Hawaii

Energy

Resource

Overviews

GEOTHERMAL

Supplement to Volume 4

The Environment:

3.   Impact: Air-Quality Data

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Areas of Concern

The following posed as questions, represent topics requiring additional evaluation, research or both:

- What kinds and quantities of data and what forms of analysis and modelling are required to carry out confusion-free baseline measurements in proximity to an active volcanic zone?

- How do micrometeorological and microtopographic features of the Puna District affect the dispersal of emissions from a geothermal power station?

- Independent of contained toxicants, how does localized deposition of steam condensate affect exposed organisms, especially with respect to susceptibility to fungi and bacteria?

- Is the prediction of multi-well field compositional impacts based upon multiplication of single-well composition and impact a valid procedure?

- Similarly, can predictions from sites and fields to regions be effected by use of simple scale-up multipliers?

- Are the biota and ecosystems of a volcanic community pre-selected by colonization for resistance to toxic gases and gas mixtures?

- What are the major compartments, transfer numbers and fates of geothermal toxicants in the Puna district?

Aerometry at HGP-A dates back to May, 1975. At that time, a semi-cleared area existed around the prospective drill site but no heavy equipment had yet located there. The area adjoins Pohoiki Bay Road, a connection between Pahoa and the Black Sand beach but was then and is now little travelled. At no time have ambient levels of CO exceeded 1 ppm, even when heavy diesel-powered equipment was in use. Similarly, NO_x concentrations have not reached the 0.1 ppm level, nor would the low traffic density lead one to expect significant levels of N-oxides, or other oxidants.

Within the sensitivity limits of tube detectors, both SO_2 and H_2S were monitored from the 1975. Occasional H_2SO_4 aeresol measurements have been taken, but in general, acidity is a potential problem only where sustained fumerolic emissions are in evidence or periodically at more remote locations as a consequence of volcanic eruptions (see above).

In addition to sulfur gases, evidence for atmospheric introductions of mercury and arsenic has been sought. As (III) arsine has not been detected using sample volumes in excess of $0.5m^3$ collected over approximately 4 hr periods. Even in the plume at ca 3 m distance from the separaters, tube detectors sensitive to 0.5 ppm are also negative. The recommended As (III) air standard is 0.05 ppm (24 hr average).

The initially relatively less sensitive detector tube procedures for SO_2 and H_2S showed no change from the predrilling stage of May '75 through subsequent periods of flow and steam

production tests up to the most recent measurements of January 1980 (Table 1). Even with more sensitive methods, the lowered detection limits of 30 ppb were not attained at 100 m downwind from the well head.

The assessment of the wells' contribution to air mercury levels was complicated by the relative proximity of active natural emission sites. Thus, in July 1976, when the well was flashed for the first time, the downwind mercury level apparently rose to 9.9 $\mu g \cdot m^{-3}$ from a previous month's value of 1.0 $\mu g \cdot m^{-3}$, and remained high into November of the same year (Table 1). In late June 1976, when the HGP-A ambient was low, the Kilauea fumeroles raised the air level at the Sulfur Bank to 47.5 $\mu g \cdot m^{-3}$ from a level of 7.6 $\mu g \cdot m^{-3}$ the previous month. And in November, at HGP-A shut down, the Sulfur Bank area still measured 17.4 $\mu g \cdot m^{-3}$. A delay of several weeks in high Hg levels between HGP-A and the Sulfur Bank area serve 40 km to the west may have been wind-related. In October, 1977, when the Sulfur Bank rose to 11.3 $\mu g \cdot m^{-3}$ from an all-time low of 0.2 $\mu g \cdot m^{-3}$, a 6-fold rise from its level of 2 months earlier.

The upsurge of air mercury levels during flashing was originally thought to have been a "burst" releasing accumulated mercury at depth. During the July 1976 testing, it was not known that in addition to Sulfur Bank activity a new East Rift Zone emission center — the Heiheiahulu spatter cone about 13 km to the west of the well — had been active for two months. Subsequently this cone was tested and found

to be a highly intensive mercury emitter and one of the probable sources of the relatively high level recorded at the flashing of HGP-A. Subsequent measurements, made in July-September 1977, show the presence at the well site not only of air mercury but also of H_2SO_4 -- although the well itself had been shut down since May 1977. The presence of these toxic gases can only be ascribed to natural area contamination, not emanating form the well itself.

Tests conducted since drilling of HGP-A began have yielded no evidence of a sustained build-up of mercury or any other potentially toxic elements at or around the well site that can be attributed to geothermal energy development operations. The conclusion reached by the researchers is that "there is no reason to assume that HGP-A itself has negative emission features other than H_2S and noise, but is influenced by its proximity to natural geotoxicant sources (Siegel and Siegel, 1977).

The dependency was well illustrated in the chronology of the 1977 Kalalua eruption by comparing air mercury levels at various Kilauea sites with those at HGP-A before, during and after the main eruptive events (Fig.1).

Mercury analyses of steam condensates reveals relatively high start up levels followed by rapid approach to an asymptotic emission rate of approximately 1 g per 24 hrs corresponding to approximately 100 K lbs.hr^{-1} mass flow after an operating time >10 hr (Fig.2).

Table 1. An Aerometric Chronology at HGP-A

Date	Well Status	Sulfur Bank Air Value ($\mu g \cdot m^{-3}$ Hg)	HGP-A Air Values (100 m) SO_2 ppb	H_2S ppb	Hg $\mu g \cdot m^{-3}$
May '75	Pre-drilling	2.6	<500*	<200+	1.1
May '76	Post-drilling	7.6	<500	<200	1.2
June '76	1st flow test	47.5	<500	<200	1.0
July '76	Flashing	-	<500	<200	9.9
Nov. '76	Shut down	17.4	-	-	10.0
Apr. '76	Shut down	-	<500	<200	-
July '77	Shut down	4.6	<300	<200	0.8
Aug. '77	Flow test	0.2	<300	<30‡	0.8
Oct. '77	Shut down	11.3	<300	<30	4.8
July '78	Shut down	3.8	<300	<30	1.2
Nov. '79	Shut down	6.0	<30**	<30	1.3
Jan. '80	Flow test	-	<30	<30	0.8

