

CALIFORNIA INSTITUTE OF TECHNOLOGY
Environmental Science & Engineering
W. M. Keck Laboratories
Pasadena, California 91125



Mr. James Krug, AICP
Falcon Waterfree Technologies
10900 Wilshire Blvd., 15th Floor
Los Angeles, CA 90024

2 October 2003

Re: Falcon Waterfree Organic Barrier vs. Water for Sewer Gas Flux

Dear Mr. Krug:

I, Michael Hoffmann received a BA degree in chemistry in 1968 from Northwestern University and a PhD degree from Brown University in 1974. In 1973, I was awarded an NIH post-doctoral training fellowship in Environmental Engineering Science at the California Institute of Technology. Over the last 28 years, I have served as a Professor of Environmental Engineering and Environmental Chemistry since 1975. From 1975 to 1980, I was member of the faculty at the University of Minnesota in Civil Engineering and since 1980 a member of the faculty at Caltech in Engineering & Applied Science. For more than 15 years, I taught fundamental aspects of water and wastewater treatment. I have published more than 220 peer-reviewed professional papers and I am the holder of 7 patents in the subject areas of environmental chemistry and engineering. I have served as the Chairman of the Gordon Research Conference, Environmental Sciences: Water and as an Associate Editor of the Journal of Geophysical Research. I am currently on the Editorial Boards of *Environmental Science and Technology* and the *Journal of Physical Chemistry*. I also serve on the Scientific Advisory Board of the Max Planck Institute for Chemistry.

In 1991, I received the Alexander von Humboldt Prize for research and teaching in environmental chemistry. In 1995, I was presented with the E. Gordon Young Award by the Chemical Society of Canada in recognition of his work in the field of environmental chemistry. I have also served as a Distinguished Lecturer at the Hebrew University (Jerusalem), the University of Sao Paulo (Brazil), and the University of Buenos Aires. In 2001, I was presented with the American Chemical Society Award for Creative Advances in Environmental Science and Technology for "fundamental and lasting contributions to the science of aquatic chemistry, to the development of aquatic remediation processes, and to understanding heterogeneous and multiphase processes in the atmospheric environment." I have been honored recently as "Davis Memorial Lecturer in Chemistry" at the University of New Orleans and the Dodge Distinguished Lecturer in Chemical Engineering at Yale, the Harold S. Johnston Lecturer in Physical Chemistry at the University of California – Berkeley, and the A. R. Gordon Distinguished Lecturer in Chemistry at the University of Toronto. In addition, I was recognized with the award of the Jack E. McKee Medal for Groundwater Protection by the Water Environment Federation.

I have performed a detailed analysis of the relative efficiencies of a conventional water-based P-trap vs. the Falcon Waterfree barrier of a dual layer of urine covered by a long-chain branched aliphatic alcohol (i.e., the sealant) against the backward flux of sewer gases such as hydrogen sulfide (H₂S) and methane (CH₄) gases. I used fundamental data on the chemical composition of

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Pasadena tapwater (pH 8) and typical human urine (pH 4.5 to 8). In addition, I factored into account the effect of a lighter than water branched aliphatic alcohol such as 2-butyl-1-octanol ($\rho = 0.83 \text{ g cm}^{-3}$) covering a column of urine.

The flux calculations were made using a conventional two-film model, which is based Fick's Law of molecular diffusion, to predicted water-to-air mass transfer rates based on the fundamental properties of H_2S and methane in water (e.g., acid-base chemistry, molecular diffusion coefficients, Henry's Law constants, film thickness values, etc.). Based on these calculations for a range of concentrations of total sulfide and methane dissolved in wastewater in flowing sewers typical of the Los Angeles area, I determined that the worst case flux of H_2S gas through a conventional 2" P-trap water barrier would be $6 \text{ ng cm}^{-2} \text{ s}^{-1}$ (i.e., 6 nanograms per square centimeter per second) at pH 4.5, while at pH 8 the predicted worst-case flux through water would fall to $0.5 \text{ ng cm}^{-2} \text{ s}^{-1}$. For methane, the corresponding flux at both pH conditions, under the worst-case condition, is predicted to be $14.6 \text{ ng cm}^{-2} \text{ s}^{-1}$.

