Transport of Tracers and Pollutants From the Geysers Geothermal Resource Area

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August 1983

**Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830**

**Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
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PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC06-76RLO 1830

Printed in the United States of America
Available from
National Technical Information Service
United States Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

NTIS Price Codes
Microfiche A01

Printed Copy

Pages	Price Codes
001-025	A02
026-050	A03
051-075	A04
076-100	A05
101-125	A06
126-150	A07
151-175	A08
176-200	A09
201-225	A010
226-250	A011
251-275	A012
276-300	A013

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ACKNOWLEDGEMENTS

The authors wish to express their appreciation to the late P.W. Nickola formerly of Pacific Northwest Laboratory (PNL) for his dedicated efforts in siting and monitoring the surface hi-volume samplers, to R.V. Hannigan (PNL) in completing the aircraft sampling flights in a professional manner, and to J.S. Wetzel (formerly of PNL) and D.E. Mollenberndt (Environmental Systems and Services) for collecting the rawinsonde data.

SUMMARY

A limited surface and aircraft sampling study was conducted in the Geysers Geothermal Resource Area to collect initial data on the short-range (5 to 20 km) transport of tracer and pollutant materials from this geothermal electrical power generation area. The sampling study was accomplished during the DOE ASCOT Cooling Tower field program in August 1981 as part of the daytime limited mixing experiments.

An initial analysis of SF_6 tracer data from the Geysers illustrates the importance that terrain, vertical wind shear, time-varying winds and stability can have on the downwind distribution of cooling tower effluents during the daytime. Atmospheric stability (neutral to unstable) and near surface winds above 3 m/s results in fumigation and surface impaction of a portion of cooling tower plumes on downwind surfaces and terrain. Vertical wind shear and possible gravity waves in upper-levels (~ 1800 - 2000 m m.s.l), in addition, to terrain influences assist in distributing plumes horizontally and in the vertical at relative short (~ 10 - 20 km) distances from the source.

Small quantities of gaseous sulfur, primarily H_2S , are transported up to 20 km or more from the Geysers area. A variety of trace materials such as sulfate, copper, zinc, arsenic, bromine, lead, antimony, selenium and barium appear to be enriched over background levels and transported downwind from the Geysers Area at times. Future work will expand and further quantify these results.

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1. INTRODUCTION

The emission, transport and dispersion of pollutants from energy production areas in complex landforms is a subject of continuing concern with respect to assessments on whether emitted pollutants may cause a significant impact on the general public and environment through the mechanisms of chemical reactions, impaction, dry deposition and acid precipitation.

A limited surface and aircraft sampling study was conducted in the Geysers-Calistoga Geothermal Resource Area (GGRA) to collect initial data on the short-range (5 to 20 km) transport of pollutant materials and a sulfur hexafluoride (SF_6) tracer from this geothermal electrical power generation area. The electrical power generating capacity of the Geysers is undergoing extensive expansion. Power plant cooling towers and geothermal wells located on mountain ridges, slopes and valleys release a variety of emissions such as carbon dioxide (CO_2), hydrogen sulfide (H_2S), methane (CH_4), ammonia (NH_3), radon gas, arsenic (As), boric acid (H_3BO_3), mercury (Hg) and other trace materials (Martin, et al. 1978). A current environmental issue in this area is the release of hydrogen sulfide and its transport to surrounding communities and agricultural areas. Since these emissions can result in an odor nuisance if concentrations exceed 30 ppb (California Air Quality Standard) it is important to assess the transport and dispersion of the Geysers emissions to surrounding areas.

The Pacific Northwest Laboratory (PNL) sampling study was accomplished during the DOE ASCOT Cooling Tower field program in August 1981 as part of the daytime limited mixing experiments (Gudiksen, 1982). On August 23 and 24, the ASCOT group conducted extensive meteorological and tracer experiments during the daytime hours. A SF_6 tracer was released from a power plant's cooling tower during the afternoon of each day. The SF_6 tracer was sampled by a surface network of samplers and a Meteorology Research, Inc. (MRI) aircraft. The PNL aircraft flew a flight track between 5 to 20 km upwind and downwind of the Geysers while the MRI aircraft flew closer to the source over the Mayacmas ridge. In addition to these two days, the PNL aircraft also sampled for gaseous sulfur (H_2S) and airborne aerosols on August 20 and 21.