*ppb <500 and <300 denote detection limit values for tube SO_2 methods

**ppb <30 denotes detection limit value for instrumental SO_2 methods

+ppb <200 deonots detection limit value for tube H_2S methods

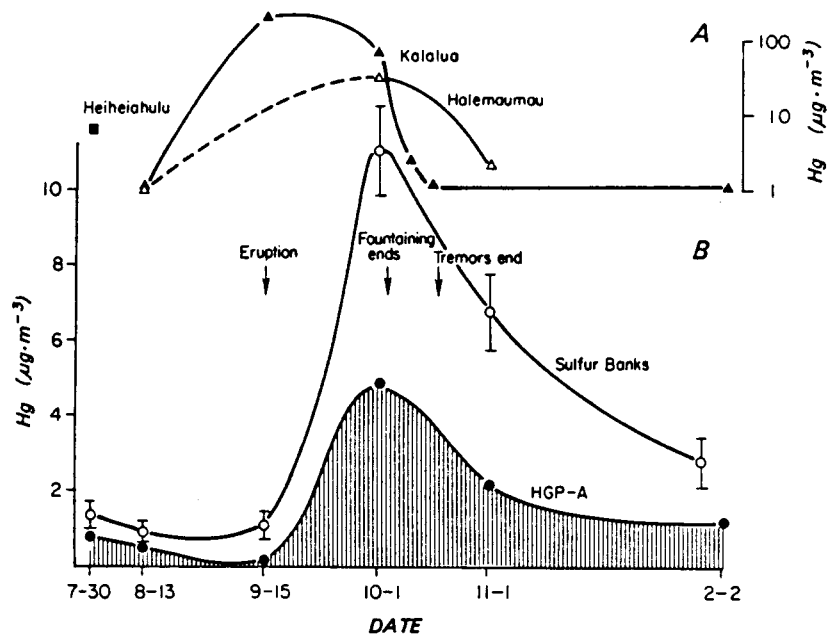‡ppb <30 denotes detection limit value for ROTEC and Houston Atlas instruments.

Figure 1 .   Time course of air mercury increase at Kilauea
sites and HGP-A during the period of the 1977 Kalalua
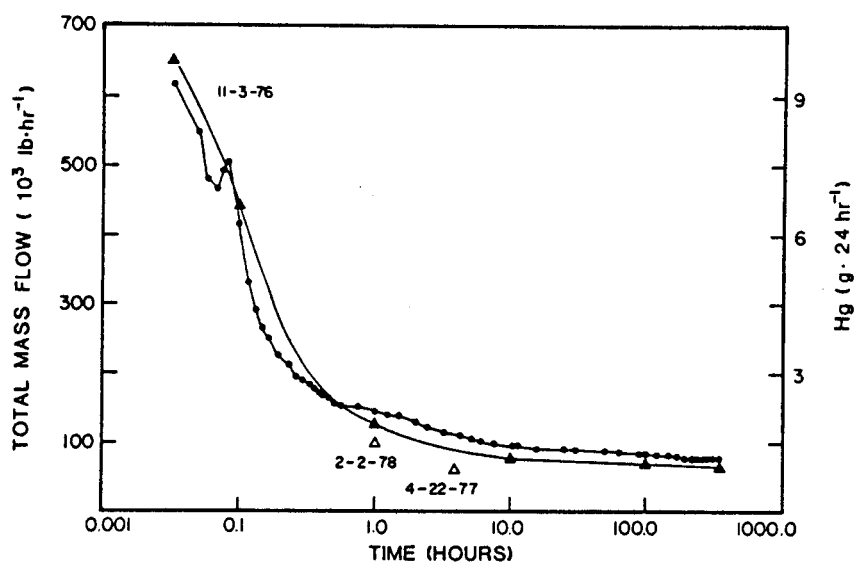eruption.

Figure 2. Relation between mass flow of geothermal fluid and release of atmospheric Hg at HGP-A.

Reference may be made here to EPA National Emission Standards
121:0461, 1976:

Incineration of wastewater, sludge

Hg allowed, 1600 g per day

Coal fired power plant

Hg allowed, 2300 g per day

Typically, Puna District residences make use of roof
top water catchments. On April 7, 1977, following an extended
8 month period of flow tests, flashings and shut downs, local
residents, near HGP-A voiced to the Hawaii County Council
their objections to derous H_2S emissions and to the introduction,
alledgedly, of toxicants into the rooftop water supplies. In
response, the District Health Office for Hawaii County under-
took an analysis of catchment water supplies. Five private
residences were selected, three downwind relative to the
normal tradewinds and 0.8-1.6 km from HGP-A; one somewhat
more distant (3.5km) and WNW from the wellhead, and one
"control" house over 8 km distant and slightly West of due
North from HGP-A (Fig., 3 , Table 2). The most serious
complaints originated from the Nanawale Estates (Reich, r-)
and to a lesser extent from the Leilani Estates residents
South of the Kuhera house (k). The results of analysis are
all within safe water quality standards for human use.

e. HGP-A Well Chemistry: Radon

i. Report of Paul Kruger, Dept. of Civil
Engineering, Stanford University 15 February, 1978

An experiment to test the feasibility of studying radon

Table 2 . State of Hawaii Department of Health Rooftop
Water Catchment Analyses near HGP-A
(Downwind Sampling, 19 April 1977)

SITE		Analysis (mg·ℓ^{-1})						
Residence (map code)	Distance HGP-A (km)	SO_2	H_2S	F^-	$SO_4^=$	NO_3^-	AS	HG
Daniels (d)[*]	>8	1.0	ND	ND	ND	ND	ND	ND
Hughes (H)	0.8	1.0	ND	ND	ND	0.038	ND	ND
Kubera (K)	1.1	1.3	ND	ND	ND	ND	ND	ND
Rothblum (rb)	1.6	0.4	ND	ND	ND	ND	ND	ND
Reich (r)	3.5	0.2	ND	ND	ND	ND	ND	ND
40 CFR 142 or USPHS Recommended Limits for Potable waters for human use.		none	2×10^{-4}	2.4	250	10	0.05	$<2 \times 10^{-3}$

[*]"Control" residence
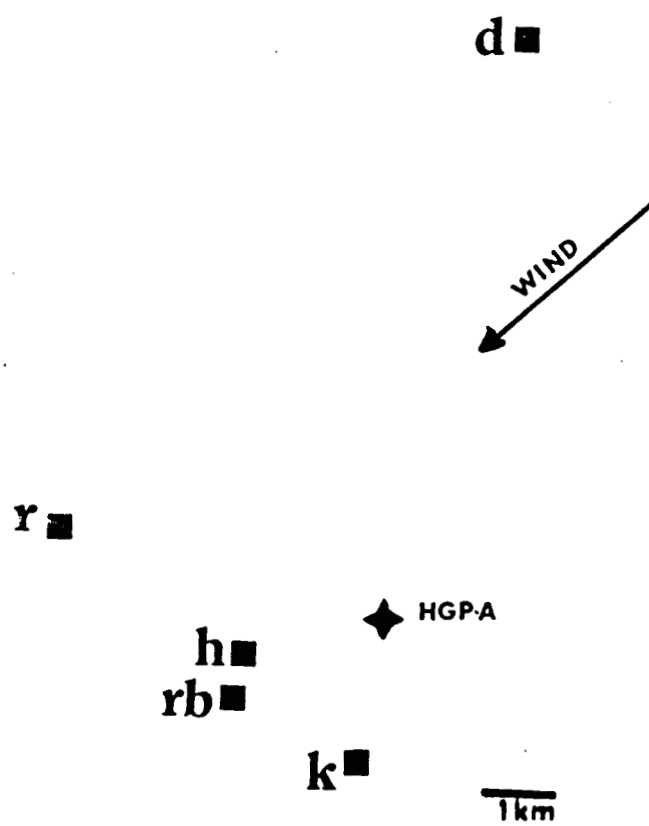
d ■

WIND

r ■

♦ HGP·A

h ■
rb ■

k ■

1 km

Figure 3. Site distribution for rooftop rain water catchings
in relation to HGP-A downwind direction.

