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**ATMOSPHERIC DISPERSION AND NOISE PROPAGATION
AT IMPERIAL VALLEY GEOTHERMAL FIELDS**

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Contents

Abstract	1
Introduction	1
Climate and Population Distribution at Imperial Valley Known Geothermal Resource Areas	2
Meteorological Aspect of Pollution Dispersion	5
Wind	5
Turbulence	6
Gas Dispersion and Concentration	8
Gas Concentration Calculations for Imperial Valley	10
Thermal Dispersion	15
Temperature Change	15
Noise Propagation	19
Known Geothermal Resource Areas Other Than Salton Sea Field	22
Brawley KGRA	22
Heber KGRA	22
East Mesa, Dunes, and Glamis KGRA's	22
Comments	22
Acknowledgment	23
References	24

ATMOSPHERIC DISPERSION AND NOISE PROPAGATION AT IMPERIAL VALLEY GEOTHERMAL FIELDS

Abstract

Quantitative estimations are made for the atmospheric dispersion of gases, heat, and noise due to geothermal energy sources in Southern California's Imperial Valley. In particular, gas concentration per

unit source strength, change in mixing ratio, relative humidity, temperature, and the ratio of heat flux to solar constant are calculated. The possibility of atmospheric refraction of source noise is also considered.

Introduction

The objective of this report is to estimate the atmospheric dispersion of typical (nonreactive) gases, water vapor, heat, and noise that may possibly be emitted at various geothermal fields in the Imperial Valley. These estimates are of importance due to the proximity of the known geothermal resource areas (KGRA's) to nearby towns, irrigated agriculture areas, and the Mexican border. Furthermore, environmental impact statements will require this type of information.

The basic solution for gas (including water vapor) and thermal discharge dispersion depends upon the validity of the statistical Gaussian equation for atmospheric dispersion from the center line of a plume. Given the appropriate meteorological

data (wind speed and direction, plus atmospheric stability information) and a discharge rate (such as g/s), one may calculate a concentration (such as g/m^3) as a function of position. This concentration may be the end result, as in the case of H_2S for instance, or it may be used to calculate other quantities, such as change in relative humidity. The prediction of noise propagation also follows a fairly standard procedure that requires a knowledge of wind speed and direction, plus temperature lapse rate.

The report begins with a discussion of the Imperial Valley climate as determined from measurements at the Yuma Proving Ground on the California-Arizona border. Atmospheric dispersion is then

discussed in relation to turbulence and stability classes. The basic dispersion equation is presented and used to estimate concentration per unit source strength of any gas, and, in particular, change in mixing ratio and relative humidity for a given mass discharge rate of water vapor.

The same basic equation is modified so as to predict possible

temperature changes and changes in the ratio of heat flux to solar constant at various locations due to heat emission at the source. Noise propagation via atmospheric refraction is discussed, and predictions are made regarding potential noise pollution. Finally, comments are presented on the results and suggestions for the field measurement of a number of parameters.

Climate and Population Distribution at Imperial Valley Known Geothermal Resource Areas

The local climate, meteorology, and population distribution are the most important factors in judging any possible environmental effect transmitted via the atmosphere from geothermal sources. The main site lies near the southern end of the Salton Sea in typical flat desert terrain. The population density is concentrated in two distinct directions: ESE to S, "the El Centro area," and WNW to NNW, "the Indio area." Table 1 shown most of the principal population centers with approximate distance and direction from the Salton Sea field.

Because wind direction is perhaps the most important meteorological parameter involved in atmospheric transport, any problem of emissions from the Salton Sea site should

occur only at times when the wind blows from WNW to N and from ESE to SSE. Besides wind direction, wind speed and atmospheric stability are the other two important factors for the prediction of gaseous, thermal, and noise pollution.

The following climatological information is a summary of data prepared by SP6 Larry G. Milligan of the ASL Yuma Meteorological Team at the Yuma Proving Ground, plus the personal observations of the writer who worked at the same "weather station" while in service during 1954-56.

In general, the desert climate is characterized by high temperatures, low relative humidity, clear skies, good visibility, and very little precipitation. A breakdown of

prevailing wind speed (m/sec) and direction at the surface and three heights above the surface (in metres)

is shown for each month in Table 2. Additional climatological information follows in Tables 3, 4, and 5.

Table 1. Populations and locations relative to Salton Sea field.

	Distance from site, km	Direction from site	Population
Calipatria	10	ESE	2,030
Niland	12	NE	800
Westmoreland	13	S	1,420
Brawley	20	SSE	14,350
Imperial	33	S-SSE	3,210
El Centro	40	S-SSE	21,100
Holtville	44	SSE-SE	3,790
Calexico	54	S-SSE	12,650
Indio area	61	NNW-WNW	30,000
Yuma	102	ESE	28,000

Table 2. Wind velocity vs height (m).

