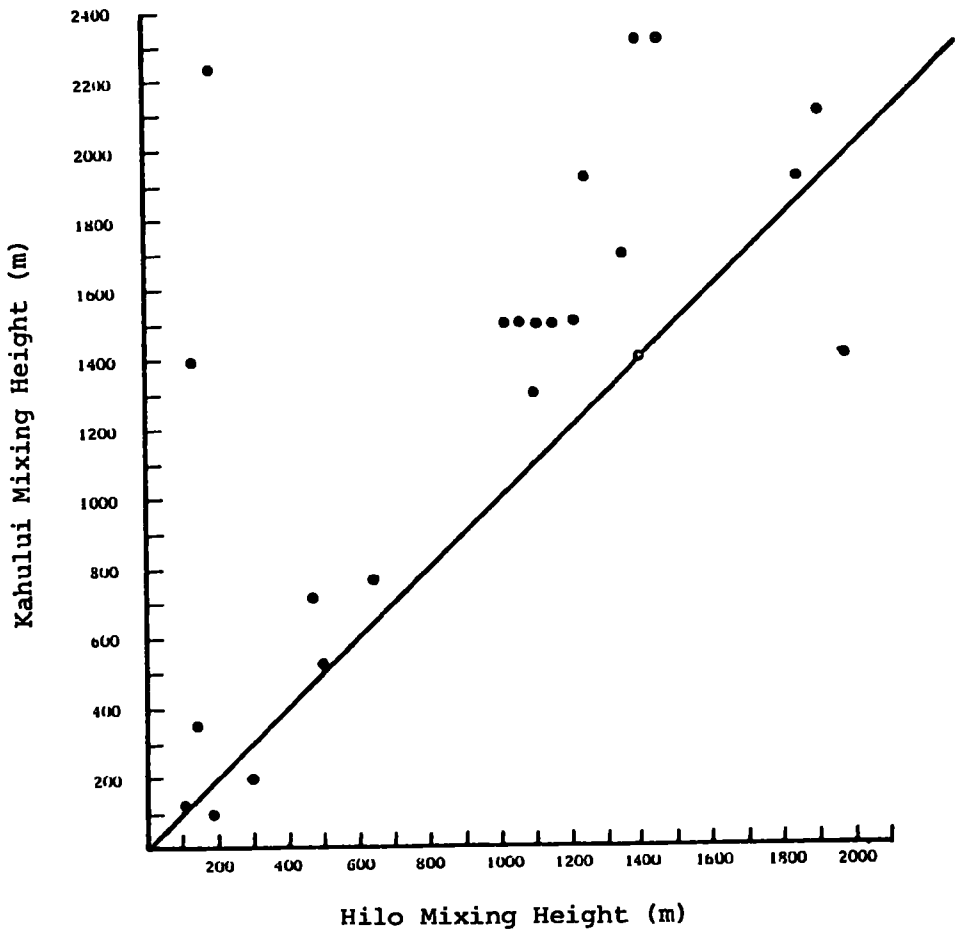

Figure 1. Comparison of mixing heights derived from corresponding Kahului and Hilo radiosondes.

For the Kahului plant, hourly arithmetic mean wind speed and vector mean wind direction values from Station 2 were used for model input during the validation study. After a brief study of the data from all three monitoring sites, the consistency between wind speed, direction, and patterns measured at Station 2 and at the NOAA station at the airport indicated that the Station 2 wind data were the most representative data.

Airport meteorological data were used for model input when running the model for the 12-month period.

Table 1 is presented to summarize the availability of meteorological data with respect to source and time period.

Temperature data which were available from the monitoring stations for a period of time less than the 6-month monitoring period were easily supplemented by airport data. Also, during the intensive study period, hourly observations from the airport were available in addition to the normal 3-hour data.

During the intensive study period plume width measurements were made using mobile-mounted SO_2 detection instruments, the Thermo Electron Company (TECO) SO_2 analyzer, and a correlation spectrometer (COSPEC). Frequently both the TECO and the COSPEC units were used simultaneously, resulting in two sets of data which were provided to Geomet for use in the modeling analysis. A value of σ_y (standard deviation of the concentration distribution in the horizontal cross-wind direction) was calculated for each occasion when there were three or more plume width measurements completed within a 60-minute period at a relatively constant distance from the power plant using either the TECO or the COSPEC unit. There were 22 values from the COSPEC unit and 26 values from the TECO unit. Subsequently, a regression analysis was made between the observed σ_y values normalized with respect to downwind distances, x and σ_θ (standard deviation of wind direction). The correlation coefficients from that analysis are presented in Table 2.

TABLE 1. METEOROLOGICAL DATA SOURCE FOR KAHULUI PLANT STUDY

	Monitoring Stations	Kahului Airport	Hilo Weather Station
Wind Speed	1	2	-
Wind Direction	1	2	-
Std Dev. of Wind Dir	1	-	-
Sky Condition	-	2	-
Temperature	-	2	-
Mixing Depth	-	3	4

1 - Hourly data available for 6-month period - February- July 1977
2 - 3-hourly data available for 12-month period - August 1976-July 1977
3 - Upper air soundings four times a day - May 14-20, 1977
4 - Upper air soundings twice a day, 12-month period - August 1976-July 1977

TABLE 2. CORRELATION COEFFICIENTS OF σ_y/x TO OBSERVED σ_Θ

σ_Θ Observed at Station	σ_y Values Determined from			
	TECO	COSPEC	TECO or	COSPEC
1	0.273	-	-	-
2	0.489	0 668	0.539 (1)	0.642 (2)
3	0 690	0 656	0 656 (1)	0 656 (2)

(1) On the occasions when a value was available from both the TECO and COSPEC for the same time and same downwind distance the TECO observation was used

(2) On the occasions when a value was available from both the TECO and the COSPEC for the same time and at the same downwind distance the COSPEC was used.

The best correlation occurred between σ_y observed using the TECO analyzer and σ_θ observed at Station 3. Based on the fact that the best correlation was found between the σ_θ values at Station 3 and the σ_y/x values from the TECO data set, and that the model performance was improved by calculating σ_y by using the coefficients from the regression line of the TECO and σ_θ from Station 3, the model was adapted to routinely calculate σ_y based on the observed σ_θ of each hour in the data set. There is no obvious reason why the correlations with measurements at Stations 2 and 3 are different. The frequency distributions of σ_θ at the two stations over the monitoring period are shown in Figure 2 to be very similar. It is concluded that these two measurements are essentially interchangeable. When the Station 3 σ_θ observation was missing, Station 2 observations were used.

Emission Data

The emission rate data for dispersion model input were calculated using reported generator output information, fuel sulfur content, and the emission factor for oil-fired boilers from EPA's (1977) published compilation of emission factors.

Hourly generation load records were provided for the intensive study period, and daily generation load data were provided for the monitoring period. For the 5 months of August 1976 through January 1977, only the fuel consumption data on a monthly basis were available to estimate emissions.

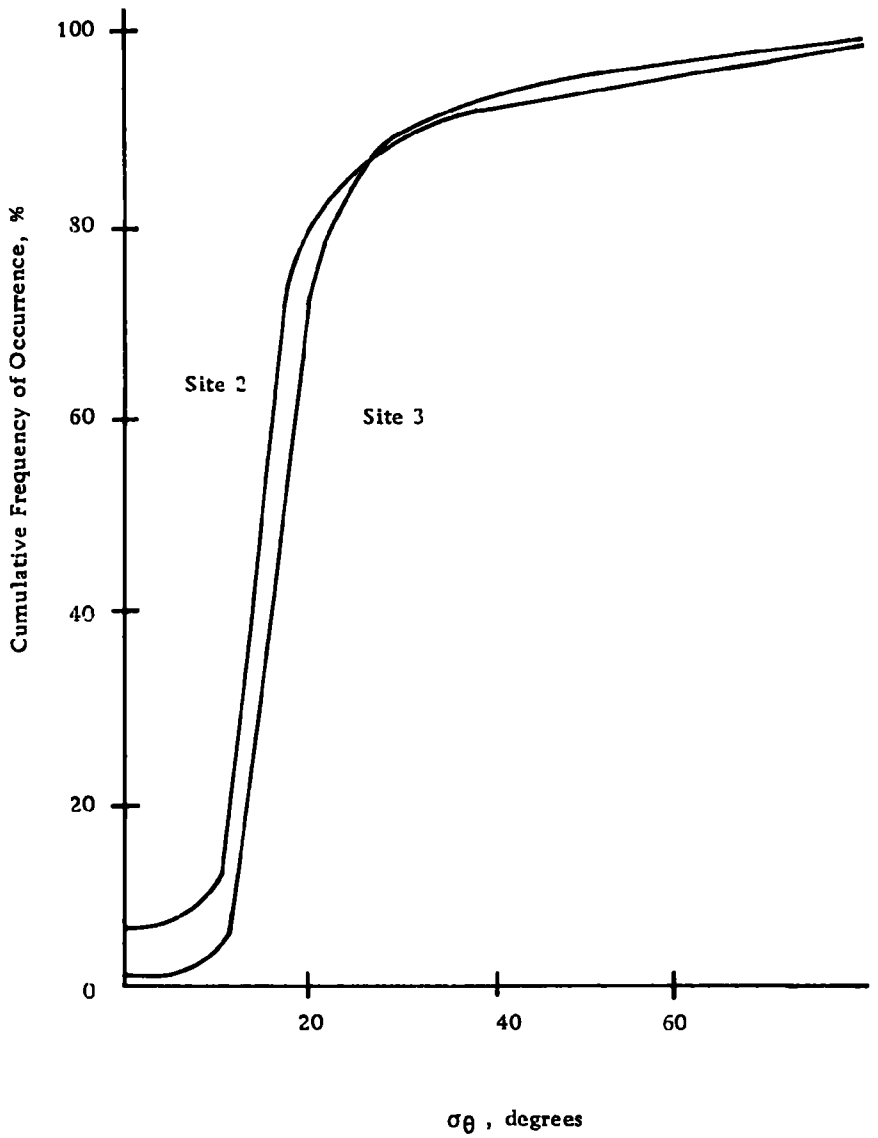

Figure 2. Distribution of σ_θ observations at Sites 2 and 3 near the Kahului plant.

Hour-by-hour estimates of the SO_2 emission from each stack were calculated from hourly generator loads using means of the fuel sulfur content,* fuel heat content, and the plant operating efficiency (in terms of heat input per unit of load output).

The power plant reports the fuel sulfur content and heat content to the FPC on a monthly basis. The fuel information used in this study included data provided directly from the plant and data obtained from the FPC.

The hourly emission rates were computed for the intensive study period, and from that information an hourly variation factor was computed by determining the average fraction of daily emissions which is emitted each hour in the intensive study period. The hourly variation factor was applied to the average daily emission rates which were computed from the daily generator loads available for the monitoring period and to the average monthly emission rates computed for the 6 months before the monitoring period. The hourly variation factor was applied to reflect the very consistent load cycle apparent in the hourly generation data provided.

KAHE POINT

Meteorological Data

Meteorological data for model input were available from the three monitoring stations located near the power plant. Hourly averages of meteorological (and air quality) parameters which were measured for the 4-month period from October 1977 through January 1978 were delivered to Geomet by Northrop Services, Inc., on magnetic tape. The hourly data included the arithmetic mean wind speed, vector mean wind speed, vector mean wind direction, and standard deviation of the wind direction from all three stations. The temperature and pyranometer data were also available from Station 1. Intensive monitoring data, including vertical wind and temperature data from a tethered balloon, were available for a few hours each day during a 2-week period.

The vertical temperature gradient from the tethersonde observations was investigated to determine how well surface pyranometer measurements represent stability classes defined by vertical temperature gradient using the scheme recommended by the Atomic Energy Commission Safety Guide 23 (1972) for the change of temperature from 10 to 100 meters above ground level. Stability class determined using solar radiation data alone matched with the vertical temperature classes, as well as solar radiation data stratified by wind speed. A comparison of three schemes for characterizing stability is shown in Table 3. The vertical temperature gradient shown for each hour is an average of the gradient from 10 to 100 meters during up and down descents

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* Fuel sulfur content (wt. %) data from Federal Power Commission records were as follows:

1976 -	August, 1.9	November, 1.8	1977 - January, 1.98	May, 1.90
	September, 1.8	December, 1.8	February, 1.98	June, 1.96
	October, 1.8		March, 1.98	July, 2.05
			April, 1.86	

TABLE 3. COMPARISON OF STABILITY CLASSES ESTIMATED THREE DIFFERENT WAYS

Date	Hour of Day	Vertical Temperature Gradient 10 to 100 m, °C/100m	NRC Stability Class	Station 1 Pyranometer Reading (No units)	Station 1 Wind Speed m/sec	Approximate Pasquill Stability Class*	Model Input Stability Class
Jan 13	12	-1.2	D	3.3	0.6	A	B
	14	-1.0	D	2.7	2.3	B	B
	16	-1.2	D	1.1	2.2	C	D
	18	-1.8	B	0.0	3.5	D	D
	19	-1.0	D	0.0	3.1	D	D
14	8	-0.9	D	0.5	2.9	C	C
	10	-1.0	D	1.5	2.9	B-C	D
16	10	-1.4	D	1.4	3.9	D	B
18	10	-0.3	E	2.8	1.6	A-B	D
23	13	-1.1	D	1.0	1.7	B	C
	15	-1.0	D	1.5	1.5	A-B	D
	17	-1.1	D	0.3	2.6	C	D
	18	-1.0	D	0.0	2.4	D	D
	19	-1.2	D	0.0	3.1	D	D
24	8	-0.5	D-E	0.7	2.4	C	C
	9	-0.8	D	2.1	4.7	B-C	C
	10	-1.6	C	2.4	3.7	B-C	D
	16	-1.1	D	0.5	3.6	C	D
	17	-1.2	D	0.0	4.5	C	D
25	8	-0.4	E	0.6	4.0	C	D
	9	-0.8	D	M†	M	-	-
	10	-1.8	B	M	M	-	-
	14	-1.6	C	2.1	1.9	A-B	D
	16	-1.1	D	1.1	1.4	B	D
	17	-1.0	D	0.3	3.5	C	B
26	11	-1.3	D	2.7	3.8	B-C	B
	13	-1.9	B	2.9	3.6	B-C	B
27	10	-0.9	D	2.8	3.4	B-C	B
	12	-1.2	D	3.5	4.0	B	A

* See text.
† Missing

closest to the indicated hour of the day. The model input stability class is the pyranometer reading rounded (i.e., $\leq$ 1.5 for D, 1.5 to 2.4 for C, 2.5 to 3.4 for B, and $\geq$ 3.5 for A). The approximate Pasquill stability categories were determined using Pasquill's (1974) scheme assuming that pyranometer readings of less than 1.5 correspond to slight insolation, 1.5 to 3.0 to moderate, and greater than 3.0 to strong insolation. These comparisons suggest that a stability classification scheme based on the pyranometer reading alone does as well or better than one taking wind speed into account in estimating stability classifications based on vertical temperature gradient. Since there is some uncertainty regarding the representativeness of the surface wind speed measurements at each of the three monitoring sites, it was decided to use a scheme which did not depend on wind speed.

The hourly averages of wind direction from the three monitoring sites showed the characteristic wind direction was different from site to site. Figure 3 shows the frequency distribution of hourly average directions from the three sites. Figure 4 shows the frequency distribution of σ_θ values from each site.

The monitoring sites were all located along the shoreline, all within 2 km of one another. For running the model for the 4-month period, the Station 2 wind data were used. Station 2 is located between Stations 1 and 3. The wind directions show a pronounced change from strongly northeast at Station 1 to almost uniform at Station 3. The strong influence of the very pronounced Waianae Mountain Range in breaking up the northeast trade winds along the west coast is clearly shown at Station 3. It was hypothesized that Station 2 would be most representative of the three sites in representing the wind direction of the plant plume, which is estimated to be the most critical meteorological parameter to be determined. This was tested by comparing hourly mean wind direction at the three sites with tethersonde wind measurements taken in the plume. Table 4 presents the comparison. Stations 1 and 2 do about equally well in predicitng the wind direction observed by tethersonde during the time the tethersonde was at plume height. Station 2 is judged best in 14 of 30 comparisons, Station 1 in 12 of 30 comparisons, and Station 3 in 4 of 30 comparisons. Data from Station 2 were selected for use in the model because of Station 2's closer proximity to the plant. All three sites were influenced to some extent by surrounding obstacles, especially trees.

Meteorological data required by the model for each hour also include mixing height and a stability class indicator. At the time the modeling effort was to be performed, the standard twice-daily upper air sounding data for the monitoring period were not available; consequently, the sensitivity of the model to this parameter and the impact of using monthly average data instead of daily values were tested. The test of the model sensitivity to mixing height input consisted of running the model using day-to-day variations of the mixing height for a 6-month period and running the model again using monthly averages of the mixing height for the same period. The results of the test showed that only minor changes occurred in the model-calculated concentrations. There were 30 receptor locations included in the sensitivity test. The overall mean from a total of 2,256 hours in the test data set was changed by less than 1 microgram per cubic meter ($\mu g/m^3$) at 13 receptors.