Table 3. Reservoir Radon Project HGP-A Puna, Hawaii
July 19, 1977
Sample Collection Data

Time (HST)	Sample No.	Bottle No.	P_{wh} (psig)	T_{wh} (°C)	Weir ht H(in)	P_{lip} (psig)	Orifice (in)
1133	Start		10	123	0	0	8
1205	1	1-3471	148	188	7.5	58.5	
1235	2	18-3290	122	180	6.75	46.0	
1305	3	13-3132	111	176	6.40	41.1	
1320	4	17-3125	105	175	6.31	39.0	
1335	5	11-3134	101	173	6.25	37.5	
1335	6	-3128	101	173	6.25	37.5	
1336	Stop						8
1422	Start		170	183	0	0	1.75
1455	7	5-3462	295	211	5.5	7.0	
1525	8	18-3432	365	225	5.5	7.5	
1555	9	19-3466	385	227	5.5	8.5	
1625	10	12-3131	395	229	5.5	8.5	
1636	Test aborted						1.75

Table 4 . Reservoir Radon Project HGP-A Puna, Hawaii July 19, 1977
Russell James Flow Calculations

Sample No.	Weir Ht (in)	W (klb/hr)	P_g (psig)	$\dfrac{W}{P^{0.96}}$	h (Btu/lb)	Q_t (klb/hr)	Q_s (klb/hr)	X
1	7.5	162	58.5	2.626	700	363	201	0.55
2	6.75	124	46.0	2.415	720	295	171	0.58
3	6.4	109	41.0	2.292	736	265	156	0.59
4	6.31	105	39.0	2.296	730	258	153	0.59
5,6	6.25	103	37.5	2.303	733	250	147	0.59
7	5.5	74.6	7.0	3.886	602	134	59	0.44
8	5.5	74.6	7.5	3.802	600	137	62	0.46
9	5.5	74.6	8.5	3.645	617	139	64	0.46
10	5.5	74.6	8.5	3.645	617	139	64	0.46

concentration dependence on flow rate conditions in an

undeveloped, steam-flashing reservoir was carried out at

the HGP-A geothermal well in Puna, Hawaii on July 19, 1977.

The well had been shut-in for an extended period under a

local agreement to restrict flow testing of the well to a

maximum of 4 hours per day. The test consisted of flowing

the well for a total period of 4 hours, two hours with an

8-inch orifice plate providing maximum flow rate and two hours

with a 1-3/4" orifice plate providing almost minimum flow

rate. Orifice plate change consumed about 46 minutes, not

sufficient to result in significant cooling of the wellbore

system.

The test was accomplished by sampling the main steam line

at the wellhead with evacuated bottles at half-hour intervals

over the two 2-hour flow-rate periods, and recording the

wellhead conditions and flow rate by the Russel James method

(1962). The sample collection data and the calculation of

flow rate by the James method are given below (Tables 3 and 4).

The radon analysis data (Table 5) and the radon, flow

rate at the 8" orifice to a value of about 250 klb/hr

consistent with a corresponding decrease in wellhead pressure

and radon concentration, except for the last sample at 1335

HST. After the orifice plate change of 46 minutes, the well

exhibited a reasonably steady flow rate, while the wellhead

pressure rose to a maximum. The radon concentration showed

a time profile similar to that at the larger flow rate.

Preliminary analysis of the data was made under the

Table 5. Reservoir Radon Project HGP-A Puna, Hawaii
July 19, 1977
Radon Analysis Data of Collected Samples

Time (HST)	P_{WH} (psig)	T_{WH} (°C)	Q (klb/hr)	Rn (pCi)	V_c (ml)	(Rn) (nCi/l_c)
1205	148	188	363	129	111	1.16
1235	122	180	295	85	98	0.87
1305	111	176	265	75	99	0.76
1320	105	175	258	68	90	0.76
1335	101	173	250	154(?)	65	2.4
1335	101	173	250	44	48	0.92
1455	295	211	134	453	470	0.97
1525	365	225	137	428	531	0.81
1555	385	227	139	368	485	0.76
1625	395	229	139	428	495	0.86

general evaluation of radon as an internal tracer for geothermal fluid transport. Radon measurements are useful for study of geothermal reservoir behavior (Stoker and Kruger, 1975). A review of some of the data potentially derivable by radon concentration measurement was reported by Kruger, Warren, and Honeyman (1977). Among them are experiments focused on the relationship between radon concentration and flow regime in producing geothermal reservoirs. Steady-state production should result in steady-state contration of radon on the basis of a constant emanation of radon from the formation and a constant permeability field in the reservoir. Serveral models can be derived depending on radon emanaiton from three types of source: (1) hydrothermally-deposited radium close to the wellbore; (2) radium in a boiling liquid below some liquid-steam interface; and (3) radium present in the pathway from steam source to the well.

Data obtained for vapor-dominated reservoirs, such as The Geysers in California and Larderello, Italy suggest a relationship in which the radon concentration changes directly with change in flow rate; the transient time dependent on reservoir characteristics. The model of flow rate dependence of Stoker and Kruger (1975) for liquid-dominated reservoirs as confined horizontal flow is based on a derivation of the relationship between radon concentration and flow rate in which the radium concentration is uniformly deposited in a large reservoir. For these conditions, the radon concentration should show transients with flow rate

proportional to $(1 - e^{-\lambda\tau})$ and for steady state flow show an equilibrium value independent of Q.

A comparison of the radon concentration and flow rates for the HGP-A well test is given in Table 6 . In contrast to the tests at the vapor-dominated fields at The Geysers and Larderello where the ratio (Rn)/Q was approximately constant over large changes in Q, in this test the radon concentration was approximately the same over a change of about a factor of 2 in Q, in agreement with the liquid reservoir model. These short-period data suggest that the drainage from the HGP-A reservoir follows a radial flow pattern over a large reservoir in which the concentration of radon does not depend strongly on flow rate (Stoker and Kruger, 1975).

The transient form of the relation has a factor of $(1 - e^{-\lambda\tau})$ where t can be expressed by the volume swept by the flow rate, Q. If the volume swept, V_ϕ, does not depend strongly on Q, the change in concentration will vary according to $(1 - e^{-a/Q})$, where $a = \lambda V_\phi$. To verify such a radon concentration change with change in flow rate, a longer experimental period is proposed.