In comparison, the branched aliphatic long-chain alcohol layer acts to retard the mass transfer of both gases through the dual barrier system provided by Falcon Waterfree Technologies. The corresponding gas flux calculations for the dual barrier Falcon system are: 1) for H_2S at pH 4.5 – $0.012 \text{ ng cm}^{-2} \text{ s}^{-1}$; this corresponds to a 500-fold reduction in the mass transfer rate compared to the conventional water trap; 2) for H_2S at pH 8.0 – $0.001 \text{ ng cm}^{-2} \text{ s}^{-1}$; this also corresponds to a 500-fold reduction in the mass transfer rate compared to the conventional water trap at pH 8; 3) for methane at both pH values – $0.03 \text{ ng cm}^{-2} \text{ s}^{-1}$; which also corresponds to another 500-fold reduction in the flux rate.

In conclusion, the dual barrier systems provided in the Falcon Waterfree Technology urinals are predicted to be 500 times more effective against the back migration of sewer gases as compared to conventional P-trap water barriers. The Falcon system, which uses a column of urine topped off by a layer of high molecular weight branched aliphatic alcohols, is a better barrier than tap water alone. Very similar reductions in water-to-air gas transfer rates have been documented in the scientific literature for oil coated water surfaces (Downing & Truesdale, *J. Appl. Chem.*, **5**, 570-581, 1955). Details of the calculations are shown in the attached document.

Sincerely,

Michael R. Hoffmann

Michael R. Hoffmann
James Irvine Professor of Environmental Science

Falcon Waterfree Organic Barrier vs. Water for Sewer Gas Flux

By

Michael R. Hoffmann
Pasadena, California

Dr. Michael Hoffmann received a BA degree in chemistry in 1968 from Northwestern University and a PhD degree in chemical kinetics from Brown University in 1974. In 1973, he was awarded an NIH post-doctoral training fellowship in Environmental Engineering Science at the California Institute of Technology. Hoffmann has served as a Professor of Environmental Engineering and Environmental Chemistry since 1975. From 1975 to 1980, he was member of the faculty at the University of Minnesota and since 1980 a member of the faculty at Caltech (Engineering & Applied Science). Prof. Hoffmann taught fundamental aspects of water and wastewater treatment for 15 years.

Dr. Hoffmann has published more than 220 peer-reviewed professional papers and is the holder of 7 patents in the subject areas of applied chemical kinetics, aquatic chemistry, atmospheric chemistry, environmental chemistry, catalytic oxidation, heterogeneous photochemistry, sonochemistry, electrochemistry, and pulsed-plasma chemistry. Dr. Hoffmann has served as the Chairman of the Gordon Research Conference, Environmental Sciences: Water and as an Associate Editor of the Journal of Geophysical Research. He is currently on the Editorial Boards of *Environmental Science and Technology* and the *Journal of Physical Chemistry*. He also serves on the Scientific Advisory Board of the Max Planck Institute for Chemistry.

In 1991, Dr. Hoffmann received the Alexander von Humboldt Prize for his research and teaching in environmental chemistry. In 1995, Dr. Hoffmann was presented with the E. Gordon Young Award by the Chemical Society of Canada in recognition of his work in the field of environmental chemistry. He has also served as a Distinguished Lecturer at the Hebrew University (Jerusalem), the University of Sao Paulo (Brazil), and the University of Buenos Aires. In 2001, Dr. Hoffmann was presented with the American Chemical Society Award for Creative Advances in Environmental Science and Technology for "his fundamental and lasting contributions to the science of aquatic chemistry, to the development of aquatic remediation processes, and to understanding heterogeneous and multiphase processes in the atmospheric environment." Prof. Hoffmann was honored recently as "Davis Memorial Lecturer in Chemistry" at the University of New Orleans and the Dodge Distinguished Lecturer in Chemical Engineering at Yale, the Harold S. Johnston Lecturer in Physical Chemistry at the University of California – Berkeley, and the A. R. Gordon Distinguished Lecturer in Chemistry at the University of Toronto. In addition, Prof. Hoffmann was awarded the Jack E. McKee Medal for Groundwater Protection by the Water Environment Federation in October 2003.

