

MEASUREMENT OF ODOR EMISSIONS
FROM A SEWAGE TREATMENT PLANT

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ABSTRACT

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Odorous emissions from several locations in an sewage treatment plant were measured using the dynamic forced-choice olfactometer technique and specific components in the gases were identified using GC/MS. Measured odor sensory levels (ED_{50}) were approximately 30 above the activated sludge aeration basins, 50 above the secondary clarifiers, 90 above the primary clarifiers and at the entrance to the aeration basins, and about 1000 at the discharge from the wet well. Hydrogen sulfide levels were approximately 0.5 ppm at each point except the wet well discharge, which was 6.5 ppm. The GC/MS analysis identified more than twenty major organic components of the emissions, but only ethyl mercaptan/dimethyl sulfide were found at concentrations above their odor threshold. Several other potentially odorous compounds with an odor threshold below the detection limit of the analytical technique were not identified.

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Introduction

Odor control engineering at municipal sewage treatment plants (STP) must become more sophisticated as public awareness demands more complete control. A recent response to this concern has been to propose totally enclosed and totally exhaust air controlled plants. A negative pressure maintained on the treatment plant buildings prevents fugitive odors from escaping to the outside atmosphere but significantly increases the amount of air to be controlled.

The odors from the treatment process may be controlled by wet scrubber systems, either packed bed or mist tower, or by oxidation and/or adsorption in a fixed bed. Odor sensory data are required to quantify the odorous emissions from various parts of the treatment process in order to design control systems that will meet the very high control levels desired by the public without unnecessary and costly overdesign.

Rather than treating all the exhaust air equally, it is more cost effective to treat the high intensity odors with one system and the less intense odors with another, simpler, system. Thus it is important to identify the degree of removal necessary for air exhausted from different parts of the plant. In addition, at very high levels of control it is necessary to identify the specific chemical compound sources of odor to insure that the method of control selected will be able to remove these chemicals to the desired level.

In this study, the forced-choice, triangle dynamic olfactometer technique was used to define the odor level and gas chromatograph/mass spectrometer (GC/MS) analyses were used to identify and quantify the specific chemical compounds contributing to the high odor emissions.

A totally enclosed, totally controlled sewage treatment plant has been proposed to be built in an industrial area in Seattle, Washington. This plant is proposed to utilize the activated sludge technique for secondary treatment. To obtain the required design data, a sampling and testing program was conducted at the Municipality of Metropolitan Seattle sewage treatment plant located in Renton, Washington.

Odor Sensory Measurement

The Renton Sewage Treatment Plant services the east and south suburbs of Seattle, Washington. The average daily flow is approximately 50 million gallons (mgd). It provides secondary treatment by the activated sludge process. The entire facil-

ity, with the exception of the wet well and initial bar screens, is outdoors. Figure 1 illustrates the treatment process in use at this location. The number of units and flows shown represents the actual use on the day the testing was carried out. There are 8 primary clarification units and 16 secondary clarifiers at the facility and all are used during higher flow periods.

Emissions of gases dissolved in the sewage will be enhanced by turbulence and aeration. The wet well is highly turbulent and very odorous. However sampling was not possible there because of potentially explosive conditions. The morning glory distributor channel (so named because of the shape of the water flow from the outlet) is the exit from the wet well. Emissions there are assumed to be approximately the same as would be expected in the wet well. The activated sludge aeration basins receive substantial air influx from a submerged fine bubble diffusion system. The sewage in these basins is highly turbulent, with a constant rolling motion.

Turbulence is minimized in the primary settling tanks to permit greases and oils to be skimmed from the surface. The surface of the tanks is below grade and the entire area is surrounded and covered by wind breaking structures although it is still open to the atmosphere. Secondary sedimentation is carried out in circular clarifier tanks, each 100 feet in diameter. The water surface is below the tank rim, but there are no protective wind break structures.

Sampling was conducted each of three days at six different locations in the treatment process. The odor sensory panel tests were conducted each morning on the samples obtained the previous afternoon.

All odor samples were collected using a Masterflex peristaltic pump to deliver the sample to a 5 gal. (18 liter) polyethylene container (Cubitainer) during an approximately 15 minute period. The sampling procedure included an initial half filling of the container with an odor sample and then exhausting it in order to equilibrate the inside surface of the container. Food grade Tygon tubing was used in the sampling.

A styrofoam box was used as a capture hood for the odor released from the surface of the water for five of the sampling points chosen (Nos. 1 through 4 and 6). The bottom surface of the box was suspended approximately 1 to 2 inches above the water surface. The sampling rate was 1.5 liters/min, which is equivalent to an upward flow through the face of the box of 0.03 ft/min or a sweep velocity of 0.06 ft/min across the surface at the box edges if the elevation were 2 inches and there was no release from the surface covered by the box. This technique provides a sample of the odor dilution ratio (ED₅₀) of the air at the surface of the area source.