For a radon half life of 3.8 days, three fourths of saturation equilibrium is attained in one week. Therefore, a test of two-week duration is suggested, one week at 8" orifice plate flow conditions and a second at 1-3/4" orifice plate flow. During the two-week period, sufficient samples will be taken at each flow rate to ensure a mean standard deviation of less than ±3% (12 samples at each flow rate

Table 6. Chamber Simulation Tests for the Phytotoxicity of·Atmospheric Mercury

Form of Hg tested	Plant Response	Coleus		Oleander		Castor Bean	
		Hg Concentration (µg·m^{-3})					
		10	50	10	50	10	50
None (10 days)	Chlorosis (% leaf surface)	0		0		7	
	Necrosis (% leaf surface)	0		0		0	
	Abscission (% leaf drop)	3		3		10	
Hg^0 (7 days)	Chlorosis	0	3	0	0	0	12
	Nicrosis	0	2	0	0	3	12
	Abscission	13	47	22	94	7	36
HgCl$_2$ (7 days)	Chlorosis	0	0	0	0	0	10
	Necrosis	0	6	2	10	9	23
	Abscission	0	4	4	8	0	0
Hg (CH$_3$)$_2$ (1.5 days)	Chlorosis	0	0	0	0	10	26
	Necrosis	0	8	3	12	5	15
	Abscission	11	32	8	24	14	32

The above results were arrived at as follows:

The average radon concentration in samples of the well fluids collected under restricted production (137 K lb H_2O/hr) was 0.85 nano curies of radon per liter of water collected . The first assumption to be made is that radon is strongly partitioned into the vapor phase when the well fluids are flashed to steam (i.e., all the radon is in the gas phase ane none in the liquid). If one·then assumes that all the water collected was condensed from steam, then the radon produced by the well is calculated as 0.85 n Ci/ℓ x 62 K lb/hr steam x 0.455 ℓ/lb = 23.9u Ci Rn/hr.

If one assumes that the water samples collected was a mixture of steam and unflashed well fluid a correction must be made to remove the water fraction; this correction is made by multiplying by the inverse of the steam quality (total discharge/steam discharge). For the present case, this factor is 2.21. Thus:

Radon discharge = 0.85 n CiRn/ℓ x 62 K lb/hr x 2.21 x

0.455 ℓ/lb = 52.8 uCi Rn/hr.

The calculation of radon concentrations in the air at the well site and down wind was made through the use of H_2S as a "tracer" for radon. The assumptions made for this calculation are (1) the H_2S and Rn partition ratios between the liquid and flashed steam phases are similar and (2) that atmospheric dilution of radon will be similar to that for H_2S.

based on a conservative individual relative standard
deviation for a single sample of ±10%). The experiences
gained during this first feasibility test indicates that
the proposed next experiment can be run successfully. The
standard deviations of the means at both flow rates should
be sufficiently small to see if a dependence of effluent
concentration with $1 - e^{-a/Q}$ exists.

ii. Report of Donald Thomas, Hawaii
Institute of Geophysics (20 September
1978)

In regard to the radon radiation hazard presented by HGP-A,
the radon concentrations in the well fluids have been determined
by Dr. P. Kruger at Stanford University. These concentrations
have been used to calculate the expected total radon output of
the well per hour as well as the expected radon concentrations
both a the well head and at a distance of 0.15 km. The results
of these calculations are as follows:

Total radon = 23.9 uCi Rn/hr (during "normal"
production)

= 192 u Ci Rn/hr (full discharge, worst
case).

Radon concentration = 6.68×10^{-3} p Ci Rn/ℓ air at
at well head   well head (during normal discharge)

Radon concentration = 5.01×10^{-5} p Ci Rn/ℓ air
at distance of   (during normal discharge)
0.15 km

= 6.8×10^{-5} p Ci Rn/ℓ air (full
discharge, worst case)

Note that EPA guidelines for upper levels of radon concentration
in habitable structures is 0.5 p Ci Rn/ℓ air (O'Connell and
Gilgan, 1978).

The H_2S concentrations in the well discharge is approximately

650 ppm while atmospheric concentrations of H_2S at the well

head are approximately 4 ppm. Assuming the same dilution

factor for radon, one may calculate:

0.85 n Ci Rn/ℓ_c = 0.85 p Ci Rn/gc 0.85 p Ci Rn/g x 4/650 =

0.0052 pci Rn/gm air

the average molecular weight of air is 28.8 g/mole and thus

one liter of air weighs 1.284 g.

5.2×10^{-3} p Ci Rn/gm air x 1.28g/ℓ = 6.68×10^{-3} p Ci Rn/ℓ.

The H_2S concentration at 0.15 km from the well head was found

to be 30 ppB. If one assumes a dilution of radon by a similar

factor (7.5×10^{-3}) the radon concentration at 0.15 km is:

6.68×10^{-3} p Ci Rn/ℓ x 7.5×10^{-3} = 5.01×10^{-5} p Ci Rn/ℓ air

The worst case calculation is done similarly using the higher

radon concentration (1.16 p Ci Rn/ℓ).

As mentioned above, EPA guidelines for habitable dwellings

is 0.5 p Ci Rn/ℓ air and is higher by nearly two orders of

magnitude than the levels observed at the well site and by

nearly four orders at a distance of 0.15 km.

iii. Report of Phillip Manly, Gamma Corporation, Honolulu, Hawaii (2 February, 1979)

Radon-222, being a naturally-occurring isotope is regulated

only by State Department of Health and Department of Occupa-

tional Safety and Health (DOSH) regulations. The regulations

of the Nuclear Regulatory Commission do not apply because the

isotope is not by-product or source material. Standards set

by the Environmental Protection Agency for drinking water

apply to radon only to the extent that radon daughters dissolved

in water must meet the alpha activity limits.

The State Department of Health regulations (Chapter 33) set occupational limits on radon and its daughters in air of 30 pCi/l for a 40 hour week and 10 pCi/l for a 168 hour week. For areas where the general public may have access, the limits are set lower by a factor of 10.

The limits set by DOSH for occupational workers are the same as those set by the Department of Health. However, the DOSH regulations also introduce the concept of working level, where one working level is equivalent to 1.3E5 MeV/l of alpha activity from any combination of alpha emitting daughters of radon. The concept of working level was developed for use in uranium mines, where radon and its daughters were always present, but hardly ever in equilibrium. Measurement and calculation of air activity was made simpler when only total alpha activity had to be measured, without relating it to air concentration of radon.

Kruger measured an average radon activity in steam condensate of 890 pCi/l and 850 pCi/l for the two tests he made (Kurger, 1977). Donald Thomas used these data, along with data on the hydrogen sulfide concentration in the steam, at the well-head, and at the perimeter, to estimate worst case air concentrations of 9E-3 pCi/l at the well-head and 6.8E-5 pCi/l at the facility perimeter (Thomas, 1978).

An alternate method for calculating worst case concentrations involves calculating the radon activity in the steam itself. The steam condensate concentrations are divided by

1670 (the volume ratio of steam to water) and multiplied by

2.21 (the steam to total discharge ratio) to obtain an

estimate of the air activity at the well-head:

$$A (pCi/l) = \frac{(890 \; pCi/l) \; (2.21)}{1670}$$

A (pCi/l) = 1.2 pCi/l   (well-head radon activity)

Using the hydrogen sulfide ratio from well-head to facility

perimeter (4 ppm/30 ppb = 133) the activity at the facility

perimeter can be estimated at:

$$A (pCi/l) = \frac{1.2 \; pCi/l}{133}$$

A (pCi/l) = 0.009 pCi/l   (facility perimeter radon activity)

The worst-case estimates for radon activity at the well-

head are a factor of 25 below the allowable limits for

occupational workers, using a 40 hour work week. In

addition, the estimates of radon activity at the facility

perimeter are a factor of 1000 below the allowable limits

for non-occupational workers, using a 168 hour residence

time. According to the regulations, only when estimates

of the exposure exceed 25% of the applicable limits should

a monitoring program be instituted to monitor exposure.