Summary of Results

I have performed a detailed analysis of the relative efficiencies of a conventional water-based P-trap vs. the Falcon Waterfree barrier of a dual layer of urine covered by a long-chain branched aliphatic alcohol (i.e., the sealant) against the backward flux of sewer gases such as hydrogen sulfide (H₂S) and methane (CH₄) gases. I used fundamental data on the chemical composition of Pasadena tapwater (pH 8) and typical human urine (pH 4.5 to 8). In addition, I factored into account the effect of a lighter than water branched aliphatic alcohol such as 2-butyl-1-octanol ($\rho = 0.83 \text{ g cm}^{-3}$) covering a column of urine.

The flux calculations were made using a conventional two-film model, which is based Fick's Law of molecular diffusion, to predicted water-to-air mass transfer rates based on the fundamental properties of H₂S and methane in water (e.g., acid-base chemistry, molecular diffusion coefficients, Henry's Law constants, film thickness values, etc.). Based on these calculations for a range of concentrations of total sulfide and methane dissolved in wastewater in flowing sewers typical of the Los Angeles area, I determined that the worst case flux of H₂S gas through a conventional 2" P-trap water barrier would be $6 \text{ ng cm}^{-2} \text{ s}^{-1}$ (i.e., 6 nanograms per square centimeter per second) at pH 4.5, while at pH 8 the predicted worst-case flux through water would fall to $0.5 \text{ ng cm}^{-2} \text{ s}^{-1}$. For methane, the corresponding flux at both pH conditions, under the worst-case condition, is predicted to be $14.6 \text{ ng cm}^{-2} \text{ s}^{-1}$.

In comparison, the branched aliphatic long-chain alcohol layer acts to retard the mass transfer of both gases through the dual barrier system provided by Falcon Waterfree Technologies. The corresponding gas flux calculations for the dual barrier Falcon system are: 1) for H₂S at pH 4.5 – $0.012 \text{ ng cm}^{-2} \text{ s}^{-1}$; this corresponds to a 500-fold reduction in the mass transfer rate compared to the conventional water trap; 2) for H₂S at pH 8.0 – $0.001 \text{ ng cm}^{-2} \text{ s}^{-1}$; this also corresponds to a 500-fold reduction in the mass transfer rate compared to the conventional water trap at pH 8; 3) for methane at both pH values – $0.03 \text{ ng cm}^{-2} \text{ s}^{-1}$; which also corresponds to another 500-fold reduction in the flux rate.

In conclusion, the dual barrier systems provided in the Falcon Waterfree Technology urinals are predicted to be 500 times more effective against the back migration of sewer gases as compared to conventional P-trap water barriers. The Falcon system, which uses a column of urine topped off by a layer of high molecular weight branched aliphatic alcohols, is a better barrier than tap water alone. Very similar reductions in water-to-air gas transfer rates have been documented in the scientific literature for oil coated water surfaces (Downing & Truesdale, *J. Appl. Chem.*, **5**, 570-581, 1955). Details of the calculations are shown below.

Fundamental Relationships used to calculate flux rates through water or urine/sealant trap systems:

Calculation of P_{H₂S} assuming available data on pH and total dissolved sulfide (S_T) in aqueous phase:

$$[S(-II)] = [H_2S_{(aq)}] + [HS^-] + [S^{2-}]$$

Assume that aqueous phase is in equilibrium with gas at fixed P_{H₂S},

$$[S(-II)] = K_H P_{H_2S} + \frac{K_H P_{H_2S} K_{a1}}{[H^+]} + \frac{K_H P_{H_2S} K_{a1} K_{a2}}{[H^+]^2}$$

then

$$P_{H_2S} = \frac{[S(-II)]}{K_H + \frac{K_H K_{a1}}{[H^+]} + \frac{K_H K_{a1} K_{a2}}{[H^+]^2}}$$

Fraction of total measure sulfide present as H₂S gas dissolved in water

$$[H_2S] = \alpha_o [S(-II)]_T$$

$$\alpha_o = \left(1 + \frac{K_{a1}}{[H^+]} + \frac{K_{a1} K_{a2}}{[H^+]^2} \right)^{-1} \text{ or } \alpha_o = \left(\frac{[H^+]^2}{[H^+]^2 + K_{a1}[H^+] + K_{a1} K_{a2}} \right)$$

$$[H_2S]_{aq} = K_H \cdot P_{so_2} \quad (\text{Henry's Law Relationships}) \quad [CH_4]_{aq} = K_H \cdot P_{CH_4}$$