(speed in m/s; wind direction is direction wind blows from)

Height z(m)	Jan.	Feb.	March	April	May	June
0	2.2 NNW	2.2 NNW	2.2 W	2.7 W	2.7 W	2.7 W
430	3.2 WNW	4.1 WNW	5.4 W	5.8 W	5.4 W	5.4 WSW
880	4.5 WNW	5.0 WNW	5.8 W	6.8 W	5.4 WSW	5.4 SW
1350	5.4 WNW	5.8 WNW	5.8 WNW	6.8 W	5.4 WSN	5.0 SW

Height z(m)	July	Aug.	Sept.	Oct.	Nov.	Dec.
0	2.7 SW	2.7 SSW	2.2 W	1.8 W	1.8 NNW	1.8 NNW
430	4.5 SSW	4.5 SW	4.5 WSW	4.5 WSW	5.4 NW	4.5 NW
880	4.5 SW	4.5 SW	4.5 WSW	5.0 WSW	5.8 NW	5.4 NW
1350	4.5 SW	4.1 SW	4.1 SW	4.5 SW	6.3 WNW	5.8 WNW

Table 3. Distribution of cloud cover (in percent).

	Jan.	Feb.	March	April	May	June
Cloudy (8/10-10/10)	29	14	19	10	6	3
Pt. cloudy (3/10-7/10)	23	21	23	23	13	10
Clear (0/10-2/10)	48	65	58	67	81	87
	July	Aug.	Sept.	Oct.	Nov.	Dec.
Cloudy	6	6	3	6	10	22
Pt. cloudy	23	23	10	16	17	23
Clear	71	71	87	78	73	55

Table 4. Average maximum and minimum temperature, average relative humidity, average precipitation, and daily average solar radiation.

	Jan.	Feb.	March	April	May	June
Avg. max, temp., °C	20	23	26	30	34	39
Avg. min, temp., °C	7	8	10	13	18	22
Avg. rel. humidity, %	41	38	30	26	26	26
Avg. precipitation, cm	1.0	0.86	0.61	0.38	0.05	0.18
Solar radiation, daily						
cal/cm ²	311	410	523	648	725	740
avg., MJ/m ²	13.0	17.2	21.9	27.1	30.3	31.0
	July	Aug.	Sept.	Oct.	Nov.	Dec.
Avg. max. temp., °C	41	41	38	32	25	20
Avg. min. temp., °C	27	27	24	16	10	6
Avg. rel. humidity, %	34	41	35	34	38	42
Avg. precipitation, cm	0.43	1.2	1.0	1.1	0.58	0.99
Solar radiation, daily						
cal/cm ²	675	620	560	448	338	284
avg., MJ/m ²	28.3	26.0	23.4	18.8	14.1	11.9

Table 5. Surface inversion data for September 1959 through August 1960.

	Jan.	Feb.	March	April	May	June
Average height (m)	460	430	410	320	350	390
$\Delta T(^{\circ}\text{C})$: top-surface	6.2	5.7	4.7	5.7	4.1	5.3
% days with inversion	93	96	100	93	97	100
Time of breakup (MST) ^a	1230	1200	1130	1100	1030	1030
	July	Aug.	Sept.	Oct.	Nov.	Dec.
Average height (m)	240	210	230	460	470	480
$\Delta T(^{\circ}\text{C})$: top-surface	5.2	2.7	4.4	6.8	4.9	6.7
% days with inversion	82	81	90	77	97	90
Time of brakeup (MST) ^a	1000	1000	1030	1130	1200	1230

^aMountain Standard Time.

Meteorological Aspect of Pollution Dispersion

This section contains a very brief introduction to some of the major factors involved in atmospheric dispersion.

Wind

Any emitted gas will tend to follow the motion of the surrounding air. In particular, and perhaps most important of all, the basic direction of motion will be downwind, a fact that places wind direction in a very important category. Unfortunately, data on winds aloft are usually not available at a given location and must be inferred from surface winds; this

inferring can result in significant errors. Surface wind direction can vary by large amounts during a given day. For example, the prevailing surface wind direction for July at Yuma is listed as SW in Table 2. Yet for the period 1966-1973, note the July averages listed by hour-direction: 1-W, 2-WNW, 3-WNW, 4-NW, 5-NE, 6-E, 7-ESE, 8-SE, 9-SE, 10-SSE, 11-SE, 12-16-SSW, 17-WSW, 18-W, 19-W, 20-SW, 21-SW, 22-S, 23-SW, 24-SW. Thus, a simple statement that the July prevailing wind is SW can be misleading. Daily and hourly variations will disperse pollutants

in various other directions than those that may be indicated by a monthly average.

Wind speed is also important, because dilution increases as the wind becomes stronger. In fact, it's easy to surmise that the dilution volume should be proportional to wind speed; hence, pollutant concentration should vary inversely as the wind speed.