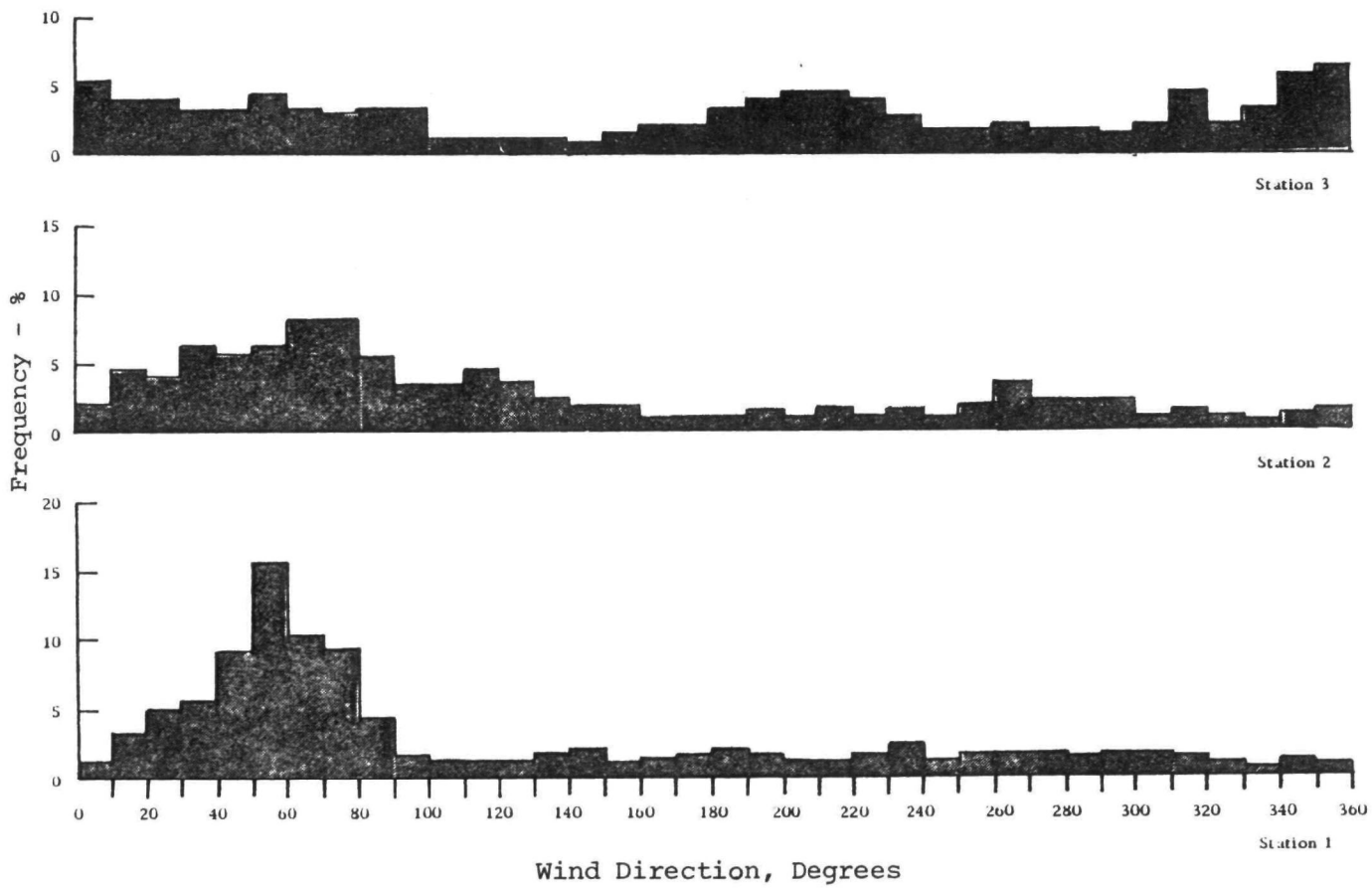

Figure 3. Distribution of wind direction, Kahe Point monitoring stations.

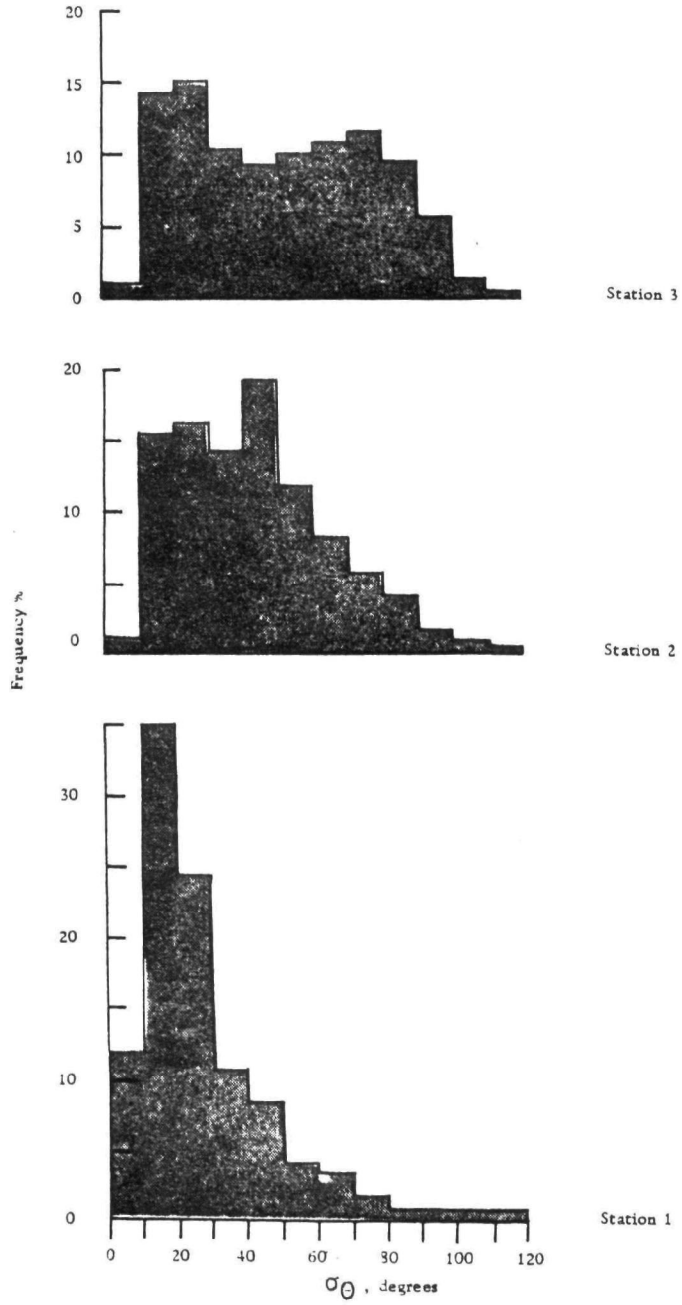

Figure 4. Frequency distribution of σ_Θ, Kahe Point monitoring stations.

TABLE 4. WIND DIRECTION OBSERVED IN TETHERSONDE AND MONITORING STATIONS DURING 2-WEEK PERIOD IN JANUARY 1978

Date (1978)	Hour of Day	Tethersonde Flight	Tethersonde Duration (min)	Tethersonde Height (m)	Tethersonde Wind Direction (Degrees)	Station 1 Wind Direction (Degrees)	Station 2 Wind Direction (Degrees)	Station 3 Wind Direction (Degrees)
January 13	14	3	11	190	200-260	202	228	226
	16	4	9	180	190-210	178	205	206
14	8	7	26	170	200-240	184	204	205
	10	8	41	150	210-240	227	259	256
	11	8	22	150	230-260	229	265	241
18	10	12	54	200	20-80	51	M *	303
	11	12	17	210	20-110	40	115	297
19	8	13	25	160	50-70	18	19	17
	10	14	57	200	10-100	42	99	131
	11	14	19	140	40-80	31	89	258
	13	15	6	140	30-60	355	357	300
23	11	18	15	130	340-70	244	275	M
24	8	24	6	200	40-60	35	72	M
	9	25	7	210	40-60	23	60	M
	10	26	60	150	20-70	35	84	M
	11	26	15	140	40-70	32	81	M
	16	27	16	240	290-340	20	55	300
	18	12	28	180	30-50	35	72	353
25	9	8	30	150	40-60	M	73	359
	10	60	31	100	10-70	M	79	15
	11	12	31	90	30-60	37	84	6
	14	39	32	100	360-50	276	294	M
	15	21	32	120	270-310	260	276	M
	17	18	34	330	360-90	9	32	M
26	11	16	35	200	20-90	101	M	35
	13	48	36	150	10-80	27	67	M
	14	18	36	150	30-90	28	88	M
27	10	50	37	130	20-100	47	115	M
	11	13	38	100	60-100	60	95	M
	12	8	38	120	40-110	35	84	M

* Missing

At the remaining 17 receptors, the mean increased in the 1-to-5 $\mu g/m^3$ range at 10 receptors, by 6 to 10 $\mu g/m^3$ at 5 receptors, and by less than 15 $\mu g/m^3$ at 2 receptors. None of the means was affected enough to change the status of any of the receptor locations from being within compliance to being out of compliance. In all instances, whenever the distribution of calculated concentrations was different due to a change in the mixing height estimate, the concentrations calculated using the monthly average mixing height were higher. Monthly mean afternoon and morning mixing heights were obtained for the Hilo radiosonde data for the periods of October 1976 to January 1977.

The mixing heights derived from Hilo soundings were higher, in general (see Figure 5), than the mixing heights from nine comparable soundings at Wheeler Air Force Base (AFB). This result indicates that the Hilo data may provide an overestimate of the mixing height at the Kahe Point plant. However, this estimate is not expected to have any effect on the maximum SO_2 concentrations which occur very close to the plant. Figure 5 shows the mixing heights from Wheeler AFB on Oahu for approximately comparable times using Hilo and Lihue data. The Lihue data indicate a more favorable comparison but the Hilo data are close enough that no significant impact would be found in the modeling results.

Tethersonde flights ranged up to 600 meters above ground level on some occasions. Mixing height data from the available radiosonde stations in Hawaii (Hilo, Lihue, Wheeler AFB) indicate mixing heights are generally higher than the maximum altitude of the tethersonde, especially during midday when most of the tethersonde data were collected. The tethersonde data provided excellent detail on the wind and temperature profile in the atmosphere below 600 m. The tethersonde temperature data did indicate low-level temperature inversions which would not show up from the radiosonde data.

The site-specific data were valuable in assessing the utility of dispersion parameters used in the model, for providing the type of meteorological data needed for input to the model, and for verification of the calculated concentrations from the model. More data, especially of the type collected in the intensive monitoring, would have extended the usefulness of that data considerably.

Plume width measurements were made during the intensive period by remote sensing using a mobile mounted COSPEC. The COSPEC data provided estimates of the plume width at locations along the coastal highway where the plume crossed the highway. The plume width data were used to evaluate the applicability of conventional methods for calculating crosswind concentration parameter, σ_y.

In modeling the power plant at Kahului, a reasonable correlation was found between the standard deviation of the observed plume width (σ_y) and the standard deviation of the wind direction (σ_θ). The data from the Kahe Point plant observations did not have as good correlation between σ_y and σ_θ, and consequently considerable effort was given to determining how the σ_y value should be determined. One of the main reasons that the Kahului relationship did not correlate well at the Kahe Point location is that the measured plume dispersion in terms of σ_y is mostly affected by the separation of stacks

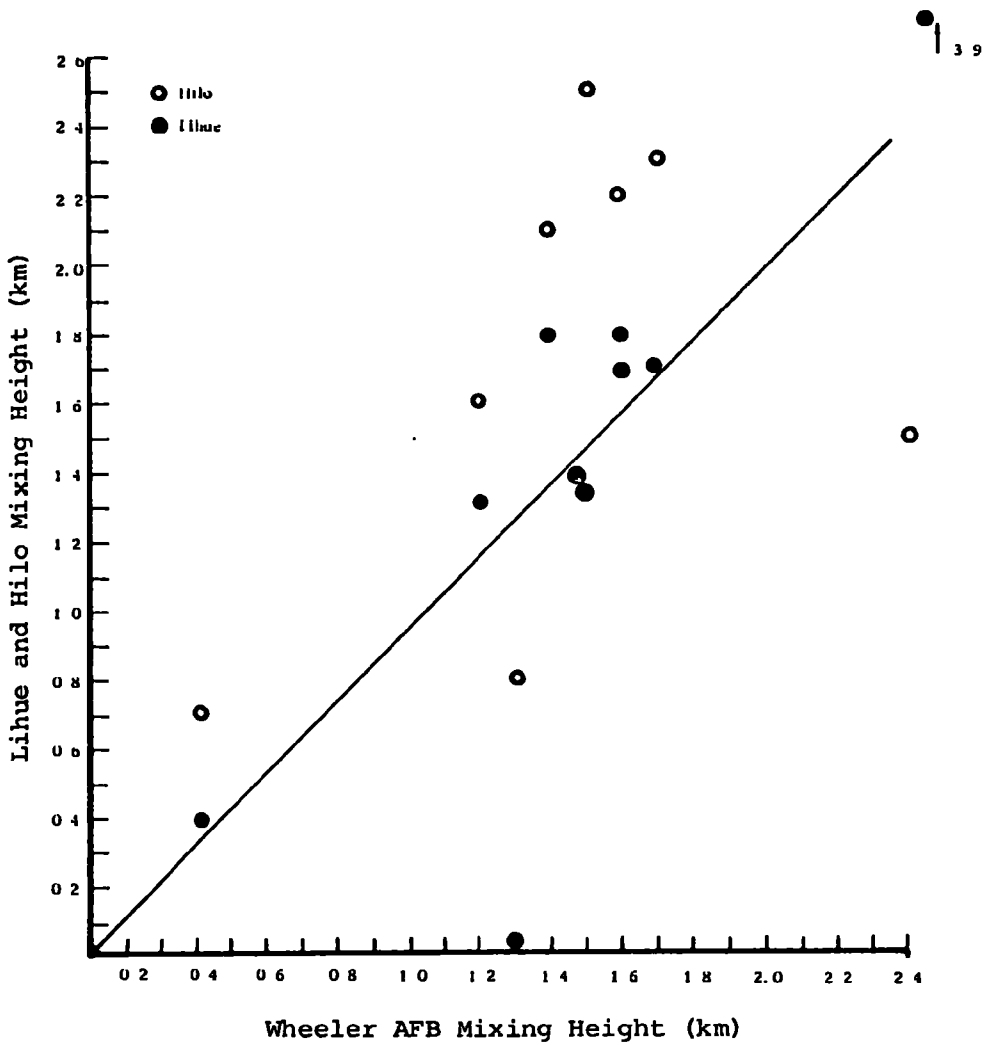

Figure 5. Comparison of mixing heights derived from Hilo and Lihue radiosondes with Wheeler AFB radiosondes.

and the orientation of the wind relative to the line of stacks. This is due to the fact that the observations were made on a road only 100 meters from the plant. This road was the only location from which the COSPEC measurements of the plume could be made. Attempts to make angular sitings through the side of the plume at some distance away were not successful. Only vertical observations made from underneath the plume produced useful data.

It might be possible to get a significant correlation between σ_θ values determined from the tethersonde observations and COSPEC σ_y measurements. However, since the measurements mostly represent one travel distance because of the influence of the wind relative to the line of stacks, this does not seem like a promising line of analysis. Perhaps future investigations can be made into this question. Such future investigations should also consider the relationship of σ_θ measured aloft to σ_θ measured at the surface or some other parameter, in order to find data for use in longer-period modeling considerations.

Since the measured plume dimensions mostly showed the influence of the wind orientation relative to the stacks and showed very little about the rate of dispersion, the model was adjusted by the cut-and-try method. The plume height, initial volume, and σ_y and σ_θ relationships were adjusted to produce the best agreement between calculated and measured hourly mean SO_2 concentrations. It was decided to relate σ_y estimates to σ_θ measurements, as the meteorological variable, since these are generally accepted as well correlated. The Kahului relationship was used as the basic starting point. A description of the modifications adopted is given in the model validation discussion.

The coefficient for vertical dispersion, σ_z, was determined using the values of the pyranometer to describe the basic meteorological influence. Hourly average values of the pyranometer data ranged from 0.0 to 4.0. The stability class determined from the pyranometer is described below. These stability classes agreed reasonably well with vertical temperature gradients observed by tethersonde data.

Pyranometer	Stability Class
≥ 3.5	A
2.5-3.4	B
1.5-2.4	C
≤ 1.5	D

Based on the modeler's experience, stability class D was further broken down to more stable classes E and F. If the wind speed was less than 5.4 meters per second (m/sec) and σ_θ was between 10 and 20 degrees, stability class E was assigned. If the wind speed was less than 5.4 m/sec and σ_θ was less than 10 degrees, stability class F was asssigned.

Emission Data

The emission rate data input to the model were calculated using generator output information, fuel content, and the emission factor for oil-fired boilers taken from EPA's published compilation of emission factors (EPA, 1977). Hourly generator output data were provided for the entire 4-month

modeling period. The hourly emission rate from each stack was determined by calculating the fuel required to generate a kilowatt of electricity, then subsequently applying the emission factor and the average sulfur content of the fuel during the corresponding time period.

