ornl

OAK RIDGE
NATIONAL
LABORATORY

MARTIN MARIETTA

ORNL/TM-12861

ENVIRONMENTAL RESOURCES OF SELECTED AREAS OF HAWAII:

CLIMATE, AMBIENT AIR QUALITY, AND NOISE

by

Douglas A. Lombardi,
T. J. Blasing,
Clay E. Easterly, and
Charles B. Hamilton

Robert M. Reed,
Project Manager

MANAGED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from the Office of Scientific and Technical Information, P.O. Box 62, Oak Ridge, TN 37831; prices available from (615) 576-8401, FTS 626-8401.

Available to the public from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Rd., Springfield, VA 22161.

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

ORNL/TM-12861

ENVIRONMENTAL RESOURCES OF SELECTED AREAS OF HAWAII: CLIMATE, AMBIENT AIR QUALITY, AND NOISE

Douglas A. Lombardi
T. J. Blasing
Clay E. Easterly[1]
Charles B. Hamilton[2]

Robert M. Reed, Project Manager
Energy Division

March 1995

---

[1] Health Sciences Research Division
[2] University of Tennessee

Prepared for
U.S. Department of Energy
Oak Ridge Operations Office

by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
managed by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-84OR21400

[Blank Page]

TABLE OF CONTENTS

Page

[Blank Page]

LIST OF FIGURES

[Blank Page]

LIST OF TABLES

[Blank Page]

ACRONYMS AND ABBREVIATIONS

CNS	central nervous system
CO	carbon monoxide
dB	decibel
dB(A)	decibels as recorded on the A-weighted scale of a standard sound level meter
DNL	day-night level
DOE	U.S. Department of Energy
EIS	environmental impact statement
EPA	U.S. Environmental Protection Agency
H_2S	hydrogen sulfide
H_2SO_4	sulfuric acid
HGP	Hawaii Geothermal Project
HUD	U.S. Department of Housing and Urban Development
IDLH	immediately dangerous to life or health
in.	inch
KERZ	Kilauea East Rift Zone
L_{90}	the A-weighted sound pressure level exceeded 90% of the time
L_{da}	day-night level
L_{eq}	equivalent sound level
m^3	cubic meter
mm	millimeter
mph	miles per hour
m/s	meters/second
µm	micron
NAAQS	National Ambient Air Quality Standards
NIOSH	National Institute for Occupational Safety and Health
NO_2	nitrogen dioxide
NWS	National Weather Service
O_3	ozone
Pb	lead
PGV	Puna Geothermal Venture
PM-10	particulate matter less than 10 microns in diameter
PM-15	particulate matter less than 15 microns in diameter
ppm	parts per million
PSD	Prevention of Significant Deterioration
SAAQS	State of Hawaii Ambient Air Quality Standards
SE	southeast
SO_2	sulfur dioxide
SW	southwest
TLV	threshold limit value
TSP	total suspended particulates
vog	volcanic smog
W	west

[Blank Page]

1. INTRODUCTION

This report has been prepared to make available and archive background scientific data and related information on climate, ambient air quality, and ambient noise levels collected during the preparation of the environmental impact statement (EIS) for Phases 3 and 4 of the Hawaii Geothermal Project (HGP) as defined by the state of Hawaii in its April 1989 proposal to Congress. The U.S. Department of Energy (DOE) published a notice in the *Federal Register* on May 17, 1994 (*Fed. Regis.* 59, 25638) withdrawing its Notice of Intent (*Fed. Regis.* 57, 5433) of February 14, 1992, to prepare the HGP-EIS. Since the state of Hawaii is no longer pursuing or planning to pursue the HGP, DOE considers the project to be terminated.

The report presents a general description of the climate and air quality for the islands of Hawaii (henceforth referred to as Hawaii), Maui, and Oahu. It also presents a literature review as baseline information on the health effects of hydrogen sulfide. The scientific background data and related information is being made available for use by others in conducting future scientific research in these areas. This report describes the environmental resources present in the areas studied (i.e., the affected environment) and does not represent an assessment of environmental impacts.

2. CLIMATE

Hawaii is the only state in the United States that is entirely surrounded by water and lies completely within the tropical trade wind belt. The state is comprised of several islands with diverse topography, but generally characterized as mountainous. These factors contribute to a mixture of climate regimes that exist within the island chain. Diverse climates can exist within relatively short distances on the same island due to topographical effects on wind direction and speed and rainfall patterns.

The predominant winds that affect the state of Hawaii are the trade winds that generally flow from the northeast. Trade winds are an outflow of air from the central North Pacific anticyclone, the center of which is normally located to the north and east of the islands. The two seasons that occur in the state, winter and summer, depend on the location of the anticyclone. Winter (October through April) occurs when the anticyclone is in its relative southern position and the trade winds are often broken by Kona storms (major rain events accompanied by winds from a direction other than the trade wind) that travel south of the island chain. Summer (May through September) occurs when the anticyclone is generally in its northern position and trade winds are rarely interrupted (University of Hawaii 1983).

Temperature range varies little over most of the state from day to day and throughout the year. On each island, daily temperatures vary with elevation—that is, warmer temperatures occur on the coastline and cooler temperatures occur at higher elevations. Other meteorological parameters, such as rainfall, humidity, and wind speed and direction, vary substantially from island to island and within any specific island (Blumenstock and Price 1967).

2.1 WINDWARD SIDE OF HAWAII

Meteorological conditions vary greatly on the windward (northeastern) side of Hawaii depending on the location of a local area relative to Mauna Loa [4170 m (13,680 ft) elevation] and Mauna Kea [4205 m (13,800 ft) elevation] and on local topographical features. Meteorological data from the Kapoho subzone have been recorded at three locations along the Puna Geothermal Venture (PGV) site boundary (see Fig. 1). Data have been collected at the southwest (SW) monitoring station since May 1990 and at the southeast (SE) and west (W) monitoring stations since August 1992. Meteorological parameters monitored at these sites include wind speed and direction, temperature, relative humidity, and precipitation. These data were measured at 10 m (33 ft) above the ground surface (Puna Geothermal Venture site data). The standard deviation of the horizontal wind direction (used to determine atmospheric stability) is calculated at these monitoring locations. Additionally, the National Weather Service (NWS) has collected surface and upper-air meteorological data at Hilo, located 34 km (21 mi) to the north (National Weather Service site data). Temperature and rainfall data for Hilo and the Kapoho section of the Lower East Rift Zone are summarized in Table 1. No meteorological data for the Kilauea Middle East Rift Zone and the Kamaili Section of the Lower East Rift Zone are available.

Along the Kilauea East Rift Zone (KERZ), daytime winds are predominantly from the northeast in the direction of the trade winds. Nighttime winds flow generally downward from the summit of Mauna Loa and split either north or south along the rift (Schroeder 1992). Therefore, nighttime winds are mainly from the west, with a northerly (from the north) component on the south side of the rift, and a southerly (from the south) component on the north side of the rift. Figures 2 through 4 display wind roses[1] for winds recorded at the PGV site boundary. All stations show predominant wind directions from the north-northeast and northwest. Higher wind speeds (those that would usually occur during the day) are predominantly from the north-northeast corresponding to the direction of the trade winds. Lower wind speeds (those that are likely to occur at night) are predominantly from the northwest. This flow corresponds to nighttime drainage winds flowing down from Mauna Loa and spilling off of the East Rift of Kilauea, which lies to the north of the PGV site (Schroeder 1992).

Winds at Hilo are predominantly from the southwest, directly opposite to the direction of the trade winds (see Fig. 5). However, for daytime winds, with higher wind speeds, the prevailing

---

[1] A wind rose is a graph in which the frequency of wind blowing from each direction is plotted as a bar that extends from the center of the diagram. Wind speeds are denoted by bar widths; the frequency of the wind speed within each direction is depicted according to the length of that section of the bar. Note that the wind rose displays directions from which the wind blows.

ORNL-DWG 95-5943

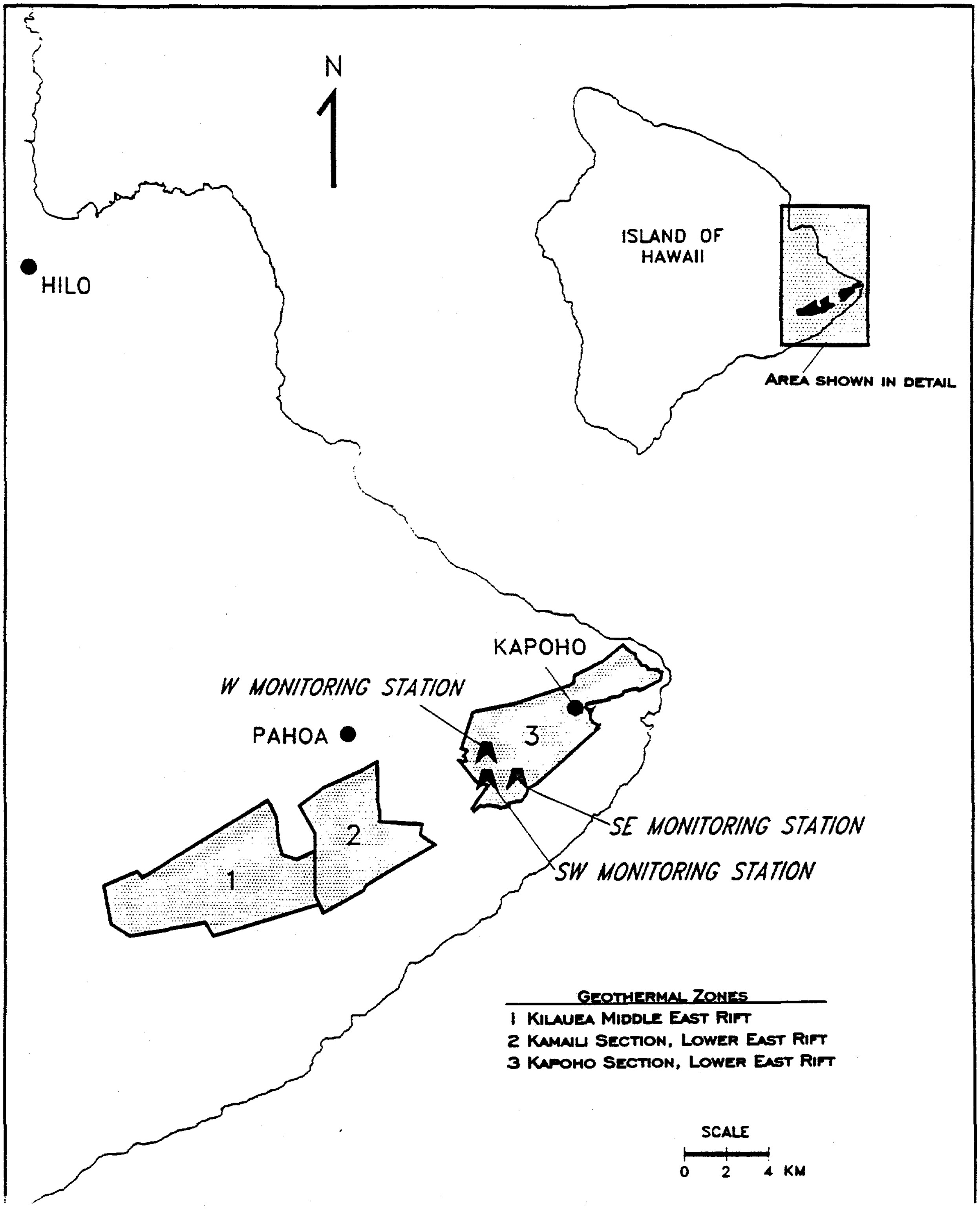

Fig. 1. Location of meteorological monitoring stations along the Puna Geothermal Venture site boundary. *Source:* ORNL staff observations made during 1992 site visit.

Table 1. Comparison of temperature and precipitation data recorded at the PGV site-SE monitoring station and General Lyman Field (Hilo)-National Weather Service monitoring station, both located on the windward side of Hawaii

Parameter	PGV site-SE monitoring station	General Lyman Field (Hilo)-NWS monitoring station
Temperature		
Average daily	22°C (72°F)[a]	23°C (74°F)[b]
Average daily maximum	23°C (74°F)[a]	27°C (81°F)[b]
Average daily minimum	21°C (69°F)[a]	19°C (66°F)[b]
Record maximum	28°C (82°F)[c]	34°C (94°F)[d]
Record minimum	15°C (58°F)[e]	12°C (53°F)[f]
Rainfall		
Average annual	2285–3800 mm (90–150 in.)[g]	3300 mm (131 in.)[b]
Maximum annual	N/A	5360 mm (211 in.)[h]
Maximum monthly	N/A	1290 mm (51 in.)[i]
Maximum 24-h	N/A	560 mm (22 in.)[j]

Abbreviations: PGV=Puna Geothermal Venture, NWS=National Weather Service, mm=millimeter, in.=inch, N/A=data not available.

[a] Recorded between May 1990 and December 1992 (*Source*: Puna Geothermal Venture Site data).

[b] Recorded between January 1961 and December 1990 (Bair 1992).

[c] Recorded in May 1992.

[d] Recorded in May 1966 (Bair 1992).

[e] Recorded in March 1992.

[f] Recorded in February 1962 (Bair 1992).

[g] Average annual rainfall range along the Kilauea East Rift Zone (University of Hawaii 1983). Rainfall is heaviest along the northern side of the East Rift.

[h] Recorded in 1990 (Bair 1992).

[i] Recorded in December 1954 (Bair 1992).

[j] Recorded in February 1979 (Bair 1992).