Turbulence

If there were no turbulence, a plume would travel downwind in a narrow cone whose lateral dimensions would be determined by molecular diffusion. In practice, turbulence completely dominates molecular diffusion; that is, turbulence will cause a large increase in dispersion and a resulting decrease in pollutant concentration in the downwind direction.

There are two main causes of turbulence: mechanical induction and thermal induction. Mechanical turbulence is caused by obstacles, such as trees, hills, buildings, etc. The absence of major obstructions at the Imperial Valley KGRA's simplifies the consideration of this cause. Thermal turbulence is due to vertical instability. The stability (or lack of it) can be determined by the variation of potential temperature

(θ) with height (z). Potential temperature is the temperature that a parcel of air would attain if brought to the 1000-mbar level by a dry adiabatic process. The approximate relation $\theta = T + \Gamma z$ holds, where Γ is the dry adiabatic lapse rate (and, typically, $\Gamma \approx 10^\circ\text{C}/\text{km}$). Thus, $d\theta/dz = dT/dz + \Gamma$, and the stability criteria are as follows: $d\theta/dz > 0$ (stable), $d\theta/dz < 0$ (unstable), $d\theta/dz = 0$ (neutral). In general, pollution concentration increases with increasing stability.

In order to determine the type of stability, one needs dT/dz , the environmental lapse rate. In most locations, experimental values of the lapse rate are unavailable. Fortunately, for the Imperial Valley, radiosonde data may be obtained from soundings taken at the Yuma Proving Ground, and the average temperature vs pressure data are duplicated in Table 6 from the surface up to the 400-mbar level for the period 1956-63, 1966-71.

As is typical of radiosonde data, the first data point above the surface is somewhat near the upper limit in height needed for pollution dispersion estimates. Thus, many data points between the surface and the 950-mbar level (approximately 540 m) would be desired in order to determine stability in the region of interest. Nevertheless, these monthly averages give a rough

Table 6. Upper air mean temperatures (°C).

Height (km)	P (mbar)	Jan.	Feb.	March	April	May	June
0.065	1000	12.1	14.4	16.5	20.5	24.6	29.3
0.54	950	13.5	15.0	16.9	20.3	23.8	29.1
0.99	900	10.7	11.9	13.6	17.1	20.7	26.2
1.46	850	8.1	8.8	10.1	13.5	17.1	22.6
1.95	800	5.6	5.7	6.6	9.6	13.3	18.6
2.47	750	3.1	2.8	3.5	5.9	9.4	14.6
3.01	700	0.2	-0.3	0.2	2.4	5.7	10.4
3.59	650	-3.2	-3.8	-3.4	-1.2	1.8	6.1
4.21	600	-7.2	-7.8	-7.6	-5.3	-2.4	1.4
4.87	550	-11.7	-12.5	-12.3	-9.9	-7.2	-3.4
5.57	500	-16.8	-17.6	-17.5	-15.2	-12.4	-8.5
6.34	450	-22.6	-23.4	-23.4	-21.1	-18.4	-14.3
7.19	400	-29.1	-29.7	-29.9	-27.7	-25.0	-21.0

Height (km)	P (mbar)	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
0.065	SFC	33.1	32.4	29.4	23.0	16.5	12.7	22.1
0.54	950	31.6	30.8	29.3	24.0	17.7	14.4	22.3
0.99	900	28.6	27.7	26.1	20.8	14.8	11.9	19.2
1.46	850	24.9	24.0	22.2	17.1	11.8	9.5	15.9
1.95	800	20.8	20.0	18.1	13.3	9.0	7.0	12.4
2.47	750	16.5	15.7	14.0	9.7	6.3	4.4	8.9
3.01	700	12.0	11.3	9.9	6.1	3.3	1.4	5.3
3.59	650	7.3	6.8	5.8	2.5	0.0	-2.0	1.4
4.21	600	2.5	2.4	1.6	-1.4	-4.0	-6.0	-2.8
4.87	550	-2.2	-2.1	-2.8	-6.1	-8.5	-10.7	-7.4
5.57	500	-7.0	-6.7	-7.6	-11.3	-13.7	-16.0	-12.5
6.34	450	-12.3	-11.9	-13.3	-17.2	-19.5	-21.9	-18.2
7.19	400	-18.4	-18.1	-19.9	-23.9	-26.0	-28.3	-24.7

indication, especially if used in conjunction with Table 5 on surface inversions. The latter, in the Imperial Valley, are typically the radiation type (which occur at night when skies are clear and winds are light).

In the absence of enough temperature readings in the height range of interest, an estimate

of stability may be made from regularly observed weather parameters, mainly wind speed, solar radiation, and cloud cover. In general, stability decreases with increasing solar radiation during the day and increases with decreasing cloud cover at night. This condition will be considered in more detail in the next section.