Emission rate data input to the model were provided for each hour for each of the five stacks. Specifically, the SO_2 emission rate was calculated using a monthly average fuel sulfur content which was 1.7 percent in October, 1.6 percent in November, 1.5 percent in December, and 1.3 percent in January. Data obtained from the FPC were used to calculate the average number of British thermal units (BTU) required to generate a kilowatt. The value of 9,970 BTU/kw was used for the emission rate calculation; the data available indicated that monthly averages would be within 0.5 percent of the value (9,970) used.

SECTION 4

AIR QUALITY DATA

KAHULUI

Ambient concentrations of sulfur dioxide were continuously measured from February 7, 1977, to July 18, 1977, at the three monitoring stations southwest of the Kahului power plant. Hourly average concentration data were computed by Northrop Services, Inc., from instantaneous measurements made every 2 minutes. These data were used to modify and validate the model. The distributions of observed SO_2 concentrations were tabulated for each hour of the day at each station by 10-degree wind sectors. The resulting tables showed that concentrations of SO_2 are very dependent on wind direction. The data collected during this study are presented in a report by Siple and Freberg (1978).

Statistical summaries of the observed SO_2 concentrations for the 6-month period are presented in Tables 5, 6, and 7. Comparison of calculated concentration to observed concentration is facilitated by these statistical summaries. Monitoring station 1 was located at 156°28'06" West, 20°53'34" North and about 0.4 km from the power plant; monitoring station 2 was located at 156°28'12" West, 20°53'18" North, and about 1.0 km from the power plant; monitoring station 3 was located at 156°28'33" West, 20°53'06" North, and about 1.7 km from the power plant.

The predominance of the Kahului power plant as a source of SO_2 at the three monitoring stations is indicated in Table 8. The average concentration for each 10-degree sector of hourly mean wind direction is shown for each monitoring station in Table 8. The data shown are the averages of the observed concentrations when the wind was from the sector indicated. It is obvious that high concentrations are observed when the wind is from the north, within the range from 330 to 070 degrees. Especially noticeable are the elevated concentrations at Station 1 when the wind is from the 41 to 50 and 51 to 60 degree sectors; at Station 2 elevated concentrations are most noticeable with wind from the 21 to 30 and 31 to 40 degree sectors, and at Station 3 when the wind is from the 31 to 40 and 41 to 50 degree sectors.

The influence of other SO_2 sources is also indicated by the data in Table 8. At Station 1 a second high is prominent when the wind is from the 1 to 10 degree sector. The wind from due north would carry emissions from ships in Kahului Harbor to Station 1. A decrease in average concentrations is apparent as the wind shifts towards the east until the power plant and Station 1 are aligned. The apparent influence of emissions from a pineapple plant

TABLE 5. CUMULATIVE FREQUENCY DISTRIBUTIONS OF OBSERVED HOURLY SO_2 CONCENTRATIONS AT KAHULUI

($\mu g/m^3$)

PERCENTILE	Station 1	2	3
HIGH	4090.000	941.000	786.000
99.5	3567.351	623.351	370.676
99.0	3370.000	500.350	320.000
95.0	2603.499	244.700	212.000
90.0	2140.000	141.000	152.000
80.0	1520.000	49.800	89.100
70.0	1110.000	21.000	52.400
60.0	741.000	10.500	31.400
50.0	414.000	5.240	15.700
40.0	152.000	2.620	10.500
30.0	34.100	2.620	7.860
20.0	7.860	2.620	2.620
10.0	2.620	0.000	0.000
5.0	0.000	0.000	0.000
1.0	0.000	0.000	0.000
0.5	0.000	0.000	0.000
LOW	0.000	0.000	0.000

TABLE 6. CUMULATIVE FREQUENCY DISTRIBUTIONS OF OBSERVED 3-HOUR SO_2 CONCENTRATIONS AT KAHULUI

($\mu g/m^3$)

PERCENTILE	Station 1	Station 2	Station 3
HIGH	3680.000	705.000	432.000
99.5	3217.451	516.000	296.726
99.0	2994.700	446.490	266.000
95.0	2404.500	215.450	183.000
90.0	1980.000	132.000	137.000
80.0	1450.000	62.080	88.200
70.0	1090.000	32.300	60.300
60.0	790.000	17.500	41.000
50.0	520.000	9.620	25.300
40.0	290.400	5.240	14.000
30.0	81.260	2.870	8.740
20.0	20.100	2.620	4.370
10.0	2.620	2.620	0.000
5.0	0.000	0.000	0.000
1.0	0.000	0.000	0.000
0.5	0.000	0.000	0.000
LOW	0.000	0.000	0.000

TABLE 7. CUMULATIVE FREQUENCY DISTRIBUTIONS OF OBSERVED 24-HOUR SO_2 CONCENTRATIONS AT KAHULUI

($\mu g/m^3$)

PERCENTILE	Station 1	Station 2	Station 3
HIGH	2360.000	311.000	193.000
99.5	2284.000	235.761	186.160
99.0	2119.599	209.400	169.440
95.0	1754.000	150.200	125.400
90.0	1584.000	115.000	105.800
80.0	1336.000	79.220	88.360
70.0	1108.000	49.840	67.880
60.0	887.000	36.860	49.520
50.0	678.000	24.400	37.800
40.0	520.400	16.700	28.060
30.0	324.400	10.860	22.200
20.0	150.600	6.108	14.580
10.0	14.520	3.544	1.986
5.0	3.516	2.216	0.000
1.0	0.000	0.000	0.000
0.5	0.000	0.000	0.000
LOW	0.000	0.000	0.000

TABLE 8. AVERAGE OBSERVED SO_2 CONCENTRATION BY WIND DIRECTION IN 10-DEGREE SECTORS

Wind Sector (Degrees)	SO_2 Concentration ($\mu g/m^3$) Station 1	2	3
181-190	9	2	9
191-200	7	6	7
201-210	7	4	6
211-220	7	6	7
221-230	6	3	7
231-240	3	0	1
241-250	6	2	3
251-260	3	2	6
261-270	5	2	3
271-280	3	2	4
281-290	4	1	3
291-300	6	2	4
301-310	8	3	3
311-320	8	2	8
321-330	12	3	7
331-340	23	8	29
341-350	28	8	62
351-360	25	9	24
001-010	538	29	53
011-020	67	47	33
021-030	62	133	40
031-040	479	250	111
041-050	1335	62	126
051-060	1538	9	29
061-070	668	5	10
071-080	217	4	10
081-090	42	8	8
091-100	4	1	7
010-110	1	0	1
111-120	4	1	2
121-130	7	3	3
131-140	9	2	3
141-150	3	1	1
151-160	3	2	2
161-170	8	1	2
171-180	8	2	8

* Observed at Station 2.

just north of Station 3 on observed concentrations at Station 3 is noticed when the wind is from the 341 to 350 degree sector.

The average concentrations for the entire 6-month monitoring period at Stations 1, 2, and 3 are 768, 45, and 50 $\mu g/m^3$, respectively. If the concentration at Station 1 is reduced by the apparent anomolous contribution from the harbor area when the wind is from the 1 to 10 degree sector, the average concentration would be approximately 755 $\mu g/m^3$. This would lower the average by 13 $\mu g/m^3$. In the same manner, if the average concentration at Station 3 is calculated with apparent anomolous contributions from the pineapple plant when the wind is from the 341 to 350 degree sector, the overall average would be lowered by 1 $\mu g/m^3$. The changes in the average concentrations which would occur if the apparent contributions from sources other than the power plant are removed are not significant and would not alter the conclusions of this study.

Assuming that 6 months of data may be used to approximate the annual average, the mean values show that concentrations at Station 1 are in serious violation of the primary air quality standard. Stations 2 and 3 are below the primary and secondary Federal air quality standards for an annual mean. The distributions of 3-hour and 24-hour concentrations shown in Tables 6 and 7, respectively, show similar results for these stations relative to Federal standards, in that Station 1 data indicated violations while Station 2 and 3 data are below the corresponding standards.

KAHE POINT

Sulfur dioxide was continuously monitored for the 4-month period October 1, 1977, through January 30, 1978, at three sites along the coast to the west of the Kahe Point power plant. Hourly averages of the observed data were computed from the instantaneous values measured every 2 minutes. The hourly SO_2 concentrations were compared with the model calculations to indicate the validity of the model. The data collected during this study are presented in a report by Siple and Freberg (1978). Monitoring Station 1 was located at 158°07'57" West, 21°21'23" North, and about 0.5 km from the power plant; monitoring Station 2 was located at 158°07'58" West, 21°21'34" North, and about 0.15 km from the power plant; monitoring Station 3 was located at 158°08'20" West, 21°22'24" North, and about 1.6 km from the power plant.

Statistical representation of the observed hourly average SO_2 concentrations from all three stations is presented in Table 9. The data shown represent approximately 2,650 individual cases at each station. The means of the hourly averages from Stations 1, 2, and 3 are 80, 402, and 20 $\mu g/m^3$, respectively.

Using the mean of all hourly averages to represent an annual mean,* the pattern of excursions above the Federal standards is similar to the results for shorter term concentrations. The primary standard for the annual average

* The 4-month monitoring period is considered representative of annual conditions because it includes both a period of persistent trade winds and a period of variable winds with a high frequency of the irregular Kona winds.

TABLE 9. CUMULATIVE FREQUENCY DISTRIBUTIONS OF OBSERVED HOURLY SO_2 CONCENTRATIONS AT KAHE POINT

($\mu g/m^3$)

PERCENTILE	STATION 1	STATION 2	STATION 3
HIGH	2050.000	3680.000	529.000
2ND	1773.000	3568.000	448.000
99.5	1098.950	3005.400	247.710
99.0	958.641	2807.700	247.710
95.0	447.850	1800.000	83.800
90.0	183.000	1320.000	39.300
80.0	68.100	744.000	18.300
70.0	39.300	414.000	13.100
60.0	26.200	189.000	10.500
50.0	18.300	62.900	7.860
40.0	13.100	26.200	5.240
30.0	10.500	12.840	5.240
20.0	7.860	5.240	2.620
10.0	5.240	2.620	2.620
5.0	2.620	2.620	2.620
1.0	2.620	2.620	2.620
0.5	2.620	2.620	2.620
LOW	2.620	2.620	2.620

of 80 $\mu g/m^3$ is exceeded at Station 2; Station 1 is exactly at the standard and Station 3 is well below the standard.

Statistics of the 3-hour average concentrations are presented in Table 10. The data in Table 10 indicate that no violations of the 3-hour secondary standard of 1,300 $\mu g/m^3$ were observed at Station 3. At Station 1 only the highest value exceeded the 3-hour standard. At Station 2, however, the distribution shows that 10 percent of the 3-hour averages exceeded the standard, indicating the standard would be exceeded about 265 times over a 1-year period.

The hourly averages within a calendar day were averaged to compute the 24-hour averages. The distribution of the 24-hour averages is shown in Table 11. Comparison of the 24-hour standard to the observed 24-hour averages shows a situation similar to the comparison of the 3-hour data, in that there are no excursions at Station 3; at least 1 percent of the data at Station 1 exceeds the 365 $\mu g/m^3$ standard while at Station 2, 30 percent of the observations (about 35 days) exceed the standard.

TABLE 10. CUMULATIVE FREQUENCY DISTRIBUTIONS OF OBSERVED 3-HOUR SO_2 CONCENTRATIONS AT KAHE POINT

($\mu g/m^3$)

Percentile	Station 1	Station 2	Station 3
HIGH	1399.080	3537.000	372.040
2ND	1236.640	3222.600	353.700
99.5	1007.521	2689.432	231.071
99.0	900.678	2231.245	203.823
95.0	422.344	1743.086	74.408
90.0	184.291	1335.152	44.540
80.0	78.338	723.644	21.825
70.0	46.374	472.648	15.720
60.0	33.274	217.303	10.480
50.0	23.580	80.434	7.860
40.0	16.239	32.540	6.105
30.0	11.345	15.720	4.375
20.0	7.860	7.860	3.485
10.0	5.240	4.721	2.620
5.0	3.485	2.620	2.620
1.0	2.620	2.620	2.620
0.5	2.620	2.620	2.620
LOW	2.620	2.620	2.620

TABLE 11. CUMULATIVE FREQUENCY DISTRIBUTIONS OF OBSERVED 24-HOUR SO_2 CONCENTRATIONS AT KAHE POINT

($\mu g/m^3$)

Percentile	Station 1	Station 2	Station 3
HIGH	702.160	2143.160	104.800
2ND	581.640	2054.080	102.180
99.5	629.848	2091.048	103.307
99.0	578.496	2028.692	100.346
95.0	327.500	1530.473	59.212
90.0	188.640	1226.422	38.252
80.0	99.560	799.100	25.200
70.0	62.880	465.836	20.960
60.0	41.920	243.136	18.340
50.0	31.440	121.830	13.100
40.0	26.200	49.780	10.480
30.0	20.960	26.462	7.860
20.0	13.100	15.720	5.240
10.0	7.860	7.860	5.240
5.0	5.240	5.240	2.620
1.0	3.144	2.620	2.620
0.5	2.620	2.620	2.620
LOW	2.620	2.620	2.620

SECTION 5

MODEL SELECTION AND MODIFICATION

The Gaussian plume dispersion model as implemented in the PTMTP program of EPA's UNAMAP system is the basic model format which was used in this study. However, extensive changes were introduced to the program to enable it to represent source characteristics found in the vicinity of the two plants being studied and to accept the types of data which were available for this study. The changes produced substantial improvements in the model-to-measurement comparisons which were used to select or reject various model modifications. The model modifications are site-specific in that different modifications were used to obtain the best agreement between model calculations and measurements at the two power plants. Some of these changes are relatively general in concept and may be applicable to other areas. Other changes include site-specific influences which are not obvious but which indirectly impact on meteorological observations. The relationships between meteorological variables and SO_2 measurements derived for the vicinity of each power plant may be different from the relationships between the same variables which are observed at other locations. Because of this indirect site-specific influence, it is recommended that any use of these relationships with the model be validated using the data selected as inputs before applying them to another location.

KAHULUI MODIFICATIONS

Initial trial runs were made with the PTMTP program using data from the 7-day intensive monitoring periods. The correspondence between observed and calculated values is shown in Table 12. Several modifications to the model were proposed. Two principal modifications to the model included a method for treating downwash effects from the power plant building and a different method of determining the horizontal dispersion coefficient. The result of applying these two modifications to the intensive monitoring data period is also shown in Table 12. Several additional steps were made to "tune" the model after these two major modifications were made.

The provision for downwash effects is based on the widely accepted hypotheses that airflow is not affected by buildings above 2.5 times the building height and that below 1.5 times the building height there is an aerodynamic cavity. The rules are based on empirical observations and wind tunnel experiments. The only additional information required to apply these rules are the heights and widths of buildings near the source which are likely to create downwash influences. The following parameters are used to estimate downwash:

B_H = building height, m

B_W = building width, m

h_s = stack height, m

d_s = stack diameter, m

v_s = stack gas exit speed, m/sec

u = wind speed at stack height, m/sec

Using these parameters, the following are calculated:

$$\ell_B = \min (B_H, B_W) \tag{1}$$

$$h_E = h_s + 2\left(\frac{v_s}{u}\ 1.5\right) d_s \tag{2}$$

TABLE 12. COMPARISON OF CALCULATED SO_2 CONCENTRATIONS USING MODEL ADJUSTMENTS WITH CORRESPONDING MEASURED VALUES AT KAHULUI DURING MAY 14-20, 1977

			SO_2 Concentrations ($\mu g/m^3$)		
			Calculated		
Monitoring Site	Statistic	Measured	Original Model	Downwash Added	New σ_y and Downwash Added
1	Mean	472	37	1070	332
	Peak	2960	662	9644	2349
2	Mean	15	44	124	52
	Peak	178	622	947	430
3	Mean	37	40	70	32
	Peak	249	482	579	378

The measurement of wind speed at stack height was not routinely available and the wind speed data from the 10-m tower at the monitoring site was used to represent u. The following rules, presented by (or derived from) Briggs (1975), are used to modify the ground concentration or the effective stack height to account for downwash effects:

1. If $h_E \geq B_H + 1.5\ell_B$ or $h_s \geq B_H + 0.25\ell_B$, no modification is required.

2. If the downwind distance from source to receptor is less than $3.5\ell_B$ and the crosswind distance is less than $0.5(B_W + \ell_B)$, then

$$\chi = \frac{KQ}{u\ell_B^2}$$

where Q = source emission rate, μg/sec

χ = ground level concentration, μg/m

$$K = \begin{cases} 0, & h_E > B_H + 0.5\ell_B \\ 1, & 0.35\ell_B < (h_E - B_H) \leq 0.5\ell_B \\ 1.5, & h_E \leq 0.35\ell_B + B_H \end{cases}$$

3. If $B_H \geq B_W$, compute plume height (h_F) as follows:

$$h_F = \begin{cases} 2h_E - B_H - 1.5B_W, & h_E > B_H \\ h_E - 1.5B_W, & h_E \leq B_H \end{cases}$$

Use $h_F = 0$, if $h_F < 0.5B_W$.