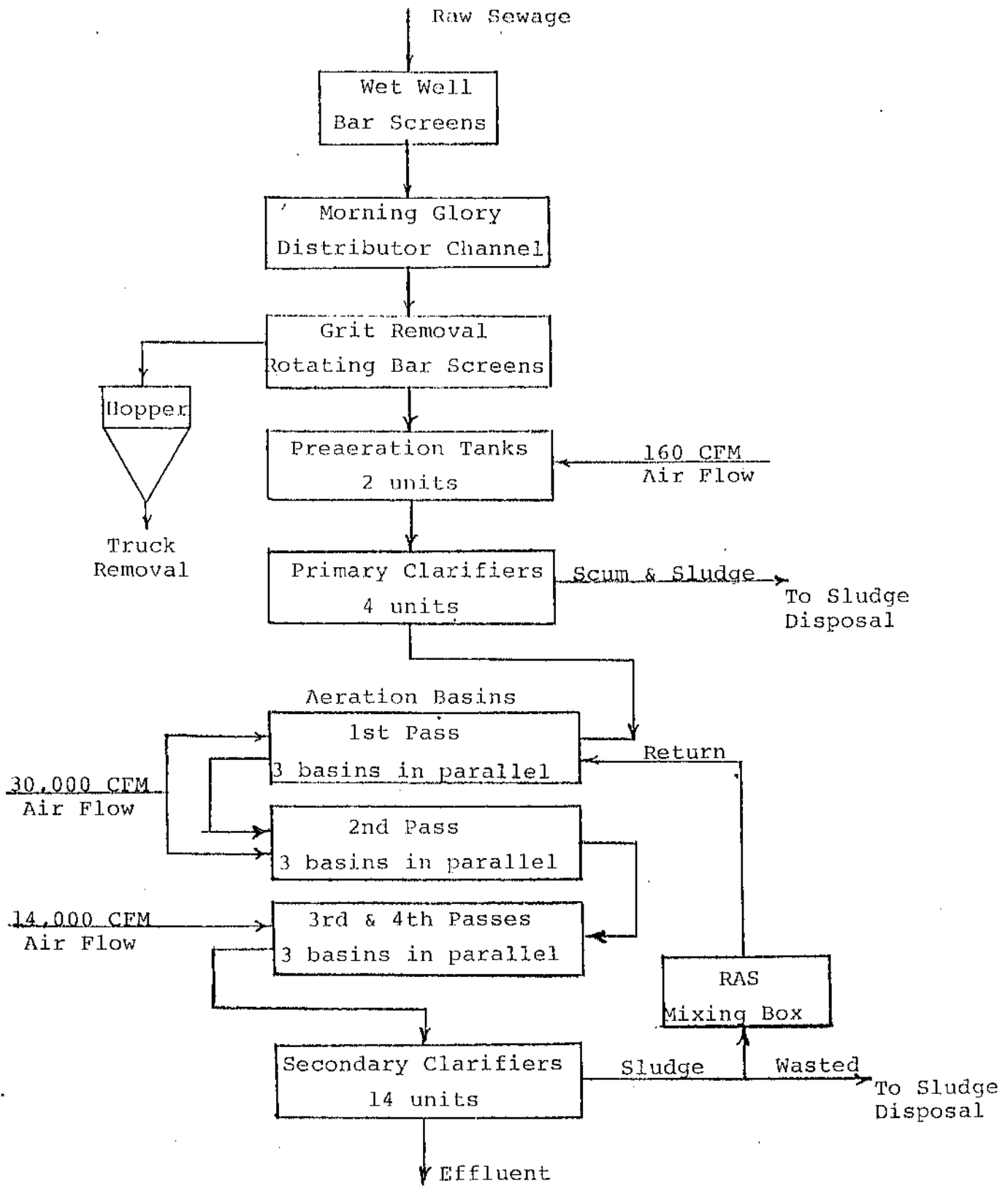


Figure 1. Flow diagram for Renton Sewage Treatment Plant, Renton, Washington.