Gas Dispersion and Concentration

The mathematical model used for calculating the various concentrations in this report is based upon the statistical Gaussian approach. The main assumption is that concentrations follow the binormal probability distribution in both the vertical and crosswind direction downwind from the source. The equation is:

$$C = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp -1/2 \left(\frac{y}{\sigma_y} \right)^2 \left[\exp -1/2 \left(\frac{z - H}{\sigma_z} \right)^2 + \exp -1/2 \left(\frac{z + H}{\sigma_z} \right)^2 \right], \quad (1)$$

where C = concentration (units/m³) at positive x, y, z ; Q = uniform rate of source emission (units per unit time) at the point $0, 0, h$; u = mean wind speed (m/s) at the height of emission; σ_y, σ_z = crosswind and vertical standard deviations (m) of the plume, respectively, x, y, z (in m) = coordinates of the receptor point for which C is calculated, with x being chosen as the downwind direction; and $H = h + \Delta h$ (m), the effective

emission height where Δh is the plume rise, namely, the difference in height between the emission point and the height at which (if ever) the plume becomes horizontal. At this time of writing, cooling tower data for Δh are unavailable. Nevertheless, an approximate equation may help to gain a feeling for this quantity. The Moses-Carson formula is:

$$\Delta h = A \frac{vd}{u} + B \frac{\dot{q}^{1/2}}{u}, \quad (2)$$

where v = stack or tower exit speed, d = tower diameter, and $\dot{q}$ = heat emission rate. The first term takes into account the vertical momentum of the emission, and the second considers the buoyancy of the emission.

Clearly, C is a function of the wind direction because of the assumption that the coordinate axes are rotated such that x is downwind. Also, wind speed u

explicitly appears in the denominator. The stability relations discussed in the previous section enter via σ_y and σ_z . The sigmas vary with the degree of turbulence, which in turn can be approximated from wind speed, solar radiation, and cloud cover. In addition, they vary with x and sampling time (here assumed to be about 10 min). The sampling time variation is due mainly to an increase in σ_y with time because of a meander of wind direction.

The Pasquill stability classification scheme may be used to determine σ_y and σ_z . Here the stabilities are divided into six classes: A (most unstable), B,C,D (neutral), E and F (most stable). The class is determined by a combination of wind speed and solar radiation during the day, and by wind speed and cloud cover at night. Once the class is fixed, σ_y and σ_z may be found at a given

distance x from standard plots, such as in Turner¹.

An analysis of the data presented in Tables 2 through 6, on wind speed, cloud cover, solar radiation, surface inversions, and lapse rate produces the estimated stability classes in Table 7.

Please note that these are estimates based upon the data presented and may be changed as new measurements in the area are taken.

There are many important assumptions involved in using Eq. (1):

- (1) Steady state conditions are assumed in both space and time.
- (2) The source is a continuous emitter.
- (3) The source is a point.
- (4) The emission is inert and stable (no chemical reactions or settling).
- (5) There is no ground adsorption (in fact, perfect reflection is assumed).
- (6) The sampling time is about 10 min.

Table 7. Pasquill stability classes.

	Jan.	Feb.	March	April	May	June
Day	B-C	B-C	B-C	B-C	A-B	A-B
Night	E	E	E	F	F	F
	July	Aug.	Sept.	Oct.	Nov.	Dec.
Day	A-B	A-B	A-B	B-C	B-C	B-C
Night	F	F	F	F	F	E

For loss due to chemical reactions, scavenging by precipitation, radioactive decay, adsorption, etc., both Shaw and Munn (in Ref. 2) and Ledbetter³ suggest that Eq. (1) be multiplied by e^{-kt} , where k is an appropriate decay constant for a given emitter type and depends upon

the type of sink (radioactivity, chemical, etc.). For deposition of particles, Stern⁴ replaces H in Eq. (1) by $H - sv/u$, and omits the factor 2; here, v is the free settling speed of the particulate under the influence of gravity.

Gas Concentration Calculations for Imperial Valley

In nearly all of the calculations to follow, the quantity in question is presented for stability classes B,C, E,F, which should be adequate to cover the Imperial Valley climate. The B column will be blank after $x = 33$ km due to inadequate data for σ_z ; judgment for class B, $x > 33$ km can be made by a comparison with class C. The distances for $x \geq 10$ km were chosen to coincide roughly with approximate distances of various population centers from the Salton Sea field (see Table 1). In each calculation, worst possible situations are assumed: the receptor point is directly in the center line of the plume for a ground-level source with no effective plume rise. Mathematically, this means that the receptor point is at $(x,0,0)$, with $H = 0$. In practice, only one azimuth angle will be downwind, and all figures should be multiplied by $\exp(-y^2/2\sigma_y^2)$; this multiplication will decrease

the calculated quantity (e.g., concentration) for all off-axis points ($y \neq 0$).