4. If $B_H < B_W$, compute plume height as follows:

$$h_F = \begin{cases} 2h_E - 2.5B_H, & h_E > 1.5B_H \\ 0, & h_E \leq 1.5B_H \end{cases}$$

Frequently rule 4 above was used to determine plume height in the downwash provision. The downwash provision is sensitive to the value used for B_H. The actual B_H of the power plant building is 22.56 meters. Little effect was shown on the calculated SO_2 concentrations when B_H was entered as 22.56 m, but using B_H = 28.0 m caused the effect to be too great. Several iterations of the program with variations of B_H determined that B_H = 24.7 m provided the best approximation of the observed SO_2 concentrations. Hour-by-hour comparisons of the calculated concentrations with measured values indicated that downwash effects should not be included in calculations during stable atmospheric conditions, i.e., when stability class was category E or F. The downwash provision is bypassed for stability category E or F, based on model-to-measurement comparisons and the fact that there are no stability criteria for downwash effects.

The method of determining the value of σ_y, the horizontal dispersion coefficient, was modified for model validation in the intensive period and the monitoring period by taking advantage of the availability of σ_θ, the standard deviation of wind direction, which was recorded at the monitoring sites.

Based on the recommendaitons of the "AMS Workshop on Stability Classification Schemes and Sigma Curves" (Hanna et al., 1977), the model was modified to compute $\sigma_y = \sigma_\theta \times f(x)$ with $f(x)$ defined by Pasquill (1974). Incorporating this method of determining σ_y improved the correlation of the calculated with the observed SO_2 concentrations over the correlation obtained using values from the Pasquill-Gifford curves for σ_y as presented in the EPA Workbook (Turner 1970). Further improvement in the correlation of calculated and observed values occurred when the regression coefficients of the relationship of σ_y/x to σ_θ observed at Station 3 were used in the equation for determining σ_y. The final version of the model calculated σ_y using the following equation whenever a value of σ_θ was available:

$$\sigma_y = (0.0441 + 0.0104\sigma_\theta)x; \text{ x in meters, } \sigma_\theta \text{ in degrees} \quad (3)$$

If the numeric value of σ_θ was measured as less than 5 degrees, it was set equal to 5 degrees when used in this equation to prevent negative values of σ_y.

On those occasions when σ_θ was not available, σ_y was computed as: $\sigma_y = a\,x^p$ with appropriate values of a and p from Table 13. These values were developed from the results of tracer experiments performed in St. Louis (McElroy and Pooler, 1968) and are recommended by an AMS Workshop on Sigma Curves (Hanna et al., 1977) for urban areas. The St. Louis values are more representative than the commonly used Pasquill-Gifford values in that they were measured over 1-hour periods in an urban area, while the Pasquill-Gifford values were mostly measured in rural areas over periods of 3 to 10 minutes. A comparison of these relationships is shown in Figure 6. The value of the vertical dispersion coefficient, σ_y, in the original version of the program was determined using the Pasquill-Gifford curves (Turner, 1970). The modified version of the model calculated σ_z as: $\sigma_z = bx^q$ with appropriate values of b and q from Table 13.

TABLE 13. FITTED CONSTANTS FOR THE McELROY-POOLER DIFFUSION PARAMETERS BASED ON TURNER (1970) STABILITY CLASSIFICATIONS

Stability Index	Crosswind Constants(1)		Constants for Vertical Diffusion Parameter(2)			
			x ≤ 600		x ≥ 600	
	a	p	b	q	b	q
A, B	1.42	0.745	0.0926	1.18	0.0720	1.22
C	1.26	0.730	0.0891	1.11	0.169	1.01
D	1.13	0.710	0.0835	1.08	1.07	0.682
E	0.992	0.650	0.0777	0.955	1.01	0.554

(1) $\sigma_y = ax^p$, where x is Downwind Distance from Source; σ_y and x are in meters.

(2) $\sigma_z = bx^q$; σ_z and z are in meters.

The model was also modified to treat the initial plume dispersion, resulting from the enhanced turbulence of the building and the hot stack gases, by adding a virtual distance to the actual source-to-receptor distance. The cross-section of the initial plume from each stack is modestly assumed to be given by the square of one-half the building height and to conform to the following elliptical shape equation:

$$\pi\ (2\sigma_y)\ (2\sigma_z) = \left(\frac{B_H}{2}\right)^2 \quad (4)$$

STL - Relationships from McElroy and Pooler
P-G - Relationships from Pasquill and Gifford
Site - Relationships derived from Kahului monitoring data

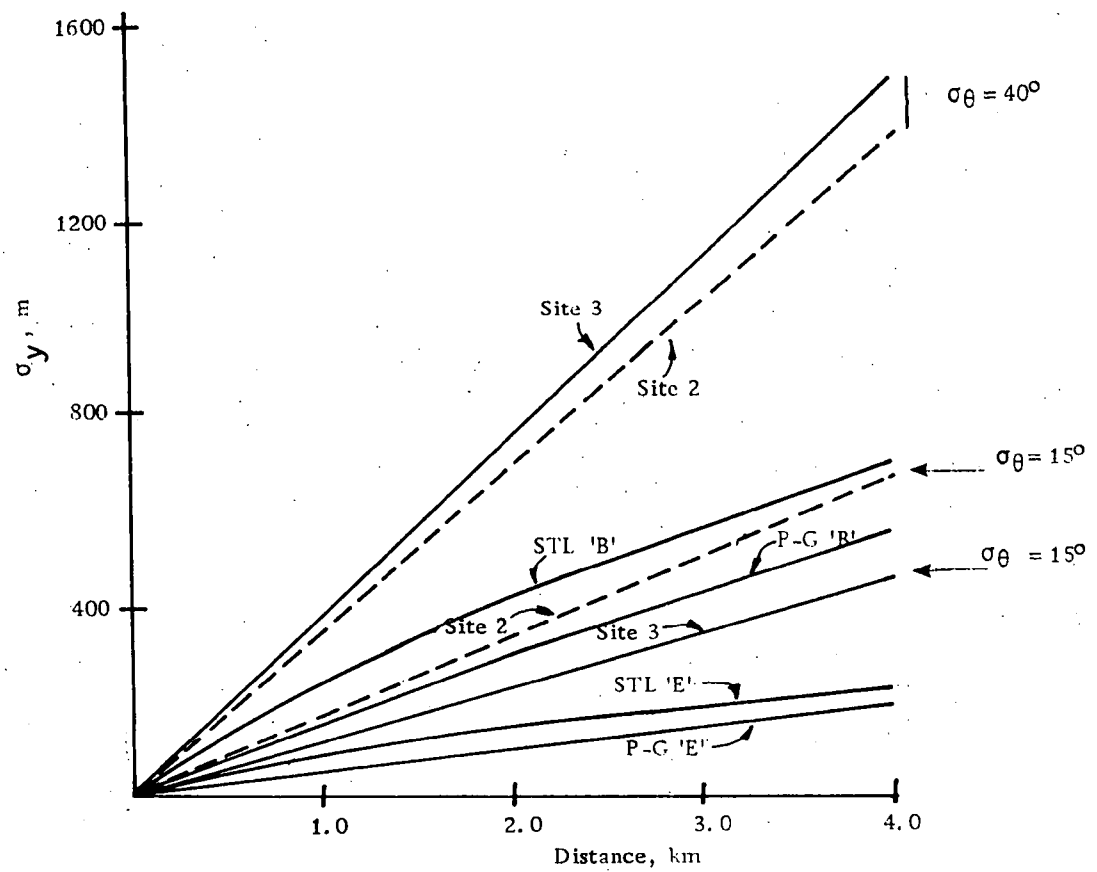

Figure 6. Comparisons among σ_y relationships.

This equation can be solved for a virtual distance by using the selected relationships for σ_y and σ_z as functions of x. The virtual distance, x_o, was determined as follows:

$$x_o = \left[\frac{B_H^2}{16\pi b(c+d\sigma_\theta)}\right]^{\frac{1}{1+q}} \tag{5}$$

or

$$x_o = \left[\frac{B_H^2}{16\pi\ ab}\right]^{\frac{1}{p+q}} \quad \text{if } \sigma_\theta \text{ was missing.} \tag{6}$$

The constants c and d are regression coefficients of the relationship of σ_y to σ_θ with values of -0.0441 and 0.0104, respectively. B_H is the height of the power plant building as used in this model (24.7 m).

VERIFICATION OF MODEL PERFORMANCE AT KAHULUI

The objective of the modeling work is to evaluate the effectiveness of several strategies designed to reduce ground level concentrations of SO_2. The confidence which can be placed in the estimated effectiveness of the strategies examined depends on the confidence that can be attributed to the ability of the model to accurately calculate the concentrations which would be observed at selected receptor locations.

Verification of the model performance for the Kahului power plant is based primarily on the comparison of the statistical summaries from observed and calculated concentrations for the monitoring period using hourly values. The results of those comparisons are shown in Tables 14, 15, and 16.

To arrive at an annual average we have run the model for an entire 12-month period. The model input data for the 12-month period were not as comprehensive as for the 6-month monitoring period, i.e., the meteorological data are only available from the airport at 3-hour intervals, and the information to calculate the emission rate is available only from fuel consumption data provided on a monthly basis. Due to the difference in the quality and quantity of the input data, it was necessary to compare the calculated concentrations for comparable time periods using the model output resulting from the various types of input. The following comparisons were made in order to estimate the validity of calculated concentrations made using only airport data at 3-hour increments.

1. The validity of the model was established by comparison of observed hourly, 3-hour, and 24-hour average concentrations with corresponding calculated values.

2. The comparison of 24-hour average concentrations, calculated using 24 values from the hourly calculations, with 24-hour average concentrations, calculated using only every third hour from the airport meteorological records, was used to establish the validity of more limited meteorological data on 24-hour means.

TABLE 14. COMPARISON OF STATISTICS FOR HOURLY OBSERVED AND CALCULATED CONCENTRATIONS FROM 7 DAYS IN THE INTENSIVE PERIOD

Station		Mean ($\mu g/m^3$)	Standard Deviation	Highest Value ($\mu g/m^3$)	Concentration ($\mu g/m^3$) at 90th Percentile	Concentration ($\mu g/m^3$) at 70th Percentile
1	Observed	472	686	2960	1608	905
	Calculated	332	515	2349	1051	489
2	Observed	15	32	178	39	5
	Calculated	52	85	430	163	43
3	Observed	37	51	249	108	33
	Calculated	32	51	378	97	41

TABLE 15. COMPARISON OF STATISTICS FOR HOURLY OBSERVED AND CALCULATED CONCENTRATIONS FROM THE 6-MONTH MONITORING PERIOD

Station		Mean ($\mu g/m^3$)	Standard Deviation	Highest Value ($\mu g/m^3$)	Concentration ($\mu g/m^3$) at 90th Percentile	Concentration ($\mu g/m^3$) at 70th Percentile
1	Observed	768	889	4090	2140	1110
	Calculated	531	615	4478	1413	754
2	Observed	45	99	941	141	21
	Calculated	96	135	1302	286	123
3	Observed	50	73	786	152	52
	Calculated	63	78	518	168	83

TABLE 16. COMPARISON OF STATISTICS FOR 24-HOUR AVERAGE OBSERVED AND CALCULATED CONCENTRATIONS FOR 6-MONTH MONITORING PERIOD

Station		Mean ($\mu g/m^3$)	Standard Deviation	Highest Value ($\mu g/m^3$)	Concentration ($\mu g/m^3$) Percentile at 90th	Concentration ($\mu g/m^3$) Percentile at 70th	Concentration ($\mu g/m^3$) Percentile at 30th
1	Observed	767	586	2360	1584	1108	324
	Calculated	526	362	1470	1010	716	310
2	Observed	45	45	311	115	50	11
	Calculated	95	69	312	189	120	44
3	Observed	50	50	193	106	68	22
	Calculated	63	40	158	116	83	33

3. A comparison of concentrations calculated at 3-hour intervals, using only airport meteorological data, with the corresponding 3-hour concentrations using monitoring station meteorological data, was used to establish the validity of limited meteorological data on 3-hour means.

By comparing the statistical summaries from each of these three modes, it was determined that the model's ability to calculate air quality levels over a 12-month period using limited meteorological data was satisfactory.

Model verification results based on comparison of the hourly concentrations for 7 days in the intensive period are shown in Table 14.

Table 15 shows a similar comparison of hourly concentrations from the 6-month monitoring period. The data presented in Table 16 show comparison of observed versus calculated statistics for 24-hour average concentrations in the 6-month monitoring period.

The comparisons shown in Tables 14, 15, and 16 indicate the model has been modified to produce results which correspond very well with the observed data. The ratio of calculated-to-observed concentrations for any of the comparisons shown in the tables for Stations 1 or 3 stay within the range of 0.6 to 1.6. At Station 2 the comparisons are not quite as good because the model calculations are consistently higher than the observed data. It should be noted that the comparisons made in Tables 14, 15, and 16 do not exclude other sources of SO_2 in the observed SO_2 data. The frequency with which the wind direction is from a direction which adds SO_2 from the major sources other than the power plant is low (~2%) so that the overall impact on both the means and the concentration distribution is small. No explanation of the difference between the comparisons for Stations 1 and 3 with Station 2 has been made, but it is interesting to note that the mean values of the observed concentrations are lower at Station 2 than at Stations 1 or 3.

A possible explanation may be that the plume is above Station 2 as it moves through that region due to heat buildup and release by the buildings in the zone between the power plant and Station 2. A conceptual possibility is that the taller buildings in the vicinity of the power plant may cause the downwash which accounts for the high concentrations at Station 1. As the plume moves toward Station 2, the heat released from the lower buildings could cause the plume to be slightly elevated as it moves across the area where Station 2 was located; then by the time the plume has moved to the vicinity of Station 3 the turbulence from the heat introduced by the residential and commercial buildings has become effective in bringing the plume to ground level again. The mean calculated and the mean observed concentrations over the 6-month period differ by a factor of 2 which is still a reasonably good comparison. The comparison of concentrations at the various percentile levels shown differs by an increasing ratio when examining comparisons towards the lower concentrations, but is obviously in better agreement when comparing the higher concentrations.

Based on the favorable comparisons which are noted above, the model was deemed to be acceptably accurate and the strategy evaluations are based on the model as described.

KAHE POINT MODIFICATIONS

The PTMTP model had been selected and modified for analysis of the Kahului plant. The version of the model as it existed in the modified form for the Kahului study was the logical starting point for modeling the Kahe Point plant. It was recognized that the plant sites are significantly different. However, the differences should be reflected in the meteorological and plant parameters. The initial run with the modified model resulted in calculated concentrations excessively higher than the observed SO_2 concentrations at the three monitoring stations. An analysis of those results indicated the downwash provision was contributing to the overestimation of the concentrations. Other program changes were made to the model so that the highest calculated concentrations nearest the plant, especially at monitoring Station 2, came closer to agreement with the observed concentrations. The degree of verification achieved was based on how well the hourly calculations approximated the corresponding observed SO_2 concentrations.

In the Kahe Point modeling study, the actual building height was input to the model. This was slightly different from the process in the Kahului plant study. For Kahului, the model verification included some adjustment to the building height value in order to obtain better correlation between the observed and calculated SO_2 concentrations.

Other modifications were made to the model to include assumptions which improved the agreement between the measured and observed distribution of hourly concentrations at all three monitoring stations, e.g., representing the plume height and the dispersion parameters, σ_y and σ_z. The plume height for evaluating downwash effects was determined by the following empirically derived method:

$$h_E = (HX + 2h_E)/3 \qquad (7)$$

where HX equals the plume height (at the downwind distance of the receptor) calculated using Briggs' equation as in the BEH072 subprogram of the UNAMAP programs, and h_E is the Briggs formula for sources affected by downwash. The value h_E is calculated as follows:

$$h_E = h_s + 2\left(\frac{v_s}{u} - 1.5\right)d_s \qquad (2)$$

where: h_s = physical stack height, m

v_s = stack gas exit velocity, m/sec

d_s = stack inside diameter, m

u = wind speed at stack height, m/sec.

If no downwash effect was present, the standard plume rise equations of the UNAMAP BEH072 subroutine based on the recommendations of Briggs were applied.

The location of the power plant is such that the plume is frequently subject to turbulence from the surrounding ridges. The initial plume

dimensions are enhanced in such conditions. One of the adjustments which was made to the model was to multiply the σ_z value by 2 (σ_z is estimated using McElroy-Pooler coefficients; see discussion for Kahului site). It would be desirable to have vertical plume measurements to get the most appropriate value of σ_z. It was noted by test model runs that increasing σ_z had the effect of increasing the means computed for the monitoring stations while having very little effect on peak concentrations. A factor of three times the standard σ_z was too big an increase, so a factor of two was adopted.

The method used to calculate σ_y at Kahului was replaced by the following scheme, which gave more spread to the plume and better agreement between measured and calculated values:

$$\sigma_y = x\sigma_\theta$$

where x = downwind distance, meters, and σ_θ = standard deviation of wind direction (Station 2), radians.