The goals of the PNL study were four fold: a) to define the types and quantities of airborne materials such as H_2S , B, As, Cd, Pb, Cr and Hg that are emitted from the geothermal operations, b) collect data on the location, height and concentration of the airborne materials and SF_6 tracer, c) examine the role of vertical wind shear in the transport of the H_2S and SF_6 tracer plumes and d) if possible, estimate the flux of pollutant material being transported from the Geysers.

The four-day study, although clearly insufficient to satisfy these four goals, nevertheless, was intended to provide initial data on the short-range (5 to 20 km) transport of pollutants from an area source (The Geysers) in complex terrain. The purpose of this interim report is to discuss the initial data analysis and results in respect to the first three goals. Final analysis and conclusions will be reported in the future as an ASCOT report.

2. EXPERIMENTAL DESIGN

2.1 SITE DESCRIPTION

The airborne and surface sampling was conducted over the GGRA located approximately 40 km north of Santa Rosa and about 65 km east of the Pacific Coast. Figure 1 shows the relative location of the GGRA and the major area of geothermal operations (The Geysers). The Geysers (shaded area in Figure 1) are located in the Mayacmas mountains which are oriented in a northwest-southeast direction. The Russian River valley lies to the west and Clear Lake lies to the north of the Geysers. Prominent mountain peaks in the area are Cobb Mountain (1439 m), Boggs Mountain (1122 m), Mt. St. Helena (1324 m), Mt. Hannah (1212 m) and Mt. Konocti (1280 m).

The ASCOT limited mixing experimental measurements were conducted in the Big Sulphur Creek valley, Anderson-Putah Creek valley and Cobb valley. The PNL sampling measurements extended the area of the ASCOT sampling measurements both east and west of the Geysers (Figure 1).

2.2 INSTRUMENTATION

2.2.1 Surface Equipment

Surface samplers were used to collect airborne aerosols during the same period that the aircraft was sampling overhead. Standard high-volume samplers were placed at seven different locations within and in the vicinity of the Geysers (Figure 1). Table 1 shows the range in elevations of the sampling sites. The location of the sampler sites were dictated by assessability and availability of power. The D and M Brangus Ranch site, although not ideal, was selected as a surface background site because of its location--5 km southwest of the Geysers operations.

Figure 1. Geographic Setting of the Geysers-Calistoga Geothermal Resource Area (GGRA), the Geysers, and Location of Aircraft Sampling Flights and Surface Hi-Volume Filter Samplers.

TABLE 1. Surface Hi-Volume Sampler Locations, Elevations, Average Flow Rates and Average Total Air Sampled

<u>Sampler Site</u>	<u>Elevation m m.s.l.</u>	<u>Average Flow Rate₃(per day) m³/min</u>	<u>Average Total Air Sampled (per day) m³</u>
1. D and M Brangus Ranch	591	0.54	198
2. Administration Center*	671	0.49 (2)	163
3. Repeater (Geysers Rock)	1116	0.47	172
4. Sawmill Flat	722	0.47	176
5. Delfino (Middletown)	341	0.46	165
6. Loran	439	0.53	188
7. Lilla Ranch	731	0.50 (2)	158

*Moved after two days to Lilla Ranch

The flow rate of each sampler was calibrated and set at approximately 0.50 m³/min. Each sampler was monitored at the beginning and end of each experimental period. Table 1 shows the average flow rate and total air sampled per day for the different sampler locations.

The Whatman No. 41 filters used in the high-volume samplers had an exposed area of 52.8 cm² (dia=8.2 cm). These filters are a tightly woven cellulose that causes the filter flow rate to decrease due to dust loading but, were chosen because of their cleanness with respect to trace element impurities.

A PNL rawinsonde located at Sawmill Flats provided upper-level data on temperature, humidity and winds at selected time periods during the four days of sampling. During the last two days, a PNL tethersonde collected temperature, humidity and wind data up to 500 m. Other meteorological and sampling data are available from the ASCOT limited mixing experiment.