ORNL-DWG 95-5944

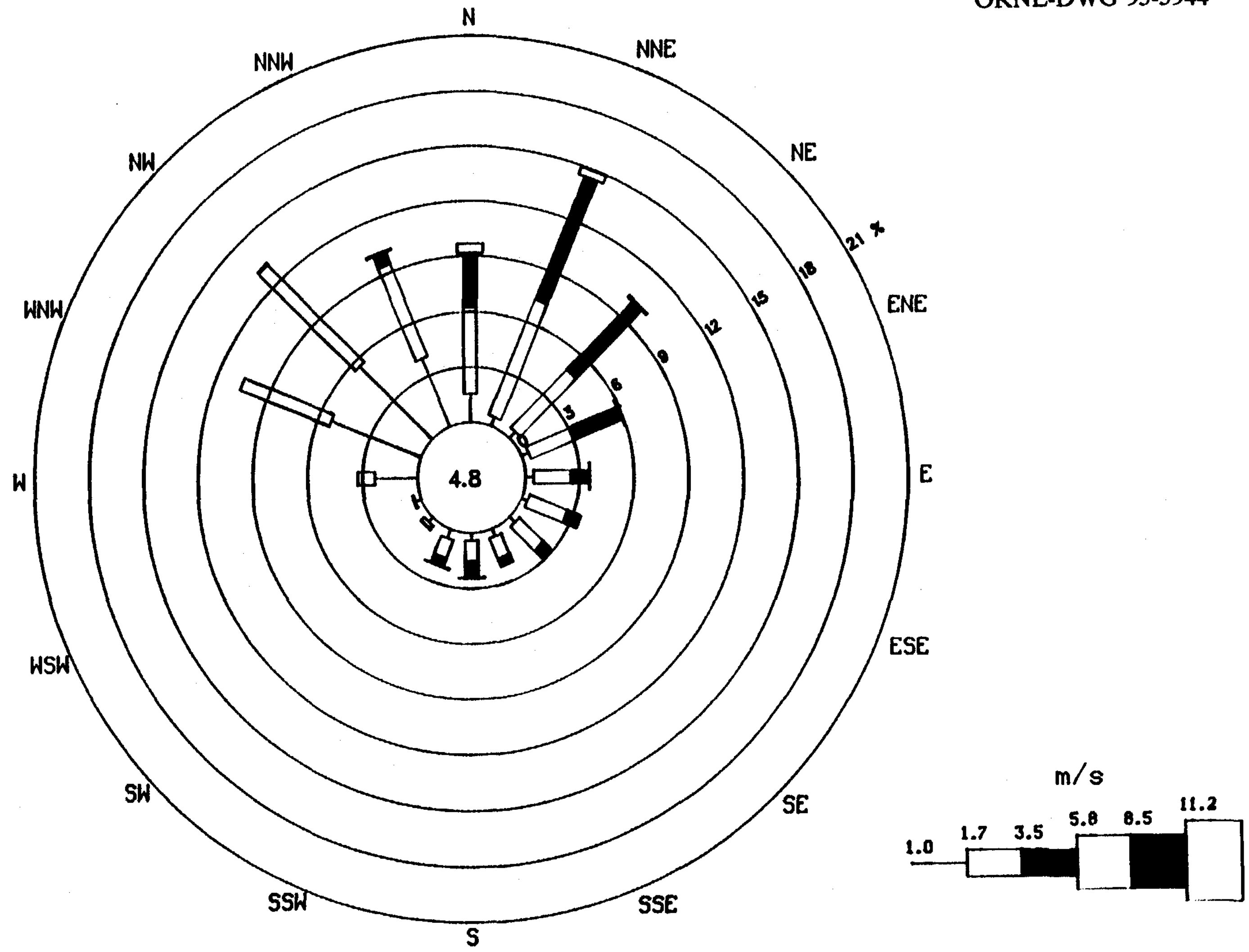

Fig. 2. Wind rose for the Puna Geothermal Venture site-SW monitoring station. The height of the wind measurement was 10 m, and the period of measurement was May 1990 to December 1992. *Source:* Unpublished site data provided to D. A. Lombardi, ORNL, by Puna Geothermal Venture in 1993.

ORNL-DWG 95-5945

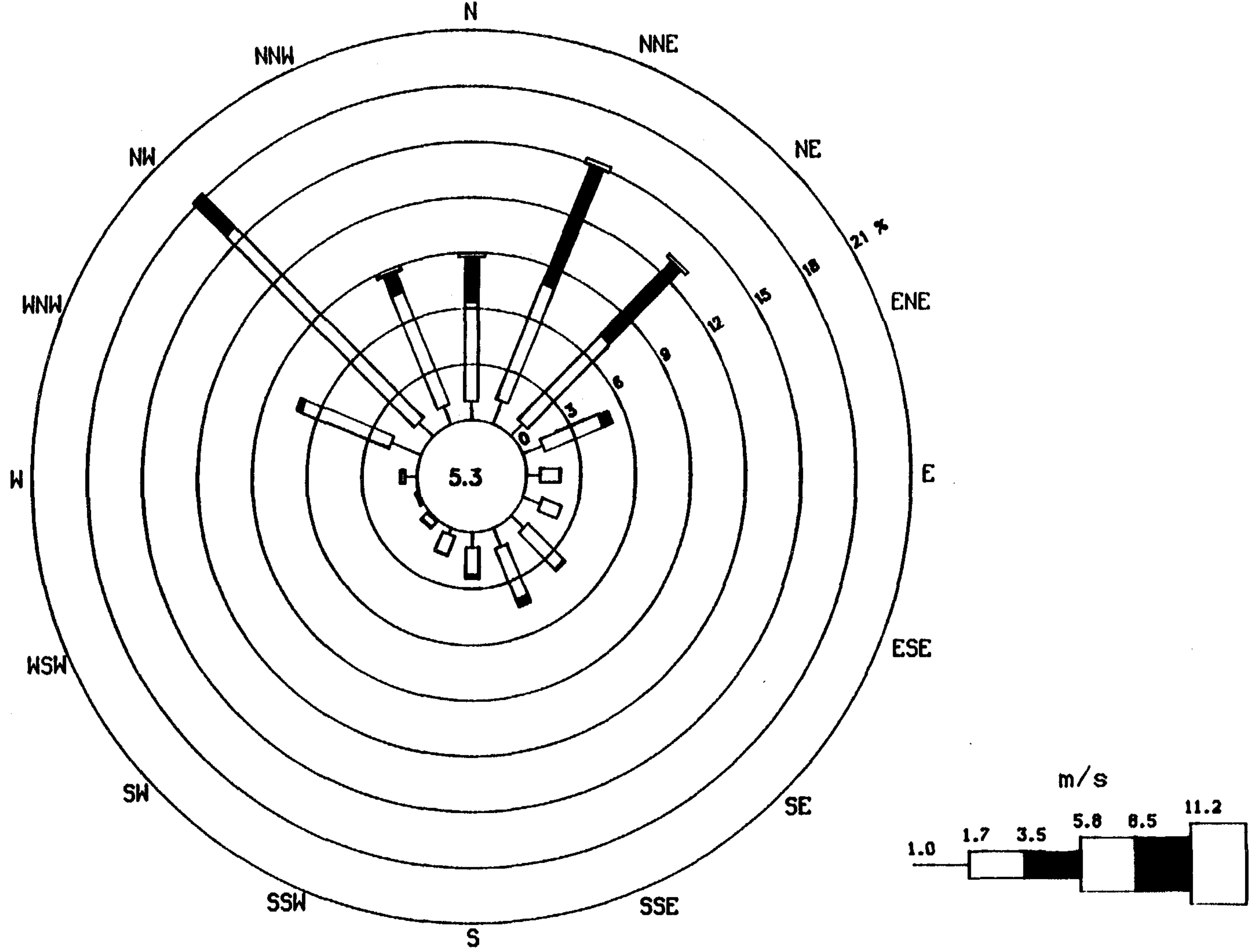

Fig. 3. **Wind rose for the Puna Geothermal Venture site-SE monitoring station.** The height of the wind measurement was 10 m, and the period of measurement was August 1992 to December 1992. *Source:* Unpublished site data provided to D. A. Lombardi, ORNL, by Puna Geothermal Venture in 1993.

ORNL-DWG 95-5946

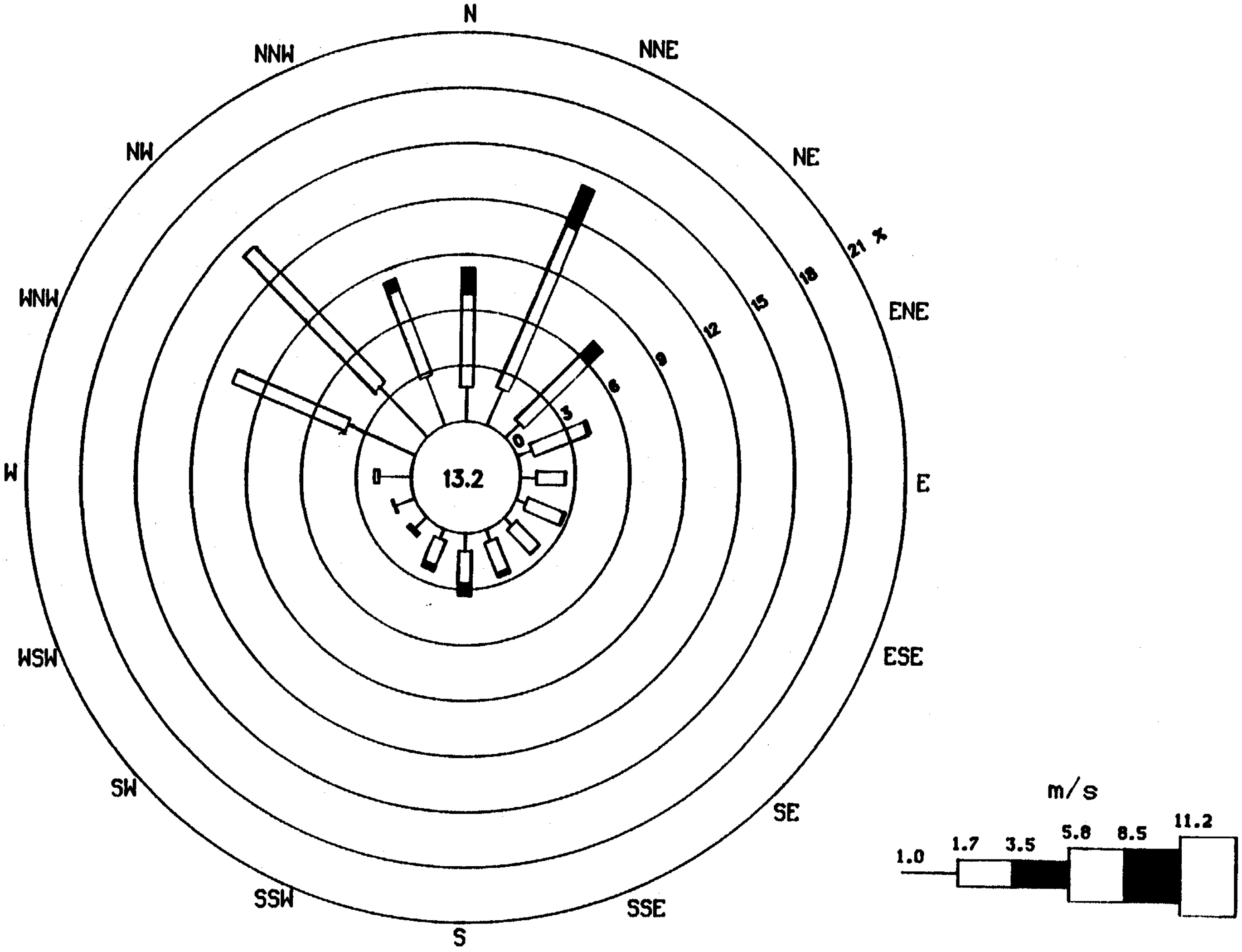

Fig. 4. Wind rose for the Puna Geothermal Venture site-W monitoring station. The height of the wind measurement was 10 m, and the period of measurement was August 1992 to December 1992. *Source:* Unpublished site data provided to D. A. Lombardi, ORNL, by Puna Geothermal Venture in 1993.

