Research and Development

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Research and Development

Summary of Environmental Mercury Concentrations and Assessment of Risk to Public Health from Mercury at the Geysers

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EXECUTIVE SUMMARY

Ambient mercury data were investigated in relation to the environment and public health at and near the vicinity of The Geysers, California. Mercury was found to occur naturally in the environment (air, water, soil, etc.) and as a result of industrial activities, although the exact contribution of each source could not be determined. Ambient air concentrations ranged from non-detectable to 630 ng/m^3. Concentrations in ambient waters ranged from non-detectable to 2.9 $\mu g/l$; the highest value exceeds all water quality criteria for the protection of health and is 30% below the level set to protect freshwater organisms from acute toxicity. Little data are available on concentrations of mercury in fish; however, the existing data suggest that some fish may be bioconcentrating the mercury. Reported data for mercury in fish were above applicable health standards (for food) in most cases. Soil mercury levels ranged from less than the detection limit to 11 $\mu g/g$. Mercury was not detected in small animals, and low and relatively insignificant mercury concentrations were found in bulk atmospheric deposition samples and in foliage.

Because total human exposure data in or near The Geysers area are not available, the above environmental data were compiled and used to assess the worst-case potential risk to public health as a result of mercury emissions (natural and industrial) at The Geysers.

The results of this study show that the highest mercury exposure to humans occurs from ingesting inorganic mercury in food. The concentrations of mercury in food are not expected to be impacted by activities at The Geysers. Under normal conditions, mercury in food accounts for approximately 99% of the total exposure to mercury.

Regardless of the route of exposure (air, water, or food), the daily total exposure of mercury to the public living at The Geysers is predicted to be 28 $\mu g/day$. According to the EPA, national average mercury exposures are

approximately 25 μg/day. It is very unlikely that any public health effects would occur since exposures of 200 μg/day of methyl mercury are necessary for toxic response to be noticeable.

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INTRODUCTION

Use of natural ore deposits and geothermal energy (steam) at The Geysers, California, has contributed to the amount of various naturally occurring environmental pollutants, including mercury. Cinnabar ore, a commercial source of mercury, was first mined in this region in 1861. Production declined and eventually ceased by about 1944. However, the mine tailings and various production facilities are obvious reminders of the once prosperous industry. Today, the same hydrothermal processes that resulted in the ore deposition are being used for energy production. Steam is being used to generate electricity, most of which contains varying trace concentrations of mercury.

This report has two objectives: to briefly summarize the existing data on environmental (air, water, vegetation, soil, etc.) mercury concentrations at The Geysers and to discuss the potential health effects from mercury exposure, with a particular emphasis on chronic exposure to the public. Correspondingly, this report is organized into two parts. The first presents the results of existing environmental mercury data and the second discusses the potential impact on public health. Occupational exposures are not discussed.

BACKGROUND

CHEMICAL AND PHYSICAL PROPERTIES

Many of mercury's environmental and health concerns stem from its unique chemical and physical properties. Mercury occurs in three oxidation states: elemental (0), mercurous (+1), and mercuric (+2). Mercurous mercury is unstable and readily reacts to form mercuric and/or elemental mercury. Elemental mercury is one of the heaviest metals and has a specific gravity of 13.5 and an atomic weight of 200.59. It is the only metal liquid at ordinary room temperatures and has a relatively high vapor pressure of 0.0019 mm of mercury at 25 degrees Celsius. A saturated atmosphere at room temperature contains elemental mercury vapor at a concentration of approximately 20 mg/m^3.

Elemental mercury is also soluble in both polar and nonpolar organic solvents. These properties make elemental mercury vapor a particular health concern because in the gas phase it can penetrate deep into the respiratory tract and be easily absorbed through the lungs and distributed throughout the body.

Mercuric mercury can occur either as inorganic or organic compounds. The most commonly occurring inorganic mercury compounds at The Geysers are cinnabar (HgS) and mercuric chloride ($HgCl_2$). Hydrothermal solutions, such as incoming steam or cooling tower condensate, contain pH and temperature dependent soluble forms of the sulfides of mercury. Under normal conditions at the Geysers (steam, air condensate, etc.) or in the troposphere, mercuric sulfide is insoluble and relatively unavailable for biological assimilation. Organic forms such as methyl or dimethyl mercury may occur at The Geysers, but the presence of sulfur, which readily reacts with mercury to form mercuric sulfide, makes the existence of organic mercury unlikely. The organic forms are highly soluble in biological membranes and are, consequently, the most toxic.

Review of environmental mercury data in the sections to follow will reveal that while a significant number of studies have been conducted at The Geysers measuring mercury in the environment, these measurements have generally been for total mercury. Virtually no measurements have been performed that define the relative amounts of organic and inorganic mercury. In addition, except for the air sampling for elemental mercury vapor, no speciation measurements have been made. Unless otherwise noted, reference to mercury measurements in the following sections of the report refer to total mercury.

MERCURY MINES AND ORE DEPOSITS

The Geysers, located within the Mayacamas quicksilver (mercury ore) district, was the second most productive quicksilver district in California. Ore bodies occur where cinnabar and/or elemental mercury were deposited from hydrothermal solutions rising through major geologic shear zones (Varekamp and Buseck 1984). Figure 1 shows the locations of the primary known mercury mines and ore deposits and their relation to PG&E's operating geothermal power plants.

HYDROTHERMAL TRANSPORT

The presense of mercury vapor in geothermal emissions suggests that elemental mercury is present in the liquid phase of geothermal systems. Concentrations of mercury in deep hydrothermal reservoirs are increased because of the increased temperature and pH, and decreased oxygen concentrations. In such reservoirs, soluble elemental mercury is many orders of magnitude more abundant than mercuric compounds. As the mercury-containing solution approaches the surface, it mixes with cool, oxygenated water. Most volatilizes as elemental mercury, and due to the decreased pH and temperature and increased oxygen, the remainder combines with sulfur and precipitates as HgS (Finlayson 1977; Robertson 1977; Varekamp and Buseck 1984).