TABLE I. ODOR SENSORY PERFORMANCE RESULTS

<u>Sampling Date</u>	<u>Sampling Time</u>	<u>Sample No.</u>	<u>Water Temp F</u>	<u>Sampling Location</u>	<u>ED50</u>
9/30/86	3:05 pm	1	65	Secondary Clarifier (#10)	62
	3:50	2	67	Aeration Basin (#2)	29
	4:25	3	67	RAS Mixing Box	52
	5:10	4	66	Primary Clarifier (#7)	71
	5:45	5		Ambient above Grit Hopper	62
	6:35	6	66	MG Distributor Channel	813
10/1/86	3:10 pm	1	66	Secondary Clarifier (#10)	39
	4:20	2	65	Aeration Basin (#2)	31
	3:45	3	66	RAS Mixing Box	88
	4:55	4	67	Primary Clarifier (#7)	94
	5:35	5		Ambient above Grit Hopper	59
	6:05	6	67	MG Distributor Channel	1120
10/2/86	2:30 pm	1	64	Secondary Clarifier (#10)	48
	3:15	2	65	Aeration Basin (#2)	94
	3:55	3	64	RAS Mixing Box	88
	4:40	4	66	Primary Clarifier (#7)	118
	5:15	5		Ambient above Grit Hopper	61
	5:45	6	66	MG Distributor Channel	1050

Notes:

Each sample was tested by the odor sensory panel the following morning, beginning at 8:00 am and concluding by 12:00 m.

Samples 1,2,3, and 4 were taken as fugitive area samples during all three days. Sample 6 was taken from an enclosed space the first day and as a fugitive area sample the second and third days.

Sample 5 was taken from the ambient air above the grit pile in the hopper.

Samples from the aeration basin were taken at a point 50 ft. upstream from the discharge end of the second pass during the first two days. On the last day, the sample was taken at a point 5 ft. downstream from the feed end of the first pass.

RAS: Return Activated Sludge

MG: Morning Glory

Sample No. 5 was taken by sampling the ambient air directly above the grit pile in the grit hopper. The Tygon tubing inlet was suspended just over the top of the grit pile.

The odor samples were evaluated using the IITRI forced-choice, triangle dynamic olfactometer^{1,2}. During the first day of panel tests, seven panel members were present. During the second and third days, nine panel members were present.

The odor sensory results obtained are relatively consistent from day to day. Previous tests on the reproducibility of results using this technique suggest that the variation represents real, daily changes in emission levels³ rather than sample scatter and variation due to small changes in panel composition or investigator technique.

The odor sensory results are summarized in Table I.

An explanation must be provided for the ED₅₀ values reported for the aeration basin. During the last day, sample No. 2 was taken near the feed end of the first pass. This resulted in an ED₅₀ of 94, compared to the ED₅₀ values of 29 and 31 obtained for sample No. 2 on the other days, taken toward the discharge end of the second pass. This suggests that considerable odor is being stripped off by the air for aeration.

A measurement of the concentration of hydrogen sulfide in the collected samples was made on the last day of the odor sensory sampling. The values shown in Table II were obtained with an Interscan, Model 1170 SP hydrogen sulfide monitor.

Gas Chromatograph/Mass Spectrometer Analyses

Samples for component analysis by gas chromatograph and mass spectrometer (GC/MS) were taken at three of the locations sampled in the odor sensory testing program: the morning glory distributor channel, the primary clarifier, and the activated sludge aeration basins. Samples were collected on Tenax tubes under the conditions shown in Table III. The tubes were prepared, and analyzed, by the Trace Organics Analysis Center at the University of Washington.

Concurrently samples were also collected in polished stainless steel cryo-capture cylinders, Tedlar bags, and polyethylene containers (Cubitainers). A comparison was made of the data from the various sampling methods and will be reported in

TABLE II. HYDROGEN SULFIDE CONCENTRATIONS (ppm)

Secondary Clarifier	0.6	Primary Clarifier	0.5
Aeration Basin	0.7	Ambient above Grit Hopper	0.4
RAS Mixing Box	0.6	MG Distributor Channel	6.5

TABLE III. GC/MS SAMPLE DATA

<u>Sample</u>	<u>Location</u>	<u>Flow (ml/min)</u>	<u>Volume (liters)</u>
1	MG Distributor Channel	200	12
2*	MG Distributor Channel	200	12
3*	Primary Clarifier	200	12
4	Primary Clarifier	200	12
5*	Aeration Basin	190	11.4
6	Aeration Basin	200	12
7	Field blank	0	0
8	Leak blank	0	0

Notes:

All samples taken on 10/9/86 between 1:00 pm and 5:00 pm

All samples taken as fugitive area samples as described for odor samples. Samples 5 and 6 were taken at the same location as the 10/1 odor samples.

Samples marked * are reported in Table V.

a subsequent paper.

The Tenax tubes were thermally desorbed at 260 °C into a cryogenic loop made by coiling 15 cm of the front of the fused silica GC column inside a cryogenic trap which is filled with liquid nitrogen. Thermal desorption and cryogenic focusing was continued for 15 minutes. The GC oven was then heated to 280 °C with a constant temperature increase over a 16 minute period.