2.2.2 Aircraft Instrumentation

The aircraft sampling was conducted with the PNL Cessna 411 aircraft which was equipped with the following measurement and sampling systems: a PNL real-time SF₆ analyzer, real-time sulfur analyzer (Melay SA285), an ozone

monitor (Bendix 8002), a MRI integrating nephelometer, and a high-volume filter sampler.

Atmospheric state parameters which were measured included air temperature, dewpoint and pressure altitude. Geographic coordinates (latitude, longitude) were obtained from a Global (GNS-500A) navigation system. These data and the real-time air quality and tracer data were recorded by a magnetic tape data acquisition system. The real time data of the SF_6 , sulfur and ozone was also monitored by strip-chart.

The filters used in the airborne high-volume sampler were Zefluor membrane filters with an exposed surface area of 21.2 cm^2 (dia=5.2 cm). Flow rates varied from .11 to .28 m^3/min . The filters have an extremely high collection efficiency and low impurity levels for trace elements.

2.3 EXPERIMENTAL PROCEDURES

The general flight procedure was to obtain airborne background measurements in the morning hours just west of the Geysers at approximately 1050 m and 1550 m (m.s.l.). In the afternoon, the H_2S , aerosol, and SF_6 sampling was conducted east (and downwind) of the Geysers between 1000 m and 1900 m. Exceptions to this flight procedure occurred on August 20 when the procedure was reversed, and on August 21 when the background was taken in the early afternoon before sampling east of the Geysers.

The principal sampling transects, shown in Figure 1, were 5 to 12 km from the Units 9 and 10 power plant within the Geysers. These transects were flown in a race track manner at three different altitudes for an hour or more for each altitude. Each transect was flown from three to five times except for a transect at 18-20 km which was flown once. On August 21 and 23 the majority of sampling took place east of Boggs Mountain on a northwest to southeast flight track.

The range of altitudes and distances for sampling H_2S and SF_6 in real-time was limited by the altitude sensitivity of the real-time samplers (baseline response varies with pressure) and the sampling of aerosols. The

aerosol measurements required flying on a fixed path and altitude for a minimum of one hour in order to collect sufficient material for analysis.

The surface-based high-volume samplers were turned on at the beginning of the aircraft flight and operated continuously 7 to 8 hours, sufficient time to coincide with the aircraft sampling.

2.4 SYNOPTIC WEATHER PATTERN

The synoptic and weather conditions during the four days of sampling were determined by the subtropical high pressure area off the California-Oregon coast and a deep, winter-like low pressure area in the northern part of the Gulf of Alaska. Between August 20 and 22, a ridge of high pressure on the Oregon-California coast induced a weak onshore pressure gradient and caused an influx of marine air into the GGRA, mainly in the afternoons. After August 22, the cold front from the Gulf of Alaska low pressure area had moved to the Washington coast and became quasi-stationary near Vancouver Island. During this period a thermal low, developed in California and moved northward into Oregon. By August 23, the thermal low had moved northward and joined a developing low pressure system near Vancouver Island, a spin-off from the Gulf of Alaska low pressure system. On August 24, this new low pressure system and a weak cold front moved inland into northern Washington. The surface front trailed southward through Oregon and northern California resulting in a slight cooling trend. With the passage of the weak front, the ridge of high pressure along the Oregon-California coast intensified resulting in an increased depth and persistence of the marine layer inland.

All afternoons of the sampling days were essentially cloudless. Extensive morning marine stratus was present over the GGRA on August 23 but this cloud layer was dissipated by noon. The weak frontal passage during August 24 caused a few widely scattered and poorly developed fair weather cumulus over the northern mountain peaks in the afternoon.

Figure 2 shows a time series of the available rawinsonde winds up to 2000 m for the four sampling days. Most all aircraft sampling flights were conducted during southwesterly to northwesterly upper-level winds. Wind

Figure 2. Horizontal Wind Direction and Speed (m/s) as a Function of Height and Time as Derived from Rawinsonde Observations for August 20, 21, 23 and 24, 1982 at Sawmill Flats. Aircraft sampling heights and times represented by dashed boxes. B - background; S - sampling.

speeds varied from 1 to 14 m/sec. During August 20 and 21, the upper-level winds were variable in direction and speeds were between 1 to 5 m/sec.