Such a program is clearly not necessary.

Situations could develop after additional construction

of facilities that could allow concentration of radon

daughter activities and lead to higher exposures. If the

steam were routed into a closed building (e.g. turbine

building) in which the radon could escape, then the par-

ticulate radon daughters might collect in the building in

concentrations much higher than estimate above. In such cases,
additional measurements of actual radon daughter activities
should be performed to determine the actual radon and radon
daughter activity levels.

Radon is continuously released from the ground. A world-
wide flux average for the radon flux is 4.25E-5 pCi/cm^2-sec
(Wilkening, et. al., 1972), or 0.095 $Ci-mi^2$-day. Some data on
uranium activity in local soils indicates that the local flux
may be 10 times less than the worldwide average (McMurtry, 1979).

At full power production the HGP-A well will be producing
3.5 MWe of power, with a steam consumption of 60,000 lbs/hr.
The release of radon from the well is estimated to be:

$$Rn \ (Cn/da) = 60,000 \ lbs/hr)(.455 \ 1/lb)(0.89E-9 \ Ci/1)$$

$$x \ (24 \ hr/da)$$

$$Rn \ (Ci/da) = 5.8E-4 \ Ci/da \ (activity \ released)$$

This release is equivalent to the release of radon from
between one tenth and one square mile of land. Although on a
worldwide scale the release is minimal, it may cause a local
purturbation in the activity levels of radon and subsequent
increase in radiation exposure.

A study has been performed comparing the radioactivity
release of coal-fired power plants with the release from nuclear-
powered plants and the new federal regulations (McBryde, et. al.,
1979). In this study, the radon released from a 1000 MWe coal-
fired plant were estimated at 0.4 Ci/yr. This release, along
with releases of other uranium and thorium isotopes, resulted

in higher population dose estimates than the emissions from a 1000 MWe nuclear-powered plant. By comparison, the HGP-A will release 0.2 Ci/yr. of radon.

After the steam is condensed, it will be allowed to percolate back into the groundwater. Depending on the time that the radon daughters have grown in from the radon in the steam before the radon was off-gassed, the activity levels in the condensate may exceed the 15 pCi/l limit for drinking water established by the EPA (the measured activity in steam condensate was 890 pCi/l). This addition of radon daughter activity to the ground water may cause in increase in alpha activity of drinking water at a well near the geothermal well.

From a preliminary assessment of the radon measurements made of steam condensate, it was concluded that the radon presented no hazard either to occupational workers or to the general public. The environmental impact was also estimated to be minimal on a worldwide scale. However, because of lack of data on the existing natural environment, the extent of the environmental impact on a local scale could not be determined. Additional sampling was recommended to determine the existing radon environment, and to measure any impact to it from the operation of the HGP- well.

b. Mercury

The addition of soil and water mercury analyses to
the techniques for geothermal exploration was implicity in
the early demonstration that the element is associated
with volcanic and fumerolic activity. (Eshleman et al,
1971; Aidin' yan and Uzerva, 1966, Karasik and Morozov, 1966)
and extensive later studies in widely separated volcanic
systems (Siegel and Siegel 1979 a,b,c; Brill et al. 1979,
McMurtry et al 1979, 1980, Siegel et al 1979, Siegel et al
1980 a,b, Phelps et al 1979).

Specific use of mercury in the condensed phase was
suggested by Matlick and Burseck (1975). Soil and ground-
water surveys were discussed in the Final Report in DOE/
ID/01713-5, Hawaii Geothermal Resource Assessment Program
(Investigation of Low Temperature Resource on the Island
of Oahu, Hawaii). In a study of the Lualualei Valley,
Waianae Coast, Oahu, the report states "The ability of
soil mercury to assist in defining areas of subsurface
thermal activity in areas which have no other obvious
surface manifestations has led to the application of this
technique. . .". It further concluded that in general soil
Hg patterns arise from thermally driven outgassing; that
mercury and radon outgassing are broadly associated, and
that ground water and soil mercury levels are closely
correlated.

Some 10 years of "roadside" sampling for atmospheric
mercury onthe four major islands also suggest the indicater

value of Hg aerometry. Understandably, air sampling at

the one meter level is subject to the usual atmospheric

perturbations. These include not only winds and convective

processes, but also the masking effects of intense sources.

Thus, Hawaii itself, with intense emissions on Mauna Loa,

at Kilauea and along Kilauea East Rift influences air levels

over the entire ESE to WSW sector of the Island, with only

NE-facing areas near baseline levels (Fig. 4).

In the case of Maui, of the six areas recognized by

standard geophysical-geochemical methods, two can be closely

confirmed by air sampling, especially the Haleakala SW rift,

two additional areas in broad agreement and two negative

(Fig. 5 Table 7).

On Oahu, the two most promising areas, one on the

Windward coast, one on the leeward Waianae coast are shown

by both procedures (Fig. 6).

And on Kauai, there are possible air Hg anomalies in

the post-erosional volcanic area, but also one unexplained

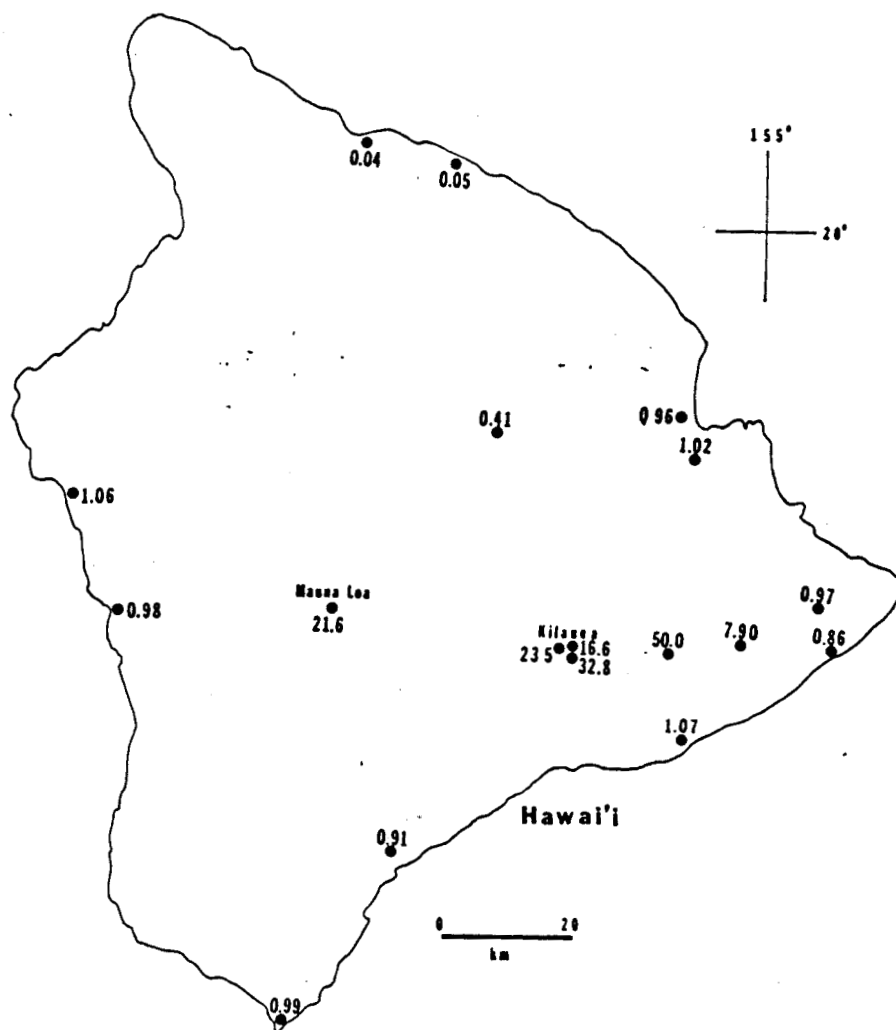high at the head of Waimea Canyon (Fig. 7).