The compounds were transferred directly to the electron collision ionizer of the mass spectrometer. A forward library searching program with the 25,000 compound National Bureau of Standards reference library was used to initially screen the data. The program applies a peak-finding algorithm to identify mass spectra representing chromatographic maxima, followed by a comparison with the reference library. If an adequate agreement is found, the sample peak is quantitated. A fitting threshold of 900 of a possible 1000 spectral agreement index was used; components not achieving this level of agreement were reported as unknown.

The calibration standard was a liquid mixture of equal volumes of the target compounds for the U.S. Environmental Protection Agency's toxic air pollutants analysis method TO-1, obtained from Supelco, Inc. plus several compound of specific interest in this study. One standard was spiked onto a Tenax tube and run as a field sample.

TABLE IV. SUGGESTED ODOROUS COMPOUNDS IN SEWAGE

	<u>Formula</u>	<u>Mol Wt</u>	<u>Odor Threshold</u>
Acetic acid	C_2H_4O	60	1000 ppb
Acetyl aldehyde	C_2H_4O	44	70
Allyl mercaptan	CH_2CHCH_2SH	74	0.1
Allyl sulfide	$(CH_2CHCH_2)_2S$	114	1
Ammonia	NH_3	17	37
Amyl mercaptan	CH_2CHCH_2SH	104	0.3
Benzyl mercaptan	$C_6H_5CH_2SH$	124	0.2
Butyl alcohol	$CH_3(CH_2)_3OH$	74	11000
Butyl aldehyde	$CH_3(CH_2)_2CHO$	74	
Butyl amine	$CH_3(CH_2)_3NH_2$	73	240
Butyl mercaptan	$CH_3(CH_2)_3SH$	90	1
Butyric acid	$C_2H_5CH_2CO_2H$	88	0.01
Cadaverine	$H_2N(CH_2)_5NH_2$	102	
Carbon disulfide	CS_2	76	210
Chlorophenol	ClC_6H_4OH	128	0.2
Dibutyl amine	$(C_4H_9)_2NH$	129	
Dimethyl amine	$(CH_3)_2NH$	45	47
Dimethyl disulfide	CH_3SSCH_3	94	8
Dimethyl sulfide	$(CH_3)_2S$	62	4
Diphenyl sulfide	$(C_6H_5)_2S$	186	0.1
Disopropyl amine	$(CH_3CH_2CH_2)_2NH$	101	85
Ethyl acrylate	$CH_2CHCOOC_2H_5$	100	0.4
Ethyl alcohol	CH_3CH_2OH	46	10000
Ethyl amine	$C_2H_5NH_2$	45	830
Ethyl mercaptan	CH_3CH_2SH	62	0.3
Ethyl sulfide	$(C_2H_5)_2S$	90	3
Hydrogen sulfide	H_2S	34	300
Indole	$C_6H_4NH(CH)_2$	117	0.1
Methyl amine	CH_3NH_2	31	21
2-Methyl indole	$CH_3NC_8H_6$	131	
Methyl mercaptan	CH_3SH	48	1
Mesityl oxide	$(CH_3)_2C:CHCOCH_3$	98	51
Phenol	C_6H_5OH	94	1
Phosphine	H_3P	96	21
Propionic acid	CH_3CH_2COOH	74	0.4
Propyl mercaptan	$CH_3(CH_2)_2SH$	76	0.5
Putresine	$NH_2(CH_2)_4NH_2$	88	
Pyrdine	$(C_6H_5)_2S$	79	4
Thiocresol	$CH_3C_6H_4SH$	124	0.1
Thiophenol	C_6H_5SH	110	0.1
Trimethyl amine	$(CH_3)_3N$	59	8
Skatole	C_9H_9N	131	1
Valeric acid	$CH_3(CH_2)_3COOH$	102	0.6

Note: Odor threshold values are best estimates from many sources. In general, the value reported is above the detection threshold and below the recognition threshold where both were available. Reported values were rounded back to minimum accuracy. This list should not be used as a primary reference.

A specific search was made for 50 compounds identified as possible sources of odors in sewage atmospheres, based on review of the literature. These compounds are listed in Table IV. Six of the compounds were not appropriate for GC/MS analysis and three were not included in the NBS library. Also listed in Table IV are the odor thresholds for these compounds reported in the literature. The reported values for any one compound varied substantially, beyond the expected differences of detection threshold and recognition threshold, and original sources for the data were seldom given.