Temperature soundings taken in the experimental area by the rawinsonde and ASCOT tether sondes indicated an elevated temperature inversion on August 23. The depth of the inversion increased from 1200 m to 1500 m (m.s.l.) between 1000 PST and 1700 PST. No significant inversions were present in the afternoon hours during the other three days. Substantial afternoon heating caused afternoon temperatures at the Sawmill site to vary from 25°C to 32°C. Maximum temperature on August 24 was 6°C cooler than that of August 23.

Clear air turbulence at flight levels was insignificant although temperature soundings indicated that moderate convective mixing should have been present over the GGRA on all afternoons.

3. RESULTS AND DISCUSSION

3.1 SF_6 TRACER TRANSPORT FROM THE GEYSERS

On August 23 and 24, a SF_6 tracer was released from Units 9 and 10 power plant cooling tower at a rate of 3 gm/s from 1300 PST to 1900 PST. Units 9 and 10 are located on a ridge southwest of Cobb Mountain at an altitude of 968 m m.s.l. (Figure 3). Since analysis is not complete, only preliminary results from August 24 will be discussed. However, August 23 was similar in many respects to August 24. Table 2 outlines some of the variables considered important in the transport of the cooling tower plume and SF_6 on August 24. The meteorological conditions were not very ideal but typical of many situations involving wind shear and time-varying wind conditions.

TABLE 2. Important Variables in the Transport and Diffusion of SF_6 From Units 9 and 10, August 24, 1981

Variable	Comments
1. Plume rise	Average maximum plume rise around 1100 m or 2060 m m.s.l. (Uthe, 1982).
2. Stability	SF_6 detected on the surface downwind from Units 9 and 10.
3. Low level wind speeds	Average wind speeds in a 350 m layer 3 to 5 m/s.
4. Horizontal and vertical wind shear	Winds were backing and increasing in speed with height.
5. Diurnal winds	Winds in lower elevations changed direction from west-southwest to west-northwest.
6. Terrain influences	Possible gravity waves at higher elevations?

The wind and stability conditions were apparently favorable for a portion of the cooling tower plume to impact at downwind locations. Figure 4 shows a portion of the plume was observed at the surface throughout the Anderson-Putah Creek area and Boggs Mountain. The plume impaction occurred toward the northeast in the early afternoon and then shifted toward the southeast later in the afternoon. This change in direction of the surface impaction matches

Figure 3. Units 9 and 10 Geothermal Power Plant and Cooling Tower Plume SF_6 Tracer Release Site.

Figure 4. SF₆ Bag Sample Site Locations, Integrated Surface Plume Boundary, Plume Arrival Hours (14 and 18 PST) and Duration of Plume at Surface (hrs) Source: Units 9 and 10, August 24, 1981. Shaded Topography ≥ 853 m (2800 ft).

some wind observations that showed wind direction changing to more northwesterly directions after 1700 PST.

The principal plume axis at the three different aircraft sampling altitudes were generally the same direction as shown near the surface i.e. toward the east and northeast (Figures 5-7). Maximum concentrations in the elevated plumes were above 200 ppt. An increase in altitude shows a more diffuse plume with secondary maxima toward Middletown and east to northeast of Mt. Hannah. The apparent maximum concentration near Mt. Hannah at around 1600 m is of interest because of the high plume rise and upper vertical wind shear present during the sampling period. Another interesting feature was revealed by the Stanford Research Institute (SRI) airborne lidar. These measurements showed wavy undulations in the aerosol boundary layer at sampling altitudes (Uthe, 1982). The presence of gravity waves may be a possible reason for the secondary SF_6 maximum just east of Mt. Hannah but this possible connection will have to be investigated in more detail in the future as will other details of other sampling passes.

3.2 GASEOUS SULFUR (H_2S) TRANSPORT FROM THE GEYSERS

One of the primary pollutants from the Geysers is gaseous sulfur in the form of H_2S although other states of gaseous sulfur can be present such as SO_2 . Surface and aircraft filter samples generally indicated sulfur (sulfate) enrichment above background levels in the collected aerosol. On the two days of SF_6 release from Units 9 and 10 (August 23 and 24), a minor amount of gaseous sulfur was contributed to the Geysers sulfur plume by SF_6 . A low concentration but measurable gaseous sulfur plume was detected on all four days in the eastern quadrants from the Geysers since the winds were generally from southwesterly to westerly directions. The range in maximum concentrations is shown in Table 3. A peak concentration of 41 ppb was observed on August 20. A brief synopsis of each day's results follows.