Assuming "the worst case" in Eq. (1) is mathematically equivalent to setting y , z , and H equal to zero, Eq. (1) then reduces to:

$$C = \frac{Q}{\pi u \sigma_y \sigma_z} \quad (3)$$

Notice that the quantity $Cu/Q = (\pi \sigma_y \sigma_z)^{-1}$ is independent of any particular local source strength, but is a function of stability and geometry. This quantity is the entry in Table 8.

In order to get a quantitative estimation of C for the various locations in the Imperial Valley, C/Q (concentrations per unit source strength) serves as the basis of further calculations. Table 9 shows C/Q with a mean annual wind speed of 2.3 m/s assumed.

Notice the following approximate comparisons for like conditions (other than stability). Class C stability results in roughly five times the concentration of B, both of which are "daytime" classes for the Valley. At night, class F produces about three times the concentration of E. On the other hand, a comparison of E (night) to C (day) shows the former to be 5 to 45 times greater than the latter, the ratio being smallest for $x = 0.5$ km and largest for $x = 102$ km;

that is, the day-night differences in concentration increase with distance.

Calculations due to Quong⁵ allow an evaluation of the change in mixing ratio as a function of position (x) due to the emission of water vapor from a proposed cooling tower to be used in conjunction with the total-flow turbine concept using hot geothermal brines. The mixing ratio w is the ratio of water vapor density to dry air density. Whereas in meteorology,

Table 8. Values of C_u/Q , 10^{-8} m^{-2} .

$x(\text{km})^a$	Pasquill stability category			
	B	C	E	F
0.5	7590	17,940	89,700	207,000
1	1863	5,060	29,900	66,700
4	115	391	3,450	8,700
7	39	147	1,590	3,900
10	20	75	990	2,400
12	14	53	740	1,900
13	12	47	680	1,700
20	4.6	22	390	1,100
33	1.9	9.2	200	570
40	-	6.3	160	460
44	-	5.6	140	420
54	-	4.0	110	330
61	-	3.1	96	300
102	-	1.3	57	170

^aDistance from plume source measured along plume centerline.

the unit is usually g of vapor to kg of dry air, the pure dimensionless ratio is more convenient here. Because the time rate of emission of water vapor mass (dm/dt) in Quong is given for a 22-MW electric generator, Table 10 will list change in mixing ratio (Δw), due to the emitted vapor from the cooling tower, per MW. If a 100-MW electric source were under consideration, all figures would be multiplied by 100. Choose $Q = dm/dt = 2.84 \times 10^3$

g/(s·MW) (from Quong); then $C = \rho_w$ is identical to the increase in water vapor density (ρ_w) per MW. The change in mixing ratio is $\Delta w = \rho_w / \rho_a$, where ρ_a = air density, taken as 1.25×10^3 g/m³. Thus,

$$\Delta w = \frac{\rho_w}{\rho_a} = \frac{\left(\frac{C}{Q}\right) \left(\frac{dm}{dt}\right)}{\rho_a} = \left(\frac{C}{Q}\right) \frac{2.8 \times 10^3}{1.25 \times 10^3} = 2.27 \left(\frac{C}{Q}\right) \text{ MW}^{-1}. \quad (4)$$

The C/Q values are found from Table 9.

Table 9. Values of C/Q, 10^{-9} sm^{-3} .^a

x(km) ^b	Pasquill stability category			
	B	C	E	F
0.5	33,000	78,000	390,000	900,000
1	8,100	22,000	130,000	290,000
4	500	1,700	15,000	38,000
7	170	640	6,900	17,000
10	87	330	4,300	10,000
12	61	230	3,200	8,300
13	52	200	3,000	7,400
20	20	96	1,700	4,800
33	8.3	40	870	2,500
40	-	27	700	2,000
44	-	24	610	1,800
54	-	17	480	1,400
61	-	14	420	1,300
102	-	5.7	250	740

^a_u = 2.3 m/s.

^b Distance from plume source measured along plume centerline.

Knowing the mixing ratio change in Table 10 allows one to estimate the change in relative humidity at various locations due to the cooling tower emission. The relative humidity is defined as $U = 100 w/w_s$, where w_s is the saturated mixing ratio and is a function of temperature and pressure. Table 11 was constructed for the change in relative humidity per MW for a pressure of 1000 mbar at three different representative temperatures of the Imperial Valley,

10°C, 25°C, 40°C. From the Smithsonian Meteorological Tables⁶, the corresponding values of w_s are 0.008 for 10°C, 0.02 for 25°C, and 0.05 for 40°C (all dimensionless, not g/kg). Then $\Delta U = 100 \Delta w/w_s$ per MW.