The analysis results are shown in Table V. If a compound listed in Table IV is not listed in Table V, it was not identified in the library search/match of the spectra. Tentatively identified compounds accounted for only 20 percent, 10 percent, and 38 percent of the total chromatographable organic mass

TABLE V. IDENTIFIED COMPOUNDS IN STP AIR SAMPLES

	MG	Dist	Primary	Aeration	Odor Threshold
		ppb	ppb	ppb	ppb
Benzene	8		1	1	3000
1-butanol	0.6		tr	0.9	11000
2-Butanol	3		0.8	3	43000
Carbon disulfide	1		tr	2	100
Carbon tetrachloride	1		-	-	21000
Chloroform	10		1	3	50000
Chlorobenzene	-		-	tr	60000
o-Dichlorobenzene	-		-	1	300
1,1-Dichloroethylene	1		1	5	85
1,2-(tr)-Dichloroethylene	0.3		-	tr	17000
Dimethyl disulfide	0.3		-	-	8
Ethanol	3		4	4	10000
Ethyl mercaptan + -Dimethyl sulfide	5		2	6	3
n-Hexane	-		tr	4	130000
Methylene Chloride	5		2	16	100000
iso-Propylbenzene	0.2		-	tr	1700
n-Propylbenzene	0.2		-	tr	
Styrene	tr		-	-	10
1,1,1-Trichloroethane	14		0.4	0.4	400000
Tetrachloroethylene	8		0.4	34	50000
Trichloroethylene	4		0.4	2	20000
Toluene	70		1	17	250
m,p-Xylenes	9		tr	3	530
o-Xylene	4		-	1	1800

Notes:

Ethyl mercaptan and dimethyl sulfide could not be distinguished one from the other in the analysis.

tr: identified but not at a sufficient level to be quantified
-: not matched

reported for the three sampling sites listed in Table V, from left to right, respectively.

The unidentified component may include target compounds or compounds represented in the mass spectral reference library but present in the sample at levels too low to permit valid spectral matching, in addition to components not previously recognized or present in mass spectral libraries.

The reconstructed ion chromatographs are shown in Figures 2, 3, and 4 for the three samples reported in Table V. The figures are all normalized to approximately the same scale.

With a few exceptions, the detection limit of the system was lower than the odor threshold of the compound for the compounds that were reported as unknown. Thus, if they are not listed in Table V, these compound may be assumed not to be contributing to the observed odor. The exceptions on the list in Table IV are allyl mercaptan, butyric acid, chlorophenol, ethyl acrylate, propionic acid, propyl mercaptan, and skatole.

Application of the Results

The primary objective of the odor sensory tests was to obtain basic data for the design of a future sewage treatment plant emissions control system. In those sections of the plant where the amount of exhaust air is primarily determined by the air supplied to the process, such as the activated sludge aeration basins, the odor concentrations measured will be an accurate measure of the concentration in the exhaust gas (adjusted for whatever additional clean air is supplied to that area).

In other areas, where the exhaust air volume flow is defined by air turnover rate requirements, the odor concentration will be a function of the surface emission rate of the odor and the amount of ventilation flow. Although the odor samples were obtained from the surface layer above each of the water surfaces they represent only the expected concentration in the surface layer under similar conditions of air flow and not the emission rate.

It is common practice to design the more odorous portions of a sewage treatment plant for approximately 12 air changes per hour. In other portions of the plant the turnover may be safely reduced to 6 air changes per hour, but in a totally enclosed plant a uniform 12 air changes per hour may be necessary in all large exposed surface water areas to avoid excessive condensation⁴. Emergency ventilation at 22 air changes per hour must also be provided to respond to any fuel or chemical spill that might create potentially explosive or hazardous conditions in an enclosed space. It is assumed that odor control is unnecessary under emergency ventilation conditions if the events are indeed rare.