ORNL-DWG 95-5947

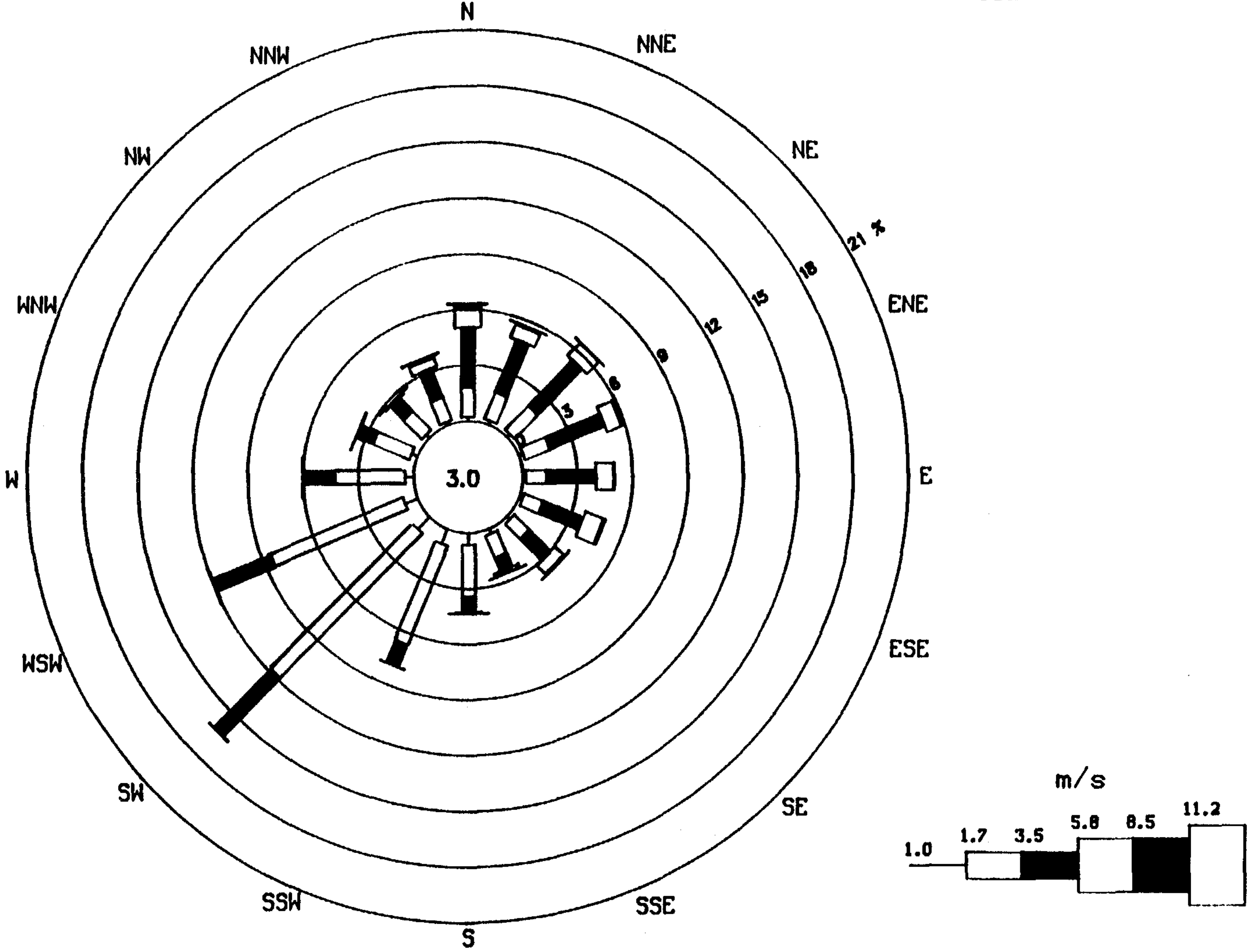

Fig. 5. **Wind rose for the National Weather Service meteorological monitoring site at General Lyman Field, Hilo, Hawaii.** The height of the wind measurement was 3 m, and the period of measurement was January 1984 to December 1989. *Source:* National Weather Service site data obtained from the U.S. Environmental Protection Agency, Support Center for Regulatory Air Models, Research Triangle Park, NC 27711.

wind is from the northeast quadrant. Wind directions from the southwest are most likely a result of nighttime drainage winds from Mauna Loa and Mauna Kea, nighttime land breeze conditions (winds blowing from the land to the sea at night due to temperature differences) that occur along the coastline, and wintertime Kona winds (winds associated with Kona storms that blow opposite the direction of the trade winds).

2.2 ISLAND OF MAUI

Wind speed and direction are recorded by the NWS at Kahului, which is located on the windward side of the island (University of Hawaii 1983). Surface winds occur predominantly from the north at Kahului, with a secondary predominant wind direction from the northeast. Predominant winds on the leeward side of Maui are expected to be from the north and northeast due to mountain downslope and land breeze conditions during the night and to trade winds blowing during the day.

Strong daytime downslope winds, known as the Kula and Lehua winds, have been recorded on Maui. The Kula winds occur along the lower slopes of Mt. Haleakala, with the strongest occurring between 610 m (2000 ft) and 1220 m (4000 ft) elevation. Wind speeds over 18 m/s (40 mph) occur once or twice each year, on the average. Wind speeds of 27 m/s (60 mph) would likely occur only once every 4 to 5 years. The Lehua winds generally occur on the western and southern side of the western Maui mountains and may reach speeds in excess of 45 m/s (100 mph). These winds have been known to demolish buildings, overturn large power transmission line towers, and uproot trees. On average, these winds occur once every 8 to 12 years (Gale Research 1985).

Precipitation on the leeward slope of Mt. Haleakala averages between 381 mm (15 in.) and 1525 mm (60 in.) per year (University of Hawaii 1983). Average temperatures at Keawakapu Beach, located on the leeward side of the island, range from 21°C (70°F) in January to 26°C (79°F) in July.

2.3 ISLAND OF OAHU

Wind speed and direction are recorded by the NWS at Honolulu on the leeward side of the island. Surface winds occur predominantly from the east-northeast, as shown in the Honolulu wind rose (Fig. 6). Wind direction is also predominantly from the east-northeast at Kaneohe, located along the windward coast (University of Hawaii 1983).

Precipitation on the windward side of Oahu averages between 1015 mm (40 in.) and 1525 mm (60 in.) per year (University of Hawaii 1983). Average temperatures at Waimanalo Beach, on the windward side of the island, range between 22°C (72°F) in January to 24°C (75°F) in July.

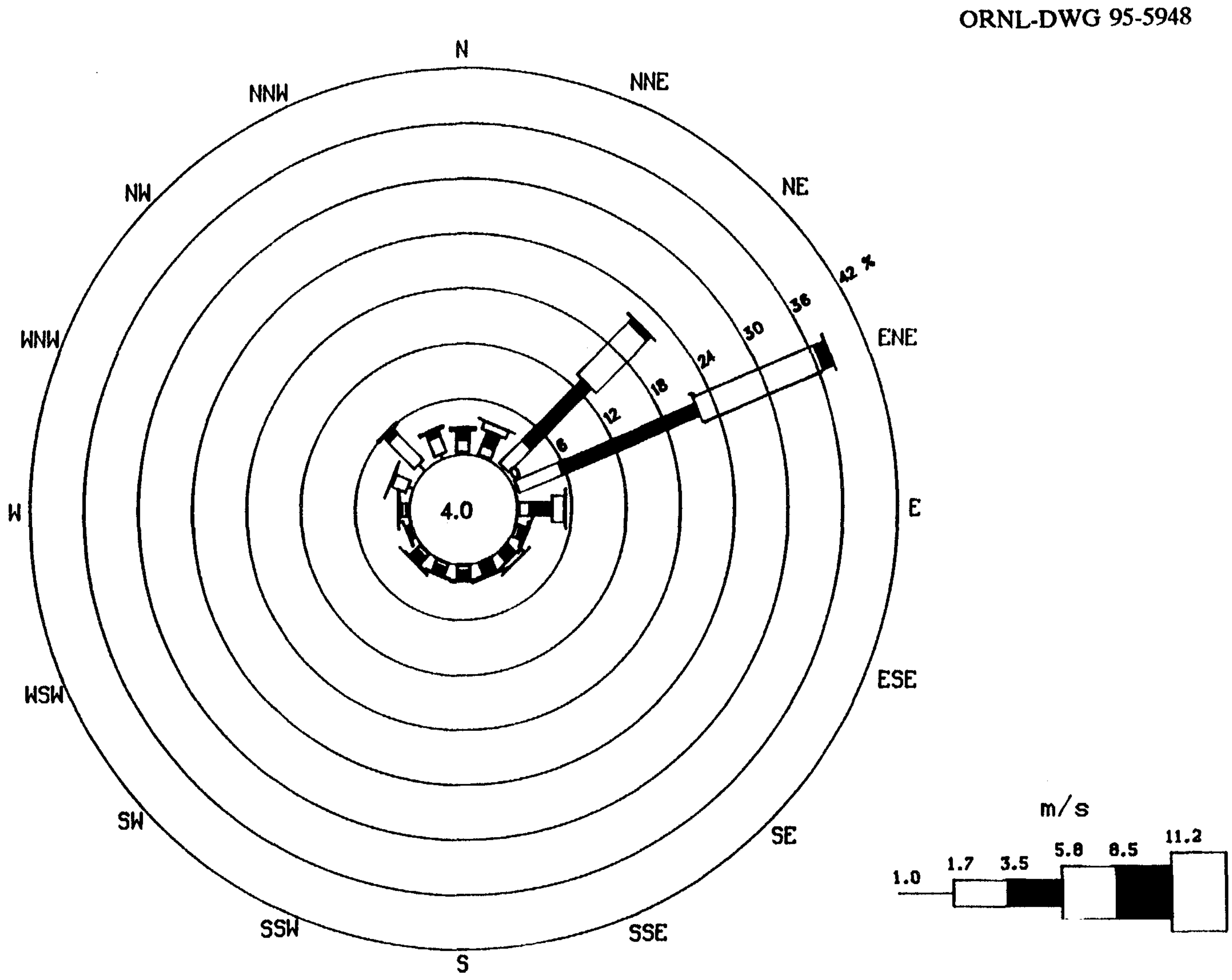

Fig. 6. **Wind rose for the National Weather Service meteorological monitoring site at Honolulu International Airport.** The height of the wind measurement was 3 m, and the period of measurement was January 1985 to December 1989. *Source:* National Weather Service site data obtained from the U.S. Environmental Protection Agency, Support Center for Regulatory Air Models, Research Triangle Park, NC 27711

2.4 SEVERE WEATHER

On average, three weather systems reach tropical storm intensity [defined as a storm in which wind speeds reach 14.5 m/s (39 mph) or greater] in the central North Pacific each year (Shaw 1981, as cited in Chiu et al. 1983). The North Pacific is defined by the NWS as being bounded by 140° W longitude, 180° W longitude, and the equator. Tropical storms normally develop between June and November. Three hurricanes have affected the Hawaiian islands directly since the end of World War II: Hurricane Dot struck the island of Kauai in 1959, Hurricane Iwa affected Oahu and Kauai in 1982, and Hurricane Iniki hit Kauai in 1992. Other tropical storms have come close enough to the islands to cause wind and wave damage (Bair 1992).

During winter, subtropical low-pressure systems may impact the Hawaiian Islands, bringing widespread heavy rains and strong winds. These low-pressure systems are known as Kona storms. Kona winds are predominately from the "kona," or leeward, direction (opposite the trade winds). The term "Kona storm" was originally applied to slow-moving subtropical cyclones that would occasionally impact the islands, but now the term is applied to any major rain event accompanied by winds from a direction other than the trade winds. Typically, there are one or two well-developed Kona storms each year, and sometimes four or five may form (Blumenstock and Price 1967). These storms can last several days, with heavy rains interrupted by periods of lighter rain or partial clearing. Severe flooding can accompany Kona storms; over 510 mm (20 in.) of rain was recorded during a 24-h period in November 1955 (Blumenstock and Price 1967).

Tornadoes, waterspouts, or funnel clouds are sighted about 20 times each year, and thunderstorms are reported 20 to 30 days each year (Blumenstock and Price 1967). Most thunderstorms occur during the winter. Blizzards can occur on the upper slopes of Mauna Loa and Mauna Kea at elevations as low as 2750 m (9000 ft); otherwise, snow is extremely rare in the state (Blumenstock and Price 1967).

3. AMBIENT AIR QUALITY

The existing air quality for the Hawaiian Islands is generally good as characterized by comparing ambient air measurements with state of Hawaii Ambient Air Quality Standards (SAAQS) (State of Hawaii 1992) and the National Ambient Air Quality Standards (NAAQS) (Pub. L. 95-95, 1977). NAAQS exist for the following criteria pollutants: particulate matter less than 10 μm in diameter (PM-10), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), ozone (O_3), and lead (Pb). SAAQS include all of these pollutants plus total suspended particulate matter (TSP) and hydrogen sulfide (H_2S). The NAAQS and SAAQS are shown in Table 2.

Table 2. State of Hawaii and National Ambient Air Quality Standards

Pollutant	Averaging time	State of Hawaii Ambient Air Standard[a] ($\mu g/m^3$)	NAAQS[b] ($\mu g/m^3$)
SO_2	3 h	1300	1300
	24 h	365	365
	annual	80	80
NO_2	annual	70	100
CO	1 h	40,000	40,000
	8 h	10,000	10,000
O_3	1 h	100	235
PM-10	24 h	150	150
	annual	50	50
Pb	3 month	1.5	1.5
TSP	24 h	150	none
	annual	60	none
H_2S	1 h	35	none

[a] *Source*: Hawaii Department of Health 1992.
[b] *Source*: 40 CFR 50.

An area is designated as an attainment area if the ambient concentrations do not exceed the NAAQS. The entire state is designated as an attainment area for all criteria pollutants (Sano 1993).

The 1-h H_2S standard was adopted by the state of Hawaii in June 1992, and is set at the concentration at which H_2S odor can be detected (Hawaii Department of Health 1992). The odor threshold air concentration for H_2S is very low in comparison to air concentrations that may cause currently identified health effects. Table 3 compares the immediately dangerous to life and health (IDLH) standard (DHHS 1990) and the hourly (or an approximation to hourly) SAAQS for some criteria pollutants. A relatively small ratio, indicating that the ambient standard is close to the IDLH, would serve to prevent any adverse acute health impacts. A relatively large ratio would indicate that the ambient standard is much more stringent than the IDLH and therefore is based on odor nuisance and concern about potential adverse effects of chronic low-level exposures. Appendix A provides some additional background information on H_2S health effects.

As shown in Table 3, the ratio of IDLH to SAAQS for H_2S is approximately two orders of magnitude greater than the next highest ratio (SO_2). All of the other ratios are approximately within a factor of ten. Based on these ratios, the state has defined good air quality as ambient air in which no H_2S odor is detectable.