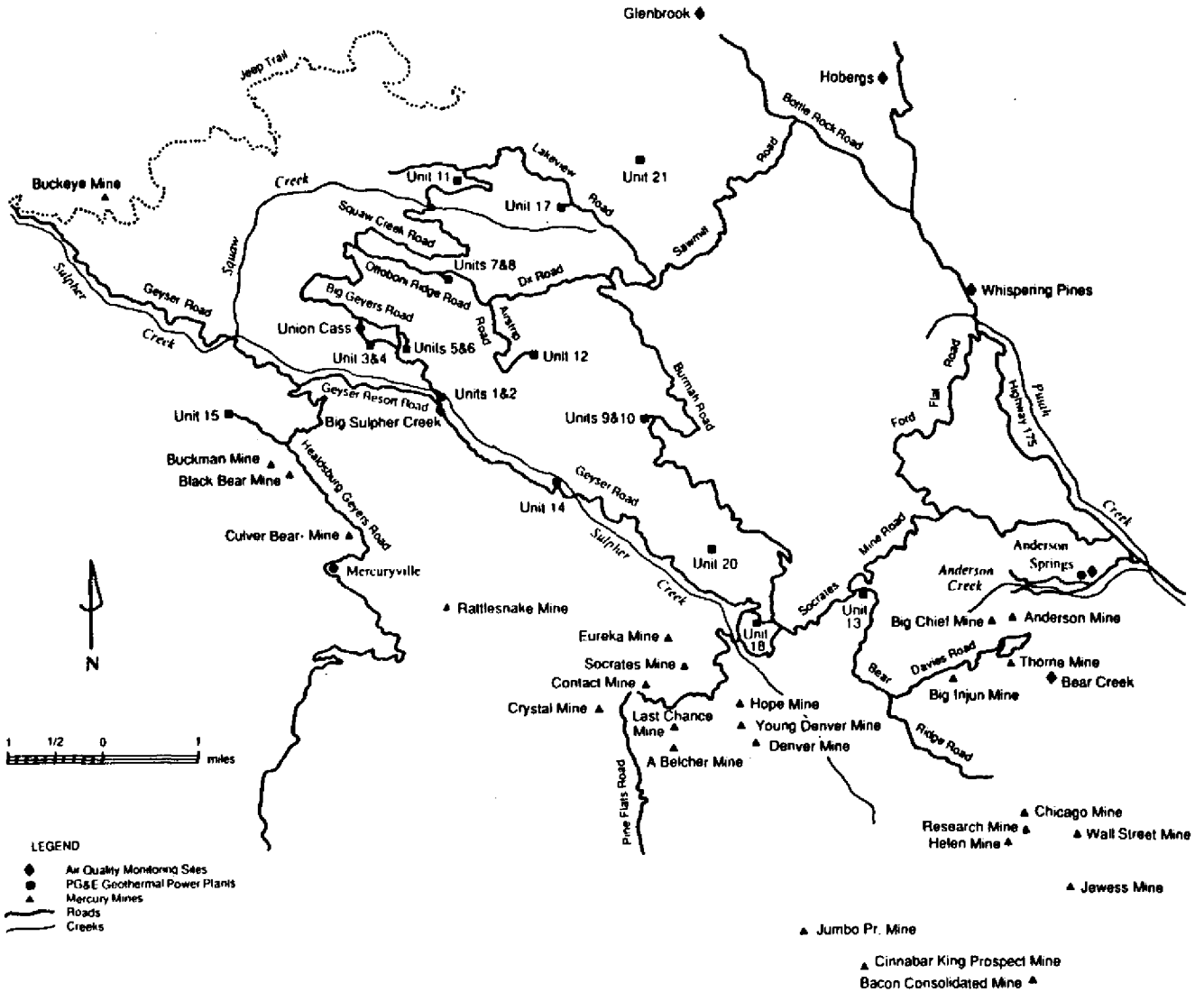

FIGURE 1. Mercury Mines in The Geysers Vicinity

STANDARDS

Current applicable environmental and occupational standards for mercury are summarized in Table 1. The Enviornmental Protection Agency (EPA) has established an ambient air standard of 1.0 $\mu g/m^3$ (30-day average), which takes into consideration the impact of the airborne burden in conjunction with water and food burdens. The World Health Organization (WHO) recommends an ambient limit of 0.8 $\mu g/m^3$ (WHO, 1976). Occupational standards recommended by the American Conference of Governmental Industrial Hygienists (ACGIH) and adapted by the Federal Occupational Safety and Health Administration (Fed OSHA) are included for comparison. The ACGIH has set the 8-hour time-weighted average for a 40-hour work week at 0.05 mg/m^3 in air and Fed OSHA uses a ceiling limit of 0.1 mg/m^3. No excursions are permitted above that level (ACGIH 1984-85, Fed OSHA 1984). Standards for mercury air emissions have also been established by the EPA through the National Emission Standards for Hazardous Air Pollutant (NESHAP). The standard of 2300 g/day applies to emissions of mercury from mercury-cell chlor-alkali plants, sludge incineration and drying plants, and mercury ore processing facilities (EPA 1984).

Criteria for the determination of a substance as hazardous waste have been set within Title 22 of the California Administrative Code. Substances with mercury levels exceeding 0.2 mg/l soluble threshold limit concentration (STLC) in water and 20 mg/kg total threshold limit concentration (TTLC) in waste are designated as hazardous waste. Wastes with concentrations exceeding 2,000 mg/kg are designated an extremely hazardous waste (California Department of Health Services 1984).

The EPA water criterion for protection of freshwater organisms is 0.2 $\mu g/l$ for an average 24-hour exposure, with a maximum exposure limit of 4.1 $\mu g/l$.

The human health water based criterion is 0.144 $\mu g/l$. This ambient water quality criterion includes a biomagnification factor of 10 based on ingestion of 18.7 g/day of mercury-contaminated aquatic organisms and 2 liters of water containing mercury at the criterion level (EPA 1980).

Table 1

APPLICABLE MERCURY STANDARDS

MEDIUM	TYPE OF EXPOSURE/EMISSION	TYPE OF MERCURY	MAXIMUM CONCENTRATION		TIME PERIOD
AIR	occupational (ACGIH)	vapor	0.05	mg/m^3	8-hr
		alkyl	0.01	mg/m^3	8-hr
		alkyl	0.03	mg/m^3	STEL
		aryl or inorganic	0.1	mg/m^3	8-hr
	occupational (Fed OSHA)	inorganic	0.1	mg/m^3	ceiling
	ambient (EPA)	total	1.0	$\mu g/m^3$	30 day avg.
	ambient (WHO)	total	0.8	$\mu g/m^3$	24-hr avg.
	emission (NESHAP)	vapor	2300	g/day	24-hr
WATER	hazardous waste (DHS)	elemental	0.2	mg/l	STLC
	drinking water (DHS)	total	2	$\mu g/l$	n/a
	human health (EPA)	total	0.144	$\mu g/l$	n/a
	chronic toxicity (EPA-freshwater life)	total	0.2	$\mu g/l$	24-hr
	acute toxicity (EPA-freshwater life)	total	4.1	$\mu g/l$	maximum
SOIL	hazardous waste (DHS)	elemental	20	mg/kg	TTLC
	extremely hazardous waste (DHS)	elemental	>2000	mg/kg	TTLC
FOOD	in fish (FDA)	total in fish	1.0	ppm	n/a
	all food (WHO)	total	0.3	mg	weekly intake
		methyl-mercury	0.2	mg	

STLC = Soluble Threshold Limit Concentration
TTLC = Total Threshold Limit Concentration
STEL = Short Term Exposure Limit

The California Department of Health Services (DHS) has established the safe level for mercury in drinking water at 2 μg/l (DHS 1977).

The Food and Drug Administration has adopted a guideline of 1.0 ppm for mercury (total) in fish (EPA 1976). WHO has set limits for weekly intake (ingestion) of total mercury at 0.3 mg and of methyl-mercury at 0.2 mg (WHO 1976).

MONITORING RESULTS

POWER PLANT EMISSION STUDIES

Knowledge of mercury concentrations within geothermal power plants is valuable for several reasons. Mercury originating from geothermal steam utilization may contribute to environmental and/or occupational contamination. Either exposure could pose a direct threat to the public or to employee health and safety or could be an indirect threat through improper disposal of hazardous waste. Data are available on mercury emission concentrations from Units 3, 4, 7, 8, 11, 12, 13, 15, 17, and 18. These studies have mostly been conducted by PG&E and by Pacific Northwest Laboratories (PNL). A synopsis of the data is presented below. For more information, the reader is referred to the list of pertinent literature cited in Appendix A.

Concentrations In Steam

Concentrations of mercury in steam at The Geysers are highly variable between the various operating units. For example, the PG&E applications for certification of Units 20 and 21 report incoming steam concentrations of 0.08 ppb and 4 ppb, respectively (PG&E 1983, PG&E 1984b). Mercury levels in noncondensable gases from an average of 61 producing wells located at The Geysers varied from 0.00031 to 0.018 ppm (PG&E 1974).