Figure 5. SF₆ Elevated Plume as Determined from Aircraft 5-sec Average Concentration. Elevation: 1120 m (3670 ft) m.s.l. Locations: MT-Middletown, C-Cobb Mtn., H-Mt. Hannah, LL-Lower Lake, K-Mt. Kocnocti, KV-Kelseyville Date - August 24, 1981

Figure 6. SF₆ Elevated Plume as Determined from Aircraft 5-sec Average Concentration. Elevation: 1300 m (4270 ft) m.s.l. Locations: MT-Middletown, C-Cobb Mtn., H-Mt. Hannah, LL-Lower Lake, K-Mt. Kocnocti, KV-Kelseyville, Date - August 24, 1981

Figure 7. SF₆ Elevated Plume as Determined from Aircraft 5-sec Average Concentration. Elevation: 1580 m (5190 ft) m.s.l. Locations: MT-Middletown, C-Cobb Mtn., H-Mt. Hannah, LL-Lower Lake, K-Mt. Kocnocti, KV-Kelseyville, Date - August 24, 1981

TABLE 3. Range of Average Maximum 20-sec
Gaseous Sulfur (H_2S) Concentrations as a Function
of Elevation for the Four Sampling Days (ppb)

Date	Elevation (m m.s.l.)				Background
	950-1200 (0-232)*	1200-1395 (232-427)	1400-1600 (432-632)	1700-1900 (518-932)	
August 20	---	16-22	9-19**	12-16	<3
August 21	---	9	4-8	4-6	<3
August 23	6	---	3-6	2-3	<3
August 24	4-6	3-5	5-6	---	<3

*Height above Units 9 and 10 in meters

**Peak concentration approximately 41 ppb

August 20

The plume was detected between 1200 and 1900 m and was found to be moving toward the north and northeast (Figure 8). Maximum concentrations varied between 9 and 22 ppb at distances 5 to 12 km from the GGRA. A definite H_2S odor was detected in the aircraft at 1500 m about 4 km from the Geysers.

August 21

The plume was first detected to the southeast with maximum concentrations of about 9 ppb and also to the east at lower concentrations (Figure 9). Concentrations were lower than on August 20 (Table 3). Later sampling to the east and northeast of the Geysers at elevations of 1500 m or more revealed an indistinct plume. Sampling in Cobb-Anderson Creek valley around 1200 m (m.s.l.) revealed an H_2S plume but concentrations were approximately half of those found on August 20 at the same altitude (Table 3).

August 23

The plume at and above 1500 m was narrow (<5 km), had low concentrations (Table 3) and was detected just east of Boggs Mountain (not shown). The plume below the temperature inversion was wider (5 to 10 km), had higher concentrations and was detected east of Cobb Mountain (~7 km). A shift of the plume axis to the north by 1 to 3 km in the higher elevations (1500 m to 1700 m) correlates with an observed 50° backing of the wind with height (Figure 2).

Figure 8. Transport of Gaseous Sulfur (H_2S) Plume from the Geysers as Depicted from Aircraft 20-sec Average Sampling Data

Figure 9. Location of Gaseous Sulfur (H₂S) Plume in Relation to the Geysers as Depicted from Aircraft 20-sec Average Sampling Data

August 24

Plume concentrations were again lower than observed on August 20 but a measurable plume was detected to be moving to the east-northeast from the Geysers similar to the SF_6 plume (not shown). A shift in the plume axis was apparently the result of the wind direction backing with height.

3.3 COMPOSITION, ENRICHMENT AND TRANSPORT OF GEYSERS AEROSOLS

The four days of sampling resulted in 41 filters. An initial selection of 23 filters (16 surface, 7 aircraft) was made for x-ray fluorescence (XRF) and neutron activation analysis (NAA) (23 by XRF; 8 by NAA). Concentrations were obtained for 55 trace materials. In general, most of the trace materials had concentrations in the ng/m^3 range with the exception of iron (Fe) and sulfur (S) which were in the $\mu\text{g/m}^3$ range (Table 4).