Figure 4. Atmospheric mercury distribution on the Island
of Hawaii. All values in $\mu g.m^{-3}$ are means of 4-40 deter-
minations over the period 1970-1979. Standard errors are
$\pm 20\%$ of their means or less.

Figure 5. Atmospheric mercury distribution on the Island of Maui. All values in μg.m^{-3} are means of 3-10 determinations over the period 1973-1979. Standard errors are $\pm$20% of their means or less.
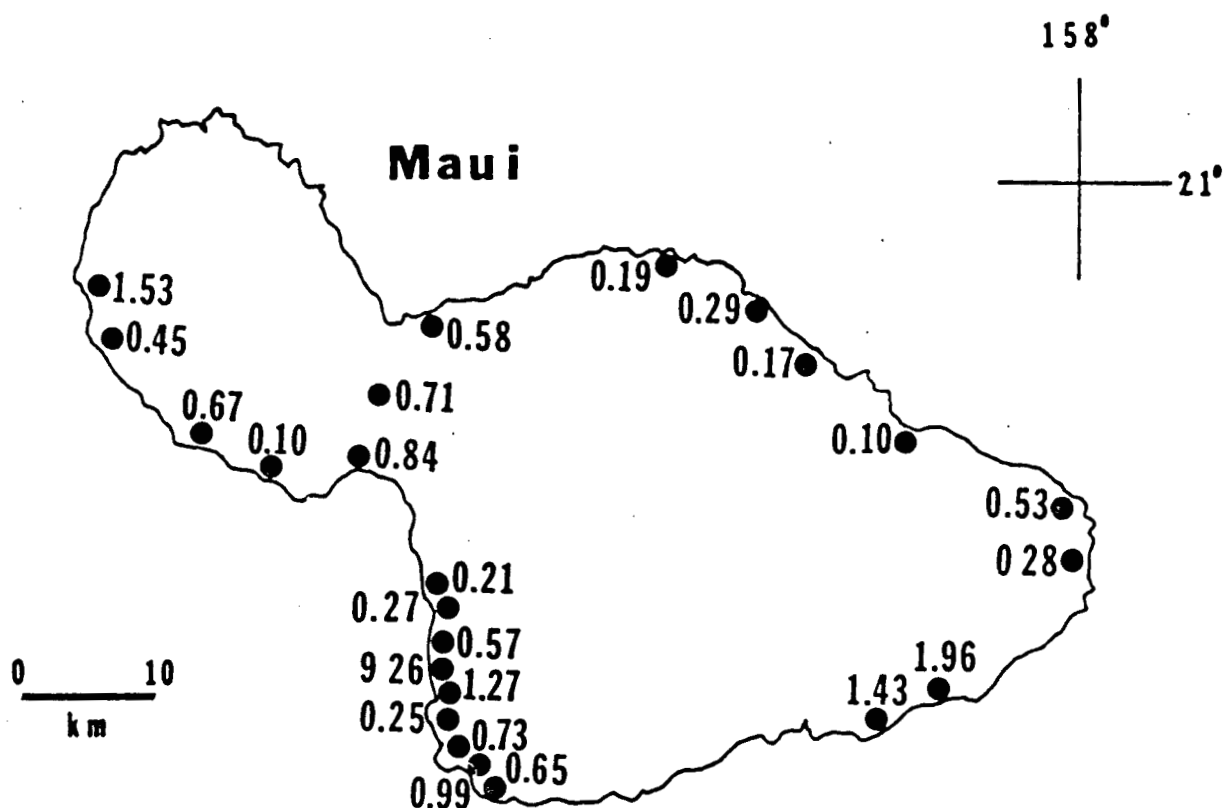
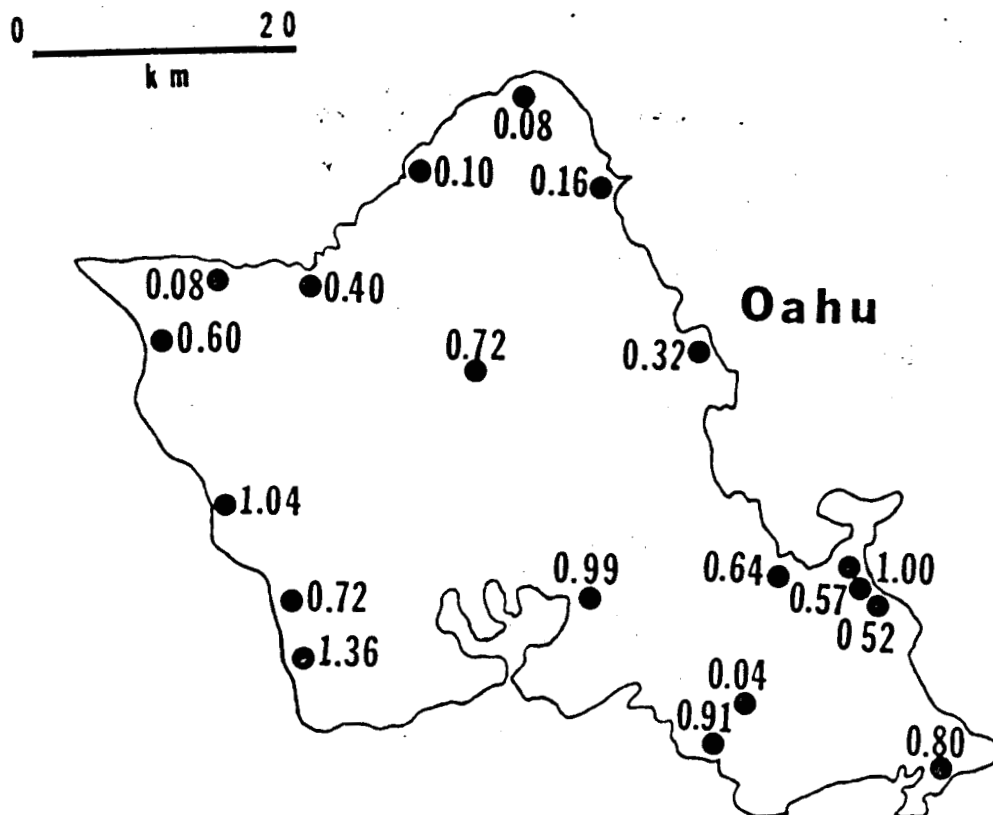Figure 6. Atmospheric mercury distribution on the Island
of Oahu. All values in $\mu g \cdot m^{-3}$ are means of 3-10 determin-
ations over the period 1969-1979. Standard errors are
$\pm 20\%$ of their means or less.
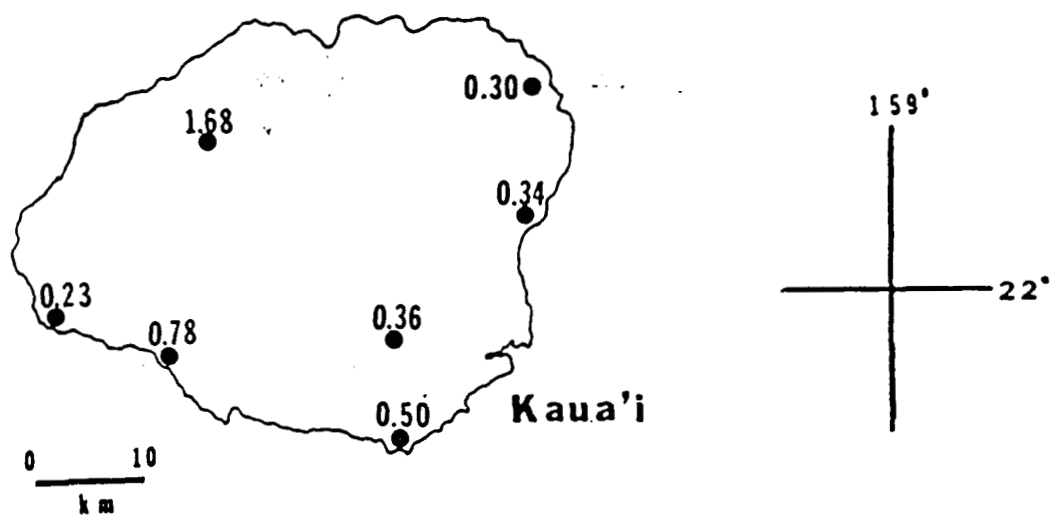
Figure 7. Atmospheric mercury distribution on the Island of Kauai. All values in $\mu g \cdot m^{-3}$ are means of 3-6 determinations over the period 1975-1979. Standard errors are $\pm 25\%$ of their means or less.