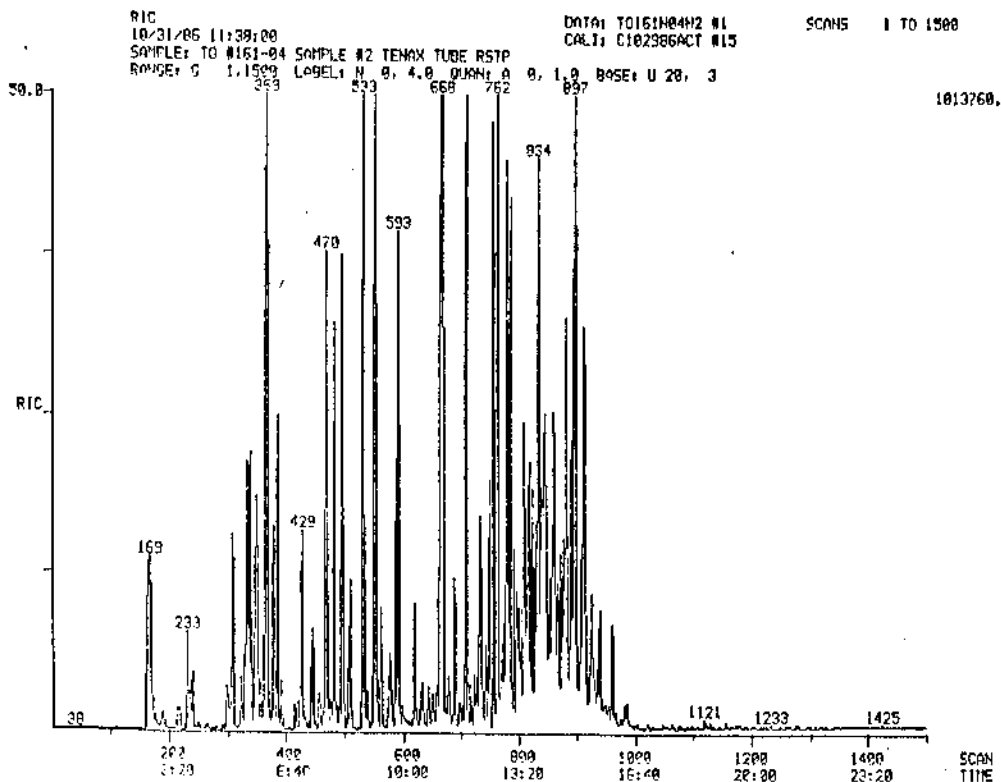


Figure 2. Reconstructed ion chromatograph for the morning glory distributor sample.

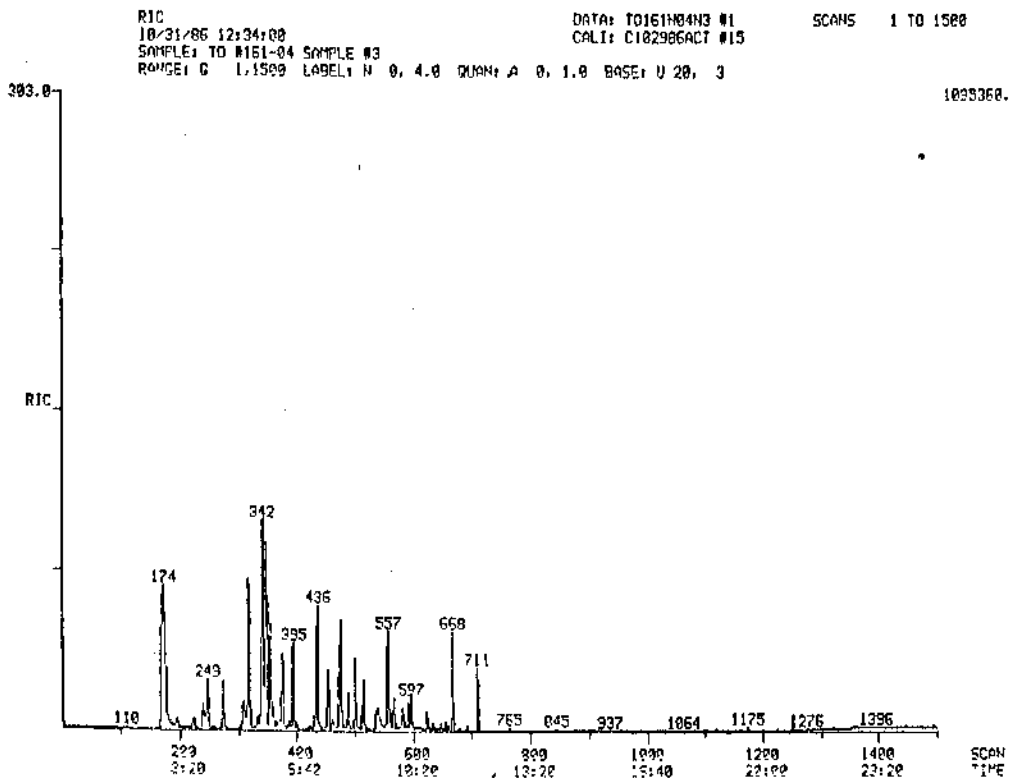


Figure 3. Reconstructed ion chromatograph for the primary clarifier sample.