Power plant studies, primarily those conducted by PNL, indicate that cooling tower exhaust is the most significant release pathway for mercury. As stated in the PG&E Geysers Unit 20 AFC (page 5-22), Robertson of PNL estimated that about 50 percent of the mercury in the incoming steam remains in the condensate and 50 percent remains with the non-condensible gases. The mercury in the condensate goes to the cooling tower, where approximately 50 to 80 percent is volatilized into the atmosphere. In units equipped with a Stretford system, the mercury remaining with the non-condensible gases is scrubbed out and none is emitted to the atmosphere. In units not equipped with a Stretford system, the fate of mercury in the non-condensible gases is not known. Mercury levels in the noncondensable gases have reached as high as 5,800 ng/l. Mercury levels in cooling tower exhaust, however, are lower

by a factor of two to three orders of magnitude because of the extremely large dilution with ambient air (Robertson 1977).

Waste Stream Characteristics

Although the concentrations of mercury entering the plant through the geothermal steam are considered trace, the large quantities of steam that flow through the turbine can result in measureable quantities of mercury being deposited in the pipes, valves, and condensate. Because approximately one-third to one-half of the mercury entering the plant remains in a condensable form, measureable levels of mercury are concentrated within the cooling tower sludge.

Mercury sampled from various waste streams occassionally exceed the hazardous waste standards in Stretford froth, Stretford sulfur cake, LO-CAT system sulfur, cooling tower sludge, spilled or contaminated Stretford solution, cooling tower end dump sludge, and contaminated debris (Table 2). End dump sludge is the sulfur sludge that is separated by filtration from the reinjected cooling tower water. Concentrations of mercury ranged from below the detection limit to values that are occasionally above the hazardous waste threshold concentration values. As a result, hazardous wastes containing mercury are transported to offsite disposal facilities in accordance with state and federal regulations.

Speciation

Mercury is present in the incoming steam predominantly in the vapor state, and approximately one-half to two-thirds of the mercury remains as a noncondensable vapor. Robertson (1977) indicated that the total mercury concentrations of incoming steam were 72 to 84% elemental mercury, <16 to 22% mercuric mercury, and <4% organic mercury.

Condensed mercury exists as a soluble sulfide species, a colloidal, or a molecular mercury sulfide (Robertson 1977). Varekamp (1984) reports that the speciation of mercury is dependent on temperature and pH. $Hg(HS)_2$ is dominant below a pH of 6, $HgS_2(2-)$ is dominant in the pH range above 8, and $Hg(HS)_3(1-)$ is dominant between pH 6 to 8. PG&E's studies of cooling

Table 2

COMMONLY FOUND MERCURY LEVELS IN GEOTHERMAL WASTE STREAMS

SAMPLE TYPE	SOLUBLE CONCENTRATION (mg/l)	TOTAL CONCENTRATION (mg/kg)
Stretford froth	<0.1	<10
Stretford solid sulfur	<0.1	<10
Stretford solution	<0.0	<10
Cooling tower sludge	<0.1	0-100 ***
End dump slurry	<0.1	44 ***
Contaminated debris ##	<0.1-1.0	20-200 ***
Sand blast residue	<0.1	<20
Sulfur Cake	<0.1	20-100 ***
Lo-Cat Sulfur	<0.1	50-100 ***

*** Exceeds the applicable hazardous waste standard.

COMMON Hg LEVELS
From Waste Profile Sheets

Solution	<0.1	<10
Froth	<0.1	<10
Cake	<0.1	0-100 (30's commonly)
Solid S°	<0.1	<10
CTS	<0.1	0-100
Lo-Cat Sulfur	<0.1	50-100

(VJGill 9-13-88)

tower condensate also reveal detectable mercury concentrations only in the soluble fraction (Table 2).

ATMOSPHERIC CONCENTRATIONS

Elemental mercury is readily emitted to the atmosphere because of its relatively high vapor pressure. It is generally assumed that the predominant form of mercury in the air is mercury vapor. However, chlorides of mercury vapors, organomercury compounds (generally unstable), and particulate bound mercury are also known to exist (Schroeder 1982). The EPA's mercury health risk assessment estimates atmospheric mercury to exist as 60% vapor, 19% inorganic ionic mercury, and 17% methyl mercury compounds (Johnson and Braman 1974). However, as stated by the EPA (1984), "it should be noted at this point that the data of Johnson and Braman are specific to the Tampa Bay area and should only be applied to other circumstances with caution until corroborating data are obtained." Deposition occurs by dry deposition, rainfall, and snowfall. Ferrara et al. (1986) reported a 20% decrease in gaseous atmospheric mercury immediately following a rain storm, indicating that washout by rain is only slightly efficient in removing mercury vapor from the air. The exact mode of transport and fate of atmospheric mercury, however, are poorly understood (Robertson 1977).

Many studies on gaseous atmospheric mercury have been conducted at The Geysers, but not all are definitive. The reliability and accuracy of the methods used are often questionable. Ambient air mercury measurements taken by PNL beyond the immediate vicinity of The Geysers were generally below the detection limit of 1 ng/m^3 but ranged from <1 to 18 ng/m^3 (Robertson 1977). Work performed for the EPA reported levels of 200 to 800 ng/m^3 at The Geysers within the geothermally developed area with a peak value of 28,100 ng/m^3 in the vicinity of a mercury mine (EPA 1978, McCarthy et al. 1970). These data were never verified or confirmed. The U.S. Geological Survey reports mercury concentrations over mercury mines ranging from 24 to 108 ng/m^3 (McCarthy et al. 1970). Other technical reviews on atmospheric mercury levels suggest the average concentration throughout the world to be 20 ng/m^3 (WHO 1976, EPA 1984). Jernelöv et al. (1983) concluded, however,

that background levels in the Northern Hemisphere are about 2 ng/m^3. The EPA assumed the atmospheric level of total mercury to be 10 ng/m^3 for its most recent assessment of mercury health effects (EPA 1984).

Ambient mercury vapor and particulate phase mercury have been measured by PG&E independently and as a participant of the Geysers Air Monitoring Program (GAMP) consortium. These measurements were made using state-of-the-art procedures and are believed to be the most valid. Vapor concentrations were measured by hourly and 24-hour intervals. Respirable particulate mercury was measured on a 24-hour basis. These data are summarized in Tables 3a, 3b, 3c, 4, and 5, and are contained in their entirety in Arcado and Lin (1983a, 1983b, 1984a, 1984b, 1984c) and Arcado (1986, 1987a and 1987b). Mercury vapor measurements began in 1982 as part of a PG&E compliance monitoring program for PG&E Unit 18. In 1983-1984, this program evolved into GAMP and monitoring was again initiated. Monitoring was initiated in 1986 (independent of GAMP) for this report at six sites: Hobergs, Glenbrook, Anderson Springs, Big Sulphur Creek, and Union Chemical Abatement Storage Shed (CASS), and Bear Creek. The first three sites (Hobergs, Glenbrook, and Anderson Springs) are within populated areas downwind of The Geysers. The 1986 program was more intensive, with site locations designated to distinguish between natural and anthropogenic emission sources (e.g., mines and power plants).

Mercury Vapor

During the 1982 pre-GAMP monitoring period, 24-hour mercury vapor was measured every sixth day at Anderson Springs and Whispering Pines from August to October and June to October, respectively. The high value was 12.1 ng/m^3 (Table 3a). Hourly mercury vapor concentrations were not measured during 1982 at either site.