The largest change in relative humidity listed in Table 11 is at $x = 0.5$ km, class F stability, which estimates a change of 25%/MW or 2500% for a 100-MW source. What this means for the 100-MW source is that one

Table 10. Change in mixing ratio (ΔW) per MW.
(all values are to be multiplied by 10^{-8})^a

$x(\text{km})^b$	Pasquill stability category			
	B	C	E	F
0.5	7500	18,000	88,000	200,000
1	180	5,000	30,000	66,000
4	110	390	3,400	8,600
7	39	150	1,600	3,900
10	20	75	980	2,300
12	14	52	730	1,900
13	12	45	680	1,700
20	4.5	22	390	1,100
33	1.9	9.1	200	570
40	-	6.1	160	450
44	-	5.4	140	410
54	-	3.9	110	320
61	-	3.2	95	300
102	-	1.3	57	170

^aThat is, the first entry is 7500×10^{-8} .

^bDistance from plume source measured along plume centerline.

Table 11. Change in relative humidity, per MW at various temperatures for P = 1000 mbar, in 10^{-3} percent.

x(km) ^a	Pasquill stability category											
	B			C			E			F		
	10°C	25°C	40°C	10°C	25°C	40°C	10°C	25°C	40°C	10°C	25°C	40°C
0.5	940	380	150	2300	900	360	11,000	4400	1800	25,000	10,000	4000
1	23	9	3.6	630	250	100	3800	1500	600	8300	3300	1300
4	14	5.5	2.2	49	20	8.0	430	170	68	1100	430	170
7	4.9	2.0	0.80	19	8.0	3.2	200	80	32	490	200	80
10	2.5	1.0	0.40	9.4	3.8	1.5	120	49	20	290	120	48
12	1.8	0.72	0.28	6.5	2.6	1.0	91	36	14	240	100	40
13	1.5	0.60	0.24	5.6	2.2	0.88	85	34	14	210	90	36
20	0.56	0.22	0.09	2.8	1.1	0.44	49	20	8	140	55	22
33	0.24	0.10	0.04	1.1	0.45	0.18	25	10	4	71	29	12
40	-	-	-	0.76	0.30	0.12	20	8	3	56	22	9
44	-	-	-	0.68	0.27	0.11	18	7	3	51	20	8
54	-	-	-	0.49	0.20	0.08	14	6	2	40	16	6
61	-	-	-	0.40	0.16	0.06	12	4	2	38	15	6
102	-	-	-	0.16	0.06	0.03	7	3	1	21	8	3

^aDistance from plume source measured along plume centerline.

should expect condensation and a visible plume to occur. As expected, the change in relative humidity (ΔU) is large for small x and low T , and small for large x and high T . At El Centro (assuming the source is at the Salton Sea site), the change in relative humidity should be approximately 0.03% for a 100-MW source at 25°C, if the wind were blowing directly towards El Centro at 2.3 m/s. Values for other locations may be read from Table 11.

Presumably gases other than water vapor, such as CO_2 and H_2S , will be discharged to the atmosphere from the geothermal fields. Whatever a chemical analysis may show, the concentration of that particular pollutant at a given distance, for a given wind speed, and for a given emission rate Q may be found from Eq. (1), or "the worst case" from Eq. (3) or Table 8.

Thermal Dispersion

In addition to gases such as water vapor already considered, the cooling towers at the geothermal sites will also reject heat directly to the atmosphere. This section considers an estimate of the possible impact of this thermal pollution as it is dispersed downwind. In particular, two quantities are treated: (a) the change in temperature at a given location for a given thermal discharge rate, and (b) a comparison of the heat flux transmitted with the solar constant.

Temperature change.

Equation (1), with Q interpreted as the amount of heat (in joules)

emitted per s per MW (dq/dt), results in C as the heat energy density at the receptor point. The problem now is to convert C into ΔT . Briefly, this is accomplished in the manner described in the following paragraphs.

Assume the equation of state for an ideal gas and that any change of state is a reversible process. Then for entropy (S) as a function of T and P , $S = S(T,P)$ giving:

$$dS = \left(\frac{\partial S}{\partial T} \right)_P dT + \left(\frac{\partial S}{\partial P} \right)_T dP.$$

Thus,

$$dq = TdS = Mc_p dT - VdP,$$

where the definition of specific heat, ideal gas equation, and a

Maxwell equation have been used. By assuming that any pressure change over the sampling period is negligible and that c_p is approximately temperature-independent, the heat transferred is simply $M c_p \Delta T$. Then:

$$C = \frac{q}{V} = \frac{M c_p \Delta T}{V} = \rho_a c_p \Delta T,$$

where ρ_a = density of air = $1.25 \times 10^3 \text{ g/m}^3$ and $c_p = 1.00 \text{ J/g } ^\circ\text{C}$. Consequently,

$$\Delta T = \frac{C}{\rho_a c_p},$$

and C is calculated from Eq. (1).

From Quong⁵ the thermal discharge rate per MW is found to be $dq/dt = 4.60 \text{ MJ/s} \cdot \text{MW}$. Table 12 shows the calculated estimates for ΔT per MW source, again for "the worst case"; that is, each receptor point is assumed to be directly in the center of the thermal plume. Note also

that this estimate doesn't take into account heat transfer modes, such as radiation, that will reduce the values below those quoted.