Table 7. Value of Mercury Aerometry in Geothermal
Exploration: A Comparison for the Islands
Lacking Current Volcanic-fumerolic Activity

Island	Sites By Standard Methods	Sites By Hg-Aerometry
Maui	Haleakala - SW Rift (1)	+
	Haleakala - E Rift (2)	±
	Pauwela (3)	−
	Lahaina (4)	±
	Olowalu-Ukumehame (5)	−
	Honokawaii (6)	+
Oahu	Waimanalo	+
	Lualualei	+
	Honolulu Volcanic	−
	Haleiwa	−
	Laie	−
	Pearl Harbor	−
Kauai	Post-Erosional Volcanic	±

Thus, in spite of its more fugitive character; Hg aerometry; a simple and inexpensive analytical procedure has genuine promise as an adjunct for exploration. As pointed out, the more detailed measurements taken at Lualualei support this conclusion.

Table 8. Environmental Toxicant Output in Relation to Scale-Up of Geothermal Energy Production

Energy Output megaWatts	Scale Factor		Possible Sources	Hg Emission[*] $g \cdot 24 \ hr^{-1}$	H_2S Emission[**] metric tons $\cdot yr^{-1}$ Abatement %		
					0	97	99
3	1	(Kapoho)	1	1.09	277	8.3[+]	2.8[‡]
25	8.33	(Kapoho)	1	9.13	–	69.1	23.3
200	66.6	(Kapoho)	1	72.6	–	562.8	186.5
500	166.6	(Kapoho)	1	181.6	–	1383.	466.2
1000	333.3	(Hawaii)	4	363.	–	2766.	932.
3000	1000	(State)	10	1089.	–	8298.	2796.

[*] 0.001 ppm wellhead maximum at 100 kilo-lb $\cdot hr^{-1}$, Steam Qual. 0.6
[**] 700 ppm wellhead maximum at 100 kilo-lb $\cdot hr^{-1}$, Steam Qual. 0.6
[+] current, using Caustic Soda and rockpile Sparger system
[‡] Projected for completed generator facility.

c.   Scale-up

Under current projections HGP-A will be a producing 3

megawatt (electric) generating station in 1981, operating

at a mass flow of 100k-lb·hr^{-1} with a steam quality of $\underline{ca}$ 0.6.

As of January, 1980, the well fluid contained about

0.001 ppm of Hg (very high estimate) and 700 ppm H_2S.

If it is assumed·that the Kapoho.reservoir is chemically

homogeneous, and that HGP-A is a representative sample of

that hydrogeothermal field, then the scale-factor for any

future generating capacity, megawattage projected/3megawatts

current can be used for projecting mercury and hydrogen sul-

fide emissions.

The most immediate future goal for geothermal develop-

ment at Kapoho is 25 megawatts. This intermediate step would

be followed, if performance and economic resources warrant,

by development into 200-500 megawatt range. The latter is a

projected ceiling for the Kapoho reservoir based on continuous

operation into the late 21st century.

Beyond this single highly promising reservoir are the

additional hydrogeothermal fields on the Island of Hawaii,

with perhaps a potential of 1000 megawatts and a total ceiling

value for the state lying between 2000 and 3000 mW.

Following present chemical emission standards, two

potential limits to the overall development of geothermal

energy resources are mercury and hydrogen sulfide. These

limits are embodied in the EPA's National Emission Standards

121:0461 (1976) and the more recent 40CFR 51.24, Fed. Reg.

43 (118):26382 (1978), the _1977_ _Clean_ _Air_ _Act_; _Prevention_ _of_
Significant _Air_ _Quality_ _Deterioration_ (PSD).

The former sets upper limits on Hg output of 1600 or
2300 g per 24 hr. period, depending upon the nature of the
facility. Using HGP-A as the operating model and assuming
the Kapoho reservoir to be broadly representative of reservoirs,
no amount of scale up, seems capable of attaining emissions
limits for Hg (Table 9),even on a state-wide level. And it
is reasonable geochemically to expect the highest Hg levels
to be associated with the Island of Hawaii.