From August through November 1983, mercury vapor concentrations were significantly higher than those obtained during the remainder of the study. Beyond November 1983 and throughout the remainder of the study period, only rare occurrences of values significantly exceeding the detection limits were

Table 3a

PG&E MONITORING OF 24-HOUR
AMBIENT MERCURY VAPOR CONCENTRATIONS (ng/m^3)
1982

	MONTHLY					
	HIGH	LOW	AVERAGE	HIGH	LOW	AVERAGE
	ANDERSON SPRINGS			WHISPERING PINES		
1982						
JUN				N/A	N/A	6.8*
JUL				12.1	3.2	6.3
AUG	5.5	3.2	4.0	7.0	2.7	4.7
SEP	6.4	1.5	4.1	4.5	3.6	4.3
OCT	6.4	2.3	3.4	3.8	2.3	3.0

(Arcado and Lin, 1983a)

detection limit: 4 ng
N/A = not available
* one sample

Table 3b

PG&E MONITORING OF 24-HOUR
AMBIENT MERCURY VAPOR CONCENTRATIONS (ng/m^3)
1983-1984

	MONTHLY								
	HIGH	LOW	AVERAGE	HIGH	LOW	AVERAGE	HIGH	LOW	AVERAGE
	ANDERSON SPRINGS			GLENBROOK			HOBERGS		
1983									
JUL***	11.1	N/A	11.1*	226.2	41.6	131.2			
AUG***	92.4	12.6	46.6	273.1	31.5	104.1			
SEP***	28.3	17.1	20.9	43.5	21.6	29.7			
OCT***	55.4	15.1	28.9	41.6	19.0	27.7			
NOV***	165.5	4.8	63.0	25.5	4.6	17.2			
DEC	2.0	N/D	2.5	9.1	1.9	5.1			
1984									
JAN	4.0	1.6	3.0	6.6	3.2	4.6			
FEB	3.9	2.2	3.2	4.9	3.2	4.2			
MAR	3.0	1.7	2.5	3.9	0.4	2.2	1.7	0.2	0.9
APR	13.9	2.2	4.8	2.2	0.5	1.7	3.1	N/D	1.2
MAY	3.6	N/D	1.3	2.3	N/D	1.3	1.6	N/D	0.8
JUN	3.6	N/D	2.4	4.8	N/D	3.1	1.8	1.1	1.5
JUL	16.6	1.0	6.4	3.1	2.5	2.9	3.9	1.3	2.3
AUG	16.2	N/D	5.5	3.2	2.1	2.5	3.1	2.9	3.0**
SEP	12.4	3.7	6.4	3.5	2.0	2.7			
OCT	4.0	2.7	3.3	8.2	1.7	3.3			

(Arcado and Lin 1983b, 1984a, 1984b, 1984c)

detection limit: 4 ng
* one sample
** two samples
*** questionable data; see text
N/A = not available
N/D = not detectable

Table 3c
PG&E MONITORING OF 24-HOUR
AMBIENT MERCURY VAPOR CONCENTRATIONS (ng/m^3)
1986

	MONTHLY AVERAGE (low-high)					
	HOBERGS	GLENBROOK	ANDERSON SPRINGS	BIG SULPHUR CREEK	UNION CASS	BEAR CREEK
JUN	2.1 (2.6-1.4)	6.1 (4.3-7.9)	5.5 (4.0-7.0)	9.5 (7.8-11.2)	10.5 (7.8-13.3)	N/A
JUL	3.9 (4.8-3.0)	6.5 (4.9-9.3)	9.4 (6.3-11.9)	8.4 (5.5-13.7)	9.5 (5.6-13.1)	6.8 (6.0-7.5)
AUG	2.7 (3.7-2.1)	5.7 (3.9-7.8)	4.5 (3.5-5.7)	8.2 (4.8-11.51)	10.9 (5.5-17.3)	4.7 (3.2-6.6)
SEP	6.5 (1.9-23.6)	5.1 (4.3-6.3)	4.2 (3.4-6.8)	6.4 (4.7-8.0)	6.3 (4.1-10.0)	3.9 (3.2-4.8)
OCT	2.6 (1.5-4.0)	4.1 (3.8-4.3)	3.2 (2.6-3.9)	4.8 (3.8-6.9)	9.2 (7.5-12.3)	3.5 (1.8-4.2)
NOV	2.6 (1.1-4.1)	7.3 (4.0-16.0)	4.7 (7.6-5.0)	6.7 (4.4-9.7)	6.4 (4.4-8.8)	5.8 (2.7-13.8)
DEC	2.5 (1.7-3.7)	4.7 (4.2-5.1)	3.6 ** (3.5-3.6)	4.5 (3.8-4.9)	5.7 (3.9-6.6)	4.3 (2.9-5.4)

SAMPLING PERIOD AVERAGE = 5.8

(Arcado 1986, 1987a, 1987b)

detection limit: 4 ng
N/A = not available
** two samples taken

Table 4

PG&E MONITORING OF HOURLY
AMBIENT MERCURY VAPOR CONCENTRATIONS (ppt)

	ANDERSON SPRINGS			GLEN BROOK		
	MONTHLY					
	HIGH	LOW	AVERAGE**	HIGH	LOW	AVERAGE
1983						
AUG*	52	N/D	5.9	48	N/D	10.9
SEP*	70	N/D	0.4	43	N/D	11.1
OCT*	33	N/D	0.5	21	N/D	0.1
NOV*	44	N/D	4.0	N/D	N/D	N/D
DEC	N/D	N/D	N/D	N/D	N/D	N/D
1984						
JAN	43	N/D	0.1	N/D	N/D	N/D
FEB	N/D	N/D	N/D	N/D	N/D	N/D
MAR	N/D	N/D	N/D	N/D	N/D	N/D
APR	N/D	N/D	N/D	N/D	N/D	N/D
MAY	N/D	N/D	N/D	29	N/D	0.1
JUN	25	N/D	0.1	N/D	N/D	N/D
JUL	N/D	N/D	N/D	N/D	N/D	N/D
1986						
JUL	N/D	N/D	N/D	N/D	N/D	N/D
AUG	N/D	N/D	N/D	N/D	N/D	N/D
SEP	12	N/D	N/D	N/D	N/D	N/D
OCT	25	N/D	0.1	12	N/D	N/D
NOV	N/D	N/D	N/D	N/D	N/D	N/D
DEC	N/D	N/D	N/D	N/D	N/D	N/D
1987						
JAN	10	N/D	N/D	N/D	N/D	N/D
FEB	N/D	N/D	N/D	N/D	N/D	N/D
MAR	18	N/D	N/D	N/D	N/D	N/D
APR	N/D	N/D	N/D	N/D	N/D	N/D

(Arcado and Lin 1983b and 1984a, 1984b, 1984c; Arcado 1986, 1987a, 1987b)

N/D = not detectable or below 90 ng/m^3
1 ppt = 8.9 ng/m^3
* questionable data; see text
** average of hourly measurements; note poor agreement with 24-hour samples because of differing detection limits

Table 5

GAMP RESPIRABLE SUSPENDED PARTICULATE
MERCURY CONCENTRATIONS ($\mu g/m^3$)

MONTHLY MAXIMUM - FINE/COARSE PARTICLES		
1982	ANDERSON SPRINGS*	WHISPERING PINES
JUL	N/A	0/.003
AUG	<.005	<.005/<.005
SEP	<.005	<.005/<.005
OCT	0	<.005/<.005
1983	ANDERSON SPRINGS	GLENBROOK
AUG	0/.001	.001/.002
SEP	.003/.001	.001/0
OCT	0/.002	0/.001
NOV	.001/0	.001/.003
DEC	.003/0	0/.001
1984	ANDERSON SPRINGS	GLENBROOK
JAN	0/.001	.001/.001
FEB	.001/0	.001/0
MAR	.001/.004	.002/0
APR	.001/.002	.003/.008
MAY	.005/.005	.003/.003
JUN	.001/.003	.002/.001
JUL	.003/.001	.004/002
1986	ANDERSON SPRINGS	GLENBROOK
JUL	.002/.001	.001/.001
AUG	.002/0	0/0
SEP	.002/.002	.002/.001
OCT	.003/.001	.001/.007

(Arcado and Lin 1983a, 1983b, 1984a, 1984b, 1984c; Arcado 1986)

detection limit = 0.001 $\mu g/m3$
samples collected every sixth day for a 24-hour sampling period
N/A = not available
* only total mercury sampled in 1982 at Anderson Springs
** fine particles = particles <2.5 μm; coarse particles = particles with sizes between 2.5 and 15 μm 1982 and 2.5 and 10 μm 1983 and later

recorded. The high values are subject to question and, as discussed below, are believed to be erroneous.