Many variations of the model were investigated in the process of obtaining the best agreement between the calculated and observed SO_2 concentrations. The three changes described above for downwash plume height, σ_z and σ_y, gave the best results based on a comparison of the frequency distribution of calculated values and the calculated means with the corresponding observed data. A listing of some of the major options that were tested, along with what the results were in terms of the mean and peak SO_2 concentrations estimated at the three monitoring stations, is shown in Table 17. Although more options for representing the plume height and dimensions could be tested, it was felt that in view of uncertainty about what the actual plume characteristics are, the final results obtained are as representative as can be reasonably expected. The relatively large difference between model estimates and measured concentrations, which differ by as much as a factor of three, indicates the nature of the uncertainty inherent in the model estimates.

The model variations which were tested in this study represent only a few of the many variations which could be tested. Although model calculations are generally not sensitive to wind profile parameters, power laws which are a function of stability are often introduced in the Gaussian model to increase the wind speed used to estimate plume transport and downwash effects. The tethersonde data could be used to suggest profile parameters which are particularly related to the monitoring site winds in estimating wind speeds at plume height. The tethersonde data suggest, at a quick glance, that the wind speed is much more variable at plume height than at ground level. Future study of this relationship might lead to improved model parameters. The McElroy-Pooler parameters were used for σ_z because these values were determined for 1-hour averages over rougher terrain than the Pasquill-Gifford or Brookhaven parameters. As more data from dispersion tests in complex terrain become available, other sets of σ_z parameters may be proposed which could also be tested. There is room for improvement in the model parameters as the results obtained so far clearly show. Also, since each stack was represented as a separate virtual point source using the equation stated in the Kahului model development to estimate the virtual distance, alternative parameters could be considered. The number of model modifications which

TABLE 17. MEAN AND MAXIMUM HOURLY SO_2 CONCENTRATIONS COMPUTED USING VARIOUS MODEL PARAMETERS AT THREE KAHE MONITORING SITES FOR THE 4-MONTH MONITORING PERIOD

			Parameters	Model Calculations ($\mu g/m^3$)					
			$\sigma y \equiv$	K	K	X	X	X	X
			$N \equiv$	1	1	1	3	2	2
Monitoring		Measured	$f_1 \equiv$	1	0	.75	.75	.75	.67
Site	Statistic	($\mu g/m^3$)	$f_2 \equiv$	0	1	.25	.25	.25	.33
1	Mean	80		352	10	35	166	119	97
	Peak	2050		17,130	1,736	3,783	4,687	5,041	3,306
2	Mean	402		1,006	6	253	922	652	496
	Peak	3680		94,320	3,453	14,490	9,514	9,766	8,488
3	Mean	20		48	39	39	45	42	42
	Peak	529		3,469	5,135	4,705	2,305	2,434	2,459

Notes on parameters:

σ_y: K means the Kahului relation $\sigma_y = (-0.0441 + 0.0104\sigma_\theta)x$
X means $\sigma_y = x\ \sigma_\theta$

$\sigma_z = N\ b\ x^q$ (see Table 13)

Plume height for downwash effect is

$$H = f_1(HE) + f_2(HX)$$

where HE = the Briggs plume height for downwash effects
HX = the Briggs plume height as given by the BEHO72 subroutine

could be tested is almost endless. The variations selected in this study are based on the experience of the modelers who performed the work in knowing how various parameters will affect the model calculations. The most opportune parameters were selected somewhat intuitively and somewhat with an eye on how the model results were responding.

VERIFICATION OF MODEL PERFORMANCE AT KAHE POINT

Many variations of the model were investigated to determine the model parameters which produce the best agreement between measured and observed SO_2 concentrations. The 1-hour-average observed data have been presented in Table 9. The comparable calculated values are presented in Table 18. The calculated means for the three monitoring site locations are 97, 496, and 42 $\mu g/m^3$ (Stations 1, 2, and 3 respectively). These values compare with the observed means of 80, 402, and 20 $\mu g/m^3$. The calculated minus measured difference as a percent of the calculated mean was 18 percent for Station 1, 23 percent for Station 2, and 52 percent for Station 3 for an average overestimate of 31 percent.

TABLE 18. HOURLY CONCENTRATIONS - CALCULATED BASE CASE

CUMULATIVE FREQUENCY DISTRIBUTION OF COMPUTED SO2 CONCENTRATIONS (μG/CU.M)

PERCENTILE	RECEPTOR 1	2	3	4	5	6	7	8	9	10
HIGH	3306.000	8488.000	2459.000	4738.000	1875.000	1631.000	1310.000	3202.000	3202.000	2718.000
2ND	3145.000	8482.000	2265.000	4293.000	1684.000	1383.000	1085.000	1882.000	1882.000	2697.000
99.5	1334.309	6260.860	992.967	2355.898	748.206	603.273	461.245	1107.385	1107.385	1361.853
99.0	976.762	5682.021	646.428	1490.865	473.870	383.642	292.068	672.868	672.868	789.897
95.0	585.760	3469.401	245.670	589.950	159.830	133.900	104.360	120.760	120.760	271.580
90.0	374.700	1983.000	143.380	300.860	87.774	74.504	59.296	23.718	23.718	84.794
80.0	106.800	377.400	11.720	32.736	6.582	5.588	4.082	0.000	0.000	1.557
70.0	7.647	12.950	0.000	0.036	0.000	0.000	0.000	0.000	0.000	0.000
60.0	0.000	0.356	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
50.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
40.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
30.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
20.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
10.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
LOW	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

(CONTINUED)

TABLE 18. (CONTINUED)

CUMULATIVE FREQUENCY DISTRIBUTION OF COMPUTED SO2 CONCENTRATIONS (µG/CU.M)

PERCENTILE	RECEPTOR 11	12	13	14	15	16	17	18	19	20
HIGH	2279.000	1868.000	2255.000	1910.000	1470.000	1215.000	935.000	635.500	728.100	6506.000
2ND	2056.000	1755.000	1936.000	1653.000	1409.000	1063.000	822.800	550.300	708.900	5248.000
99.5	1151.299	964.228	747.673	596.663	617.604	376.003	279.136	215.154	273.565	3063.722
99.0	609.078	509.854	404.069	337.195	354.168	195.844	159.248	128.272	172.592	2012.000
95.0	190.120	162.520	131.900	104.330	92.557	61.747	49.289	42.944	53.901	931.740
90.0	50.736	42.900	61.754	50.034	28.376	36.672	29.628	18.800	16.982	356.340
80.0	0.399	0.021	1.790	1.423	0.000	1.697	1.124	0.016	0.000	19.380
70.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
60.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
50.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
40.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
30.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
20.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
10.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
LOW	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

(CONTINUED)

TABLE 18. (CONCLUDED)

CUMULATIVE FREQUENCY DISTRIBUTION OF COMPUTED SO2 CONCENTRATIONS (µG/CU.M)

PERCENTILE	RECEPTOR 21	22	23	24	25
HIGH	7884.000	11500.000	16410.000	5388.000	3780.000
2ND	4893.000	10220.000	10480.000	5237.000	3388.000
99.5	3935.656	8328.038	3086.347	3821.627	2164.433
99.0	3384.244	7475.301	2695.042	3256.440	1757.467
95.0	1803.101	3735.102	921.180	1873.501	893.690
90.0	610.720	881.558	26.838	1007.200	487.680
80.0	26.610	5.439	0.093	65.832	84.654
70.0	0.002	0.008	0.000	1.475	2.609
60.0	0.000	0.000	0.000	0.001	0.000
50.0	0.000	0.000	0.000	0.000	0.000
40.0	0.000	0.000	0.000	0.000	0.000
30.0	0.000	0.000	0.000	0.000	0.000
20.0	0.000	0.000	0.000	0.000	0.000
10.0	0.000	0.000	0.000	0.000	0.000
5.0	0.000	0.000	0.000	0.000	0.000
1.0	0.000	0.000	0.000	0.000	0.000
0.5	0.000	0.000	0.000	0.000	0.000
LOW	0.000	0.000	0.000	0.000	0.000

The distribution of the hourly values can be compared in Tables 18 and 19. The highest calculated concentrations at Stations 1 and 2 as compared to measured concentrations are high by factors of 1.6 and 2.3, respectively. At Station 3 the highest calculated value is too high by a factor of 4.6. The calculated-to-observed ratios are maintained fairly well though the distribution goes down to the 70th percentile where the calculated values drop off sharply. Therefore control measures designed to meet criteria based on these results will favor the safe side from a health-effects point of view, i.e., will overestimate. The comparison of calculated-to-observed concentrations throughout the distribution, from highest to lowest, was considered when the model modifications were being made. Attempts to distribute the calculated concentrations over a wider range by altering the model parameters were not successful. The distributions as shown were considered the best possible within the period of model experimentation which was available.

The model performance capabilities of the Kahe Point location are summarized by the results presented in Table 19. It may be seen that the calculated and measured values for the mean and second highest 3-hour and 24-hour concentrations show good agreement at Station 1, in that the ratio of calculated-to-measured values ranges from 0.75 to 1.21. At Station 2 the ratio of calculated-to-measured concentration of SO_2 is 1.23 and 1.09 for the mean and 24-hour periods, respectively. For the 3-hour period the ratio is 2.00. At Station 3 the ratios are higher varying from 2.10 for the mean to 2.47 for the second highest 24-hour period to 2.99 for the second highest 3-hour period. It may be noted that the mean ratio of calculated-to-measured values is near 1.5 averaged over the three stations for the mean and the second highest 24-hour estimates. For the second highest 3-hour estimate, the mean ratio for the three stations is about 2.0. On the average it may be expected that the model overestimates the air quality standards of interest by a factor of 1.5 to 2. Under some conditions, it may underestimate slightly or overestimate by as much as a factor of three based on the results observed at the three monitoring stations.

TABLE 19. RATIOS OF MEASURED-TO-CALCULATED SO_2 CONCENTRATIONS ($\mu g/m^3$) AT THE KAHE POINT SITE

Monitoring Site	Mean			Second Highest 24-Hour			Second Highest 3-Hour		
	Measured	Calculated	C/M	Measured	Calculated	C/M	Measured	Calculated	C/M
1	80	97	1.21	582	435	0.75	1237	1320	1.07
2	402	496	1.23	2054	2240	1 09	3223	6450	2.00
3	20	42	2.10	102	252	2.47	354	1060	2.99
Mean	167	212	1.51	913	976	1.44	1605	2943	2.02

SECTION 6

MODELING RESULTS AND EVALUATION OF STRATEGIES

KAHULUI RESULTS

The computations made for validation indicate the results from the model are generally reliable estimates of the expected concentrations at the monitoring station sites. When running the model, 30 receptor locations were selected to represent the effects of the power plant emissions. Receptor locations were concentrated near the power plant (mostly within 2 km), but a few were spotted up to 7 km away. The configuration of the receptor array is indicated in Figure 7. Receptor locations 16, 17, and 18 represent the locations of monitoring Stations 1, 2, and 3, respectively.

The receptor locations were selected to represent the maximum concentrations which would be expected under different stability conditions and wind directions. Some receptors represent locations where exposure is particularly sensitive, e.g., the nearby shopping center and residential areas.

The model computations show the mean values of the hourly, 3-hourly, and 24-hourly averages of SO_2 over the 6-month data period. The highest mean values were estimated for receptor locations 16, 19, 17, and 18, in that order. Table 20 lists the receptors where the model computations indicate the air quality standards are exceeded. Locations 17 and 18 (which correspond to monitoring Stations 2 and 3) have also been included.

The highest 3-hour and 24-hour concentrations and the estimated frequencies with which the 3-hour and 24-hour Federal SO_2 standards are exceeded are listed in Table 20. The percent frequency was determined from calculations for the 156-day monitoring period.

The mean of the hourly values and the mean of the values calculated every third hour from the same data set correspond very well. The highest value in the distribution of the 3-hour averages was always lower than the highest value from the every-third-hour calculations. The root mean absolute difference between the highest 3-hour mean and the highest third-hour value at the six locations listed in Table 20 is 874 $\mu g/m^3$ or 33 percent of the six-station mean calculated for every third hour of 2,620 $\mu g/m^3$. This difference is representative of the difference of the second-highest estimate as well as the highest estimate. The mean absolute difference between highest 24-hour concentrations calculated using every-hour and every-third-hour data for the same six stations is 97 $\mu g/m^3$ or 12 percent of the six-station mean

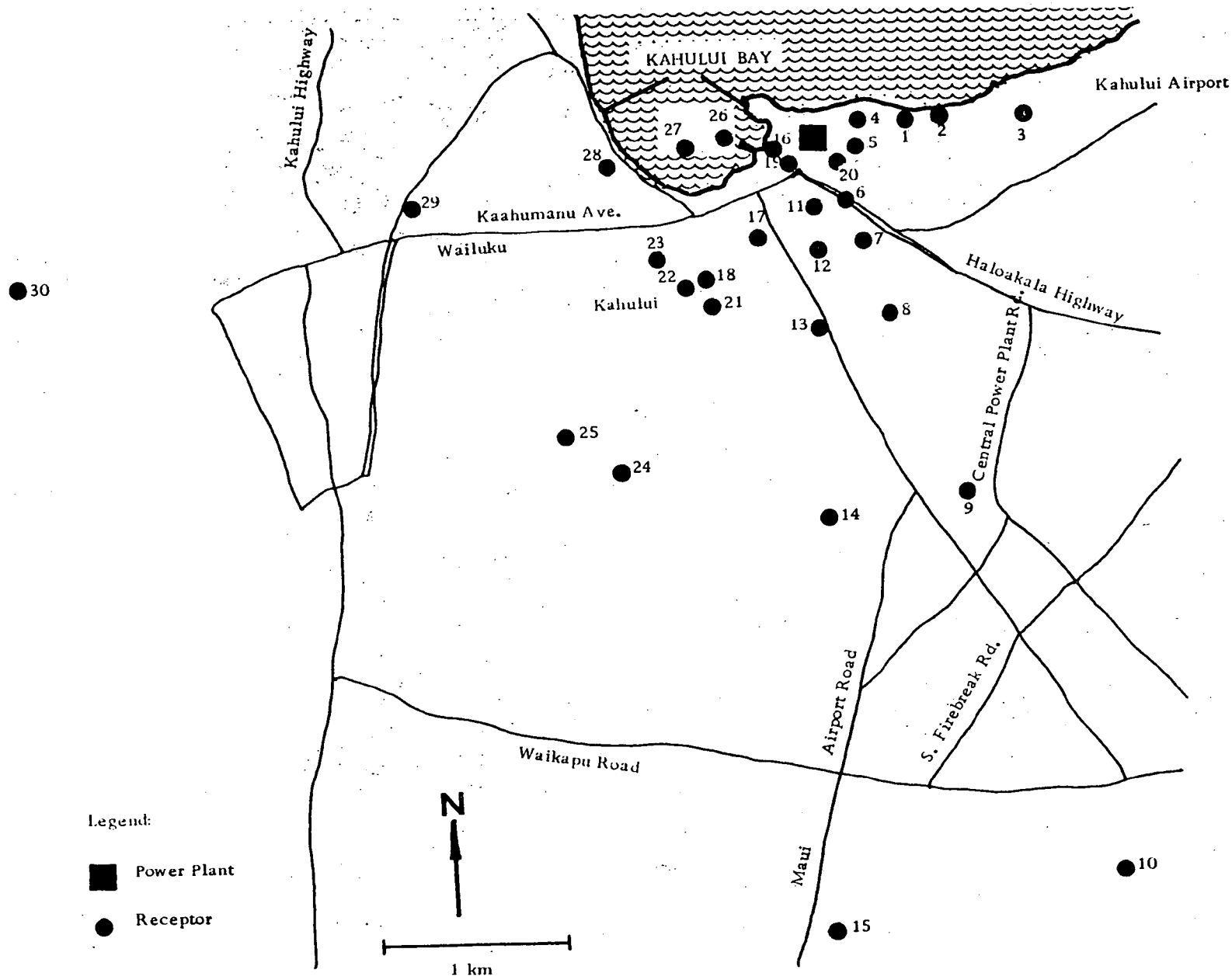

Figure 7. Receptor locations near the Kahului power plant.

TABLE 20. RECEPTOR LOCATIONS WHICH MAY EXCEED AIR QUALITY STANDARDS WITHOUT USE OF CONTROL STRATEGIES

Receptor Number	Mean ($\mu g/m^3$) 3-Hour Average	Mean ($\mu g/m^3$) Every 3rd Hour	Highest Value ($\mu g/m^3$) 3-Hour Average	Highest Value ($\mu g/m^3$) Every 3rd Hour	Highest Value ($\mu g/m^3$) 24-Hour Average	Highest Value ($\mu g/m^3$) 24-Hour Average Based on 3rd Hour Data	Estimated Frequency of Federal Standard Exceedances (%) 3-Hour	Estimated Frequency of Federal Standard Exceedances (%) 24-Hour
5	14	12	1850	2926	379	632	(1)	(1)
16	531	538	2850	3584	1470	1530	9	68
17	96	93	575	944	312	352	0	0
18	63	61	361	504	158	177	0	0
19	411	402	2770	4470	1620	1830	7	55
20	52	46	2070	3295	544	413	(1)	(1)
Federal Standard	80	80	1300	-	365	-	-	-

(1) Only the highest value exceeded air quality standard.

calculated for every third hour of 822 $\mu g/m^3$. Although the use of every-third-hour values results in overestimation of the high 3-hour concentrations, there was reasonable agreement between 24-hour concentrations using every-hour and every-third-hour data. The results show that the 24-hour concentrations are four times the standard of 365 $\mu g/m^3$ while the 3-hour concentrations are only two times the standard of 1,300 $\mu g/m^3$. Since the 24-hour concentration can be accurately estimated by every-third-hour data, and since the 24-hour concentration is the critical one to limit by controls, it was prudent for expediency and economy to make additional model runs for evaluating control strategies using every-third-hour data. Strategies which could be evaluated using emission alterations to modify the file of present hourly concentrations were evaluated using hourly data. New model runs were required to evalute strategies based on new stack heights. The control strategy evaluation results proved that the 24-hour concentration was indeed the critical limiting condition requiring the greatest degree of control. Results for 3-hour concentrations based on every-third-hour input data can be considered to be on the order of 33 percent too high based on the comparisons between 3-hour and third-hour maximum concentrations. Subsequent calculations to evalute the effectiveness of extended stack height control strategies were made using every-third-hour data from the 6-month data.