Another evaluation of the geothermal heat impact is a comparison of the heat flux with the solar constant of $8.12 \text{ J/cm}^2 \cdot \text{min}$, or $1.35 \text{ kJ/m}^2 \cdot \text{s}$. The flux of thermal energy from the source may be found by multiplying the thermal energy density C in J/m^3 from Eq. (1) by the mean transport speed, taken again as $u = 2.3 \text{ m/s}$. Thermal flux in $\text{J/m}^2 (\text{s} \cdot \text{MW}) = (C/Q)(dq/dt)u$:

$$\begin{aligned} \frac{\text{Thermal flux}}{\text{Solar constant}} &= \frac{C}{Q} \frac{(4.6 \times 10^6) (2.3)}{1350} \\ &= 7.83 \times 10^3 \left(\frac{C}{Q} \right) \text{MW}^{-1}. \end{aligned}$$

Thus the ratio is found simply by multiplying 7.83×10^3 by each entry in Table 9. The results are shown in Table 13.

Table 12. Temperature change ($^{\circ}\text{C}$) per MW for $dq/dt = 4.60 \text{ MJ/s}\cdot\text{MW}$ and $u = 2.3 \text{ m/s}$.

$x(\text{km})^a$	Pasquill stability category			
	B	C	E	F
0.5	0.12	0.3	1.43	3.3
1	0.03	0.08	0.48	1.1
4	0.002	0.006	0.06	0.14
7	0.0006	0.002	0.02	0.06
10	0.0003	0.001	0.02	0.04
12	0.0002	0.0008	0.01	0.03
13	0.0002	0.0007	0.01	0.03
20	0.00007	0.0004	0.006	0.02
33	0.00003	0.0001	0.003	0.007
40	--	0.0001	0.002	0.007
44	--	0.00009	0.002	0.007
54	--	0.00006	0.002	0.005
61	--	0.00005	0.002	0.005
102	--	0.00002	0.001	0.003

^aDistance from plume source measured along plume centerline.

Table 13. Ratio of heat flux to solar constant per MW for $dq/dt = 4.60 \text{ MJ/s} \cdot \text{MW}$.

(all values to be multiplied by 10^{-5})^a

x(km) ^b	Pasquill stability category			
	B	C	E	F
0.5	26,000	61,000	310,000	700,000
1	6300	17,000	100,000	230,000
4	3900	13,000	12,000	30,000
7	1300	500	5400	13,000
10	68	260	3400	7800
12	48	180	2500	6500
13	41	160	2300	5800
20	16	75	1300	3800
33	6	31	700	2000
40	--	21	600	1600
44	--	19	500	1400
54	--	13	400	1100
61	--	11	300	1000
102	--	4	200	600

^aThat is, the first entry is $26,000 \times 10^{-5}$.

^bDistance from plume source measured along plume centerline.

Noise Propagation

Water falling in a cooling tower, mechanical fans, venting steam, electric generators, etc., all produce noise at a geothermal site. The purpose of this section is to examine noise propagation by refraction through the atmosphere, and hence the possibility of source noise being detected at much greater distances than via direct surface waves. The procedure is simple and may be found in Cox.⁷

A sound wave projected at any angle above the horizontal will be refracted back to the surface only if the net speed at any altitude exceeds the net surface speed. By net speed is meant speed of sound in still air plus the component of wind velocity in any particular direction of interest. In still air the speed of sound (c) may be expressed as $c = 20\sqrt{T}$ m/s, where T is in °K. To be more precise, T should actually be virtual temperature, which will automatically take into account humidity. For the purpose of this analysis in the Imperial Valley, the distinction may be neglected.

If wind speed were zero at all heights, the propagation would be isotropic above the surface, and refraction (hence the possibility of a long distance focus) would occur

only if the temperature aloft at any height exceeded the surface temperature. This latter condition is the normal one during nights and persists until 10 AM or noon (see Table 5) in the Imperial Valley, depending upon the season.

From Table 6, the speed of sound in still air up to about 1350 m was calculated and is shown in Table 14 for monthly averages. Because an inversion top is often reached before $z = 430$ m, the maximum temperature may be above that listed in the tables. The tentative result (for $u = 0$ everywhere) is that one should expect a shallow refraction of noise in all directions. When wind velocity is considered at any height, the wind speed adds to c downwind and subtracts upwind. Thus, the usual problem case for noise refraction is downwind. Notice the very close correspondence between noise pollution and gas and thermal dispersion: all increase in the downwind direction (compared with upwind) and increase with increasing atmospheric stability.