An investigation of the high values observed from August through November 1983 was performed, paying particular attention to the possibility of contribution from natural sources, weather conditions, and instrument or human error. On November 18, 1983, and November 21, 1983, manifold pumps were removed from Anderson Springs and Glenbrook. With very few exceptions, values recorded after these dates are near or below the detection limit. It is possible that a malfunction in the manifold pump caused air (possibly contaminated with mercury) inside the sampling trailer to be recirculated. Although PG&E cannot reproduce this phenomenon, the sudden drop of concentrations to background levels makes procedure error or sample contamination a likely explanation.

During the 1986 monitoring period, average values for the 24-hour mercury concentrations ranged from 1.1 to 23.6 ng/m^3 (Table 3c). The overall average was 5.8 ng/m^3 for the entire time period (June through December). Hourly mercury concentrations in 1986 and 1987 ranged from nondetectable to 25 ppt (222.5 ng/m^3); virtually every measurement was nondetectable (Table 4).

Particulate Mercury

Adsorption of atmospheric mercury to particulate matter is poorly understood. According to the National Academy of Sciences, it is believed that 1 to 10% of the total atmospheric mercury burden is particulate-phase mercury (Schroeder 1982, EPA 1984). Sampling for particulate mercury is difficult since the conventional high volume and low volume sampling methods can result in the volatilization of a measureable amount of the mercury. Data collected through GAMP revealed low to undetectable concentrations of mercury in fine and course particulate matter (Table 5). With only a few exceptions, the concentrations were at or below the detection limit (1 ng/m^3). The maximum concentration for the entire sampling period (1982 through 1986) was 8 ng/m^3.

Bulk Deposition

Bulk deposition is the process by which atmospheric wet and/or dry deposition occurs on surfaces. Bulk deposition was measured around PG&E Units 5, 6, 13, 17, and 18 at various times during the Geysers Vegetation Stress Monitoring Study. This was done to estimate the rate of deposition of cooling tower drift (PG&E 1984b, 1986). Five-gallon buckets with a funnel assembly served as collectors designed to measure long-term (annual) deposition. The sampling layout and intensity were not designed to produce data suitable for analysis of either time trends or spatial patterns. Detectable amounts of mercury were contained in one of eight bulk deposition samples at Units 5 and 6 during the 1982 sampling.

This resulted in a deposition rate of 0.007 kg/ha-yr, based on an average of the eight buckets. The report states that cooling tower and steam wells (such as Thermal 4, which blows continuously) may be contributing to levels observed near Units 5 and 6. During the same sampling period, three of eight sites surrounding Unit 13 had mercury concentrations above the detection limit. The maximum deposition rate was determined to be 0.02 kg/ha-yr (PG&E 1986).

At PG&E Unit 17, mercury deposition was detected only at the innermost station north of the cooling tower. During the 1984 dry-season sampling period, a deposition rate of 0.004 kg/ha-yr was detected. During the subsequent 1985 dry season, a deposition rate of 0.035 kg/ha-yr was detected. No mercury was detected in the drift at Unit 18 (PG&E 1986).

AQUATIC CONCENTRATIONS

Mercury monitored in aquatic environments at The Geysers include geothermal operations, natural mercury mines, and ore deposits in the area. Erosion and leaching of these areas into the waterways may potentially contaminate drinking water supplies and/or fish. Although the aquatic concentrations have been generally at or below the detection limits, mercury has been detected in higher concentrations within The Geysers vicinity during high flow periods.

In aquatic environments, mercury levels in sediment (insoluble) are generally found in much higher concentrations than in water (soluble) (Finlayson 1977). Mercury was monitored in the sediment of Dry Creek and Big Sulphur Creek in 1977 and found to be highest during the high flow seasons (Finlayson 1977). Mercury sediment concentrations ranged from 970 to 13,000 ppb dry weight at Big Sulphur Creek, with the highest concentration occurring upstream near The Geysers and the lowest occurring downstream near the Russian River. Concentrations in Dry Creek ranged from 40 to 6,800 ppb. The source of mercury contamination was cited to be erosion and leaching of soils from geothermal springs, cinnabar deposits, and ore tailings into the waterways (Finlayson 1977).

Since that time, total mercury has been monitored systematically in the Big Sulphur Creek drainage from 1981 to 1985 and in Putah Creek and Kelsey Creek drainages from 1981 to 1983. Monitoring was conducted in accordance with the Unit 20 license application and the Known Geothermal Resource Area-Aquatic Resources Monitoring Program (Gilbert 1981, McMillan 1985). The highest concentrations were detected during the first year of sampling (1981) in the Big Sulphur Creek drainage during high flow periods. Reported values ranged from below the detection limit of 0.1 μg/l to a high of 2.9 μg/l. The highest value exceeded the DHS drinking water (2 μg/l) and the EPA human health water quality criteria (0.144 μg/l), and is only 30% below the value of 4.1 μg/l set by the EPA for acute toxicity in freshwater organisms (Table 1). The source of the contamination was reported to be runoff from the abandoned mercury mines (Eureka and Socrates Mine) as a result of heavy rainfall (Gilbert 1981).

All other monitoring stations had somewhat lower mercury concentrations during the 1981-1983 monitoring period. Concentrations ranged from below the detection limit of 0.05 μg/l up to 0.66 μg/l (McMillan 1985). The high value occurred in January within the Kelsey Creek drainage and was the only value above the detection limit that year. Although mercury was detected at all other stations during both low summer and high winter stream

flows, laboratory contamination or error was given as a possible explanation for the levels that occurred in the low flow, summer months.

Results for the 1984 monitoring period in Big Sulphur Creek drainage indicate slightly elevated concentrations during November, with levels ranging from below the detection limit of 0.2 μg/l to 0.7 μg/l. Elevated mercury concentrations coincided with periods of heavy rainfall, high stream flows, and elevated suspended solid levels. Disturbance of soils from construction may have also influenced the values in previous years. No concentrations above the detection limit were reported in 1985 (Gilbert 1986b, McMillan 1985).

The study area waters are typically used for recreation, irrigation, wildlife, and freshwater aquatic habitats as well as for domestic uses by the local population. The Big Sulphur Creek drainage directly supplies domestic water to a maximum of five people. The Putah Creek drainage supplies domestic water to approximately 400 people. Water from the Kelsey Creek drainage supplies a total population of approximately 1,240 (McMillan 1985).

In summary, concentrations of mercury at the various monitoring sites are highly variable and dependent on suspended sediment levels (from erosion and/or construction), stream flow, and rainfall. Aquatic mercury levels are clearly dependent on the location of mercury mines and tailings, as well as natural geothermal activity. The highest concentrations were measured during the first years of sampling when some values exceeded water quality standards for the protection of human health and approached 70% of the EPA standard to prevent acute toxicity to freshwater life. Concentrations declined during the subsequent years; in 1985, mercury was below the detection limit for the analysis.