A crustal enrichment factor was computed for all 55 elements associated with the 23 filters. The crustal enrichment factor

$$EF_c = (C_x/C_{Fe})_{\text{aerosol}} / (C_x/C_{Fe})_{\text{crust}} \quad (1)$$

expresses the relative enrichment of an element as compared to its crustal abundance. An EF_c less than 1 indicates depletion of an element, whereas a value greater than 1 indicates enrichment of a given element relative to its crustal abundance. Generally, an enrichment factor of 10 or more is considered significant with respect to anthropogenic input to the atmosphere (Rahn, 1971). Table 5 shows the enrichment factors for various trace elements analyzed in the surface and aircraft filter samples. These results include all the surface stations shown in Tables 1 and 4 except the two most distant stations, Loran and Lilla Ranch.

Trace elements of particular interest because of their potential toxicity hazard and environmental contamination are sulfur (S), selenium (Se), boron (B), bromine (Br), lead (Pb), zinc (Zn), antimony (Sb), arsenic (As), barium (Ba), silver (Ag), cadmium (Cd), copper (Cu), manganese (Mn), fluorine (F) and mercury (Hg). As Table 5 shows several of these elements were significantly enriched above background levels within and downwind of the Geysers area at

TABLE 4. Trace Element Concentrations in Aircraft and Surface Samples
Upwind, Within and Downwind of the Geysers (ng/m³) (by XRF)

	Element														
	S	Cl	Fe	Ni	Cu	Zn	Ga	As	Se	Br	Cd	Sb	Ba	La	Pb
<u>AIRCRAFT</u>															
ZF-33(BK)	79	*	1076	6	5	12	*	5	5	*	*	*	65	406	*
ZF-31	159	8	1707	8	5	40	*	5	*	*	*	63	312	647	3
ZF-18	491	*	930	8	*	79	*	6	4	4	*	52	534	230	*
ZF-38(BK)	397	*	904	8	10	8	4	22	*	*	*	*	*	*	*
ZF-26	299	26	596	1	*	14	1	20	*	*	*	*	*	99	*
ZF-45	*	*	715	*	38	30	*	*	*	*	-	-	-	-	*
ZF-41	158	38	403	*	13	*	2	*	9	*	*	*	*	*	*
<u>SURFACE</u>															
B-20	609	305	4425	22	148	26	*	*	*	29	*	*	*	*	106
A-20	809	113	1912	11	53	15	2	*	*	6	*	*	*	*	23
R-20	1395	251	8872	32	545	47	3	*	*	17	*	*	*	*	54
S-20	1077	163	2938	14	92	15	*	*	*	9	*	*	*	*	30
B-21	1049	366	4320	25	125	25	*	*	*	14	*	*	*	*	53
A-21	906	165	2257	12	27	16	2	*	*	7	*	*	*	*	22
R-21	1116	129	2894	12	239	25	*	*	*	13	*	*	*	*	46
S-21	977	54	1272	6	79	8	*	*	*	9	*	*	*	*	29
B-23	954	68	875	4	206	10	*	*	*	5	*	*	*	*	14
R-23	1209	214	1228	5	233	12	2	*	*	8	21	*	*	*	19
S-23	1029	73	617	2	17	6	*	*	*	8	*	*	*	*	8
D-23	656	127	1008	15	1680	48	*	*	*	4	*	*	*	*	10
B-24	302	47	738	8	394	13	*	*	*	*	*	*	*	*	*
R-24	1091	291	9303	35	188	31	4	*	*	13	48	*	*	*	27
S-24	323	38	787	3	24	9	*	*	*	*	*	*	*	*	*
D-24	416	252	1007	25	4290	113	2	*	*	5	*	*	*	*	*

KEY TO TABLE 4:

<u>Aircraft</u>	<u>Date</u>	<u>Elevation (m m.s.l.)</u>	<u>Surface (see Table 1)</u>
ZF-33	August 20	945-1128	B - Brangus Ranch (background)
ZF-31	August 20	~1006	A - Administration Center
ZF-18	August 20	1494-1524	R - Repeater site
ZF-38	August 21	1478-1524	S - Sawmill Flats
ZF-26	August 21	1494-1524	D - Del Fino (Middletown)
ZF-45	August 23	853-1066	
ZF-41	August 24	~1189	