Table 3. Comparison of immediately dangerous to life and health (IDLH) ambient air concentrations to some hourly (or approximation to hourly) average state of Hawaii Ambient Air Quality Standards (SAAQS)

	Pollutant ambient air concentrations (ppmv)				
	H_2S	SO_2	CO	O_3	NO_2
IDLH[a]	300	100	1500	10	50
SAAQS[b]	0.025	0.4[c]	35	0.12	0.53[d]
IDLH / SAAQS	12,000	250	43	83	100

[a] *Source*: DHHS (1990).

[b] *Source*: Hawaii Department of Health 1992.

[c] Suggested (not yet law) hourly average standard for SO_2 (58 FR 21351).

[d] No hourly average standard is proposed for NO_2. For comparison purposes, the hourly average was estimated as ten times the annual average (0.053 ppmv).

3.1 ISLAND OF HAWAII

The only major natural source of H_2S emissions on Hawaii is the Kilauea Volcano and degassing sources along the east rift (hereafter called the Kilauea Volcano system). However, H_2S ambient air concentrations resulting from the Kilauea Volcano system are limited by the following low temperature reaction of SO_2 with H_2S:

$$2H_2S + SO_2 = 2H_2O + 3S \quad ,$$

and the air-oxidation of H_2S to SO_2:

$$H_2S + O_2 = SO_2 + H_2 \quad .$$

The first reaction takes place in a few minutes after emission and, because of the high emission rate of SO_2 from the Kilauea system, effectively removes a large quantity of H_2S from the ambient air. The second reaction takes up to one day (Graedel 1977, as cited in Sutton, Elias, and

Navarrete 1994) and removes most of the remaining H_2S from the ambient air. Therefore, though high H_2S emissions occur from the Kilauea Volcano system, these emissions have a minor impact on the ambient air quality of Hawaii (Sutton, Elias, and Navarrete 1994).

Currently, the State Department of Health operates four monitors in the KERZ that record ambient H_2S air concentrations. These monitors are located in the area surrounding the PGV site (see Fig. 7). The maximum measured 1-h concentration in 1992 was 14 $\mu g/m^3$, or 40% of the state ambient air standard for H_2S. The maximum measured 1-h concentration in 1991 was 92 $\mu g/m^3$ (263% of the state standard). However, this concentration was associated with the June 12–14 geothermal well (KS-8 well) blowout at the PGV site (State of Hawaii, Department of Health ambient air quality open-file data). This concentration is not considered representative of background levels. Outside the period of the well blowout, the maximum measured 1-h concentration in 1991 was 14 $\mu g/m^3$. Ambient H_2S concentrations were measured near the summit caldera of the Kilauea Volcano between October 1986 and August 1990 (Sutton, Elias, and Navarette 1994). The maximum identified H_2S concentration at this site was 220 $\mu g/m^3$ (629% of the state standard) (Table 4). This high concentration reflects the nearby source of the volcano.

State monitoring of ambient SO_2 concentrations was discontinued on Hawaii in September 1986 because of the low level of measurements recorded (State of Hawaii 1986). The National Park Service has been monitoring ambient SO_2 levels near the summit caldera of the Kilauea Volcano in Hawaii Volcanoes National Park since October 1986. Additionally, measurements of ambient SO_2 concentrations were made at the Mauna Loa Observatory, at an elevation of 3400 m (11,152 ft), during a 1-year period beginning in December 1988 (Luria et al. 1992). Measurements of SO_2 were also made at the upper Leilani residential area between May and September 1983 (Houck and Pritchett 1985). The Leilani residential area borders the PGV site to the southwest. Maximum and average ambient air SO_2 concentrations measured at these sites are detailed in Table 5.

Sulfur dioxide data measured at the Kilauea Volcano indicate that the 24-h SAAQS and NAAQS for SO_2 were exceeded 50 times between 1987 and 1990 (Elias 1992). Kona winds and light easterly winds characterized the meteorological conditions during these exceedances. The maximum 1-h SO_2 concentration at this site in 1992 was 2360 $\mu g/m^3$ (182% of the 3-h SAAQS for SO_2). The average SO_2 concentration at this monitoring station was <66 $\mu g/m^3$ (<83% of the applicable SAAQS) (Sutton, Elias, and Navarette 1994). For all other sites, the maximum 1-h, 24-h, and average annual SO_2 concentrations were less than 15% of the applicable SAAQS. The discrepancy between the ambient SO_2 concentrations measured at the summit of the Kilauea Volcano and the state of Hawaii monitoring stations at Hilo and Kona has been attributed to a variety of factors. At Hilo, the location of the station was predominantly upwind from the volcano summit, and sampling was infrequent (once every six days) (Murrow 1991). At Kona, sufficient atmospheric dispersion and conversion of SO_2 to sulfate particles was likely, due to distance from the source.

Ambient TSP concentrations are not currently measured on Hawaii. The state of Hawaii Department of Health discontinued TSP measurements on Hawaii in September 1986 (State of

ORNL-DWG 95-5949

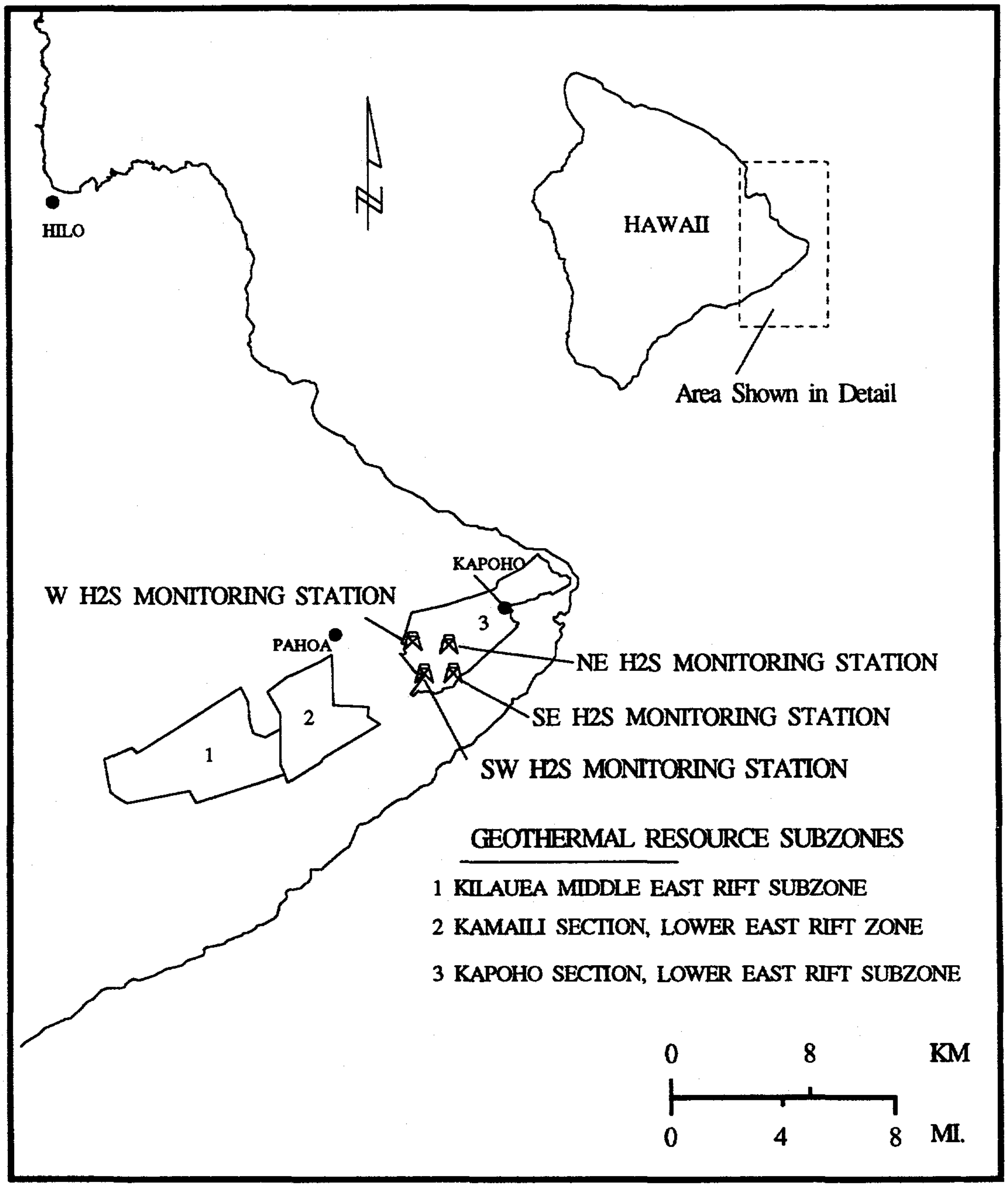

Fig. 7. Location of hydrogen sulfide (H_2S) ambient air monitoring stations near the Puna Geothermal Venture site. *Source:* Oak Ridge National Laboratory staff observations made during the 1992 site visit.

Table 4. Ambient air concentrations of hydrogen sulfide (H_2S) on Hawaii

Measurement site	Monitoring period	Averaging time	State of Hawaii ambient air standard[a] ($\mu g/m^3$)	Maximum background concentration ($\mu g/m^3$)	Percent of standard
Hawaii Volcanoes National Park	Oct. 1986–Aug. 1990	1 h	35	220[b]	629
Puna District (near the PGV geothermal power plant site)	Jan. 1991–Dec. 1992	1 h	35	14[c]	40

[a] *Source*: State of Hawaii, Department of Health 1992.
[b] *Source:* Sutton, Elias, and Navarrete 1994.
[c] *Source:* State of Hawaii, Department of Health ambient air quality open-file data.

Table 5. Ambient air concentrations of sulfur dioxide (SO_2) on Hawaii

Measurement site	Monitoring period	Averaging time	State of Hawaii ambient air standard[a] (μg/m³)	Concentration (μg/m³)	Percent of standard
Hawaii Volcanoes National Park	Jan.–Dec. 1992	1 h	1300[b]	2360[c,d]	182[b]
		annual	66	80[c,d]	<83
Mauna Loa Observatory	Dec. 1988–Dec. 1989	1 h	1300[b]	113[c,e]	9[b]
Hilo	Jan. 1985–Sept. 1985	24 h	365	6[c,f]	2
		period of record	80[f,g]	<5[f,h,i]	<6[d]
Kona	June 1985–July 1986	24 h	365	8[c,f]	2
		annual	80	<5[f,h,i]	<6
Upper Leilani	May 1983–Sept. 1983	1 h	1300[b]	>160[j,k]	>12[b]

[a] State of Hawaii, Department of Health 1992.

[b] One-hour concentrations were compared to the 3-h standard. The maximum 3-h average concentration would be less than the maximum 1-h concentration. Therefore, the comparison with the 3-h standard is an overestimate.

[c] Maximum measured concentration.

[d] *Source:* Sutton, Elias, and Navarrete 1994.

[e] *Source:* Luria et al. 1992.

[f] *Source:* State of Hawaii, Department of Health 1986.

[g] Period of record concentration was compared to the average annual standard. Annual average concentration was likely to be less. Therefore, the comparison with the average annual standard is an overestimate.

[h] Average concentrations over the entire monitoring period.

[i] The less-than symbol (<) indicates that average concentrations were below the detection threshold of the instrument.

[j] *Source:* Houck and Pritchett 1985.

[k] The greater-than symbol (>) indicates that concentrations exceeded the maximum detection range of the instrument.

Hawaii 1986). Concentrations of TSP and particulate matter less than 15 µm in diameter (PM-15) were recorded at the upper Leilani residential area from December 1982 to December 1983 (Houck and Pritchett 1985). Maximum and annual average ambient TSP concentrations measured at these sites are shown in Table 6. Maximum 24-h and average annual particulate matter concentrations measured at these sites were less than 25% of the applicable SAAQS. No measurements of CO, NO_2, O_3, and Pb are made on Hawaii (Hawaii Department of Health 1991).

3.2 VOLCANIC SMOG

Volcanic smog (vog) occurs mainly on the leeward side of Hawaii and is caused primarily by atmospheric aerosol emissions from the continuing Kilauea eruption. These aerosols are transported around the southern tip of the island and northward along the Kona coast by complex lee eddy flow patterns formed by trade wind interaction with Mauna Loa and Mauna Kea (Robinson 1991). Air flow within the eddy that develops along the Kona coast is relatively stagnant, and consequently, vog is formed. During Kona wind conditions, vog may form on the windward side of the island.

The principal components of these aerosols are sulfates [50% of the total mass on an annual averaging basis and 70% of the total mass during peak episodes (Murrow 1991)]. Sulfates were measured as PM-10 at Captain Cook, located on the Kona coast of Hawaii. Annual PM-10 concentrations averaged 13 $\mu g/m^3$, which is 26% of the NAAQS for PM-10 (50 $\mu g/m^3$). Maximum 24-h concentrations were approximately 40 $\mu g/m^3$, or 27% of the 24-h NAAQS for PM-10 (150 $\mu g/m^3$). Maximum sulfuric acid (H_2SO_4) levels measured were 10 $\mu g/m^3$(1% of the maximum allowable 8-h exposure limit) (Murrow 1992; DHHS 1990). There are currently no NAAQS or SAAQS for H_2SO_4.

3.3 ISLAND OF MAUI

Ambient air concentrations of PM-10 and SO_2 are monitored on Maui. Sulfur dioxide is monitored in Kihei, located on the leeward side of the island. Measurements made between January and December 1989 are the latest full year of data available at that location. Ambient air concentrations of PM-10 are recorded at Lahaina, on the western tip of Maui. The latest data with a complete 1-year record available at this location were measured between August 1989 and July 1990 (State of Hawaii 1991). Table 7 gives recent data for PM-10 and SO_2 on Maui. Maximum 24-h and average annual SO_2 concentrations measured at Kihei were less than 6% of the applicable SAAQS, and maximum 24-h and average annual PM-10 concentrations measured at Lahaina were less than 30% of the standards.