SOIL CONCENTRATIONS

The forms and concentrations of mercury in soils depend not only on nearby sources but also on the soil type and the presence of organisms capable of biologically transforming the mercury. Humic and fulvic acids and other

organic soil components, as well as inorganic clays, can bind mercury and retard the leaching of mercury compounds (EPRI 1978). Perhaps, the most important component of soils at The Geysers is sulfur, which preferentially reacts with mercury to form cinnabar, a relatively insoluble and biologically unavailable (inert) compound.

As part of the conditions for approval to operate PG&E Units 13 and 17, the California Energy Commission required PG&E to conduct The Geysers Vegetation Stress Monitoring Study (PG&E 1984b, 1986). The study began in 1979 and continued through 1986. Mercury was monitored in the soils, vegetation, and cooling tower drift. Results of the soil analyses are discussed below and are summarized in Table 6.

Mercury was measured in the soil near PG&E Units 5, 6, 13, 17, and 18 from 1979 to 1985. Concentrations ranged from a high of 11.0 μg/g at Units 5 and 6 to a low of <0.10 μg/g (the detection limit) at Unit 17. The values for Units 13, 17 and 18 fall within normal ranges (0.001 to 0.5 μg/g) defined for similar soil types. Contaminated soils near mercury deposits may reach as high as 250 μg/g (PG&E Annual Report 1986).

The highest mercury concentration was observed near Units 5 and 6 at a site with a history of natural geothermal activity, which was adjacent to the first producing steam well at The Geysers. This suggests that the primary source of observed mercury may be natural geothermal activity, since the concentrations did not vary as a function of soil depth. Furthermore, evaluation of the data for Units 5 and 6 show no significant trends of accumulation in the soils or vegetation over the 6-year study period. In contrast, mercury levels at Unit 13 show a decreasing trend from 1979 to 1982. It should be noted that the small sample size used to evaluate these trends does not allow for a high level of confidence in the conclusions. Potential trends of accumulation at Units 17 or 18 were not investigated.

Mercury levels found in soils around Units 3, 4, and 11 have been reported by Robertson (PNL 1980). Relatively high concentrations of mercury were present around Unit 11. Elevated concentrations extended over a radius of

Table 6

SUMMARY OF MERCURY LEVELS OBSERVED
IN SOIL AND FOLIAGE AT THE GEYSERS

UNIT	MERCURY CONCENTRATION ($\mu g/g$) LOW-HIGH	
	SOIL	FOLIAGE
5, 6 (1980)	<0.2-9.8	0.06-0.17
(1982)	0.08-11.0	0.09-0.63
13 (1981)	0.07-0.14	0.01-0.2
(1985)	0.06-0.1	0.04-0.2
17 (1981)	<0.1 -0.4	<0.4
(1985)	<0.1-0.3	<0.4
18 (1982)	0.2-7.6	<0.4-2.7
(1985)	<0.4-5.4	<0.4
NORMAL RANGE FOR UNCONTAMINATED SOIL	0.001-0.05	0.005-0.15

(PG&E 1986)

about 200 yards. The highest concentration observed, 2.9 μg/g, was attributable to power plant emissions. At Units 3 and 4, elevated concentrations were detected, but no direct correlation could be made to power plant emissions. No significant variations occurred as a function of depth, suggesting that the elevated levels are due to natural hydrothermal activity. Only about 0.1% was determined to be leachable from these soils (PNL 1980).

In 1981, UNOCAL conducted a soil monitoring study in the vicinity of the Thermal 4 blowout well (an uncontrolled well) near the UNOCAL Headquarters. A maximum concentration of 250 μg/g occurred in the soil in the northwest quadrant of this area. As a comparison, background concentrations of 0.16 and 0.12 μg/g were measured at Mercuryville (Fielder 1981).

CONCENTRATIONS IN FISH AND SMALL MAMMALS

Fish can bioaccumulate mercury either by direct uptake through the gastrointestinal tract, gills, and skin or through the food chain. Animals, including humans, can uptake mercury by inhalation or ingestion. Dermal absorption is negligible. Organic species of mercury and mercury vapor have a retention in fish and animals of nearly 95% and 80%, respectively. Inorganic species such as cinnabar, which are much more prevalent at The Geysers, have a retention of approximately 10% (EPA 1984).

Concentrations in Fish

One of the first detailed studies of mercury concentrations in fish and invertebrates within the Dry Creek and Big Sulphur Creek basins was conducted by Finlayson (1977). Mercury concentrations in fish varied by species, season, and station. Whole body concentrations in fish sampled in the Dry Creek drainage varied from 30 to 1,350 ppb wet weight. Invertebrate concentrations at the same locations ranged from 0 to 210 ppb. In the Big Sulphur Creek drainage, mean fish concentrations ranged from 120 to 560 ppb while invertebrate concentrations ranged from 20 to 220 ppb. The concentrations in fish and invertebrates were strongly correlated to levels

of mercury in the sediment in the Dry Creek drainage, but not in the Big Sulphur Creek drainage.

A study by the University of San Francisco (Brown et al. 1985) identified trace element concentrations in fish at The Geysers. Such studies are valuable for assessing total human exposure and the potential for bioaccumulation. The muscle tissues of trout and sucker were analyzed for 27 elements. Four metals, including mercury, were present in high concentrations. Mercury concentrations were very similar for both species in Little Sulphur Creek (sucker, 0.7 ppm; trout, 0.7 ppm) and for the Unit 14 (sucker, 0.6 ppm) and Pine Flat (trout, 0.6 ppm) sites on Big Sulphur Creek. The only value below 0.5 ppm for either species was the sucker sample collected downstream at the PG&E General Construction Camp (0.4 ppm) (Brown et al. 1985). It is noteworthy that the highest concentrations occurred in undeveloped Little Sulphur Creek, whereas the lowest concentrations occurred downstream from the main Geysers geothermal development area in the General Construction Camp.

Studies reporting high concentrations of mercury in fish have been conducted at nearby Clear Lake (Fan 1987 and Stratton 1987). These data are similar to those reported in The Geysers area.

The U.S. Department of Commerce (1978) estimates the average concentration of mercury in trout to be 0.42 ppm. No values were given for suckers. Average concentrations in most freshwater fish are below 0.2 ppm. Mercury concentrations in pike may frequently exceed 1 ppm, and values as high as 28 ppm have been reported in fish from heavily polluted waters (EPA 1984). Concentrations of mercury in saltwater fish often approach or exceed the FDA standard of 0.5 ppm (EPRI 1978).

Concentrations in Small Mammals

The University of San Francisco also conducted a study of element content in small mammals in the vicinity of The Geysers. Twenty-eight elements were analyzed in the kidney and liver of four rodent species. Levels of

mercury were consistently below the minimum analytic detection limit of 0.08 ppm (Brown et al. 1985).

CONCENTRATIONS IN PLANTS

Mercury concentrations in plants can indicate spatial patterns of contamination and can be useful to a limited extent, for understanding environmental bioaccumulation. The uptake of mercury by plants has not been extensively studied. General research (not Geysers-specific) indicates that turf grass roots and apple tree roots and foliage do not uptake mercury when exposed to mercury-containing pesticides. Direct uptake of mercury vapor has been reported in wheat and rose leaves (EPA 1984). It has also been noted that alfalfa may accumulate mercury through roots and leaves (EPA 1984). It is unlikely, however, that terrestrial plants will accumulate concentrations of mercury above that in soil (EPRI 1978). Blanton (in EPRI 1978) found little relationship between mercury levels in four desert plant species and the cinnabar-rich soil in which they are grown.