* - Concentrations near detection limit

- - Missing Data

BK - Aircraft Background

TABLE 5. Enrichment Factors Greater Than or Equal to 10 for
Trace Element Concentrations in Aircraft and Surface Samples
Upwind, Within and Downwind of the Geysers

	S	Cl	Ni	Cu	Zn	Ga	As	Element Se	Br	Cd	Sb	Ba	La	Pb	Hg
<u>AIRCRAFT</u>															
ZF-33(BK)	16	*	<	<	<	*	160	5750	*	*	*	<	707	*	*
ZF-31	20	<	<	<	19	*	94	*	*	*	10370	24	711	<	*
ZF-18	114	*	<	*	68	*	195	4682	94	*	15800	76	464	*	*
ZF-38(BK)	95	*	<	11	<	15	745	*	*	*	*	*	*	*	*
ZF-26	109	19	<	*	19	<	1048	*	*	*	*	*	311	*	*
ZF-45	*	*	*	55	34	*	*	*	*	-	-	-	-	*	*
ZF-41	85	41	*	34	*	18	*	26560	*	*	*	*	*	*	*
<u>SURFACE</u>															
B-20	30	30	<	34	<	*	*	*	146	*	*	*	*	108	*
A-20	92	26	<	28	<	<	*	*	73	*	*	*	*	53	*
R-20	34	12	<	63	<	<	*	*	43	*	*	*	*	27	*
S-20	79	24	<	32	<	*	*	*	71	*	*	*	*	47	*
B-21	53	37	<	30	<	*	*	*	71	*	*	*	*	55	*
A-21	87	31	<	12	<	<	*	*	75	*	*	*	*	45	*
R-21	83	19	<	84	<	*	*	*	99	*	*	*	*	71	*
S-21	166	18	<	64	<	*	*	*	153	*	*	*	*	103	*
B-23	236	34	<	242	<	*	*	*	127	*	*	*	*	74	*
R-23	213	76	<	194	<	<	*	*	143	4771	*	*	*	68	*
S-23	361	52	<	28	<	*	*	*	294	*	*	*	*	62	*
D-23	141	54	11	1706	38	*	*	*	92	*	*	*	*	44	*
B-24	89	27	<	546	15	*	*	*	*	*	*	*	*	*	*
R-24	25	13	<	21	<	<	*	*	32	1465	*	*	*	13	284
S-24	89	21	<	31	<	*	*	*	*	*	*	*	*	*	*
D-24	89	108	19	4360	90	<	*	*	119	*	*	*	*	*	*

KEY: < -- Less than 10
* -- Concentration near detection limit
- -- Missing data

times. However, there are a number of factors that need to be considered with respect to the collection and analysis of some elements. These are:

- 1) The surface samples showing Cu enrichment were probably contaminated by the high-volume samplers although precautions were taken to prevent it (Lynch et al., 1980).
- 2) The aircraft sampling periods were limited by operational restrictions thus reducing the amount of material collected on filters. Less abundant element concentrations were therefore frequently near or below the respective detection limits.
- 3) Some of the elements may be associated with larger aerosols and thus fallout near the sources.
- 4) Some of the elements such as Hg, Br and As have a gaseous component which was not sampled by filters (Robertson et al., 1977, Moyers et al., 1972, Grosch et al. 1978). A possible example is the particulate Br/Pb ratio, assuming that the automotive source (construction traffic, etc.) dominates the source for bromine and lead. The particulate Br/Pb average ratios for surface and aircraft samples were 0.34 and 0.29 (upper limit), respectively. These values are less than the ethyl fluid ratio of Br/Pb = 0.39 suggesting a possible loss of bromine to the gas phase.
- 5) Boron (B) a major element in geothermal steam, and fluorine (F) have yet to be analyzed in the samples.
- 6) Some differences were noted between the NAA and XRF analysis. The NAA analysis showed significant enrichment (>10) for arsenic in four surface samples that were not indicated by XRF analysis. Three of the aircraft filters that were analyzed by NAA showed little enrichment (<10) for arsenic. NAA showed five surface samples enriched with antimony that were not indicated by XRF.
- 7) The high enrichment of cadmium for the repeater sites on August 23 and 24 may have been due to resuspended material as a result of construction activity near the site. However, the NAA results do not show any significant enrichment for cadmium these days.