Table 6. Ambient air concentrations of total suspended particulate matter and particulate matter less than 15 microns in diameter on Hawaii

Measurement site	Monitoring period	Averaging time	State of Hawaii ambient air standard[a] (μg/m³)	Concentration (μg/m³)	Percent of standard
		Total suspended particular matter			
Hilo	Jan. 1985–Sept. 1985	24 h	150	28[b,c]	19
		period of record	60[d]	15[c,e]	25[d]
Kona	June 1985–July 1986	24 h	150	22[b,c]	15
		annual	60	12[c]	20
Upper Leilani	Dec. 1982–Dec. 1983	annual	150	18	12
		Particular matter less than 15 microns in diameter			
Upper Leilani	Dec. 1982–Dec. 1983	annual	50	9.5[g]	19[g]

[a] *Source*: State of Hawaii, Department of Health 1992.

[b] Maximum measured concentration.

[c] *Source:* State of Hawaii, Department of Health 1986.

[d] Period of record concentration was compared to the average annual standard. Annual average concentration was likely to be less. Therefore, the comparison with the average annual standard is an overestimate.

[e] Average concentrations over the entire monitoring period.

[f] Annual average PM-15 concentrations were compared to the annual average PM-10 standard. Annual concentrations of PM-15 would be higher than annual average PM-10 concentrations; therefore, the comparison is an overestimate.

[g] *Source:* Houck and Pritchett 1985.

Table 7. Ambient air concentrations of sulfur dioxide (SO_2) and particulate matter less than 10 microns in aerodynamics diameter (PM-10) on Maui

Pollutant	Averaging time	State of Hawaii ambient air standard[a] ($\mu g/m^3$)	Concentration ($\mu g/m^3$)	Percent of standard
SO_2[b]	24 h	365	< 5[c,d,e]	< 1[c]
	annual	80	< 5[d,e]	< 6[c]
PM-10[f]	24 h	150	31[c,e]	21
	annual	50	14[e,f]	28

[a] *Source*: State of Hawaii, Department of Health 1992.

[b] Ambient SO_2 concentrations were measured at Kihei between January and December 1989.

[c] Maximum measured concentration.

[d] The less-than symbol (<) indicates that average concentrations were below the detection threshold of the instrument.

[e] *Source:* State of Hawaii, Department of Health 1991.

[f] Ambient PM-10 concentrations were measured at Lahaina between August 1989 and July 1990.

3.4 ISLAND OF OAHU

Sulfur dioxide, CO, O_3, Pb, TSP, and PM-10 are monitored on Oahu. All ambient concentrations are below the SAAQS, except for O_3. The O_3 standard was exceeded four times between October 1991 and September 1992, the latest full year of data available. During this period, O_3 measurements did not exceed the NAAQS. SAAQS for O_3 (100 $\mu g/m^3$) are much more stringent than the NAAQS for O_3 (235 $\mu g/m^3$). Ozone is measured at Sand Island, approximately 2 km (1.2 mi) from downtown Honolulu. PM-10 is monitored at Waimanalo Beach, located on the windward side of the island. Sulfur dioxide, CO, Pb, and TSP are measured in downtown Honolulu (Hawaii Department of Health 1991).

Table 8 lists ambient air concentrations recorded on Oahu during 1991 and 1992. Maximum 24-h and average annual SO_2 concentrations measured at Honolulu were less than 6% of the applicable SAAQS. Maximum 1-h and 8-h CO concentrations, measured at the same site, were less than 35% of the SAAQS, and measurements of Pb were only 1% of its standard. Maximum 24-h and average annual particulate matter concentrations measured at Waimanalo were less than 60% of the applicable SAAQS.

3.5 PREVENTION OF SIGNIFICANT DETERIORATION AREAS

Prevention of Significant Deterioration (PSD) Class I areas are designated to greatly restrict the degradation of ambient air quality. Less stringent PSD requirements exist for Class II areas, which presently include all areas of the United States that are not designated Class I. Pollutants with PSD increments (a numerical amount indicating the additional pollutant that would be allowed through the combined effects of all new growth in a particular area) are PM-10, SO_2, and NO_2. PSD increments for these pollutants are detailed in Table 9.

There are two Class I PSD areas in the state of Hawaii: Hawaii Volcanoes National Park and Haleakala National Park. Hawaii Volcanoes National Park is located on the island of Hawaii, about 2.7 km (1.7 mi) from the western boundary of the KERZ. Haleakala National Park is located on Maui.

4. NOISE

4.1 AMBIENT NOISE

The Puna District of Hawaii is largely a rural community characterized by widely separated residences, small amounts of farming, and essentially no industry. Consequently, most of the noise generated during the day is along roadways and in agricultural areas. Along roadways, automobile and truck traffic are the dominant sources of noise, while farm equipment and aircraft, particularly helicopters, are occasional noise sources. Helicopters are used primarily to provide tourists with a view of volcanoes and lava flows. Nighttime noise is primarily from distant motor vehicle traffic

Table 8. Ambient air concentrations of criteria air pollutants on Oahu

Pollutant	Averaging time[a]	State of Hawaii ambient air standard[b] ($\mu g/m^3$)	Concentration ($\mu g/m^3$)	Percent of standard
SO_2[c]	24 h	365	3[d]	<1
	annual	80	1	<6
CO[c]	1 h	40,000	9600[d]	24
	8 h	10,000	3200[d]	32
O_3[e]	1 h	100	120[d]	120
Pb[c]	calendar qtr.	1.5	0.02[c]	1
TSP[c]	24 h	150	88[d]	59
	annual	60	30	50
PM-10[g]	24 h	150	28[d]	56
	annual	50	17	34

[a] Maximum and average concentrations were measured in the period between October 1991 and September 1992, except for CO, which was measured between January and December 1992. These represent the latest available complete year of data. *Source:* State of Hawaii, Department of Health 1991.

[b] *Source*: State of Hawaii, Department of Health 1992.

[c] Ambient concentrations were measured in downtown Honolulu.

[d] Maximum measured concentration.

[e] Ambient O_3 concentrations were measured on Sand Island, located 2 km (1.2) from downtown Honolulu.

[f] Ambient PM-10 concentrations were measured at Waimanalo Beach.

Table 9. Allowable increment for the Prevention of Significant Deterioration (PSD)

Pollutant	Averaging time	PSD increments ($\mu g/m^3$)	
		Class I	Class II
SO_2	3 h	2	20
	annual	5	91
	24 h	25	512
NO_2	annual	2.5	25
PM-10	24 h	4[a]	17[a]
	annual	8[a]	30[a]

[a] Effective June 3, 1994 (*Fed. Regis.* 58: 31622-31638).

and natural phenomena such as wind and insects. As a result of the lack of noise-producing sources, nighttime noise levels are quite low in comparison to levels in more highly developed areas. Noise levels between 30 and 35 dB(A) are reported to be present 90% of the time in the areas surrounding geothermal exploration areas in the Puna District (Fluor Technology, Inc. 1987). Noise levels are typically well below those of urban areas.

Local terrain and vegetation features buffer ambient noise by acting as absorbers or reflectors. The Puna District exhibits a large variation in terrain features and vegetation. Vegetation cover varies from light to dense, and consists of papaya orchards, woodlands, and other natural vegetation, interspersed with unvegetated areas of barren lava (Fluor Technology, Inc. 1987). Volcanic hills (pu'u) may have considerable local noise-shielding effects.

The County of Hawaii Planning Department was in the process of developing geothermal noise level guidelines and best management practices for commercial enterprises at the time of this study (Fluor Technology, Inc. 1987; Moulds 1993). Exceedances of these guidelines may occur primarily when sound is reflected from air layers in the atmosphere and/or stable conditions.

Typical residential construction techniques and requirements differ between the continental United States and the state of Hawaii. Because of construction requirements, most residences in the continental United States have sound attenuation characteristics greater than residences in Hawaii, especially rural Hawaii. In most U.S. settings, sound attenuation is on the order of 15 to 20 dB(A) between outside and inside the residence, and this attenuation level is the basis for the U.S. Department of Housing and Urban Development's regulatory guidance (HUD 1985). In Hawaii, noise reduction is more likely to be about 10 dB(A) less. [Residential units in Hawaii, especially in rural areas, are often constructed with a single wall and do not contain insulation. Such construction practices would have reduced sound attenuation in the order of 10 dB(A) (Thumann and Miller 1986).] Because of this generally lower attenuation, the guidelines developed for the U.S. mainland (EPA 1974, HUD 1985, which provide for indoor levels of 40 to 45 dB(A) during the daytime and 30 to 35 dB(A) during the nighttime, may be too high to allow for satisfactory speech communication during the day and acceptable sleeping conditions during the night in many Hawaiian residences. Residences at risk for noise interference by new industrial developments should be monitored over a 24– to 48-h period prior to construction. Initial site-specific background measurements would be obtained for comparison with predicted noise levels from construction activities.

Noise measurement data for the Puna District is limited. An environmental noise survey conducted by Fluor Technology, Inc. (1987) provides typical environmental noise levels for residential areas within the study area. Noise monitoring stations were located at two residential locations near the PGV site. Background noise levels during the survey ranged from 34.2 dB(A) (at 7 p.m.) to 53.2 dB(A) (at 5 a.m.) levels, which exceed the county nighttime noise guidelines of 45 dB(A). High precipitation in the area during the noise survey may have been the reason for this exceedance as early morning rains were observed during the period of data accumulation. Monitored noise levels from the PGV study are presented in Table 10. In general, background noise levels remained well below 45 dB(A) during most hours of the survey.

4.2 NOISE POLICY AND REGULATIONS

4.2.1 Public exposures

In 1972, Congress enacted the Noise Control Act (PL 92-574). This act assigned responsibility to the administrator of the U.S. Environmental Protection Agency (EPA) to coordinate all federal programs relating to noise research and noise control. It also directed the EPA to identify noise levels requisite to protect the public health and welfare with an adequate margin of safety, without regard to technical feasibility or economic costs. The result of the EPA's effort was the publication of a report entitled *Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety* (EPA 1974). This document is often referred to as the "Levels Document." Within this document, the EPA identified the L_{eq} (equivalent sound level) and its variation, L_{dn} (the day–night level, or DNL), as the primary descriptors of cumulative noise exposure to correlate with health and welfare effects. The DNL includes a 10-dB(A) nighttime penalty that reflects the potential for added annoyance due to sleep disturbance, speech interference, and other effects.

Chronic annoyance is the implicit basis for such noise-related habitability criteria as those adopted by the Department of Defense (DOD 1978) and the Department of Housing and Urban Development (HUD 1985).

Table 10. Noise monitoring data for locations in the vicinity of the study area

		Off-site residence Brees Station		Off-site residence Gilman Station	
Time period (hour ending)	Applicable county guidelines [dB(A)]	L_{90}[a] [dB(A)]	L_{eq}[b] [dB(A)]	L_{90}[a] [dB(A)]	L_{eq}[b] [dB(A)]
13:00	55	36	51.8	--	--
14:00	55	35	43.9	36	53.3
15:00	55	35	43.3	34	46.7
16:00	55	34	42.7	32	40.7
17:00	55	35	44.6	32	59.2
18:00	55	33	43.2	35	37.1
19:00	55	32	34.2	40	43.7
20:00	45	35	36.7	50	52.1
21:00	45	34	36.6	39	41.8
22:00	45	34	35.8	39	41.2
23:00	45	34	36.0	38	44.8
0:00	45	35	36.8	41	44.5
1:00	45	35	37.0	42	44.3
2:00	45	35	37.2	44	49.4
3:00	45	35	37.0	48	50.1
4:00	45	35	37.1	49	51.9
5:00	45	34	36.6	51	53.2
6:00	45	34	36.4	50	52.2
7:00	45	35	46.4	43	47.3
8:00	55	34	43.9	35	43.8
9:00	55	34	46.8	36	43.3
10:00	55	34	48.4	35	42.9
11:00	55	37	43.6	34	43.8
12:00	55	40	46.3	33	43.0
13:00	55	—	—	34	51.2

[a] L_{90} is the A-weighted sound pressure level that is exceeded 90% of the time. The specified time period is 1 h. The L_{90} is commonly used as an indicator of the ambient background noise level.

[b] L_{eq} is the equivalent sound level, which is the energy average of the A-weighted sound pressure level. The specified time period is 1 h. The energy average is the constant noise level for 1 h that has the same energy as the actual fluctuating level during the hour.

Source: Fluor Technology, Inc., 1987.

The state of Hawaii currently has no statewide noise regulations, but they are being developed. Oahu has noise rules, and rules on other islands are expected to be similar. For land that is zoned residential on Oahu, the rule specifies a noise level of 55 dB(A) from 7 a.m. to 10 p.m. and 45 dB(A) from 10 p.m. until 7 a.m., as measured at the property line. Further, these values may not be exceeded for periods lasting more than 2 min out of 20. The County of Hawaii Planning Department has developed Geothermal Noise Level Guidelines (Fluor Technology, Inc. 1987). These guidelines are the same as the Oahu noise rule but add an allowable noise limit for impact noise (e.g., caused by pipes and tools clanging together). This impact limit is 10 dB(A) higher than the overall daytime and nighttime limits.