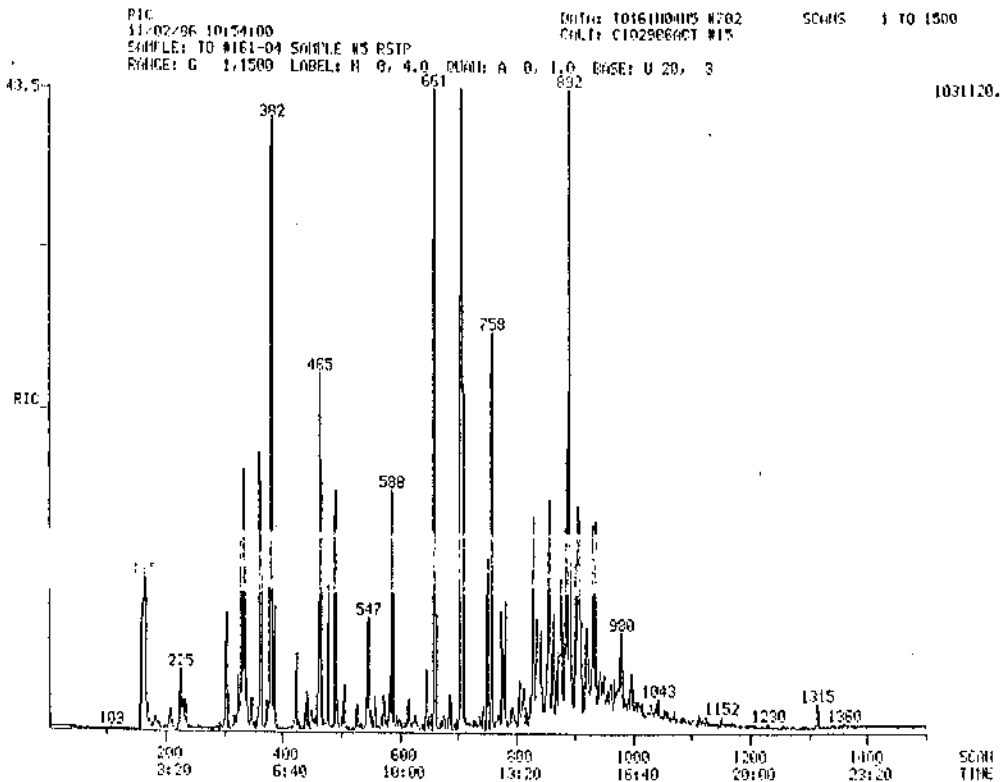


Figure 4. Reconstructed ion chromatograph for the aeration basin sample.

At 12 air changes per hour, the crossflow wind velocity will not exceed 24 feet per minute, or 0.3 miles per hour, for a 120 foot fetch and will be smaller for smaller rooms. This is much less than the 1 meter per second that is generally taken as representing quiescent atmospheric conditions. Therefore the crosswind flow from internal ventilation will not be a consideration in the evolution of odors from water surfaces in a totally enclosed facility. Surface-layer eddies from flow and thermal movement can be expected to be the dominant force in mass transfer at the water-air interface.

Aerated surfaces

The activated sludge aeration tanks at the Renton STP are ventilated from below through a fine bubble diffusion system. Oxygen transfer for this system is estimated at 12 percent (percent of incoming oxygen transferred to the water phase). With such a high level of oxygen transfer it is entirely reasonable to assume that these bubbles reach equilibrium with the surrounding water, and any odorous gases dissolved in it, by the time they reach the surface.

The first and second passes of the aeration basins in the Renton treatment plant have a total forced air flow of 30,000 cu ft/min for a surface area of 57,000 sq ft. The third and fourth passes have a total inlet air flow of 14,000 cu ft/min,

also with a surface area of 57,000 sq ft. Depending on the relative humidity of the incoming air, the loss of oxygen may be just balanced by the water vapor added or may result in up to a 1.2 percent loss of volume. As the air will be saturated, no additional surface evaporation can be expected.

If the aeration tanks are covered, with the aeration air exhausted to the control system from beneath the covers, the measured ED₅₀ will govern the design. If the tanks are uncovered and the total room air must be cleaned, the ED₅₀ will be reduced by the amount of ventilation air that must be added. If an 18 foot high ceiling is assumed, the total flow to meet the 12 air change standard will be 205,200 cfm. If the odor dilution ratio in the aeration air is 60, the formula

$$ED_{50} = ED_a AF / (VF + AF)$$

where ED_a is the initial, aeration air odor dilution ratio,
VF is the ventilation system flow, and
AF is the aeration flow,

predicts the resulting odor dilution ratio in the ventilation air, ED₅₀, will be approximately 9 for the first and second pass area and 4 for the third and fourth pass area. It is generally assumed that air with an ED₅₀ this low will present no odor problems if exhausted without any further controls.

Non-aerated surfaces

The emission rate from non-aerated surfaces will be determined by equilibria processes between the air and the water surface. The odor emission rate can be estimated from the relation⁵

$$E_i = (18 \times 10^{-6}) K_i C_i A$$

where E_i is the emission rate of compound i, in g/sec
K_i is the overall mass transfer coefficient, in
gmol/sec/cm²
C_i is the concentration of compound i in the water, in
mg/l, and
A is the area of the water surface.