The model was also run using only the data available from the airport observations for meteorological input. This was done to evaluate how well the 6-month monitoring period represented conditions over a full year. The evaluation compared the annual average and distribution of air quality levels at 30 sites based on 12 months of airport data with the same characteristics based on 6 months of airport data. The 6-month period corresponded to the monitoring period, so that the comparison to 12-month data could be easily related to the other sets of input data available for the same period.

The means and the distributions of the calculations using 6 months of airport data correspond very closely to the calculations using 12 months of input. It can be assumed that the closeness occurs because the 6-month data period represents the full range of meteorological conditions which occur over the course of a full year. A comparison between the statistics (mean and frequency distribution) of hourly concentrations calculated using 6 months of airport meteorological data is shown in Table 21 for six locations. About 60 percent of the compared concentrations are within 10 percent of each other. The largest percentage differences occur when the hourly concentrations are below 80 $\mu g/m^3$. A comparison was made between calculations using airport meteorological data and calculations using monitoring site data for the same 6-month period. The concentrations calculated using the airport data were generally lower by a factor of two. The reasons for these differences lie in differences between the two data sets since the model is the same in both cases. An examination of the data sets over selected periods showed that the wind speed observed at the airport generally averaged 50 percent greater than the values observed at Station 2 (the value selected from the monitoring stations). Station 2 data still showed better agreement with airport wind data than the data from Stations 1 and 3, which appeared by visual comparison of measurements to differ by an even greater amount. Another difference is due to the method by which the standard deviation of wind direction (σ_θ) is estimated from airport data. Table 22 lists the mean and the standard deviation of σ_θ observed at Station 3 when each of the six Pasquill stability classes was observed at the airport. The mean value found for each class was used as the model input value for σ_θ corresponding to that class. The fact that the actual range of σ_θ associated with each stability class is quite large (e.g., the standard deviation is 50 percent or more of the mean as shown in Table 22) indicates that the use of an average value introduced an underestimate of calculated concentrations.*

STRATEGIES EVALUATED AT KAHULUI

To determine what abatement measures might be employed to bring the power plant emissions down to a level which would not cause ambient concentrations to exceed the SO_2 air quality standards, the following eight abatement strategies were evaluated:

1. Reduce sulfur emissions by (1) 50%, (2) 75%, and (3) 90%;

2. Increase the stack heights to (4) 38 m, (5) 57 m, and (6) 91 m;

3. Increase stack height to 57 m (2.5 times building height) and limit fuel sulfur content to (7) 1.0% or (8) 0.5%.

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* This is because σ_θ is in the denominator of the equation used to calculate concentration. The average of concentrations calculated using σ_θ equal to 10 and 30 will be higher than the concentration calculated using σ_θ equal to 20. For example:

$$\frac{K}{2}\left(\frac{1}{10}+\frac{1}{30}\right) > \frac{K}{20}, \text{ where } K = \text{variable.}$$

TABLE 21. COMPARISONS OF CALCULATED CONCENTRATION STATISTICS FROM 6 MONTHS AND 12 MONTHS OF DATA

Receptor	Months in Data Period	Mean ($\mu g/m^3$)	Standard Deviation ($\mu g/m^3$)	Highest Concentration ($\mu g/m^3$)	Concentration ($\mu g/m^3$) at Percentile						
					99.5	99	95	90	50	70	60
5	6	9	66	1273	460	161	0	0	0	0	0
	12	7	77	1728	355	162	0	0	0	0	0
16	6	275	325	2110	1345	1172	930	742	531	387	269
	12	273	344	2499	1540	1312	947	769	572	394	242
17	6	34	81	731	537	387	194	117	41	11	3
	12	45	92	839	491	441	230	153	78	24	5
18	6	31	92	1879	445	389	144	84	38	14	3
	12	36	91	1672	551	436	159	102	54	23	5
19	6	156	287	2858	1434	1223	788	525	266	113	52
	12	192	321	2858	1531	1321	868	670	374	164	71
20	6	24	171	3344	1116	764	6	0	0	0	0
	12	23	150	3325	1179	663	35	0	0	0	0

TABLE 22. MEAN AND STANDARD DEVIATION OF σ_θ OBSERVED AT MONITORING STATION 3 FOR CORRESPONDING PASQUILL STABILITY CLASS OBSERVATIONS AT THE KAHULUI AIRPORT

Stability Class	σ_θ (degrees)		Number of Cases
	Mean ($\mu g/m^3$)	Standard Deviation (%)	
A	18.1	3.8	8
B	29.8	17.8	96
C	19.7	11.6	765
D	19.2	10.2	2039
E	23.9	16.5	475
F	32.6	25.0	378
All	21.5	14.4	3761

Sulfur emissions can be reduced by reducing the sulfur content of the fuel or by using a scrubber. A 50-percent reduction in sulfur emissions would correspond to reducing fuel sulfur to 1 percent or using a 50-percent efficient scrubber; a 75-percent reduction in sulfur emissions would correspond to using 0.5 percent sulfur fuel or a 75-percent efficient scrubber. Reducing emissions by 90 percent was assumed to be possible using a 90-percent efficient scrubber.

The stack heights were selected on the following bases:

1. 38 m - to raise the stack to more than 1.5 times the building height in order to assure that the plume is above the aerodynamic cavity caused by the power plant building.

2. 56 m - to raise the stack to 2.5 times the building height to avoid all downwash effects associated with the building.

3. 91 m - to raise the stack to a level high enough to prevent significant ground-level concentrations in the vicinity of the stack.

Table 23 shows the results of the strategies evaluated. As previously mentioned, the strategies were evaluated using meteorological data from the monitoring stations which cover a 6-month period. The highest 1-hour calculations do not relate directly to an air quality standard but are displayed to indicate the effectiveness of the control strategies. The concentration at the 99.5 percentile is indicative of the probability that the standard will be exceeded more than once in the course of a year. It is an interpolated value which, for 24-hour concentrations, is higher than the second-highest concentration, since the data period consists of 156 days. The annual mean is represented by the mean concentrations over the 6-month period.

The data presented in Table 20 indicate that if air quality standards at receptor 16 (monitoring Station 1) and receptor 19 can be met, the standards would be met at any of the receptor sites modeled. The strategies which bring the calculated concentrations below the primary air quality standards at receptors 16 and 19 are strategy 3 (90-percent reduction of sulfur emissions), strategy 6 (stack 91 m tall), and strategy 8 (stack 57 m tall or 2.5 times the building height and fuel sulfur limited to 0.5 percent).

At receptors 16 and 19, the annual mean is above the primary standard for strategies 1, 2, 4, and 5. Strategy 7 results in an annual mean above the primary standard at receptor 16. The highest 3-hour average (estimated by a single concentration calculated every third hour for strategies 4, 5, 6, 7, and 8) exceeds the Federal standard at the same receptors using strategies 1 and 4. Strategy 2 exceeds the 24-hour standard at receptor 19, and strategy 5 exceeds the 24-hour standard at receptor 16.

KAHE POINT RESULTS

Receptor coordinates were specified for locations in the vicinity of the Kahe Point plant. The receptor locations are indicated in Figure 8 with the

TABLE 23. EXPECTED CONCENTRATIONS USING ABATEMENT STRATEGIES AT THE KAHULUI PLANT

Receptor	Strategy	Annual Mean (µg/m³)	Highest Concentration (µg/m³)			Second Highest Concentration (µg/m³)			Concentration at 99.5 Percentile* (µg/m³)		
			1-Hour	24-Hour	3-Hour	1-Hour	24-Hour	3-Hour	1-Hour	24-Hour	3-Hour
1	1	-	2511	190	925	2112	116	800	327	132	304
	2	3	1255	95	462	1056	58	400	164	66	152
	3	1	502	38	185	422	23	160	65	26	61
	4	3	1095	138	-	-	-	-	98	91	-
	5	1	558	70	-	253	32	-	31	40	-
	6	21	58	32	-	-	-	-	1	18	-
	7	1	279	35	-	127	16	-	15	20	-
	8	0	129	17	-	63	8	-	8	1[illegible]	-
16	1	265	2239	735	1415	2102	7[illegible]0	1395	1377	731	1334
	2	133	1120	638	71[illegible]	1051	365	698	689	365	567
	3	53	447	117	285	4[illegible]0	146	279	277	146	227
	4	294	2242	855	1170	1874	814	1270	1431	823	1142
	5	169	1776	625	1030	1667	598	934	1048	604	858
	6	9	806	288	483	737	282	483	541	283	447
	7	84	888	31[illegible]	515	834	299	467	524	302	429
	8	42	444	156	308	417	150	234	262	151	214
17	1	48	651	156	388	472	145	277	331	147	234
	2	24	3[illegible]5	79	144	236	73	138	166	4	117
	3	9	130	31	58	94	29	55	66	29	47
	4	77	788	254	135	651	243	403	485	245	362
	5	58	737	233	394	580	209	368	443	214	318
	6	4	675	279	314	454	162	305	346	166	258
	7	29	368	116	197	290	174	184	222	107	159
	8	14	181	58	98	145	52	92	111	[illegible]4	[illegible]0
8	1	31	259	79	180	252	77	175	194	77	145
	2	15	130	39	90	126	38	88	97	39	72
	3	6	52	16	36	50	15	35	39	15	29
	4	56	550	153	339	142	498	295	330	144	244
	5	44	546	148	33[illegible]	498	137	278	283	139	213
	6	4	359	121	247	326	114	241	233	166	174
	7	22	273	71	166	249	68	139	142	70	106
	8	11	136	37	83	124	34	70	71	35	53
19	1	206	2413	810	1385	2235	720	1325	1405	740	1150
	2	103	1206	405	692	1118	360	662	703	370	575
	3	41	483	16[illegible]	[illegible]7	447	144	265	281	148	230
	4	191	1670	679	1140	1569	625	1110	1198	637	9[illegible]8
	5	10[illegible]	1168	389	8[illegible]3	1140	116	800	904	432	714
	6	5	585	190	377	565	159	365	424	166	321
	7	51	584	244	11[illegible]	570	208	400	452	216	357
	8	26	292	122	206	285	104	200	226	108	178
20	1	26	2095	274	274	1035	1738	232	990	240	698
	2	13	1047	137	518	869	116	495	467	120	349
	3	5	419	54	207	348	46	198	187	48	140
	4	16	1454	203	851	1435	117	774	754	159	486
	5	9	1018	141	664	980	105	567	576	113	344
	6	1	684	68	467	623	60	320	326	62	208
	7	5	509	70	332	490	52	284	288	56	172
	8	2	254	35	166	245	26	142	144	28	86

*Interpolated values.

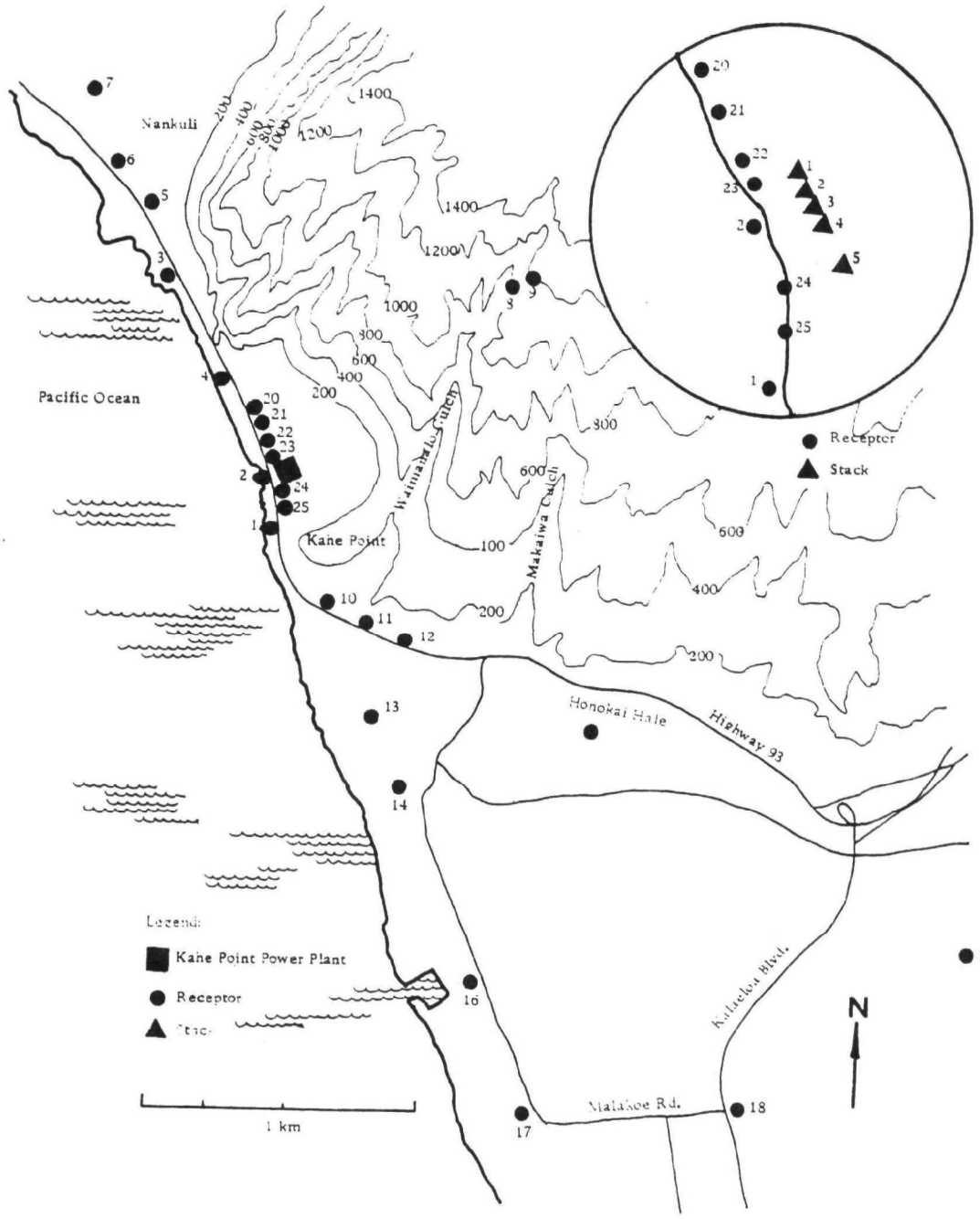

Figure 8. Receptor site locations - Kane Point

corresponding identification numbers in Tables 24 and 25. Receptors 1, 2, and 3 correspond to monitoring Stations 1, 2, and 3. The receptor locations were selected at places where maximum concentrations would be expected and that were representative of residential areas. Receptors 8 and 9 represent results for locations on the ridge behind the plant. The effectiveness of the model in representing the impact of the plume on this ridge has not been validated, since no monitoring data were collected on the ridge and attempts to observe the plume remotely with the COSPEC instrument at positions other than directly above the highway west of the plant were not successful. To a lesser extent, results computed for the receptors to the southeast of the plant also represent the unvalidated influences of flow over complex terrain. The concentrations estimated for receptors 10 through 19 are in this category. The effects of the plume over the water just off the coast were not estimated, although technically this also could be considered ambient air. The emphasis is on locations where people are likely to be exposed for significant periods of 3 to 24 hours.

The calculated 3-hour average concentrations shown in Table 24 indicate that the 1,300 $\mu g/m^3$ standard for a 3-hour average would be exceeded by the second highest 3-hour period at 10 locations, all of which are within approximately 1 km of the power plant.

The calculated 24-hour average concentrations are presented in Table 25. The 24-hour average standard of 365 $\mu g/m^3$ is exceeded by the second-highest value at 11 of the 25 receptor sites listed. Again, the excursions all occur at the receptors within 1 km of the power plant. It can be expected that the actual occurrences of excursions may not be as drastic as indicated in Tables 24 and 25 due to the fact that the verification results showed the model overestimates these short-term concentrations.