The Geysers Vegetation Stress Monitoring Study (PG&E Annual Report 1984b, 1986) reports foliage mercury concentrations at various locations from 1979 through 1986. These data are summarized in Table 6. Mean concentrations in big leaf maple trees surrounding PG&E Units 5 and 6 were 0.09 μg/g in 1980 and 0.25 μg/g in 1982. In 1979, six black oaks were sampled at Unit 13. They contained a mean concentration of 0.06 μg/g. In 1982, mean mercury concentrations in black oaks were 0.10 μg/g.

Mercury was not measured above the detection limit, <0.4 μg/g, at Units 17 and 18 with one exception. In 1982, the knobcone pine sample tree at Unit 18 contained 2.7 μg/g of mercury. This tree is located 10 m downslope from the Unit 18 fence and may have been contaminated by some construction emissions. By 1985, no mercury concentrations were detectable (PG&E Annual Report 1986).

MERCURY HEALTH RISK ASSESSMENT

BACKGROUND

The following section summarizes the toxic effects of mercury, with an emphasis on potential health effects arising from long-term, low-level exposures. Exposures from concentrations of mercury existing at The Geysers are compared to average nationwide mercury exposures. The methodology for the comparison is adapted from the EPA health risk assessment for mercury (EPA 1984).

TOXIC EFFECTS AND DOSE RESPONSE RELATIONSHIPS, LITERATURE REVIEW

The major behavioral effects caused by mercury in humans are usually described as erethism. This includes a number of psychological effects such as introversion, emotional lability, irritability, anxiety, and short-term memory loss. Smith et al. (1970) found an increase in complaints of insomnia, objective tremor, loss of appetite, weight loss, and shyness associated with long-term occupational exposure (8-hour day and 40-hour work week) to mercury vapor at concentrations ranging from 150 to 270 $\mu g/m^3$ (time-weighted average). Similar symptoms have also been reported at occupational exposure levels as low as 50 $\mu g/m^3$ (Smith et al. 1970, EPA 1984). Hallucinations, delusions, and mania, such as the "mad-hatters" disease are noted in the more severe forms of erethism that occur at much higher concentrations (EPRI 1978, EPA 1984).

Neurological signs, such as a slight tremor, may also occur with long-term exposure to levels above 100 mg/m^3. As effects become more severe, the tremors may become more debilitating and the peripheral nerves may be affected. Nephrotic (kidney) symptoms, such as proteinurea (mainly albumin) and edema, may be accompanied by oral effects such as excessive salivation and tenderness of the gums at the early stages of exposure. The nephritic syndrome is a serious but usually reversible health effect.

Limited information is available on the reproductive and developmental effects of mercury vapor. Effects on the estrus cycle may result from higher exposures.

Organic methyl mercury damages the central nervous system in adults and prenatal infants. The fetus is about three times more sensitive than the adult to methyl mercury exposures (EPA 1984). Little positive evidence has been provided supporting the mutagenicity or carcinogenicity of mercury, although very few studies have been conducted. One study claimed to be positive, however.

Recovery usually takes place after poisoning from mercury. Motor effects, such as tremors, disappear more rapidly than the psychological effects. The fact that motor changes are more easily detected and more likely to be reversed suggests that the most harmful health hazard from mercury poisoning is from emotional alterations (EPA 1984).

Evidence supports the possibility of a threshold mechanism, although this theory is widely disputed. This phenomenon can be explained by the saturation of the oxidation process occurring in the red blood cells. At low concentrations, mercury is more readily oxidized to the divalent form and is less available for transport to the brain. As concentrations increase above a threshold level, the oxidative capacity is used up and more mercury is available in the brain to manifest a toxic response (EPA 1984). The threshold ambient air concentration for at least mild occupational mercury intoxication appears to be about 50 mg/m^3, (Smith et al. 1970, EPRI 1978). The threshold value for oral routes of methyl mercury exposure is believed to be 200 μg/day.

RELATIVE CONTRIBUTIONS OF VARIOUS MEDIA TO HUMAN EXPOSURE

The three major media contributing to total human exposure to mercury are air, drinking water, and food. The estimates of total human exposure presented in this report are based on average nationwide concentrations, as cited by the EPA, and maximum and minimum levels observed at The Geysers, as reported in Section I.

The scientific methodology for performing total human exposure assessments is lacking. Therefore, it is necessary to make several assumptions to assess the potential for human health effects. These assumptions are outlined below and were adapted directly from the EPA (1984).

1. The toxicity of mercury is dependent on the chemical species present. For purposes of estimating the human exposure, it was assumed that atmospheric mercury exists as 60% vapor, 19% inorganic ionic mercury, and 17% methyl mercury. Because particulate mercury accounts for such a small percentage of total atmospheric mercury (4%), it was not included in the calculations. Drinking water and non-fish food were assumed to contain 100% inorganic mercury (Hg(+2)). Estimates for mercury intake from fish are based on the assumption that 80% is in the form of methyl mercury and the remainder is inorganic mercury compounds.

2. Although individual exposure to mercury may vary considerably throughout the exposed population, it was necessary to use standard ingestion and ventilation rates for purposes of calculation. The following parameters were used: an average daily ventilation rate of 20 m^3 per day; an average consumption of 2 liters of water per day; an average daily intake of 18.7 g of fish per day; and an average daily consumption of 2 kg of non-fish food items per day.

3. To assess any potential threat to human health, it is important to distinguish between exposure to a material and actual bodily retention. For example, only about 10% of ingested inorganic mercury found in food and water is absorbed through the gastrointestinal tract and is retained in the body. Approximately 95% of ingested methyl mercury is retained. Because very little is known

about the retention of the various forms of atmospheric mercury, an 80% retention of all forms of inhaled mercury was used. Absorption through the skin was not considered in this assessment.

4. Mercury is believed by most to exhibit its toxic effect via a threshold mechanism. A threshold in biological systems is defined as the dose below which no toxic effects occur or can be observed.

   This can be contrasted with carcinogenic substances that may act through non-threshold mechanisms to produce a toxic response (cancer) at any dosage level. The threshold of effects for mercury appears to be near 200 μg/day for ingested mercury, and 50 μg/day for inhaled mercury vapor.

The estimates for total human exposure to mercury both nationwide and at The Geysers are presented in Tables 7 and 8. Values in Table 7 represent the EPA's estimates of nationwide mercury exposure (EPA 1984). The EPA data were gathered from large nationwide surveys conducted either by the FDA or the Department of Commerce.

Table 7

Estimated Average Daily Intake (Retention) of Mercury Compounds in in the U.S. Population not Occupationally Exposed to Mercury (EPA 1984)

(EPA 1984)

Exposure	Estimated mean daily intake, ng/day (retention)		
		compounds of mercury	
	Mercury vapor	Inorganic	Methyl
Atmosphere	120(100)	40(30)	30(30)
Food			
Fish	-	940(90)	3,800(3,600)
Non-fish	-	20,000(2,000)	-
Drinking water	-	50(10)	-
TOTAL	120(100)	21,000(2,100)	3,800(3,600)

Table 8

Estimated Daily Intake (Retention) of Mercury Compounds
in Populations in the Vicinity of The Geysers

Exposure	Estimated most likely daily intake, ng/day (retention)		
		compounds of mercury	
	Mercury vapor	Inorganic	Methyl
Atmosphere	70(60)	20(20)	20(20)
Food			
Fish	-	1,500(150)	6,000(5,700)
Non-fish	-	20,000(2,000)*	-
Drinking water	-	100(10)	-
Total	70(60)	22,000(2,200)	6,000(5,700)

* specific data not available on The Geysers; EPA data used.