Mass flux across an interface using a classical two-film theory model

$$F = -D \frac{dC}{dz}$$

$F = \text{mol cm}^{-2} \text{ s}^{-1}$ or $\text{g cm}^{-2} \text{ s}^{-1}$, D (diffusion coefficient) = $\text{cm}^2 \text{ s}^{-1}$, dC/dz (concentration gradient) mol cm^{-4} through film thickness, dz (cm), C (concentration) moles or mass cm^{-3}

$$F = F_a = F_w$$

$$F_a = -\frac{D_a}{z_a} (C_a - C_{a/w})$$

$$F_w = -\frac{D_w}{z_w} (C_{w/a} - C_w)$$

$$H = \frac{C_{w/a}}{C_{a/w}} = K_H RT$$

$$F = \frac{1}{v_w^{-1} + v_a^{-1} H} (C_w - C_a H) - \text{water or urine alone}$$

$$F = \left(\frac{1}{v_w^{-1} + v_a^{-1}H + v_s^{-1}K_{s/w}} \right) (C_w - C_aH) - \text{urine covered by layer of sealant}$$

$$v_w = \frac{D_w}{z_w}; v_a = \frac{D_a}{z_a}; v_s = \frac{D_s}{z_s}$$

$$D_w \cong 1.0 \times 10^{-5} \text{ cm}^2 \text{ s}^{-1}; D_a \cong 1.0 \times 10^{-1} \text{ cm}^2 \text{ s}^{-1}; D_{s/w} \cong 1.0 \times 10^{-5} \text{ cm}^2 \text{ s}^{-1}$$

$$0.1 \leq z_a \leq 1.0 \text{ cm}; 0.005 \leq z_w \leq 0.05 \text{ cm}; 0.5 \leq z_s \leq 5 \text{ cm}$$

$$K_{s/w} \cong 1$$

Critical Constants

Henry's Law data – H₂S

Henry's Law constant (water solution) $\text{H} \begin{array}{c} \text{S} \\ \diagup \quad \diagdown \\ \text{H} \quad \text{H} \end{array}$

k_H° = Henry's law constant for solubility in water at 298.15 K (mol/kg*bar)

k_H° (mol/kg*bar)	$d(\ln(k_H))/d(1/T)$ (K)	Method	Reference	Comment
0.087	2100.	M	De Bruyn, Swartz, et al., 1995	
0.10	2000.	L	Lide and Frederikse, 1995	
0.10	2300.	Q	Dean, 1992	Only the tabulated data between T = 273. K and T = 303. K from Dean, 1992 was used to derive k_H and $-\Delta k_H/R$. Above T = 303. K the tabulated data could not be parameterized by equation (reference missing) very well. The partial pressure of water vapor (needed to convert some Henry's law constants) was calculated using the formula given by Sander, Lelieveld, et al., 1994. The quantities A and α from Dean, 1992 were assumed to be identical.
0.10	2200.	L	Carroll and Mather, 1989	
0.097	2200.	X	Kavanaugh and Trussell, 1980	
0.10	2100.	L	Edwards,	

			Maurer, et al., 1978	
0.10	2100.	L	Wilhelm, Battino, et al., 1977	
0.10		R	Hine and Weimar, 1965	
0.0010	2300.	X	Loomis, 1928	The value is taken from the compilation of solubilities by W. Asman (unpublished).

References

Go To: Top, Henry's Law data, Notes / Error Report

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Henry's Law data - Methane

Henry's Law constant (water solution)

k_H° = Henry's law constant for solubility in water at 298.15 K (mol/kg*bar)