- 8) In general when one considers the enrichment above the possible background values in aircraft samples and at the surface the results appear a little inconsistent. However, the results do suggest that such elements as sulfate, copper, zinc, antimony, cadmium, selenium, mercury and arsenic may be transported from the Geysers at times. Lead, bromine and sulfate can be transported into the area from other sources but construction and vehicle activity at the Geysers can be sources for these materials as well.

4. TENTATIVE CONCLUSIONS

This limited surface and aircraft sampling study in the Geysers area of California has extended the ASCOT study beyond the nighttime studies of nocturnal drainage winds of previous years. In this study the role of daytime synoptic-mesoscale winds in relation to the transport of pollutants from the total area of the Geysers has been examined. The four-day study, although clearly insufficient to define all the aspects of the transport problem for the Geysers nevertheless has provided initial data regarding the short-range transport of tracers and pollutants from the Geysers geothermal operations.

The initial analysis of the SF_6 tracer transport data from the Geysers illustrates the importance that terrain, vertical wind shear, time-varying winds and stability can have on the downwind distribution of cooling tower effluents during the daytime. Atmospheric stability (neutral to unstable) and near-surface winds above 3 m/s results in fumigation and surface impaction of a portion of cooling tower plumes on downwind surfaces and terrain. Vertical wind shear and possible gravity waves in upper levels (~ 1800 - 2000 m m.s.l.), in addition to terrain influences assist in distributing plumes horizontally and in the vertical at relative short (~ 10 - 20 km) distances from the source.

The surface and aircraft sampling revealed that small quantities of gaseous sulfur, primarily H_2S , and a variety of trace materials may be transported from the Geysers area. In this study, only one day was observed to have gaseous sulfur concentrations above 30 ppb. On this day H_2S was detected as a distinct odor at 1500 m (m.s.l.) at around 4 km or more from the Geysers. Small quantities (ng/m^3) of trace materials such as sulfur (sulfate), copper, zinc, arsenic, bromine, lead, antimony, selenium and barium appear to be enriched above background levels and are transported downwind from Geysers area. Future work is anticipated to complete the analysis of remaining data and to assist in quantifying and expanding the results.

REFERENCES

- Grosch, M., W. Grosch, G. Wolf and H. Kreyling, 1978. "Quantitative Analysis of Mercury, Arsenic and Bromine in Atmospheric Aerosols." Atmos. Environ., 12:1235-1237.
- Gudiksen, P.H., 1982. ASCOT Data from the 1981 Cooling Tower Plume Experiments in the Geysers Geothermal Area. UCID-19332, ASCOT-82-4, Vols. 1 and 2, Lawrence Livermore National Laboratory, Livermore, California.
- Lynch, A.J., N.R. McQuaker and D.F. Brown, 1980. "ICP/AES Analysis and the Composition of Airborne Soil Materials in the Vicinity of a Lead/Zinc Smelter Complex." JAPCA, 30(3):256-260.
- Martin, J.B. et al., 1978. Environmental, Safety and Health Standards Identification for Geothermal Energy. Report 1: Airborne Emissions. PNL-2583-1, Pacific Northwest Laboratory, Richland, Washington
- Moyers, J.L., W.H. Zoller, R.A Duce and G.L. Hoffman, 1972. "Gaseous Bromine and Particulate Lead, Vanadium and Bromine in a Polluted Atmosphere." Environ. Sci. and Tech., 6(1):68-71.
- Rahn, K.A., 1971. Sources of Trace Elements in Aerosols--An Approach to Clean Air. Ph.D. Thesis and Ann Arbor Report C00-1705-9, University of Michigan, Ann Arbor, Michigan.
- Robertson, D.E., E.A. Crecelius, J.S. Fruchter and J.D. Ludwick, 1977. "Mercury Emissions from Geothermal Power Plants." Science, 196(4294):1094-1097.
- Uthe, E.E., 1982. Airborne Lidar Study of Plume Behavior in the Geysers Geothermal Area. UCID-19332, ASCOT-82-4, Vols. 1 and 2, Lawrence Livermore National Laboratory, Livermore, California.

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