The overall mass transfer coefficient can be calculated from the liquid and gas phase resistances to mass transfer. Hydrogen sulfide and the polar odorous organic compounds will generally be liquid phase controlled in water near pH 7, which is the expected acidity of sewage in the Seattle system. In a totally-enclosed facility the cross-flow velocities will be very small, thus permitting the approximation of $K = k_L$, with $k_L = 2$ to 3 cm/hr at low wind speeds⁶. In English units, this is approximately 0.25 lb-mole/ft²-hr.

Using this approximation the emission rate can be estimated and when combined with a cross-flow volumetric rate, the re-

sulting expected concentrations may be calculated and the net ED₅₀ of the flow estimated or an adjustment made to the measured value.

An alternative approach is to estimate the escape velocity from a quiescent water surface of the air necessary to carry away the evaporating water. For example, the observed average daily evaporation of an open reservoir in Seattle, Washington during the summer is 0.144 inches⁷. If the air leaving the surface is 50 percent saturated at 70 °F, the required vertical air motion will be 0.9 ft/min. The ED₅₀ of the design air flow may then be scaled against this value for the flow during the odor sensory measurements.

If the tanks are covered, with the air exhausted to the control system from beneath the covers, the scaled ED₅₀ may be used directly. If the tanks are uncovered and the total room air must be cleaned, the ED₅₀ will be reduced by the amount of ventilation air that must be added in the same manner as previously discussed.

Discussion

Although analyses similar to the one reported here have been conducted by a number of investigators, with varying degrees of success, few have been published in the open literature. Ando⁸ has reported results from an extensive GC/MS analysis of emissions from the Chubu treatment plant in Yokohama, Japan. Hagenuth, et al.⁹ give a detailed report of a GC/MS analysis (although no quantitation is reported) of emissions from a pumping station and a sludge treatment plant. Their data are summarized in Table VI.

An ED₅₀ can be computed from the measured compounds and the reported odor threshold values using the formula

$$\text{Measured/Threshold} = \text{ED}_{50}$$

However, the computed ED₅₀ for hydrogen sulfide is no more than 30 for the morning glory distributor channel, compared to a measured ED₅₀ of about 1000, and no more than an additional 5 can be added for ethyl mercaptan, the only other identified significant source of odor.

A variety of reasons may be advanced to explain this discrepancy. It is possible that the concentrations of odorous substances have been badly mismeasured or that significant sources of odor have not been identified or are below the detection limits of the GC/MS procedure. However, the similarity of the data reported here to the data reported by Ando suggests that these are not the best candidate explanations. Alternatively, perhaps some of the important odorants are not well captured by, retained by, or released by the Tenax adsorb-

TABLE VI. REPORTED COMPOUNDS IN STP AIR SAMPLES

	Ando ⁸		Hagenguth ⁹
	Primary	Aeration	Pump station
Acetic acid	7 ppb	1 ppb	-
Acetyl thiophene	-	-	yes
Ammonia	134	56	-
Benzene/Chloroform	7	9	-
Benzyl mercaptan	-	-	yes
iso-Butyric acid	1	-	-
n-Butyric acid	1	-	-
Carbon tetrachloride	10	15	-
Dimethyl disulfide	-	-	yes
Dimethyl sulfide	1	-	yes
Ethyl benzene	5	5	-
Hydrogen sulfide	12	4	-
Indole	-	-	yes
Methyl mercaptan	2	2	-
Methyl sulfide	1	2	-
Methyl thiophene	-	-	tr
Propionic acid	1	0.1	-
Propyl thiophene	-	-	yes
Toluene	12	18	-
iso-Valeric acid	-	0.2	-
n-Valeric acid	0.1	-	-
m,p-Xylene	8	7	-
o-Xylene	5	3	-
Propyl benzene	tr	tr	-
Skatole	-	-	tr
Phenol	-	-	yes

Notes:

Results have been rounded and edited to simplify presentation

tr: identified but not at a sufficient level to be quantified

-: not matched

ant. Also, it is possible a simple addition of component ED₅₀ values calculated as shown is not a valid approach. The synergistic effects of the odorants may be much more significant than their individual calculated ED₅₀ values would indicate.

The detection and identification of individual odorous species in a complex mixture by chemical analysis is, by necessity, an interactive process, with human sensory evaluation directing and informing the chemical separations and analyses. Further, the role of interactive effects between odorants renders the prospects for chemical mass balance approaches to odor prediction poor. The present results highlight the need for fundamental studies of key odor contributors and key indicator compounds, if the full potential of highly sensitive chemical measurement technology applied to the assessment and design of

ventilation control for odorous environments is to be realized.

Given the current difficulty in making such specific identifications, a more useful approach for engineering design studies may be the separate measurement of hydrogen sulfide, total organic sulfur compounds, total amines, and total polar and non-polar organics.

Acknowledgements

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