k_H° (mol/kg*bar)	$d(\ln(k_H))/d(1/T)$ (K)	Method	Reference	Comment
0.0014	1600.	L	Lide and Frederikse, 1995	The parameterization given by Lide and Frederikse, 1995 (parameters A, B, C) doesn't fit the data in the same paper for this substance. Therefore the parameterization of the solubility data (X_1) was recalculated.
0.0013	1900.	Q	Dean, 1992	Only the tabulated data between $T = 273. K$ and $T = 303. K$ from Dean, 1992 was used to derive k_H and $-\Delta k_H/R$. Above $T = 303. K$ the tabulated data could not be parameterized by equation (reference missing) very well. The partial pressure of water vapor (needed to convert some Henry's law constants) was calculated using the formula given by Sander, Lelieveld, et al., 1994. The quantities A and α from Dean, 1992 were assumed to be identical.
0.0015		Q	Yaws and Yang, 1992	Yaws and Yang, 1992 give several references for the Henry's law constants but don't assign them to specific species.
0.0013		L	Mackay and Shiu, 1981	
0.0013	1800.	X	Kavanaugh and Trussell, 1980	
0.0014	1700.	L	Wilhelm, Battino, et al., 1977	
0.0015		V	Hine and Mookerjee, 1975	
0.00097		C	Liss and Slater, 1974	
0.0014		R	Hine and Weimar, 1965	
0.0092		V	Butler and Ramchandani, 1935	

References

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Hine, J.; Mookerjee, P.K., *The intrinsic hydrophilic character of organic compounds. Correlations in terms of structural contributions*, **J. Org. Chem.**, 1975, 40, 292-298.

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Hine, J.; Weimar, R.D., Jr., *Carbon basicity*, **J. Am. Chem. Soc.**, 1965, 87, 3387-3396.

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Butler, J.A.V.; Ramchandani, C.N., *The solubility of non-electrolytes. Part II. The influence of the polar group on the free energy of hydration of aliphatic compounds*, **J. Chem. Soc.**, 1935, 952-955.

pH of Urine - 4.5 to 8

Urine pH is used to classify urine as either a dilute acid or base solution. Seven is the point of neutrality on the pH scale. The lower the pH, the greater the acidity of a solution; the higher the pH, the greater the alkalinity. The glomerular filtrate of blood is usually acidified by the kidneys from a pH of approximately 7.4 to a pH of about 6 in the urine. Depending on the person's acid-base status, the pH of urine may range from 4.5 to 8. The kidneys maintain normal acid-base balance primarily through the reabsorption of sodium and the tubular secretion of hydrogen and ammonium ions. Urine becomes increasingly acidic as the amount of sodium and excess acid retained by the body increases. Alkaline urine, usually containing bicarbonate-carbonic acid buffer, is normally excreted when there is an excess of base or alkali in the body. Secretion of an acid or alkaline urine by the kidneys is one of the most important mechanisms the body uses to maintain a constant body pH.

A highly acidic urine pH occurs in:

- Acidosis
- Uncontrolled diabetes
- Diarrhea
- Starvation and dehydration
- Respiratory diseases in which carbon dioxide retention occurs and acidosis develops

A highly alkaline urine occurs in:

- Urinary tract obstruction
- Pyloric obstruction
- Salicylate intoxication
- Renal tubular acidosis
- Chronic renal failure
- Respiratory diseases that involve hyperventilation (blowing off carbon dioxide and the development of alkalosis)

In people who are not vegetarians, the pH of urine tends to be acidic. A diet rich in citrus fruits, legumes, and vegetables raises the pH and produces urine that is more alkaline. Most of the bacteria responsible for urinary tract infections make the urine more alkaline because the bacteria split urea into ammonia and other alkaline waste products. The urine pH varies in different types of acidosis and alkalosis. Control of pH is important in the management of several diseases, including bacteriuria, renal calculi, and drug therapy.

The formation of renal stones is related to the urine pH. Patients being treated for renal calculi are frequently given diets or medications to change the pH of the urine so that kidney stones will

not form. Calcium phosphate, calcium carbonate, and magnesium phosphate stones develop in alkaline urine; when this occurs, the urine is kept acidic. Uric acid, cystine, and calcium oxalate stones precipitate in acidic urine; in this situation, the urine should be kept alkaline or less acidic than normal. Drugs such as streptomycin, neomycin, and kanamycin are effective in treating urinary tract infections if the urine is alkaline. During treatment with sulfa drugs, alkaline urine helps prevent formation of sulfonamide crystals.