By combining the results in Table 14, on c in still air, with Table 2 on wind velocity, Table 15 may be constructed showing the mean monthly net speed of sound at various heights for the Imperial Valley. The

direction listed for each month shows the expected direction from which sound may be refracted down to the surface. For example, if one considers the Salton Sea site, it appears that noise in the populated areas should be a potential problem (if at all)

only in the winter months, November through February. Any noise at a given location would most likely be worse at night for two reasons: an inversion typically exists ($dT/dz > 0$), and less local masking from other sources.

Table 14. Speed of sound (m/s) in still air at various heights for Imperial Valley.

Height (m)	Jan.	Feb.	March	April	May	June
0	338	339	340	343	345	348
430	339	339	340	342	345	348
880	337	338	339	341	343	346
1350	335	336	336	338	341	344

Height (m)	July	Aug.	Sept.	Oct.	Nov.	Dec.
0	350	350	348	344	340	338
430	349	349	348	345	341	339
880	347	347	346	343	339	338
1350	345	345	344	341	338	336

Table 15. Net speed of sound (m/sec) = speed of sound in still air plus wind speed.

Height (m)	Jan.	Feb.	March	April	May	June
0	340.2	341.2	342.2	345.7	347.7	350.7
430	342.2	343.1	345.4	347.8	350.4	353.4
880	341.5	343.0	344.8	347.8	348.4	351.4
1350	340.4	341.8	341.8	344.8	346.4	349.0
	NW ^a	NW	W	W	W	WSW

Height (m)	July	Aug.	Sept.	Oct.	Nov.	Dec.
0	352.7	352.7	350.2	345.8	341.8	339.8
430	353.5	353.5	352.5	349.5	346.4	343.5
880	351.5	351.5	350.5	348.0	344.8	343.4
1350	349.5	349.1	348.1	345.5	344.3	341.8
	SW ^a	SW	WSW	WSW	NW	NW

^aExpected direction from which sound may be refracted down to surface.

Known Geothermal Resource Areas Other Than Salton Sea Field

Much of the preceding analysis has been independent of the specific location of the site, although many references were made to the possible impact of the Salton Sea field. But there are other possible locations that should be considered. The results will differ only in wind direction of a receptor point from a specific site if one assumes everything else to be approximately the same, including topography.

An analysis of the other sites produces the following qualitative predictions for gas and thermal dispersion and noise refraction:

Brawley KGRA.

The spring and fall westerlies should have very little effect on centers of population (whereas the Salton Sea site effluents may

strike Calipatria). Summer SW winds will affect very little, and winter should be just like the Salton Sea field. Thus, the main problem should exist from November through February.

Heber KGRA.

There may be a problem from November through February in the Calixico and Mexicali areas. The westerlies in March through June, and September and October should produce little adverse effect, whereas in July and August some emissions may be directed into Holtville.

East Mesa, Dunes, and Glamis KGRA's.

All three are relatively safe from pollution at all times due to their locations, prevailing winds, and lack of population downwind.

Comments

The reader should be reminded that the estimations calculated in this report are just that: estimations. Recall that the data were taken at the Yuma Proving Ground, about 100 km east of the KGRA's, and thus all conclusions are based on similar meteorological assumptions.

The determination of the stability class for a given month is somewhat dependent upon individual judgment. The results for gas and thermal dispersion rely upon many assumptions, some of which were listed previously. In particular, the assumption of a point source deserves mention; see, for

example, Strauss.⁸ If Eq. (1) is evaluated with x approaching zero, the concentration tends towards unlimited values along the plume centerline. Thus, one should not count on near-zone validity. Mathematically, Eq. (1) is much like an asymptotic approximation and must not be extrapolated too close in. A qualitative conclusion is that near-zone calculations tend to be too large. The quantitative definition of "near-zone" is arbitrary.

There are a few random comments to be made regarding thermal and water vapor ejection into the atmosphere. Tebbens (in Ref. 4) points out that water vapor enhances corrosion of surfaces by acid-type pollutants, joins SO_3 to form sulfuric acid, and also acts as a catalyst in many reactions. Other possible adverse effects of either or both heat and water vapor emission may be found listed in Refs. 9 and 10. Some of these effects are fog, icing, cloud formation, precipitation, and severe weather effects. It is doubtful

that any of these except possibly very local fog, probably during early cold winter mornings, will materialize at the KGRA's.

Finally, a comment on simple measurements and instrumentation. Among the items of information needed are background concentrations due to nongeothermal sources; these data will serve as a base for determining (or defending) any effect due to actual operation. The same can be said for meteorological parameters, such as surface winds, temperature, and relative humidity. At the sites, a tall tower instrumented at various levels with anemometers, wind vanes, and thermometers will give sufficient information for using Eq. (1); i.e., wind direction and speed, and $\Delta T/\Delta z$ to be used for stability classes. To supplement the latter, solar radiation and cloud cover should be recorded. It would also be desirable and practical to measure surface wind speed and direction at carefully chosen locations surrounding each geothermal field.

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