All of the locations where standards are exceeded are along the coast to the west of the plant or on the ridge above the plant. The locations not exceeding Federal standards are those to the north of location 4 and those to the south and southeast of location 10. All of the stations near the coast, except station 10, are within or on the edge of the bowl-shaped terrain which encompasses the plant. The maximum impact of the plume is estimated at locations 2, 21, 22, and 24. These locations are almost directly across the street from the plant. Locations 2 and 22 are directly downwind of the low stacks when they are affected by the prevailing trade winds. The extent to which locations 20 and 4 are also sites of major effects from the plant is partly dependent on the extent to which the frequency of wind directions observed at location 2 represents the actual frequency of wind directions of the plume. The 2 weeks of daytime tethersonde wind data collected in January suggest that there is a pronounced tendency of the northeasterly trade winds to turn northward around the southern tip of the Waianae Mountain Range. The wind direction observations at Station 2, which were used in the model estimates, strongly reflect this tendency. In any case, the most critical estimates which are predicted for locations 2 and 22 due to the effect of the northeast trade winds on the four lowest stacks of the plant are reasonable. The reduction of these estimates by control strategies provides a reasonable control objective.

TABLE 24. 3-HOUR AVERAGE CONCENTRATIONS - CALCULATED BASE CASE

CUMULATIVE FREQUENCY DISTRIBUTION OF COMPUTED SO2 CONCENTRATIONS (µG/CU.M)

PERCENTILE	RECEPTOR 1	2	3	4	5	6	7	8	9	10
HIGH	1470.000	7240.000	1330.000	2200.000	973.000	823.000	642.000	1520.000	1520.000	1720.000
2ND	1320.000	6450.000	1060.000	2120.000	835.000	708.000	561.000	1300.000	1300.000	1450.000
99.5	1110.151	5364.351	778.480	1665.801	595.351	486.450	369.290	719.382	719.382	1054.351
99.0	868.883	4513.506	542.740	1440.000	372.671	312.290	248.251	519.701	519.701	784.454
95.0	484.000	2849.000	227.350	556.450	148.450	125.000	98.695	169.800	169.800	245.050
90.0	316.900	1880.000	129.600	297.300	79.330	68.340	54.000	53.680	53.680	116.900
80.0	176.600	785.400	53.280	96.800	33.300	28.260	21.560	1.372	1.372	29.040
70.0	70.370	176.300	7.317	19.370	5.887	3.839	2.865	0.000	0.000	3.621
60.0	15.200	8.514	0.017	0.600	0.003	0.001	0.000	0.000	0.000	0.013
50.0	0.037	0.377	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
40.0	0.000	0.006	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
30.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
20.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
10.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
LOW	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

(CONTINUED)

TABLE 24. (CONTINUED)

CUMULATIVE FREQUENCY DISTRIBUTION OF COMPUTED SO2 CONCENTRATIONS (µG/CU.M)

PERCENTILE	RECEPTOR 11	12	13	14	15	16	17	18	19	20
HIGH	1310.000	1130.000	1380.000	1150.000	1010.000	724.000	547.000	283.000	514.000	3760.000
2ND	1110.000	879.000	888.000	743.000	630.000	479.000	365.000	249.000	382.000	2920.000
99.5	728.725	687.740	610.206	487.221	435.221	288.610	218.160	176.091	189.015	2217.251
99.0	602.502	503.320	481.580	350.771	326.450	192.931	151.160	148.450	151.160	1779.004
95.0	181.000	154.000	118.450	94.370	90.900	59.470	46.845	41.250	54.485	891.900
90.0	82.890	70.900	61.630	48.640	42.090	31.880	24.850	21.580	22.320	344.900
80.0	15.220	11.260	23.180	19.880	6.034	13.280	10.580	5.768	1.984	106.600
70.0	1.067	0.091	3.224	2.794	0.000	2.407	1.771	0.097	0.000	12.760
60.0	0.000	0.000	0.010	0.005	0.000	0.003	0.003	0.000	0.000	0.145
50.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
40.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
30.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
20.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
10.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
LOW	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

(CONTINUED)

TABLE 24. (CONCLUDED)

CUMULATIVE FREQUENCY DISTRIBUTION OF COMPUTED SO2 CONCENTRATIONS (µG/CU.M)

PERCENTILE	RECEPTOR 21	22	23	24	25
HIGH	3870.000	8570.000	6340.000	3620.000	1950.000
2ND	3730.000	8400.000	3490.000	3600.000	1880.000
99.5	3270.000	7565.952	2737.705	3071.602	1520.151
99.0	2868.701	6864.111	2312.900	2468.701	1418.701
95.0	1584.500	3033.500	857.100	1479.000	705.750
90.0	690.900	1440.000	208.900	913.700	493.400
80.0	158.800	146.800	2.380	350.000	199.000
70.0	17.540	4.190	0.079	52.310	59.500
60.0	0.067	0.039	0.001	2.744	6.302
50.0	0.000	0.000	0.000	0.016	0.022
40.0	0.000	0.000	0.000	0.000	0.000
30.0	0.000	0.000	0.000	0.000	0.000
20.0	0.000	0.000	0.000	0.000	0.000
10.0	0.000	0.000	0.000	0.000	0.000
5.0	0.000	0.000	0.000	0.000	0.000
1.0	0.000	0.000	0.000	0.000	0.000
0.5	0.000	0.000	0.000	0.000	0.000
LOW	0.000	0.000	0.000	0.000	0.000

TABLE 25. 24-HOUR AVERAGE CONCENTRATIONS - CALCULATED BASE CASE

CUMULATIVE FREQUENCY DISTRIBUTION OF COMPUTED SO2 CONCENTRATIONS (µG/CU.M)

PERCENTILE	RECEPTOR 1	2	3	4	5	6	7	8	9	10
HIGH	585.000	3060.000	343.000	662.000	234.000	196.000	152.000	408.000	408.000	346.000
2ND	436.000	2240.000	252.000	620.000	175.000	143.000	110.000	397.000	397.000	322.000
99.5	494.856	2563.904	287.945	636.590	198.305	163.935	126.590	401.345	401.345	331.480
99.0	425.710	2208.500	245.700	601.520	171.640	140.690	108.740	354.580	354.580	316.750
95.0	328.900	1718.000	189.850	420.350	120.700	101.530	78.770	108.000	108.000	192.400
90.0	238.500	1522.000	129.700	327.400	85.550	71.160	57.320	88.680	88.680	100.490
80.0	165.600	1076.000	60.440	138.000	39.860	33.260	26.520	40.640	40.640	62.680
70.0	122.700	715.000	33.920	74.950	22.680	18.690	14.940	23.100	23.100	42.040
60.0	89.120	381.000	22.460	52.380	15.060	12.420	9.640	8.298	8.298	30.400
50.0	61.100	159.500	15.700	37.350	10.750	9.370	7.820	1.530	1.530	16.000
40.0	33.680	34.300	10.920	25.640	6.798	6.046	5.506	0.205	0.205	6.712
30.0	13.490	2.900	3.931	14.930	3.920	3.099	2.522	0.000	0.000	3.502
20.0	0.677	0.220	1.296	2.780	0.926	0.611	0.451	0.000	0.000	0.300
10.0	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
LOW	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

(CONTINUED)

TABLE 25. (CONTINUED)

CUMULATIVE FREQUENCY DISTRIBUTION OF COMPUTED SO2 CONCENTRATIONS (µG/CU.M)

PERCENTILE	RECEPTOR 11	12	13	14	15	16	17	18	19	20
HIGH	250.000	210.000	284.000	236.000	146.000	150.000	114.000	43.700	80.300	1010.000
2ND	230.000	202.000	174.000	138.000	129.000	80.100	60.100	42.600	67.000	762.000
99.5	237.900	205.160	217.450	176.710	135.715	107.711	81.391	43.035	72.254	859.961
99.0	221.810	193.390	169.800	133.800	128.790	78.588	59.197	42.579	66.055	760.950
95.0	146.300	115.950	95.045	73.885	79.530	51.690	38.490	34.390	42.410	540.400
90.0	94.020	98.250	57.230	46.060	61.050	29.120	22.990	25.190	29.260	451.800
80.0	47.420	39.780	36.140	27.980	24.660	17.500	13.480	11.660	15.160	212.600
70.0	30.690	22.820	24.300	19.600	17.500	12.170	10.147	7.151	8.180	100.800
60.0	19.200	14.300	16.460	13.920	8.462	8.902	6.892	4.970	4.578	62.900
50.0	11.950	10.350	11.800	9.660	3.740	5.940	4.695	3.555	1.835	38.250
40.0	5.956	3.016	5.406	4.544	1.338	3.486	3.052	1.760	0.374	30.440
30.0	1.287	0.783	2.830	2.789	0.045	2.076	1.710	0.603	0.000	16.410
20.0	0.114	0.001	0.845	0.961	0.000	0.576	0.389	0.000	0.000	2.508
10.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
LOW	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

(CONTINUED)

TABLE 25. (CONCLUDED)

CUMULATIVE FREQUENCY DISTRIBUTION OF COMPUTED SO2 CONCENTRATIONS (UG/CU.M)

PERCENTILE	RECEPTOR 21	22	23	24	25
HIGH	1870.000	6170.000	1720.000	1660.000	757.000
2ND	1260.000	2360.000	1010.000	1310.000	740.000
99.5	1500.953	3864.966	1290.453	1448.251	746.715
99.0	1228.500	2343.200	979.130	1297.400	719.210
95.0	771.250	1635.499	701.250	902.000	431.950
90.0	639.800	1124.000	430.600	801.500	362.900
80.0	410.800	663.400	175.600	447.200	239.800
70.0	207.100	452.300	72.250	303.600	165.600
60.0	137.600	290.200	37.740	188.600	106.800
50.0	87.550	170.000	14.150	100.650	71.800
40.0	40.100	48.740	2.374	40.580	32.540
30.0	25.950	6.168	0.306	5.599	10.830
20.0	3.142	0.812	0.008	0.080	0.428
10.0	0.000	0.000	0.000	0.000	0.000
5.0	0.000	0.000	0.000	0.000	0.000
1.0	0.000	0.000	0.000	0.000	0.000
0.5	0.000	0.000	0.000	0.000	0.000
LOW	0.000	0.000	0.000	0.000	0.000

STRATEGIES EVALUATED AT KAHE POINT

Evaluation of the observed results from Tables 10 and 11 by linear rollback considerations indicated that the necessary reduction in fuel sulfur content was 90 percent, i.e., the fuel used would have to be approximately 0.2 percent sulfur. A 90-percent efficient scrubber would allow the plant to meet the necessary emission reduction and would reduce ambient air concentrations to levels prescribed by the standards.

An alternative strategy was to assume a stack height of 2.5 times the building height. Tables 26 and 27 show the expected concentrations for the 3-hour and 24-hour averages with the stacks raised to 2.5 times the building heights. In this strategy, stacks 1 and 2 were modeled as being 87.6 m tall, stacks 3 and 4 as being 94.0 m tall, and stack 5 as being 115.8 m tall.* With this strategy the 3-hour secondary standard was exceeded by the second-highest value at receptors 20, 21, 22, and 24. The 24-hour average standard was exceeded by the second-highest value at receptor 21. These results indicate that raising the stacks to 2.5 times the building height is not sufficient to meet the Federal air quality standards.

Another strategy was evaluated to determine the effect of raising stacks 1 through 4 to 115 m to be equal in height to stack 5 at the Kahe plant. Significant reductions to the 4-month mean occurred with this stack configuration. The 3-hour and 24-hour averages were also significantly reduced. However, the second-highest 3-hour concentration estimated at site 21 exceeds the Federal standard.

One further strategy which was investigated was raising all stacks to a height 2.5 times the respective building heights combined with limiting the fuel to a maximum sulfur content of 1.0 percent. This strategy permits all receptor locations to comply with all Federal standards. Evaluation of control strategies at Kahe Point is presented in Table 28.

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* At the onset of this modeling work, data were provided which stated the height of the stacks to be 42 m for stacks 1 and 2, 45 m for stacks 3 and 4, and 92.7 m for stack 5. These data were input to the model. The building height data input to the model were derived from the stack height data by dividing the stack heights by 1.2 for stacks 1 through 4 and by 2 for stack 5, giving building heights of 35 m for stacks 1 and 2, 38 m for stacks 3 and 4, and 46 m for stack 5. If the building heights for stacks 1 through 4 are all 38 m and these stacks are all 45 m tall, the impact on the model results does not affect the conclusions of this study.

TABLE 26. 3-HOUR AVERAGE CONCENTRATIONS,
CALCULATED STACKS 2.5 x BUILDING HEIGHT

CUMULATIVE FREQUENCY DISTRIBUTION OF COMPUTED SO2 CONCENTRATIONS (µG/CU.M)

PERCENTILE	RECEPTOR 1	2	3	4	5	6	7	8	9	10
HIGH	674.000	861.000	642.000	644.000	588.000	535.000	457.000	998.000	998.000	737.000
2ND	640.000	782.000	541.000	633.000	526.000	477.000	409.000	880.000	880.000	534.000
99.5	559.045	618.725	389.290	507.457	351.305	316.290	263.290	541.744	541.744	368.091
99.0	448.290	416.450	283.021	468.160	241.580	214.030	175.480	394.061	394.061	291.541
95.0	225.450	149.200	152.000	268.350	115.700	98.340	79.640	145.700	145.700	102.350
90.0	138.800	20.090	74.840	136.600	62.920	54.440	44.360	39.580	39.580	50.130
80.0	53.020	2.844	25.840	41.000	24.400	21.140	16.260	0.717	0.717	10.280
70.0	15.800	0.416	2.097	4.464	2.067	1.650	1.584	0.000	0.000	0.367
60.0	1.590	0.067	0.000	0.036	0.000	0.000	0.000	0.000	0.000	0.000
50.0	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
40.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
30.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
20.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
10.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
LOW	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

(CONTINUED)

TABLE 26. (CONTINUED)

CUMULATIVE FREQUENCY DISTRIBUTION OF COMPUTED SO2 CONCENTRATIONS (µG/CU.M)

PERCENTILE	RECEPTOR 11	12	13	14	15	16	17	18	19	20
HIGH	617.000	614.000	906.000	820.000	767.000	594.000	469.000	245.000	453.000	1400.000
2ND	569.000	484.000	564.000	520.000	492.000	388.000	310.000	219.000	340.000	1330.000
99.5	353.290	372.305	356.106	319.136	314.236	232.030	184.595	153.076	167.435	1064.351
99.0	317.641	299.671	251.701	215.151	246.740	149.030	124.740	129.610	134.000	867.735
95.0	97.435	105.350	72.835	65.185	77.845	42.435	35.890	36.635	51.825	362.800
90.0	41.380	38.370	39.430	35.480	36.450	24.300	19.580	18.490	18.900	133.900
80.0	4.024	3.732	12.020	10.940	2.846	9.302	7.018	3.364	1.188	20.660
70.0	0.094	0.002	0.869	0.674	0.000	0.701	0.525	0.005	0.000	0.584
60.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
50.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
40.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
30.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
20.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
10.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
LOW	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

(CONTINUED)

TABLE 26. (CONCLUDED)

CUMULATIVE FREQUENCY DISTRIBUTION OF COMPUTED SO2 CONCENTRATIONS (μG/CU.M)

PERCENTILE	RECEPTOR 21	22	23	24	25
HIGH	1950.000	1800.000	960.000	1450.000	1150.000
2ND	1820.000	1600.000	896.000	1340.000	1030.000
99.5	1610.000	1375.801	786.061	714.272	726.435
99.0	1221.602	1167.402	532.450	349.320	456.883
95.0	345.900	245.050	67.815	96.375	164.250
90.0	118.700	62.340	14.060	32.370	82.180
80.0	9.424	2.936	0.153	5.302	19.760
70.0	0.466	0.108	0.003	0.453	3.258
60.0	0.001	0.002	0.000	0.021	0.137
50.0	0.000	0.000	0.000	0.000	0.000
40.0	0.000	0.000	0.000	0.000	0.000
30.0	0.000	0.000	0.000	0.000	0.000
20.0	0.000	0.000	0.000	0.000	0.000
10.0	0.000	0.000	0.000	0.000	0.000
5.0	0.000	0.000	0.000	0.000	0.000
1.0	0.000	0.000	0.000	0.000	0.000
0.5	0.000	0.000	0.000	0.000	0.000
LOW	0.000	0.000	0.000	0.000	0.000

TABLE 27. 24-HOUR AVERAGE CONCENTRATIONS,
CALCULATED STACKS 2.5 x BUILDING HEIGHT

CUMULATIVE FREQUENCY DISTRIBUTION OF COMPUTED SO2 CONCENTRATIONS (µG/CU.M)