Here are important points to remember about urinary pH:

- An accurate measurement of urinary pH can be done only on a freshly voided specimen. If urine must be kept for any length of time before analysis, it should be refrigerated.
- During sleep, decreased pulmonary ventilation causes respiratory acidosis. As a result, a first waking urine specimen is usually highly acidic.
- Bacteria causing a urinary tract infection or bacterial contamination will produce alkaline urine.
- A diet rich in citrus fruits, most vegetables, and legumes will keep the urine alkaline.
- A diet high in meat and cranberry juice will keep the urine acidic.
- Urine pH is an important screening test for the diagnosis of renal disease, respiratory disease, and certain metabolic disorders.
- If urine pH is to be useful, it is necessary to use pH information in comparison with other diagnostic information.

Data on the ranges of total sulfide (i.e., [S-(II)]) and methane in wastewater systems are taken from the literature.

Sewer Gas

Sewer gas is a complex mixture of toxic and non-toxic gases that can be present at varying levels depending upon the source. It is formed during the decay of household and industrial waste. Highly toxic components of sewer gas include hydrogen sulfide and ammonia.

Sewer gas also contains methane, carbon dioxide, sulfur dioxide, and nitrous oxides. In addition, chlorine bleaches, industrial solvents, and gasoline are frequently present in municipal and privately owned-sewage treatment systems.

Sewer gas can enter a home through a floor drain, from a leaking or blocked plumbing roof vent, or (if the gases are in soil adjacent to the house) through cracks in foundations. Sanitary and farm workers can be exposed to sewer gas during the cleaning and maintenance of municipal sewers, manure storage tanks, and home septic tanks.

The principal risks and effects associated with exposure are:

- Hydrogen sulfide poisoning. Exposure to low levels of hydrogen sulfide causes irritation of the eyes and respiratory tract. Other symptoms include nervousness, dizziness, nausea,

headache, and drowsiness. This gas smells like rotten eggs, even at extremely low concentrations. Exposure to high concentrations can interfere with the sense of smell, making this warning signal unreliable. At extremely high levels, hydrogen sulfide can cause immediate loss of consciousness and death.

- Asphyxiation. Methane acts like carbon monoxide, blocking oxygen in the blood, and can similarly cause suffocation and death at high levels. Exposure to lower levels can produce flu-like symptoms such as headache, nausea, and drowsiness. Breathing undiluted sewer gas, even for short periods, as in a municipal sewer line or a manure storage tank, can result in suffocation and death. Sewer gas diffuses and mixes into indoor air, and will be most concentrated where it is entering. It can accumulate in basements.
- Explosion and fire. Methane and hydrogen sulfide are flammable and highly explosive.

Symptoms of headache, nausea, dizziness, or drowsiness may indicate exposure to an odorless gas like methane or carbon monoxide, or to hydrogen sulfide, which smells of rotten eggs. Persons experiencing severe symptoms should seek immediate medical care.

Measured Methane Concentration in Anaerobic Wastewaters

Dissolved Methane	(mg/l)
Raw leachate	9.980
Aeration tank 1	4.610
Aeration tank 2	1.840
Aeration tank 3	0.486
Aeration tank 4	0.133
Aeration tank 5	0.102
Final effluent	0.095

References

Attal, A., M. Brigodiot, P. Camacho and J. Manem (1992). "Biological Mechanisms of H₂S Formation in Sewer Pipes." *Water Science and Technology* **26**(3-4): 907-914.

The purpose of this study is to gain a better understanding of the biological phenomena involved in the production of hydrogen sulfide in urban wastewater (UWW) systems. It is found that the UWW itself naturally possesses the biomass needed to consume the sulfates. These heterotrophic sulfate-reducing bacteria populations, though immediately active in strict anaerobic

conditions, are present only in very low concentrations in the UWW. A concentration of them was studied within the pressure pipes, in the form of deposits, and this justifies the high concentrations of sulfides measured in certain wastewater networks. There are two reasons why the ferrous sulfate used as a treatment in any wastewater networks should not cause the production of additional sulfides. Firstly, the sulfate consumption kinetics are always too slow, relative to the residence time of the water in the pipe, for all of the sulfates to be consumed anyway. Secondly, the amount of assimilable carbon, soluble carbon, and carbon from suspended solid (SS) hydrolysis is insufficient.

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Delgado, S., M. Alvarez, L. E. Rodriguez-Gomez and E. Aguiar (1999). "H₂S generation in a reclaimed urban wastewater pipe. Case study: Tenerife (Spain)." Water Research **33**(2): 539-547.