4.2.2 Occupational exposures

Occupational exposures to noise are regulated by the Occupational Safety and Health Administration in accordance with 29 CFR 1910.5, amended at *Fed. Regis.* 39,194638. The primary focus is on the conservation of hearing. It is considered that, if noise is controlled so that hearing loss does not occur, other health impacts of noise will be avoided. The American Conference of Governmental Industrial Hygienists has developed threshold limit values (TLVs) for noise (Table 11) (ACGIH 1993). TLVs refer to sound pressure levels and durations of exposure that represent conditions to which it is believed nearly all workers may be repeatedly exposed without adverse long- or short-term effects on their ability to hear and understand normal speech. A hearing conservation program with audiometric testing is an important part of an occupational health program when workers are exposed to noise levels at or above the TLV levels (ACGIH 1993).

Table 11. Threshold limit values for occupational noise exposure

Duration per day (hours)	Sound level [dB(A)]
16	80
8	85
4	90
2	95
1	100
1/2	105
1/4	110
1/8	115[a]

[a] No exposure to continuous or intermittent in excess of 115 dB(A).

Source: ACGIH 1993–1994.

6. REFERENCES

ACGIH (American Conference of Government and Industrial Hygienists). 1993. *Threshold Limit Values for Chemical Substances and Physical Agents and Biological Exposure Indices.* Cincinnati.

Bair, F. E. 1992. *The Weather Almanac.* 6th ed., Gale Research, Inc., Detroit.

Blumenstock, D. I., and S. Price. 1967. "Climates of the States: Hawaii," in *Climatography of the United States.* Environmental Sciences Service Administration, U.S. Department of Commerce, Washington, D.C.

Casadevall, T. J., et al. 1987. "SO_2 and CO_2 Emission Rates at Kilauea Volcano, 1979–84," in *Volcanism in Hawaii.* U.S. Geological Survey, Professional Paper 1350, Denver.

Chiu, A. N., et al. 1983. *Hurricane Iwa, Hawaii, November 23, 1982*, Committee on Natural Disasters, Commission on Engineering and Technical Systems, National Research Council, National Academy Press, Washington, D.C.

Department of Health. 1986. *Hawaii Air Quality Data for the Period of January 1985–December 1987*, State of Hawaii, Environmental Protection and Health Services Division, Staff Services, Honolulu, Hawaii, 1986.

Department of Health. 1991. *Hawaii Air Quality Data: January 1988–December 1990*, State of Hawaii, Department of Health, Clean Air Branch, Honolulu.

Department of Health. 1992. Amendment and Compilation of Chapter 11-50, House Administrative Rules, State of Hawaii, Department of Health, Honolulu.

DHHS (U.S. Department of Health and Human Services). 1990. *Pocket Guide to Chemical Hazards*, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health. Washington, D.C.

DOD (U.S. Department of Defense), Departments of the Air Force, the Army, and the Navy. 1978. *Planning in the Noise Environment*, AFM 19-10, TM 5-803-2, and NAVFAC P-970 Washington, D.C.

Elias, T. 1992. "The Effect of Volcanic Air Emissions on Ambient Air Quality in Hawaii Volcanoes National Park [abs.]," in *Proceedings from the Earthquake, Tsunami, and Volcano Hazards Seminar, August 6, 1992*, Center for the Study of Active Volcanoes, University of Hawaii at Hilo, Hawaii.

EPA (U.S. Environmental Protection Agency). 1974. *Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety*, EPA-550/9-74-004, Office of Noise Abatement and Control, Washington, D.C.

EPA (U.S. Environmental Protection Agency). 1982. *Guidelines for Noise Impact Analysis*, EPA-550/90-82-105, National Technical Information Service (PB82-219205), Springfield, Va.

Fluor Technology, Inc. 1987. *Puna Geothermal Venture Environmental Impact Statement*, prepared for Thermal Power Co., Honolulu.

Gale Research Company. 1985. *Climates of the States*, 3rd ed., Gale Research Co., Detroit.

Houck, J. E., and L. C. Pritchett. 1985. *Baseline Air Quality, Kilauea East Rift, Puna and Ka'u Districts, County of Hawaii: Summary Report*, State of Hawaii, Department of Planning and Economic Development, Honolulu.

HUD (U.S. Department of Housing and Urban Development). 1985. *The Noise Guidebook*, Office of Environment and Energy, Environmental Planning Division, Washington, D.C.

Luria, M., et al. 1992. "Atmospheric Sulfur Dioxide at Mauna Loa, Hawaii," *Journal Geothermal Research* 97(D5), 6011–22.

Moulds, J. 1993. Personal communication, C. E. Easterly, ORNL, with J. Moulds, Hawaii County Planning Department, Hilo, Hawaii.

Murrow, J. W. 1991. " The Atmospheric Fate of Sulfur Gases from Kilauea Volcano [abs.]," in *Proceedings from the Vog and Laze Seminar, July 29, 1991*, Center for the Study of Active Volcanoes, University of Hawaii at Hilo.

Murrow, J. W. 1992. "Volcanic Air Pollution in Captain Cook Hawaii [abs.]," in *Proceedings from the Earthquake, Tsunami, and Volcano Hazards Seminar, August 6, 1992*, Center for the Study of Active Volcanoes, University of Hawaii at Hilo.

Public Law 95-95. Clean Air Act Amendments, 91 Stat. 731, Part C, Prevention of Significant Deterioration of Air Quality 1977.

Robinson, E. 1991. "Atmospheric Circulation of Hawaiian Volcanic Gases [abs.]," *Proceedings from the Vog and Laze Seminar, July 29, 1991*, Center for the Study of Active Volcanoes, University of Hawaii at Hilo, Hilo.

Sano, W. 1993. Personal communication with D. A. Lombardi, Oak Ridge National Laboratory, February 9.

Schroeder, T. 1992. Personal communication D. A. Lombardi, Oak Ridge National Laboratory, with T. Schroeder, University of Hawaii, Honolulu, August 4.

Schultz, T. J. 1978. "Synthesis of Social Surveys on Noise Annoyance," *Journal of the Acoustical Society of America* 64(2), 377–405.

Sutton, A. J., T. Elias, and R. Navarrete. 1994. "Volcanic Emissions and Their Impact on Ambient Air Character at Kilauea Volcano, Hawaii," U.S. Geological Survey Open-file Report 94-xxxx, Hawaii National Park, Hawaii, in press.

Thumann, A., and R. K. Miller. 1986. *Fundamentals of Noise Control Engineering*, The Fairmont Press, Inc., Atlanta.

University of Hawaii. 1983. *Atlas of Hawaii*, The University Press of Hawaii, Honolulu.

7. LIST OF PREPARERS

Oak Ridge National Laboratory

Robert M. Reed, Research Staff, Energy Division
Contribution: Project management and review
Education: Ph.D., Plant Ecology, 1969, Washington State University

Douglas A. Lombardi, Research Staff, Energy Division
Contribution: Air quality
Education: B.S., 1987, Mechanical Engineering

T. J. Blasing, Research Staff, Energy Division
Contribution: Review of and assistance with air quality
Education: Ph.D., Meteorology, 1975, University of Wisconsin

Clay E. Easterly, Research Staff, Health Sciences Research Division
Contribution: Noise and hydrogen sulfide
Education: Ph.D., Physics (minor in Health Physics), 1972, University of Tennessee—Knoxville

Consultant

The following individual prepared contributions as indicated under subcontract with Oak Ridge National Laboratory:

Charles B. Hamilton
Technical contribution: Hydrogen sulfide
Education: Ph.D., Health Sciences, 1973, University of North Carolina
Professional affiliation: University of Tennessee—Knoxville

APPENDIX

BASELINE INFORMATION ON HYDROGEN SULFIDE AND HUMAN HEALTH

A1. INTRODUCTION

Hydrogen sulfide (H_2S) occurs naturally in the ambient atmosphere in the Puna District on the island of Hawaii because it is emitted from volcanoes and vents and from existing geothermal operations. This appendix presents a review of the existing literature on the health effects of H_2S.

Hydrogen sulfide is a flammable, colorless, moderately water-soluble, noncondensable gas. It is a constituent of geothermal steam, natural gas, and decaying organic material and is a by-product of various industrial processes. It is classified as both an asphyxiant and an irritant (Green 1989). Hydrogen sulfide has corrosive properties and will blacken such materials as copper, silver, and lead-based paints. More dense than air, H_2S has a specific gravity of 1.92g/L and tends to accumulate in low-lying and underground locations (Lilis 1986, Waldbott 1978), which increases the potential for heavy concentrations.

A2. HYDROGEN SULFIDE ODOR

The most distinctive feature of H_2S gas is the nauseating "rotten-egg" odor. The H_2S odor threshold—minimum air concentration level at which humans can smell this gas—varies rather widely (Amoore and Hautala 1983). Anspaugh and Hahn (1980) reported the median threshold as 0.005 parts per million (ppm). However, odor detection thresholds as low as 0.0002 ppm (National Safety Council 1988), 0.0005–0.01 ppm (Ruth 1986), 0.002 ppm (Layton and Anspaugh 1981), and 0.003–0.02 ppm (NIOSH 1977b) have been reported. General agreement exists that the odor is clearly detectable and offensive at a level of 3–5 ppm (Milby 1962).

The odor threshold may be higher for those whose sensitivity to smell has diminished with age (Glass 1990), for smokers, and perhaps for those who have experienced long-term exposure to H_2S (Waldbott 1978). With constant exposure, people may tend to become accustomed to even an unpleasant odor (Ruth 1986). However, Cain (1980) has suggested that repeated exposure may enhance odor detection and recognition. In addition to variability of olfactory powers among persons and prior experience with an odor, the ability to detect a given odor may be strongly influenced by the degree of attention given to the matter (Amoore and Hautala 1983). Environmental odor as a stimulus to physiological symptoms is addressed more fully in Sect. A8. Non-Specific Symptoms.

Although the odor of H_2S is distinctive at low concentrations, the presence of odor does not serve as a reliable warning signal for exposures to more toxic concentrations exceeding

100 ppm (Wasch et al. 1989; Amoore and Hautala 1983; and Milby 1962). At this level, reversible olfactory fatigue may develop during an exposure period of several minutes, with paralysis of the olfactory (first cranial) nerve occurring at approximately 150 ppm (Lilis 1986; Beauchamp et al. 1984; Ahlborg 1951; NIOSH 1977a,b). Because of this characteristic impact, concentrations capable of producing human fatalities may not be detected by a warning odor. A minority viewpoint contends that the evidence for paralysis or fatigue of the olfactory nerve is not convincing and should be seriously reexamined (Smith 1989).

A3. EXPOSURE PATHWAYS

The principal entry route of H_2S to humans is inhalation of the gas with rapid absorption into the blood through the lungs. Percutaneous absorption of gaseous H_2S is not established as a likely or important route (Wasch et al. 1989; Beauchamp et al. 1984). Poisonings by ingestion of solutions of H_2S are believed to be extremely rare (Smith 1989). Localized effects can occur to moist membranes such as the eyes and respiratory tract. The following section discusses the asphyxiant and irritant properties of H_2S.

A4. PHYSIOLOGICAL EFFECTS OF ACUTE EXPOSURES

A dose-response relationship has been defined for H_2S (see Table A-1) with ranges that appear to be highly consistent at concentrations above 100 ppm. Factors relevant to the ultimate outcome of health effects include the intensity and duration of the exposure and individual susceptibility (Anderson and Oyama 1987). Accidental exposures to high H_2S levels leading to acute poisoning have been well-characterized although accurate measurements of the gas clouds or dose levels in these incidents are doubtful (Glass 1990; Ammann 1989). The toxic effects of H_2S as an asphyxiant are discussed prior to examining its role as an irritant.

Prolonged exposure at 200 ppm will lead to pulmonary irritation and edema, which allows fluid leakage into the lung (Wasch et al. 1989). The danger of respiratory failure from systemic intoxication increases with the level of concentration. Nearing 500 ppm, systemic symptoms may be present within 1 h or less; at approximately 700 ppm, rapid unconsciousness may be anticipated. Unless the exposure is interrupted and respiration reestablished, respiratory center paralysis and death will follow. At sublethal concentrations (500–1000 ppm), extremely rapid breathing (hyperpnea) is stimulated. This response appears paradoxical because the known mechanism of H_2S toxicity is depression of nervous system function manifested as paralysis of ventilation (Ammann 1986). At concentrations over 1000 ppm, one or two breaths may be sufficient to bring immediate collapse and death. Due to the sudden onset of collapse, unprotected persons may succumb during attempts to rescue others.

Table A.1. Human exposure to hydrogen sulfide

Concentration (ppm)	Generalized effects
0.025–0.2	Detectable odor
10	Threshold limit value-time weighted average for 8-hr workday
15	Threshold limit value-short term exposure limit (15 min)
10–50	Irritative action to eyes
50–100	Irritative action to respiratory tract
150	Olfactory nerve paralysis
150–300	Maximum concentration which can be inhaled for 1 h without serious consequences (National Safety Council 1988)
200–500	Pulmonary edema
500	Systemic symptoms within 0.5–1 h
500–700	Subacute poisoning
700	Rapid unconsciousness, possibly fatal unless rescued
1000	Immediate systemic effects, respiratory paralysis imminent, rapidly fatal

Note: Reported dose-response relationships vary, but not by substantial amounts.

Sources: Beauchamp et al. 1984; Puna EIS 1987; Glass 1990; Goddard and Goddard 1980; Watson and Etnier 1981.