Table 8 presents a most likely mercury uptake value for persons living in the area populated immediately downwind (east) of The Geysers area. Values were computed using realistic environmental concentrations. For air, this is the average over the 1986 sampling period. For water, the detection limit was used because during the 1985 monitoring period mercury was not detected above this limit. For fish, insufficient data were available to establish a most likely value. Therefore, an arbitrary value midway between the maximum observed level and the national average was used. The following discussion further describes the derivation of Tables 7 and 8. All estimates of intake, retention, and total have been rounded to two significant figures.

Inhaled Mercury Vapor

Assuming an average daily ventilation rate of 20 m^3 and an 80% retention for the average 70-kg adult, the maximum daily inhaled intake was calculated for The Geysers area using the peak hourly ambient air concentration observed at The Geysers, 70 ppt or 630 ng/m^3. The most likely estimate of exposure was calculated using the 1986 sampling period average of 5.8 ng/m^3, 2 orders of magnitude lower. The EPA used an ambient air concentration of 10 ng/m^3 in its assessment of the national average exposure.

Ingested Mercury

Assuming a national average concentration of 25 ng/l for drinking water, with an average daily consumption of 2 liters and a gastrointestinal absorption rate of 10%, the EPA's estimated daily retention of mercury from drinking water is approximately 5 ng. We calculated maximum and most likely exposures from environmental doses at The Geysers of 2,900 ng/l and 50 ng/l, respectively.

The estimates for total mercury intake from fish are based on the assumption that 80% of the mercury in fish is in the form of methyl mercury and that the remainder is inorganic mercury compounds. The national average daily intake was calculated on the assumption that the fish contained 0.25 $\mu g/g$ and that fish consumers eat an average of 18.7 g of fish per day. Our analysis of the exposure to mercury from eating fish from The Geysers

assumes a maximum dose of 0.7 μg/g and a more likely dose of 0.5 μg/g. It should be emphasized that these calculations are very speculative since the consumption of fish and the mercury concentrations in fish are highly variable.

Mercury concentrations in most meat and vegetables are near or below the detection limit. The FDA surveys indicate most foodstuffs have total mercury levels below 20 ng/g wet weight. The data on mercury concentrations in foliage at The Geysers are speculative and only exist for foliage not used for human consumption (maple and oak trees). Additionally, no data are available to suggest that consumption patterns of most meat and vegetables are different at The Geysers than from the national average. Because of these factors, we used the same values for meat and vegetables as the EPA. For purposes of calculation, non-fish food items are assumed to contain 10 ng/g wet weight, in the form of inorganic mercury compounds. Assuming that a 70-kg adult consumes 2 kg of food per day, with a retention of 10%, the total daily intake is estimated to be 20,000 ng with 2,000 ng retained. This calculation is subject to large error since the concentrations in many non-fish food items may be zero.

Assessment of Risk from Concentrations Observed at The Geysers

As can be seen from Tables 7 and 8, ingested mercury in food, specifically from fish, greatly exceeds other routes of exposure such as air and water. Contributions from air and water are not considered significant. For both the national average exposure and the most likely, plausible exposure to mercury at The Geysers, the expected intake from food (mainly non-fish) exceeds 99% of the exposure. As was noted above, public eating habits and exposure to mercury in food should be no different at The Geysers than throughout the rest of the United States. Based on this, the concentrations of mercury in food were derived from EPA estimates and should not be influenced by activities at The Geysers. Although the concentrations of mercury in air and water may be higher at The Geysers than nationally, the increase is virtually insignificant when compared to exposures through food.

The data from Tables 7 and 8 are summarized in Table 9. The total exposures across all routes of entry and from all chemical species of mercury are summed in the right column. The most likely estimate of exposure at The Geysers, 28 μg/day, is very similar to the national average of 25 μg/day.

Analysis of these figures reveals that concentrations of mercury at The Geysers represent a negligible risk to the health of the maximally exposed individual. The lowest observed effect level (through ingestion) for adults is approximately 200 μg/day of methyl mercury compounds, eight times higher than the predicted exposure in this study.

Table 9

Summary of Tables 7 and 8

Exposure	Estimated daily intake (retention), ng/day			
		compounds of mercury		
	Mercury vapor	Inorganic	Methyl	Total
Table 7 - EPA total	120(100)	21,000(2,100)	3,800(3,600)	25,000(5,800)
Table 8 - Most likely total	70(60)	22,600(2,200)	6,000(5,700)	28,000(8,000)
Lowest Observed Effect Level (oral exposure)				200,000*

* Equals 200 μg/day

CONCLUSIONS

Sulfur is an important scavenging agent for mercury in geothermal systems at The Geysers because of its ability to react with mercury and form stable compounds. Rather than being emitted directly to the atmosphere, one-third to one-half of the mercury reacts to form a soluble sulfide species which is reinjected into the steam field. Some mercury accumulates within the various process waste streams.

Power plant studies, primarily those conducted by PNL, indicate that cooling tower exhaust is the most significant release pathway for mercury. As stated in the PG&E Geysers Unit 20 AFC (page 5-22), Robertson of PNL estimated that about 50 percent of the mercury in the incoming steam remains in the condensate and 50 percent remains with the non-condensible gases. The mercury in the condensate goes to the cooling tower, where approximately 50 to 80 percent is volatilized into the atmosphere. In units equipped with a Stretford system, the mercury remaining with the non-condensible gases is scrubbed out and none is emitted to the atmosphere. In units not equipped with a Stretford system, the fate of mercury in the non-condensible gases is not known. Mercury levels in the noncondensable gases have reached as high as 5,800 ng/l. Mercury levels in cooling tower exhaust, however, are smaller by a factor of two to three orders of magnitude because of the extremely large dilution with ambient air.

As previously stated, there are virtually no data on the state (organic vs. inorganic) or species of mercury present in the environmental mercury data at The Geysers. If further studies are implemented at The Geysers, it would be valuable to collect data to quantify the relative presence of organic and inorganic mercury as well as speciate the mercury compounds.

Atmospheric concentrations of mercury vapor ranged from nondetectable to 630 ng/m^3. While there has been considerable variation in the mercury vapor values, average concentrations appear to be near 6 ng/m^3. Particulate mercury and mercury deposited to the ground have not proved to be significant pathways of contamination.

Maximum concentrations of non-soluble mercury in aquatic environments have reached levels above applicable standards. The levels in water were one-time peaks, presumably due to erosion of mercury-containing soil into the waterways or erroneous results due to laboratory contamination. However, as construction in The Geysers area has diminished, so have the concentrations of mercury. Mercury levels were at or below the analytic detection limits during the last sampling period in 1986.

While the levels of mercury in fish were consistently above allowable levels, mercury was not detected in small, terrestrial mammals.

Concentrations of mercury at The Geysers should not pose a threat to public health. An exposure assessment indicates that people living in The Geysers area may receive approximately 28 μg/day. National average exposures, as calculated by the EPA, are 25 μg/day.

Mercury in food accounts for the largest portion of the total human exposure. Under realistic conditions, the contribution from food exceeds 99%. Food (non-fish) consumption habits of persons living at The Geysers are not expected to differ from national average consumption habits. Therefore, activities at The Geysers (natural or man-induced) are not expected to affect the exposures of mercury received from food. The only routes of exposure potentially impacted from activities at The Geysers are air and water. However, because the exposures from air and water are small (<1%), their contribution to total exposure is not considered significant.

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APPENDIX 1

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