The present work is part of an experimental study carried out in a completely filled gravity pipe, 61 km long, which transports reclaimed urban wastewater (RUWW), for crop irrigation with an average water residence time of 42 h, in the island of Tenerife (Spain). Field studies were conducted from November 1994 to June 1995. H₂S generation has been observed in the pipe when anaerobic conditions appear. A direct relation between sulfide generation and the organic matter measured as COD has been seen. S(II) build-up in this pipe is compared with the predicted S(II) according to equations proposed by Boon and Lister (1975), Hvitved-Jacobsen et al. (1988) and Boon (1995) for sewers [Boon, A. G. and Lister, A. R. (1975) Formation of sulphide in rising main sewers and its prevention by injection of oxygen. *Prog. Water, Technol.* 7(2), 289-300; Hvitved- Jacobsen, T., Juette, P. H., Nielsen, P. H. and Jensen, N.Aa. (1988) Hydrogen sulphide control in municipal sewers. In *Pretreat. in Chem. Wat. and Wast. Treat.*, Proceedings of 3rd International Gothenburg Symposium, eds. H. H. Hahn and R. Klute, pp. 239-247. Springer Verlag, Gothenburg, Sweden; Boon, A. G. (1995) Septicity in sewers: causes, consequences and containment. *Water Sci. Technol.* 31(7), 237-253.]. Changes in oxidation-reduction potential (ORP) during transportation are presented and an empirical equation which relates S(II) concentration in wastewater with the oxidation-reduction potential (ORP) and sulfate has been developed. (C) 1998 Elsevier Science Ltd. All rights reserved.

Einarsen, A. M., A. Aesoy, A. I. Rasmussen, S. Bungum and M. Sveberg (2000). "Biological prevention and removal of hydrogen sulphide in sludge at Lillehammer Wastewater Treatment Plant." Water Science and Technology **41**(6): 175-182.

Formation of H₂S and other odorous compounds in sludge can be prevented efficiently by controlled dosage of nitrate. Lillehammer WWTP (N) had problems with malodour that originated mainly from the sludge treatment. High levels of H₂S caused poor working conditions, and resulted in an overloaded hypochlorite scrubber. In addition, neighbours were complaining. Controlled dosing was necessary to avoid increased loads on the nitrogen removal process and floating sludge in the thickener, and to keep the H₂S concentration and chemical costs low. This resulted in considerably better working environment and eliminated complaints from neighbours. A cost- benefit for Nutriox(R) Septicity Control has been performed.

Hao, O. J., J. M. Chen, L. Huang and R. L. Buglass (1996). "Sulfate-reducing bacteria." Critical Reviews in Environmental Science and Technology **26**(2): 155-187.

The corrosion of sewers and the control of odor are the major operational and maintenance problems in wastewater collection systems. The generation of hydrogen sulfide and subsequent sulfuric acid results from microbially mediated reactions, by sulfate-reducing bacteria (SBR) and sulfide-oxidizing bacteria. This review covers pertinent information about sulfate reduction-induced problems in general and SBR in particular. Metabolism with respect to carbon, energy, and sulfur sources, ecology, growth factors (dissolved oxygen, temperature, pH, and sulfide), and the competitive effects of methane-producing bacteria on SBR are discussed. Because metals react with sulfide to form metal sulfide precipitates with extremely low solubilities, metal interactions in sulfate reduction environments are discussed.

Holder, G. A. (1986). "Prediction of Sulfide Buildup in Filled Sanitary Sewers." Journal of Environmental Engineering-Asce **112**(2): 199-210.

Hvitved-Jacobsen, T., J. Vollertsen and N. Tanaka (2000). "An integrated aerobic/anaerobic approach for prediction of sulfide formation in sewers." Water Science and Technology **41**(6): 107-116.

A conceptual framework for microbial transformations of organic matter and sulfur components in sewers has been developed. This concept is a new basis for integrated process engineering analysis, planning, design and management of the urban wastewater system. Based on the concept, a model (WATS, Wastewater Aerobic/anaerobic Transformations in Sewers) has been developed for simulation of wastewater quality transformations and sulfide formation in sewers. The paper will outline the concept and give examples of engineering applications. The model has been used as a design tool for simulation of carbon and sulfur wastewater transformation under dissolved oxygen limited conditions in a 50 km intercepting gravity sewer being planned in the Emscher catchment, Germany.