Hydrogen sulfide is considered a noncumulative poison because of its rapid oxidation in the blood to inactive compounds, such as sulfates and thiosulfate, and because of the reversible inhibition of respiratory enzyme systems (Layton, Anspaugh and O'Banion 1981; Waldbott 1978). Similar in toxic action to hydrogen cyanide, H_2S inhibits the enzyme cytochrome oxidase, resulting in cessation of cellular metabolism of oxygen (Wasch et al. 1989; Smith and Gosselin 1979; and NIOSH 1977a). This classical biochemical mechanism of H_2S has been confirmed by various researchers (Schenker 1989). Unlike carbon monoxide, H_2S does not combine with hemoglobin in the blood (Waldbott 1978). In contrast to other commonly encountered gases, H_2S is unique in its ability to halt respiration (Peterson 1991).

Various biological responses are possible with this "broad-spectrum toxicant" (Roth and Hannah 1989). However, pulmonary edema and neurotoxicity appear to be two of the hallmarks. Nervous and cardiac tissues, which have the highest demand for oxygen, are the most sensitive to this toxin (Ammann 1986). Neurophysiological symptoms associated with exposure suggest that the central nervous system (CNS) is the major target organ for H_2S toxicity (Roth and Hannah 1989). However, knowledge of the toxicology pathophysiologic effects of H_2S remains deficient (Green 1989).

Acute effects of the inhalation of sulfur oxides are unlikely at ambient levels due to the atmospheric oxidation of H_2S to sulfur dioxide (SO_2), which subsequently will oxidize to sulfate aerosols (Layton, Anspaugh, and O'Banion 1981). Accidental exposures to relatively high concentrations of H_2S, especially in confined spaces, are not uncommon. Due to the number of attributed fatalities, H_2S is considered to be one of the most hazardous toxic gases in occupational settings (Schenker 1989). Standard occupational safety practices have been developed to provide protection from these occurrences.

Hydrogen sulfide has been linked to mass disaster. One often cited classic case in Poza Rica, Mexico, in 1950 resulted in over 300 persons requiring hospitalization with 22 dying. The disaster was produced by an accidental discharge of H_2S from a natural gas plant for 30 min, combined with a low-level thermal inversion, a heavy fog, and absence of wind. The gas was unable to disperse in the atmosphere. Those who survived reported eye irritation, severe headaches, cough, shortness of breath, loss of sense of smell, nausea, vomiting, unconsciousness, vertigo, difficulty in speaking, and aggravation of epilepsy (Waldbott 1978; McCabe and Clayton 1952).

At a subacute level, systemic H_2S intoxication may produce effects suggestive of neurological damage and gastritis. These effects include headache, dizziness, staggering, excitement, nausea, and diarrhea (NIOSH 1977a). Also, fatigue and changes of personality, intellect, and memory have been identified (NIOSH 1977b). Recovery is usually complete.

A5. IRRITANT EFFECTS FROM H_2S EXPOSURE

At concentrations of 50–500 ppm, H_2S becomes an irritant to the moist membranes of the eye and respiratory tract by forming alkali sulfide in the tissue fluids (NIOSH 1977a). Ruth (1986) reported the threshold of irritation to humans as 14.0 mg/m^3 (10 ppm). Other than reaction to odor, eye irritation is the most common and early complaint associated with human exposure to H_2S. The epithelia of the conjunctiva and cornea become dry and inflamed, producing "sore eye" (Ammann 1986). Eye irritation may occur at prolonged exposures of 10 ppm (Peterson 1991), with serious damage possible at 90 ppm. Damage to the eye may include palpebral edema, bulbar conjunctivitis, keratoconjunctivitis, ocular lesions, and photophobia (NIOSH 1977a).

Direct irritation of the respiratory tract may cause rhinitis, pharyngitis, bronchitis, and pneumonia (NIOSH 1977a). Deep penetration of H_2S into the lungs may lead to diffuse alveolar injury. This injury of the alveolar-capillary membrane involves the more serious pulmonary edema noted in the previous section as well as abnormalities of gas exchange (Green 1989).

A6. PHYSIOLOGICAL EFFECTS OF CHRONIC EXPOSURE

Compared to acute and subacute exposures, scientific investigation of long-term exposure to low levels of H_2S has been insufficient, and experimental data on potential effects are scant (Glass 1990; Wasch et al. 1989; Roth and Hannah 1989; and Schenker 1989). The estimation of health risks from environmental exposures is best accomplished by epidemiologic study using human data (Aldrich and Griffith 1993). However, these data are very difficult to generate in limited exposure situations in which risks are considered to be very low.

Reiffenstein, Warenycia, and Mele (1989) observed that "little experimental data exist for effects of chronic exposure on the CNS." Green (1989) agreed that "it is still not known whether exposure to H_2S has long-term health consequences." Several researchers have contended that health problems are unlikely. Ellis (1977) claimed that the main problem to humans from geothermal H_2S emission is "one of aesthetics." Layton, Anspaugh, and O'Banion (1981) cited the "primary consequence of H_2S is odor annoyance rather than acute effects." Waldbott (1978) indicated that H_2S is "relatively harmless in low concentrations." Beauchamp et al. (1984) stated more specifically that there is "no known consequence to human health up to 30 ppm." Glass (1990) similarly observed that "there is little evidence of persistent or cumulative effects where exposure is kept below 20 ppm."

However, Beauchamp et al. (1984) suggested that if chronic intoxication to H_2S exists, neurasthenic symptoms of a more subjective nature would be involved. These effects would include fatigue, headache, dizziness, irritability, and perhaps nausea. Nausea, insomnia, shortness of breath and headaches have been identified at H_2S concentration levels of 0.30 ppm under conditions of continual exposure (Fluor Technology, Inc. 1987). Chronic exposure of the public to H_2S concentrations as low as 0.10 ppm has been cited as stimulating symptoms such as headache, nausea, sinus congestion, and irritation of the mucous membranes (Anspaugh and Hahn 1979). Roth and Hannah (1989) described H_2S as a mild general depressant at very low concentrations. In addition to those symptoms cited above, Roth and Hannah (1989) listed other neuropsychological symptoms that have been associated with long-term exposure to low levels, including nervousness, anxiety, poor memory, drowsiness, weakness of extremities, convulsions, vertigo, and delirium.

Smith (1989) noted that recent experimental work has suggested the possibility for adverse health effects of long-term, low-level H_2S exposure, but he offered no specifics. One conclusion from in vitro studies by Roth and Hannah (1989) was that low-dose, chronic exposure to H_2S may interfere with the growth of the developing CNS, leading subsequently to abnormal function. The researchers observed that low-level H_2S toxicity is subtle in effect. However, their work suggests the biological plausibility of H_2S impacting the CNS in low-dose concentrations (Schenker 1989).

Respiratory toxicity is also an issue of consideration. Of the common outcomes affecting the lung, variable air flow obstruction is considered to be a likely adverse effect of H_2S exposure (Enarson 1989). However, few epidemiologic studies of lung effects related to H_2S exposures have been conducted; present methodology is limited in attempting to measure changes in functional ability (Enarson 1989).

In addition, the possibility exists that the intrapulmonary antibacterial defense system in humans may be affected by chronic exposure to H_2S (Anderson and Oyama 1987). Given available experimental evidence on the effects of SO_2, Green (1989) inferred that H_2S is likely to have adverse effects on lung defense mechanisms. She noted that H_2S has many similarities to SO_2 and that gases with similar properties are likely to have similar effects. If Green is correct, pulmonary infections may be more easily established in the chronically exposed population.

A7. POPULATIONS EXPOSED TO LOW-LEVEL CONCENTRATIONS OF H_2S

The health experience of Rotorua, New Zealand, is of interest because of decades of known low-level exposure of the population. This geothermal area has natural ambient H_2S of 0.1 to 0.3 ppm more than half of the time (Siegel 1985; Ellis 1977). Siegel examined several respiratory/pulmonary diseases that can arise from exposure to chemical substances. These included pneumonia, chronic bronchitis, emphysema, and bronchopneumonia. Also, he reviewed tuberculosis, which is associated with decline of immunobiological defenses. Siegel concluded that there was no disease correlation with H_2S exposure in the Rotorua urban area, compared with other nonexposed communities in New Zealand.

In a critique of the Siegel study, Anderson (1985) emphasized that the mortality data exclusively used by Siegel were not sufficiently sensitive to detect the probable impacts of low-level H_2S exposure on human health. He indicated that adverse effects with long-term exposure are eye and upper respiratory tract irritation and possible nervous system changes, which would require collection and analysis of morbidity data (Anderson 1985).

An early 1984 health interview survey of residents in Puna, Hawaii, living downwind of a 3-MW geothermal power plant was conducted to examine health status (Anderson and Oyama 1987). The 1-h average level of H_2S did not exceed 0.011 ppm during the year preceding the survey. The researchers found no direct association between H_2S exposure and self-reported acute or chronic respiratory conditions in the exposed community compared to a control group.

A8. NONSPECIFIC SYMPTOMS: INTERPRETATION DIFFICULTIES

Self-reported "symptoms may be the most sensitive measure of effects of low-level chemical exposure" (Lipscomb, Satin, and Neutra 1992). Those in proximity to environmental odor sources may report the acute onset of symptoms at concentration levels near the odor threshold for the substance but clearly below the established thresholds for respiratory irritation or systemic toxicity. Nausea, vomiting, malaise, headache and similar symptoms may result as reflex responses to the odor itself. These effects are difficult to distinguish from toxicity (Raffle, Lee, McCallum, and Murray 1987). Nonspecific symptoms are largely subjective and cannot be rationally explained by classical toxicologic or irritative mechanisms (Shusterman 1992).

Shusterman (1992) postulated that nontoxicologic odor-related mechanisms may offer a more sound basis for explanation of effect. These mechanisms include innate odor aversions, aversive conditioning phenomena, exacerbation of underlying medical conditions (especially bronchial asthma), stress-induced illness, and possible pheromonal reactions.

If the odor source is interpreted by concerned individuals as a health risk, acute stress may be precipitated by the odor (Shusterman 1992). The possible causal role in development of stress-related chronic illnesses remains conjectural at this point.

In an effort to establish symptom prevalence reference rates useful for environmental epidemiologic studies, Lipscomb, Satin, and Neutra (1992) analyzed comparison populations in three community-based survey studies. Their analysis revealed that gender, race, and degree of respondent's environmental concern influence the prevalence of self-reported symptoms. They found that concern over nearby environmental conditions ("environmental worry") was more strongly associated with irritant symptoms (eye and skin irritation) than with stress-related symptoms (sleep disturbances and fatigue).

A9. PROTECTIVE STANDARDS

Eye irritation is considered the "critical effect" or most sensitive endpoint for H_2S exposure. Eye effects were the basis for establishing the occupational threshold limit value (TLV) for H_2S (Ammann 1989). The American Conference of Governmental Industrial Hygienists (ACGIH 1993) adopted TLVs of 10 ppm time-weighted average for a normal 8-h workday and 15 ppm as the short-term exposure limit. The latter TLV is the maximum allowable concentration to which workers can be exposed for a period of up to 15 min. Such short-term exposures must not occur more than four times per day with 60 min between exposure periods. The permissible exposure limit was set by the Occupational Safety and Health Administration (OSHA) at a ceiling limit of 20 ppm. This ceiling threshold should not be exceeded even briefly. The National Institute for Occupational Safety and Health (NIOSH) established 10 ppm for a time-weighted 8-h exposure as the recommended exposure limit. The Standards Completion Program, a joint effort by OSHA and NIOSH, also defined 300 ppm as the immediately dangerous to life or health (IDLH) level relative to respirator selection. In the case of respirator failure, H_2S exposure of 30 min at the IDLH level should not prove eventful (NIOSH 1985).

In addition to standards developed for occupational settings, some states have developed ambient air quality standards. The California standard, based on defining an average annoyance threshold, was set at 30 ppb (0.03 ppm) averaged over a 1-h period.

The Hawaii Department of Health established a statewide H_2S ambient air quality standard in 1992 set at 35 $\mu g/m^3$ (25 ppb) averaged over a 1-h period. The standard also requires that abated H_2S emissions must be less than 5.0 lb/h.

The National Ambient Air Quality Standards (NAAQS) set for the major air pollutants by the U.S. Environmental Protection Agency (EPA) do not address H_2S emissions. The National Emissions Standards set by the EPA for other hazardous pollutants (e.g., asbestos and benzene) also do not identify H_2S as requiring an emission standard (Bingham and Meader 1990).

International standards offer some basis for comparison. New Zealand is of particular interest because natural emissions of H_2S are significantly high in some locales. The New Zealand Department of Health adopted guidelines to assist with policy decisions on air quality. These guidelines established 70 mg/m^3 (50 ppm) as the 1-h mean calculated every 10 min and 7 mg/m^3 (5 ppm) as the 24-h mean. These levels have not been used as measures of compliance.

In 1992, the New Zealand Ministry for the Environment proposed national ambient air quality guidelines. The guideline for H_2S is set to "prevent nuisance to affected communities" (Ministry for the Environment 1992). For those areas with significant natural emissions above the nuisance level (e.g., Rotorua), the guideline seeks to prevent increases in the ambient level and is set at 70 mg/m^3 (50 ppm) using a 1-h averaging time. For other areas unaffected by natural emissions, a second guideline of 7 mg/m^3 (5 ppm) averaged over 1 h is the proposed level. The proposal also recommended that the method of measurement be flame photometry with either a SO_2 scrubber or a gas chromatograph. The New Zealand report (Ministry for the Environment 1992) revealed that Canada has established 15 mg/m^3 (1-h average) and 5 mg/m^3 (24-h mean) as the maximum acceptable but has defined the maximum desirable as 1 mg/m^3 (1-h mean). Also reported is the Netherlands standard of 2.5 mg/m^3 (1-h average).