The PSD limit for geothermal H_2S from any specific source
is 250 tons per year. For present purposes, we define the
Kapoho field as a source, hence, the 250 ton limit would ap-
ply not only to HGP-A as a generating facility, but to all
subsequent wells and power stations on the Kapoho reservoir.
Obviously, HGP-A itself, unabated is itself marginal assuming
continuous operation at a mass flow of 100 Kilo-lb$\cdot$hr^{-1} and
that the 700 ppm H_2S content is a steady state value under
operating conditions.

Results of the well tests completed in January, 1980,
show that of the 700 ppm wellhead H_2S, 22 ppm are released
after caustic soda treatment and the use of the rockpile
sparger system (L. Lopez, Geothermal-Generator Project Personal
Communication, February, 1980). This gives an abatement value
of 97%. At this efficiency, any power rating up to _ca_ 90
megawatts would fall within PSD limits. It is expected, however,
that the generating facility at HGP-A will provide readily for

Table 9. HGP-A Drillsite Soil and Plant Mercury
Levels as Related Well Status

Date	Well Status	Air µg·m⁻³	Water µg·ℓ⁻¹	Mercury Content Cyperus Soil	Plant	Metrosideros Soil	Plant
						µg·kg⁻¹	
May 75	Pre-drilling	1.1	–	43	130	d 59	263
May 76	Post-drilling	1.2	5.0	141	160	356	571
July 76	Flashing	9.9	4.6	140	171	381	584
Nov. 76	Shut down	10.0	1.0	207	189	474	608
Aug. 77	Flow test	0.8	1.0	130	117	250	522
July 78	Shut down	1.2	0.4	178	138	397	572

99% abatement. Accordingly, the upper PSD limit Kapoho would become <u>ca</u> 268 megawatts ($\frac{250}{2.8}$ x 3 mW), at 99% abatement, the 932 tons of H_2S produced on the Island of Hawaii with 1000 mwatts output would be permissable if 4 or more of the 7 identified reservoirs were able to divide the emission burden more or less equally.

Aidin 'yan, N. and N. Ozerova. 1966. Geochemistry of mercury during volcanism. Priblemy Volkanizima (Petroparlovsle-Kamchatskil Dal'nevost. Kn. 1zd.) Sbornik 30-32.

Brill, R., G. McMurtry, B.Z. Siegel, and S.M. Siegel. 1979. Mercury and Antarctic Volcanism I. A Comparative Aerometric Study. Paper presented at Lunar and Planetary Inst. Workshop. "Remote Sensing of Volcanic Gases: Current Status and further Needs." Feb. 26-27. University of Hawaii, Honolulu. p. 15.

Eshleman, A., S.M. Siegel and B.Z. Siegel. 1971. Is Mercury from Hawaiian Volcanoes a Natural Source of Pollution? Nature, Vol. 233, No. 5320, pp. 471-472.

James, R. 1962. Steam-water Critical Flow through Pipes, Inst. Mech. Engrs. Proc. 176 No. 26, 741.

Karasik, M. and V. Morozov. 1966. Distribution of Mercury in the products of mud volcanism in the Kerch-Tarnern Province. Geochem. Int. 3:497-507.

Kruger, P. 1977. Preliminary Evaluation of Results, HGP-A Puna, Hawaii Radon Test July 19, 1977. Progress Report, Stanford University Civil Engineering Dept.

Kruger, P., G. Warren and B. Honeyman. 1977. Radon as an Internal Tracer in Geothermal Reservoirs, paper presented at 3rd International Conference on Nuclear Methods on Environmental and Energy Research (ANS/ERda), U. of Missouri, Oct. 10-12.

Matlick, J. and P. Buseck. 1975. Explorations for Geothermal areas using mercury: A new geochemical technique. U.N. Geotherm. Conf. San Francisco v. 1p785792.

McMurtry, G. 1979. Department of Geology and Geophysics, University of Hawaii, Private Communication.

McMurtry, G., R. Brill, B.Z. Siegel and S.M. Siegel. 1979. Mercury and Antarctic Volcanism II. Anomalous distribution between atmosphere and substratum. Paper presented at Lunar and Planetary Inst. Workshop. "Remote sensing of Volcanic Gases: Current Status and further needs." Feb. 26-27. University of Hawaii, Honolulu. p. 31.

McMurtry, G., R. Brill, B.Z. Siegel and S.M. Siegel. 1980. Antarctic Volcanism and Comparative Mercury Distribution. U.S. Antarctic J. In Press.

Phelps, D., B.Z. Siegel, S.M. Siegel, P. Buseck, J. Copp, M. Hinkle and T. Casadevall. 1979. The distribution of Hg in the Puhimau Area, Hawaii Volcanoes National Park. Am. Geophysical Soc. Abstr. Ann. Mtg. Seattle, Washington. May 30, 1979.

Siegel, B.Z. and S.M. Siegel. 1977. Measurements at HGP-A During the Kalalua Eruption of September 1977. Hawaii Geothermal Project. Geotoxicology Supplement (HGP 4.1).

Siegel, B., S. Siegel, G. McMurtry and R. Brill. 1979. Mercury and Antarctic Volcanism III. The Biotic Connection. Paper presented at Lunar and Planetary Inst. Workshop. "Remote Sensing of Volcanic Gases: Current Status and Further Needs." Feb. 26-27. University of Hawaii, Honolulu. p. 35.

Siegel, B.Z. and S.M. Siegel. 1979a. Progress Report Geotoxicology. January 1978-March 1979. The Hawaii Geothermal Project.

Siegel, B.Z. and S.M. Siegel. 1979b. Kapoho Geothermal Reservoir Assessment, Final Report. 30 June 1979. The Hawaii Geothermal Project.

Siegel, B.Z. and S.M. Siegel. 1979c. Mercury and other Toxic Emissions from Kilauea: Site and Time Patterns. Presented before the Division of Environmental Chemistry. ACS/CSJ Chem. Congr., Honolulu, Hawaii. April 1979 Abstr. Part 1, No. 30.

Siegel, S.M., B.Z. Siegel and G. McMurtry. 1980. Atmosphere-Soil Mercury Distribution: The Biotic Factor. Water, Air, & Soil Pollution. In Press.

Siegel, S.M., Joan Okasako, Pamela Kaalakea and B.Z. Siegel. 1980. Volatile Mercury from Soils and Non-vascular Plants. Organic Geochem. In Press.

Stoker, A. and P. Kruger. 1975. Radon in Geothermal Reservoirs. Proceedings of the 2nd U.N. Symposium on the Dev. and Use of Geothermal Resources, San Francisco, CA.

Thomas, D. Hawaii Institute of Geophysics, University of Hawaii, letter of Sept. 20, 1978 to Sanford Siegel.

Wilkening, M.H., W.E. Clements, and D. Stanley. 1972. Radon 222 Flux Measurements in Widely Separated Regions: Presented at the Second International Symposium on the Natural Radiation Environment. Houston, Texas.