Kitagawa, M., T. Ochi and S. Tanaka (1998). "Study on hydrogen sulfide generation rate in pressure mains." Water Science and Technology **37**(1): 77-85.

Experimental facilities comprising 1.8 km of pipeline, 100 mm in diameter and pumping equipment, were installed in a wastewater treatment plant and operated continuously for more than one year to clarify the main factors governing hydrogen sulfide generation in pressure mains. The effects of temperature, organic matter, and sulfate on sulfide generation rate were investigated based on observed values. The sulfide generation rate depended significantly on wastewater temperature. It was confirmed not empirically but experimentally that the effect of temperature (T) was expressed by $(1.065)(T-20)$. In respect of organic matter; it is considered that there is a little effect of organic matter concentration on sulfide generation rate when the fluctuation of soluble organic matter concentration is slight. However, based on observed values, it was found that sulfide generation rate clearly depended on sulfate concentration when the biofilm was rather thick like these experiments. Also, partial penetration of sulfate into biofilm was confirmed using a biofilm model. Furthermore, biofilm model as a sound method for predicting sulfide generation rate was discussed. (C) 1998 IAWQ. Published by Elsevier Science Ltd.

Lawrence, N. S., J. Davis and R. G. Compton (2000). "Analytical strategies for the detection of sulfide: a review." Talanta **52**(5): 771-784.

reductions were largely due to the effective precipitation of sulfide with Fe(III) and Fe(II) and the limited volatilization of H₂S, respectively. Oxidation of sulfide in the presence of Fe(II) and minute amounts of O₂ may have occurred. A combination of Fe(III) and Fe(II) proved more effective than either salt alone. By using excess Fe(III), dissolved sulfide can be reduced to undetectable levels. No specific relation between the concentration of Fe or Fe(III)/Fe(II) blend ratio and sewer crown pH was inferred. Iron salts may retard crown corrosion rates by precipitating free sulfide and reducing its release to the sewer headspace as H₂S. A mechanism to inhibit certain responsible bacteria was not established in the 40-km (25 mi) sewer.

Pomeroy, R. D. and J. D. Parkhurst (1977). "Forecasting of Sulfide Buildup Rates in Sewers." Progress in Water Technology 9(3): 621-&.

Tanaka, N., T. Hvitved-Jacobsen and T. Horie (2000). "Transformations of carbon and sulfur wastewater components under aerobic-anaerobic transient conditions in sewer systems." Water Environment Research 72(6): 651-664.

Wastewater quality changes in the carbon and sulfur cycles in pressure sewers and in a gravity sewer that followed a pressure sewer were studied. The primary focus was on changes in chemical oxygen demand (COD) components during transports which were investigated using oxygen uptake rate measurements and volatile fatty acid analyses. Sulfide formation in the pressure sewers and sulfide oxidation in the gravity sewer were also studied. Anaerobic hydrolysis, which resulted in a net production of readily biodegradable substrate in the pressure sewers, was quantified. A process model description, which included the main aerobic and anaerobic processes in the water phase and in the biofilm, was presented; model parameters were determined based on calibration. This simulation procedure made it possible to consider integrated aspects of hydrogen sulfide and variations in COD components in sewers such as odor and sewer corrosion by hydrogen sulfide and the inadequacy of advanced wastewater treatment because of the input of low- quality wastewater. It is possible to include wastewater quality changes and, thereby, process aspects for sewer design and operation.

Vapor Pressure Prediction for 2-butyl-1-octanol

$$\Delta S = 36.6 + 8.31 \ln(T_b) = 88.50756$$

$$BP = 516.15$$

$$\Delta H_{vap} = \Delta S(T_b) = 45679.28$$

$$8.2764$$

$$\ln(P_2/P_1) = (\Delta H/R)(1/T_1 - 1/T_2) \quad 7.824368$$

$$P_{vap} (25^\circ C) = \quad 3.94E-04 \text{ atm} \quad 0.299188 \text{ torr}$$

$$n/v = P/RT = 0.012244 \quad 2.281379 \text{ g/L}$$