A10. SUMMARY

The hazards to health associated with acute exposure to H_2S are not scientifically disputable or at major issue in this review. Hydrogen sulfide, classified as both irritant and asphyxiant, is a noncumulative poison which at increasing concentration levels adversely impacts humans by odor annoyance, eye irritation, respiratory irritation, and death from anoxia. In confined areas of extremely high concentrations, death most likely will occur immediately.

Most humans can easily detect the presence of low levels of H_2S by odor and are aware generally of the health consequences of acute exposures. Thus, public perception of risk should be anticipated among those in proximity to potential anthropogenic sources. Persons who have experienced low-level exposures to H_2S have reported a variety of nonspecific symptoms, especially of a neurological nature. The biological plausibility for an impact to the CNS has been suggested by toxicologic studies, but more investigation of low-level H_2S toxicity is warranted.

Preliminary studies suggest that lung function may be altered, especially variable air flow obstruction and the intrapulmonary antibacterial defense system. However, researchers caution that these effects are subtle and extremely difficult to assess. There are unconfirmed beliefs that some persons (e.g., young children, asthmatics, and others with hyperactive airways) will be more susceptible to negative effects. The potential interactions of H_2S with other toxic gases is clearly an area in need of scientific exploration because most ambient situations will involve multiple exposures.

A11. REFERENCES

Ahlborg, G. 1951. "Hydrogen Sulfide Poisoning in Shale Oil Industry," *Archives of Industrial Hygiene and Occupational Medicine* 3, 247–66.

Aldrich, T., and J. Griffith. 1993. *Environmental Epidemiology and Risk Assessment*, Van Nostrand Reinhold, New York.

ACGIH (American Conference of Governmental Industrial Hygienists). 1993. *Threshold Limit Values for Chemical Substances and Physical Agents and Biological Exposure Indices*, Cincinnati.

Ammann, H. M. 1986. "A New Look at Physiologic Respiratory Response to H_2S Poisoning," *Journal of Hazardous Materials* 13(3), 369–74.

Ammann, H. M. 1989. "Health and Exposure Information Relevant to Standard Setting," pp. 15–28 in *Proceedings of International Conference on Hydrogen Sulphide Toxicity*, June 18–21, ed. M. G. Prior et al., Banff, Alberta, Canada.

Amoore, J. E., and E. Hautala. 1983. "Odor as an Aid to Chemical Safety: Odor Thresholds Compared with Threshold Limit Values and Volatilities for 214 Industrial Chemicals in Air and Water Dilution," *Journal of Applied Toxicology* 3(6), 272–90.

Anderson, B. S. 1985. Letter to Leslie Matsubara, Director of Health, State of Hawaii, December 4.

Anderson, B. S., and N. M. Oyama. 1987. *A Study of the Health Status of Residents in Puna, Hawaii Exposed to Low Levels of Hydrogen Sulfide*, R & S Report, Hawaii State Department of Health, Issue 56.

Anspaugh, L. R., and J. L. Hahn. 1979. *Human Health Implications of Geothermal Energy*, Conference Report UCLR-83382, Lawrence Livermore National Laboratory, Livermore, Calif.

Anspaugh, L. R., and J. L. Hahn. 1980. "Human Health Implications of Geothermal Energy," pp. 565–80 in *Health Implications of New Energy Technologies*, ed. W. N. Rom and V. E. Archer, Ann Arbor Science Publishers, Ann Arbor.

Beauchamp, R. O., et al. 1984."A Critical Review of the Literature on Hydrogen Sulfide Toxicity," *CRC Critical Reviews in Toxicology* 3(1), 25–97.

Bingham, E., and W. V. Meader. 1990. "Governmental Regulation of Environmental Hazards in the 1990's," *Annual Review of Public Health* 11, 419–34.

Cain, W. S. 1990. "The Case Against Threshold Measurement of Environmental Odors," *Journal of Air Pollution Control Association* 30, 1295–95.

Coe, B. A. 1991."The State Versus Pele: Structure and Leadership in Geothermal Energy Development," *Environmental Impact Assessment Review* 11, 333–52.

Ellis, A. J. 1977. "Geothermal Fluid Chemistry and Human Health," *Geothermics* 6(3–4), 175–82.

Enarson, D. A. 1989. "Identifying Populations at Risk," pp. 205–9 in *Proceedings of International Conference on Hydrogen Sulphide Toxicity*, June 18–21, ed. M. G. Prior et al., Banff, Alberta, Canada.

Fluor Technology, Inc. 1987. *Puna Environmental Impact Statement*. Puna Geothermal Venture Project, Irvine, Calif.

Glass, D. C. 1990. "A Review of the Health Effects of Hydrogen Sulphide Exposure," *Annals of Occupational Hygiene* 34(3), 323–27.

Goddard, C. B., and W. B. Goddard. 1980. *Effects of H_2S on Humans, Animals, and Vegetation*, Goddard and Goddard Engineering, Calif.

Green, F. H. Y. 1989. "Health Problems Associated with Inhalation of Toxic Gases," pp. 158–69 in *Proceedings of International Conference on Hydrogen Sulphide Toxicity*, June 18–21, ed. M. G. Prior et al., Banff, Alberta, Canada.

Hinds, A., B. Reynolds, and M. Dellinger. 1990. "Working It Out: Geothermal Conflict Resolution in the Geysers," *Geothermal Resources Council Transactions* 14(11), 1141–48.

Layton, D. W., and L. R. Anspaugh. 1981. *Health Impacts of Geothermal Energy*, NTIS DE81023661.

Layton, D. W., L. R. Anspaugh., and K. D. O'Banion. 1981. *Health and Environmental Effects Document on Geothermal Energy: 1981*, NTIS DE82007989.

Lilis, R. 1986. "Diseases Associated with Exposure to Chemical Substances," pp. 617–763 in *Public Health and Preventive Medicine*, 12th ed., ed. John M. Last, Appleton-Century-Crofts, Conn.

Lipscomb, J. A., K. P. Satin., and R. R. Neutra. 1992. "Reported Symptom Prevalence Rates from Comparison Populations in Community-Based Environmental Studies," *Archives of Environmental Health* 47(4), 263–69.

McCabe, L. C., and C. D. Clayton. 1952. "Air Pollution by Hydrogen Sulfide in Poza Rica, Mexico: An Evaluation of the Incident of November 24, 1950," *Archives of Industrial Hygiene* 6, 199–213.

McLarty, L., and M. J. Reed. 1992. "The U.S. Geothermal Industry: Three Decades of Growth," *Energy Sources* 14(4), 443–55.

Milby, T. H. 1962. "Hydrogen Sulfide Intoxication—Review of the Literature and Report of Unusual Accident Resulting in Two Cases of Non-fatal Poisoning," *Journal of Occupational Medicine* 4, 431–37.

Ministry for the Environment. 1992. *Air Quality Guidelines: A Discussion Paper on Proposed Ambient Air Quality Guidelines for New Zealand*, New Zealand.

National Safety Council. 1988. *Fundamentals of Industrial Hygiene*, 3rd ed., ed. Barbara A. Plog, National Safety Council, Chicago.

NIOSH (National Institute for Occupational Safety and Health). 1977a. *Criteria for a Recommended Standard: Occupational Exposure to Hydrogen Sulfide*, U.S. Department of Health, Education, and Welfare, Center for Disease Control, Cincinnati.

NIOSH (National Institute for Occupational Safety and Health). 1977b. *Occupational Diseases: A Guide to Their Recognition*, U.S. Department of Health, Education, and Welfare, Center for Disease Control, Cincinnati.

NIOSH (National Institute for Occupational Safety and Health). 1985. *Pocket Guide to Chemical Hazards*, U.S. Department of Health and Human Services, Centers for Disease Control, Cincinnati.

Peterson, J. E. 1991. *Industrial Health*, 2nd ed., American Conference of Governmental Industrial Hygienists, Cincinnati.

Raffle, P. A. B., W. R. Lee, R. I. McCallum, and R. Murray, eds. 1987. *Hunter's Diseases of Occupations*, Little, Brown, Boston.

Reiffenstein, R. J., M. W. Warenycia, and F. G. Mele. 1989. "Sulphide Selectively Alters Rat Brain Aminoacids," Paper presented at International Conference on Hydrogen Sulphide Toxicity, Banff, Alberta, Canada, June 18–21.

Roth, S. H., and R. S. Hannah. 1989. "The Neurophysiological Effects of Low Concentrations of Hydrogen Sulphide on the Developing and Mature Nervous Systems," pp. 139–156 in *Proceedings of International Conference on Hydrogen Sulphide Toxicity*, June 18–21, ed. M. G. Prior et al., Banff, Alberta, Canada.

Ruth, J. H. 1986. "Odor Thresholds and Irritation Levels of Several Chemical Substances: A Review," *American Industrial Hygiene Association Journal* 47, 142–151, March.

Schenker, M. 1989. "'Quo Vadis?' Summary of the International Conference on Hydrogen Sulphide Toxicity," pp. 221–28 in *Proceedings of International Conference on Hydrogen Sulphide Toxicity*, June 18–21, ed. M. G. Prior et al., Banff, Alberta, Canada.

Shusterman, D. 1992. "Critical Review: The Health Significance of Environmental Odor Pollution," *Archives of Environmental Health* 47(1), 76–87.

Siegel, S. M. 1985. *Hydrogen Sulfide and Health*, Final Report, prepared for Hawaii Natural Energy Institute and Hawaiian Electric Industries, Honolulu.

Siegel, S. M., and B. Z. Siegel. 1984. "Geothermal Hydrogen Sulfide and Health in Rotorua, New Zealand," NTIS DE85901283.

Smith, R. P. 1989. "Hydrogen Sulphide: Overview, History, Theories and Unknowns," pp. 1–13 in *Proceedings of International Conference on Hydrogen Sulphide Toxicity*, June 18–21, ed. M. G. Prior et al., Banff, Alberta, Canada.

Smith, R. P., and R. E. Gosselin. 1979. "Hydrogen Sulfide Poisoning," *Journal of Occupational Medicine* 21, 93–97.

Waldbott, G. L. 1978. *Health Effects of Environmental Pollutants*, 2nd ed., C. V. Mosby Co., Saint Louis.

Wasch, H. H., et al. 1989. "Prolongation of the P-300 Latency Associated with Hydrogen Sulfide Exposure," *Archives of Neurology* 46, 902–4.

Watson, A. P., and E. L. Etnier. 1981. "Health and Safety Implications of Alternative Energy Technologies, I: Geothermal and Biomass," *Environmental Management* 5(4), 313–27.

[blank page]

ORNL/TM-12861

INTERNAL DISTRIBUTION

1. T. J. Blasing
2. G. E. Courville
3. C. E. Easterly
4. F. M. Glenn
5. D. A. Lombardi
6. C. H. Petrich
7. H. D. Quarles, III
8-17. R. M. Reed
18. D. E. Reichle
19. J. W. Saulsbury
20. A. C. Schaffhauser
21. S. M. Schexnayder
22. R. B. Shelton
23. B. M. Sorensen
24. W. P. Staub
25. V. R. Tolbert
26. A. K. Wolfe
27-28. Laboratory Records
29. Laboratory Records-RC
30. Document Reference Section
31. Central Research Library
32. ORNL Patent Section

EXTERNAL DISTRIBUTION

33. Office of the Assistant Manager for Energy Research and Development, Department of Energy, Oak Ridge Operations, P. O. Box 2001, Oak Ridge, TN 37831
34. Andrea Campbell, Department of Energy, Oak Ridge Operations, Bldg. 2714-J, SE-311, Oak Ridge, TN 37831-8739
35. Virginia H. Goldstein, Director, Hawaii County Planning Commission, 25 Aupuni Street, Room 109, Hilo, HI 96721
36. Charles B. Hamilton, 9023 Fox Lonas Road, Knoxville, TN 37923
37. Hugo Huntzinger, Superintendent, Hawaii Volcanoes National Park, P. O. Box 52, Hawaii Volcanoes National Park, HI 96718-0052
38. Maurice H. Kaya, Energy Program Administrator, Department of Business, Economic Development & Tourism, 335 Merchant Street, Suite 108, Honolulu, HI 96813
39. Allan J. Jelacic, Office of Renewable Energy Conversion (EE-12), U.S. Department of Energy, Forrestal Building, 1000 Independence Ave. SW, Washington, DC 20585
40-44. Roland R. Kessler, Director, Office of Renewable Energy Conversion (EE-12), U.S. Department of Energy, Forrestal Building, 1000 Independence Ave. SW, Washington, DC 20585
45. Mike Lee, Chief, Operations Division, Honolulu Engineer District, Building 230, Fort Shafter, HI 96858-5440
46. John Naughton, Pacific Area Office, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, 2570 Dole Street, Honolulu, HI 96822-2396
47. Manuel Nathenson, U.S. Geological Survey, Geologic Division, Branch of Volcanic and Geothermal Processes, 345 Middlefield Road, M/S 910, Menlo Park, CA 94025
48. Robert Smith, Director, Pacific Island Office, U.S. Fish and Wildlife Service, Prince Kuhio Building, Room 6307, 300 Ala Moana Boulevard, Honolulu, HI 96850
49-53. Judith C. Stroud, ER-10, Department of Energy, Oak Ridge Operations Office, P. O. Box 2001, Oak Ridge, TN 37831-6600
54. Carl C. Trettin, Center for Forested Wetland Research, Southeastern Forest Experiment Station, 2730 Savannah Highway, Charleston, SC 29414
55. Lillian D. Trettin, 712 Wakendaw Blvd., Mount Pleasant, South Carolina 29464
56-57. Office of Scientific and Technical Information, P. O. Box 62, Oak Ridge, TN 37831