PERCENTILE	RECEPTOR 1	2	3	4	5	6	7	8	9	10
HIGH	260.000	202.000	173.000	223.000	146.000	131.000	110.000	277.000	277.000	145.000
2ND	194.000	176.000	121.000	201.000	109.000	97.100	82.500	275.000	275.000	139.000
99.5	220.070	186.270	141.540	209.690	123.615	110.491	93.363	275.790	275.790	141.370
99.0	192.530	167.390	121.000	199.530	108.790	96.827	82.038	244.760	244.760	137.320
95.0	155.300	99.330	99.285	158.750	84.240	71.895	57.890	83.455	83.455	73.100
90.0	113.400	74.480	67.120	126.000	59.060	50.340	42.900	71.360	71.360	41.060
80.0	70.460	38.060	35.120	67.800	27.360	22.900	19.240	35.660	35.660	24.660
70.0	48.370	21.170	18.970	35.910	15.740	14.240	11.840	20.340	20.340	17.010
60.0	28.120	10.340	14.920	27.620	12.320	10.720	8.828	7.478	7.478	12.480
50.0	16.100	3.020	11.000	18.450	9.670	8.690	7.080	1.345	1.345	5.680
40.0	11.120	0.337	7.650	13.420	5.580	5.062	4.804	0.123	0.123	2.990
30.0	1.986	0.085	3.251	7.398	3.700	2.882	2.169	0.000	0.000	1.325
20.0	0.055	0.013	0.700	1.296	0.905	0.606	0.404	0.000	0.000	0.053
10.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
LOW	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

(CONTINUED)

TABLE 27. (CONTINUED)

CUMULATIVE FREQUENCY DISTRIBUTION OF COMPUTED SO2 CONCENTRATIONS (µG/CU.M)

PERCENTILE	RECEPTOR 11	12	13	14	15	16	17	18	19	20
HIGH	142.000	129.000	184.000	167.000	111.000	123.000	97.300	37.700	75.000	358.000
2ND	116.000	111.000	110.000	96.900	108.000	65.500	51.400	37.400	59.300	327.000
99.5	126.270	118.110	139.230	124.590	109.185	88.213	69.531	37.519	65.502	339.245
99.0	113.060	107.178	108.110	94.338	106.005	62.476	48.964	36.749	58.271	320.280
95.0	81.035	70.660	56.005	53.870	67.425	34.410	26.670	30.750	40.555	240.900
90.0	47.500	54.740	35.070	32.300	45.540	21.500	18.240	20.840	25.840	167.900
80.0	25.540	28.180	21.680	18.480	22.360	12.320	10.028	9.588	13.860	82.500
70.0	15.260	15.810	15.420	13.870	13.550	9.138	7.214	5.664	7.043	37.660
60.0	11.060	9.136	10.300	9.472	7.556	6.796	5.412	4.326	4.298	23.720
50.0	6.710	5.245	6.935	6.120	2.245	4.130	3.475	2.890	1.275	15.250
40.0	1.774	0.976	3.232	2.778	0.589	2.424	2.128	1.358	0.257	9.992
30.0	0.411	0.162	1.432	1.456	0.007	1.374	1.161	0.243	0.000	4.618
20.0	0.026	0.000	0.358	0.267	0.000	0.191	0.118	0.000	0.000	0.159
10.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
LOW	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

(CONTINUED)

TABLE 27. (CONCLUDED)

CUMULATIVE FREQUENCY DISTRIBUTION OF COMPUTED SO2 CONCENTRATIONS (μG/CU.M)

PERCENTILE	RECEPTOR 21	22	23	24	25
HIGH	434.000	365.000	184.000	297.000	297.000
2ND	419.000	337.000	173.000	295.000	264.000
99.5	424.925	348.060	177.345	295.790	277.035
99.0	411.230	331.540	167.960	275.680	251.400
95.0	288.650	224.650	101.615	93.090	127.250
90.0	224.100	175.300	70.260	48.720	85.160
80.0	98.660	61.200	19.880	27.200	44.520
70.0	42.870	34.930	8.040	10.336	25.550
60.0	28.500	19.520	4.824	4.660	11.640
50.0	12.800	6.200	0.801	2.185	5.955
40.0	5.900	1.560	0.251	0.633	2.894
30.0	1.368	0.291	0.018	0.050	0.583
20.0	0.091	0.014	0.000	0.000	0.002
10.0	0.000	0.000	0.000	0.000	0.000
5.0	0.000	0.000	0.000	0.000	0.000
1.0	0.000	0.000	0.000	0.000	0.000
0.5	0.000	0.000	0.000	0.000	0.000
LOW	0.000	0.000	0.000	0.000	0.000

TABLE 28. EXPECTED CONCENTRATIONS USING ABATEMENT STRATEGIES AT KAHE POINT PLANT

Receptor	Strategy*	Mean Concentration (μg/m³) 4-month	Highest Concentration (μg/m³) 24-Hour	Highest Concentration (μg/m³) 3-Hour	Second Highest Concentration (μg/m³) 24 Hour	Second Highest Concentration (μg/m³) 3-Hour	99.5 Percentile Concentration (μg/m³) 24-Hour	99.5 Percentile Concentration (μg/m³) 3-Hour
1	1	62	377	957	281	947	319	700
	2	31	188	478	140	474	160	350
	3	10	58	147	44	132	49	111
	4	40	260	674	194	640	220	559
	5	26	168	530	147	432	155	360
	6	30	211	646	169	600	186	507
2	1	314	1970	4260	1320	3910	1577	3265
	2	157	985	2130	660	1955	788	1632
	3	50	306	724	224	645	256	536
	4	22	202	861	176	782	186	619
	5	14	131	506	114	506	121	371
	6	10	76	370	73	326	74	260
8	1	18	256	924	249	852	252	455
	2	9	128	462	124	426	126	228
	3	3	41	152	40	130	40	72
	4	22	277	998	275	880	276	542
	5	15	178	608	169	584	172	333
	6	20	227	802	227	711	227	474
10	1	29	253	1140	234	1010	242	727
	2	15	126	570	117	505	121	364
	3	4	35	172	32	145	33	105
	4	17	145	737	139	534	141	368
	5	12	110	432	88	420	96	248
	6	14	123	464	115	391	118	280
20	1	85	654	2420	488	1880	554	1425
	2	42	327	1210	244	940	272	712
	3	13	101	376	76	292	86	222
	4	51	358	1400	327	1330	339	1064
	5	32	218	852	212	810	214	664
	6	41	303	1250	273	1200	285	982
21	1	141	1210	1490	811	2400	969	2101
	2	71	605	1245	406	1200	484	1050
	3	22	187	387	126	373	150	327
	4	60	434	1950	419	1820	425	1610
	5	38	270	1188	264	1110	266	983
	6	43	331	1600	323	1480	326	1341
22	1	268	3980	5520	1590	5420	2534	4752
	2	134	1990	2760	795	2710	1267	2376
	3	42	617	857	236	840	386	757
	4	46	365	1800	337	1600	348	1374
	5	29	218	1160	214	942	216	848
	6	28	234	1200	224	1090	228	880

(CONTINUED)

TABLE 28. (CONCLUDED)

Receptor	Strategy*	Concentration	Highest Concentration (μg/m³)		Second Highest Concentration (μg/m³)		99.5 Percentile Concentration (μg/m³)	
			24-Hour	3-Hour	24-Hour	3-Hour	24-Hour	3-Hour
23	1	80	1110	3730	654	2250	834	1820
	2	40	555	1865	327	1125	417	910
	3	13	172	634	101	349	129	274
	4	18	184	960	173	896	177	786
	5	11	112	620	108	546	110	484
	6	12	122	664	118	645	120	546
24	1	161	1070	2400	877	2340	953	2022
	2	81	535	1200	438	1170	476	1011
	3	25	166	362	131	360	145	307
	4	20	297	1450	295	1340	296	714
	5	13	232	1138	192	786	208	462
	6	11	218	1140	206	2050	211	482
25	1	88	489	1270	477	1260	482	1084
	2	44	244	635	238	630	241	542
	3	14	76	195	74	188	75	152
	4	29	197	1150	264	1030	277	726
	5	19	208	908	192	618	198	468
	6	20	239	1060	228	935	232	599

* Strategies:

(1) Limit fuel to maximum sulfur content of 1.0 percent.
(2) Limit fuel to maximum sulfur content of 0.5 percent.
(3) Reduce present emissions by 90 percent.
(4) Raise stack heights to 2.5 times building heights.
(5) Raise stack heights to 2.5 times building heights and limit fuel to maximum sulfur content of 1.0 percent.
(6) Raise all stacks to a height of 115 meters.

SECTION 7

FEASIBILITY OF A SUPPLEMENTARY CONTROL SYSTEM

A supplementary control system to control air quality in the vicinity of a major source of pollution requires that a fairly sophisticated decision process be instituted at the source which takes measurements of meteorological conditions and air quality levels into account when determining the operating level of the source and consequent air pollution emissions. In order for such a system to be feasible, it must be possible to identify meteorological conditions which separate acceptable and unacceptable air quality levels for a given level of emissions.

KAHULUI PLANT

The monitoring data collected over a 6-month period near the Kahului plant showed that the 3-hour and 24-hour Federal standards for SO_2 were frequently exceeded at Station 1, about 0.4 km from the plant. The other two stations showed no excursions of the Federal SO_2 standards. The periods of the highest 24-hour and 3-hour mean concentrations were examined to determine the nature of the concentration patterns on these days and to identify significant meteorological parameters which set them apart from other periods.

The 24-hour concentration of SO_2 at Station 1 exceeded the Federal standard of 365 $\mu g/m^3$ on 107 days out of the 156-day monitoring period. Even if the emissions were reduced by a factor of two so that all measured concentrations would theoretically be reduced by 50 percent, the standard would still be exceeded on 80 out of 156 days. If the emissions were reduced by 75 percent, the measured concentrations were theoretically reduced to a point where the standard would be exceeded on 23 out of 156 days. This is perhaps a reasonable number of days on which to reduce emissions further by a supplementary control system.

In reviewing the pattern of hourly concentrations at Station 1 on the days when the 24-hour concentration is among the 12 highest values, one finds a large-to-moderately-high concentration occurs for nearly every hour. This suggests a strongly persistent wind direction for 24 hours. The range of wind directions, and also other meteorological parameters (including wind speed, standard deviation of wind direction, and mixing height) for the 12 days with the highest 24-hour measured SO_2 concentrations, are listed in Table 29. The narrow range of wind directions associated with these days over a 24-hour period is noteworthy. The range varies from 15 degrees on March 6 to 53 degrees on July 13; however, 10 of the 12 days had ranges of 33 degrees or less. An example of a possible control strategy based on this information is to limit the plant load to 60 percent of its maximum capacity

on days when the range of hourly mean wind directions is less than 33 degrees. Assume the plant also burns only 0.5 percent sulfur fuel oil. During the 6-month monitoring period, there were 55 days out of 156 when the wind direction range was 33 degrees or less. If the plant emissions were limited to 60 percent of capacity on these days, there would only have been 4 days on which the monitored 24-hour SO_2 concentrations exceeded 365 $\mu g/m^3$. On these 4 days the wind direction range exceeded 33 degrees. This is a significant improvement over 23 days without the load reduction.

A more detailed analysis of meteorological variables is required to develop sharper criteria than are indicated in the above example for separating conditions which produce high air quality levels from conditions which do not. Combinations of meteorological variables may determine conditions in which the joint occurrence of two or more meteorological variables provides useful separation categories. For example, none of the days with high SO_2 concentrations includes low wind speed or high values of the standard deviation of wind direction. It is also possible that variables other than the range of wind direction may better indicate the significance of wind variability, e.g., variance of wind direction over 24 hours. The results presented in Table 29 suggest that the meteorological conditions associated with excursions can be identified.

The ability to forecast the occurrence of meteorological conditions which result in high SO_2 concentrations needs to be tested. The forecast problem consists of the ability to predict periods when a well-developed, persistent trade wind will occur with almost no diurnal variation. This appears to occur about 50 percent of the time. The capability to forecast situations which have generally persistent winds from situations which have critically persistent winds and unfavorable dispersion conditions needs to be developed and proven. The practical operation of a supplementary control system must provide the plant with an acceptable operating level which does not require frequent curtailment of operations. A control system requiring that the plant operate at no more than 60 percent of maximum load on 50 percent of all days might not be an economically desirable system.

In general, the feasibility of a supplementary control system, as demonstrated to date, can be summarized as follows:

- A model exists which reliably estimates the distribution of short-term concentrations over a long period of time; the ability to accurately predict air quality on a day-to-day basis needs further testing.

- The meteorological conditions associated with high SO_2 concentration levels are identified; they have an undesirably high frequency of occurrence. More refined and limiting conditions are desirable, if they can be identified.

- The emissions of SO_2 can be accurately estimated from the plant load and fuel sulfur content and can be effectively controlled by reducing the rate of fuel combustion.

TABLE 29. RANGE OF METEOROLOGICAL VARIABLES OBSERVED ON DAYS WITH HIGHEST MEASURED CONCENTRATIONS OF SO_2

Date	Wind Direction (degrees)	Speed (m/sec)	Standard Deviation of Wind Direction (degrees)	Mixing Height (m)	Observed SO_2 ($\mu g/m^3$)
July 4	29-56	3.4-8.5	10-29	341-1588	2463
July 7	30-52	3.0-8.4	11-20	277-1559	2255
July 8	34-56	3.8-7.1	10-25	226-1822	1994
June 1	31-52	4.4-8.6	10-24	100-1893	1985
March 4	22-55	3.0-8.6	9-23	139-1615	1896
March 6	41-56	3.8-8.3	11-24	1046-2422	1853
June 20	19-63	4.3-8.3	11-24	100-1563	1842
July 9	26-51	2.9-7.9	11-22	102-1943	1835
March 7	31-59	2.9-8.7	9-26	153-1994	1833
May 24	23-51	2.7-7.1	10-22	100-2276	1752
July 13	358-51	2.1-6.1	12-24	310-1750	1730
July 11	23-53	2.1-6.2	9-61	176-1400	1699

- The extent of emissions curtailment necessary in terms of the frequency of curtailment of the plant operations has not been established. The frequency may be high enough to make the supplementary control system an uneconomical alternative in comparison with other options such as scrubbers and tall stacks.

KAHE POINT PLANT

The monitoring data collected over a 4-month period near the Kahe Point plant showed that the 3-hour and 24-hour Federal standards for SO_2 were frequently exceeded at Station 2, about 150 m from the plant. The 24-hour standard was exceeded about 4 percent of the time at Station 1, about 500 m south of the plant. The periods of the highest 24-hour and 3-hour mean concentrations were examined to determine the nature of the concentration patterns on these days and to identify significant meteorological parameters which set them apart from other periods.

In contrast to the situation at Kahului, the highest SO_2 concentrations occur under a range of observed meteorological conditions. A summary of the winds which were observed at Station 2 on the 15 days with highest 24-hour SO_2 concentrations is given in Table 30. Although the wind direction is generally from the northeast, it is extremely variable. The large standard deviations of wind direction observed also indicate the high degree of turbulence. Northeast winds with the same degree of turbulence occur on other days on which much lower SO_2 values are measured. The meteorological differences between high and low SO_2 days are not evident from the surface meteorological conditions. The tethersonde data collected during the intensive monitoring periods do show the presence of large turbulent eddies. It

TABLE 30. RANGE OF WIND OBSERVATIONS AT STATION 2 ON DAYS WITH HIGHEST SO_2 CONCENTRATIONS AT STATION 2

Date 1977	Wind Direction (degrees)	Wind Speed (m/sec)	Standard Deviation of Wind Direction (degrees)	24-Hour Measured SO_2 ($\mu g\ m^{-3}$)
Nov. 4	26-159	0.3-2.9	41-101	2140
Oct. 26	53-95	1.2-3.6	34-75	2050
Nov. 5	54-114	1.5-3.1	34-64	1900
Nov. 3	29-86	1.1-3.8	32-80	1830
Nov. 14	287-108	0.4-2.3	24-79	1760
Nov. 6	37-107	0.7-2.6	31-69	1530
Nov. 13	10-105	0.4-1.9	27-107	1530
Oct. 25	348-178	0.5-5.6	34-103	1410
Nov. 2	10-96	1.2-3.4	23-65	1350
Oct 27	10-125	0.1-2.9	30-110	1310
Oct. 17	18-174	0.2-4.9	24-105	1270
Oct. 16	112-141, 257-276	0.6-2.9	18-86	1240
Dec. 16	37-121	1.0-3.4	28-76	1240
Dec. 17	272-98	0.4-3.5	36-102	1160
Oct. 20	16-153	0.6-2.8	28-83	1100

may be possible to make a more detailed analysis of the turbulence spectrum and find meteorological parameters which distinguish between low and high SO_2 concentrations at ground level. This more detailed analysis has not been performed for this study. It is not clear that it will produce the desired separation of high and low SO_2 days.

Some of the high concentrations occur on days with above-average output loads from the plant and thus higher-than-normal SO_2 emission rates. However, the SO_2 concentrations are much higher relative to their mean than are the emission rates which tend to be very consistent from day to day. It is possible that a small portion of the variation in SO_2 concentrations can be attributed to SO_2 emission rates.

Until evidence is developed to indicate the meteorological difference between high and low SO_2 days, it does not seem feasible to consider a supplementary control plan for the Kahe Point plant.

The concentrations listed in Table 30 all occur during the months of October, November, and December, and none occur in January. This is because the listed values are 24-hour concentrations which are highest when the wind direction is most persistent. During January the trade winds are weakest and least persistent. This fact accounts for the absence of any high 24-hour SO_2 concentrations in January. On the other hand, there is a much greater variety of complex windflow situations in January. All three types of windflow situations, i.e., trade, sea breeze, and Kona winds, have more nearly equal frequencies of occurrence in January than at any other time of the year.

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