SEWER SIPHON ASSESSMENT AND AIR JUMPER DESIGN

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ABSTRACT

In response to customer complaints about sewer odor, Orange County Sanitation District (OCSD), California launched a project to investigate the ventilation requirements of existing sewer siphons, to verify adequacy of existing air jumper operation, and determine the need for new air jumpers or additional air jumper capacity. The challenge was assessing sewer siphon air jumper adequacy without clear industry standards or guidance for comparison and to then develop air jumper sizing guidelines and recommendations for retrofit replacement or addition of air jumpers at 17 of the existing 87 OCSD sewer siphon locations.

A literature search for sewer siphon air jumper sizing guidance was conducted. For each of the 17 sewer siphons studied: siphon inlet and outlet structures were inspected; sewer flow was measured; headspace air pressure or vacuum was measured; air flow into or out of the upstream and downstream siphon structures was measured; and dissolved and headspace hydrogen sulfide levels were measured. Relationships were theorized and developed between: depth of wastewater flow in the sewers; velocity of wastewater flow; sewer headspace airflow rates; and sewer headspace pressure or vacuum with manhole covers in place. General design guidelines for sewer siphon air jumpers were developed and recommended and these guidelines were applied to the field data for each of the studied 17 siphons. Sewer siphon air jumper retrofit replacement or additions are currently in the final design phase with construction scheduled to start in February 2007.

KEYWORDS

Sewer, wastewater, inverted siphon, air jumper, vent, headspace, drag, d/D, depth/diameter, hydrogen, sulfide, H_2S, reduction factor, odor control, vacuum, pressure, water column, depressed sewer

BACKGROUND

The Orange County Sanitation District consists of a service area of 471 square miles, including 21 city and three special district member agencies. The regional transmission system owned and maintained by OCSD includes 475 miles of interceptor and trunk sewer lines. The local collection sewers are owned and maintained by the member agencies.

The OCSD system also includes 17 pump stations and two regional wastewater treatment plants treating a total average daily flow of 243 million gallons per day (mgd).

The regional OCSD sewer transmission system includes 87 sewer siphons. These inverted sewer siphons range in size from 15 to 60 inches in diameter and typically cross under large storm drain box culverts within heavily congested, multi-lane boulevard intersections in Orange County, California.

OCSD is very sensitive to odor complaints from the public. It is OCSD's goal to eliminate all sources of OCSD sewer system related odor complaints. OCSD has maintained a Geographical Information System (GIS) tracking of the location of all odor complaints. It was determined that there are a number of odor complaint "hotspots" in the vicinity of many of the siphons, despite a very pro-active siphon cleaning and maintenance program. OCSD prioritized the odor complaint hotspots in the vicinity of siphons and then moved forward with this project to investigate the adequacy of air jumpers for the siphons with the most odor complaints. The need for air jumpers and how to adequately size the air jumpers for each of these odor hotspot locations is the subject of this paper.

In the past, the OCSD's primary method of sewer siphon odor control has been to provide a "siphon vent" or "air jumper" and to seal manholes in the vicinity of sewer siphons. Of the 17 siphons reviewed in this project, six siphons do not have an air jumper, due possibly to oversight or to physical limitations accepted in the original project designs. It was suspected, and confirmed, that for most of the siphons possessing air jumpers, the existing air jumpers were not adequately sized to avoid upstream sewer headspace pressurization and release of malodorous air. This is partially evidenced by the chronic odor complaints for these siphon areas. The escaping airflow rate, intensity of odor, and location of escape are transitory and very difficult to determine or control. This often results in a public nuisance in the form of unpleasant odors.

Currently, OCSD utilizes odor control mitigation through sealing upstream and downstream manholes near the siphons, which drives the release of malodorous air to some other typically unknown location.

Typical OCSD Sewer Siphon

Figure 1 shows a typical OCSD sewer siphon, "Siphon 70." This particular siphon has a 27-inch diameter open channel flow gravity sewer approaching the sewer siphon inlet box on the right-hand side of Figure 1. The space between the water surface in the approach or exit sewer and the top of the pipe (crown) is defined herein as "headspace" or "headspace air."

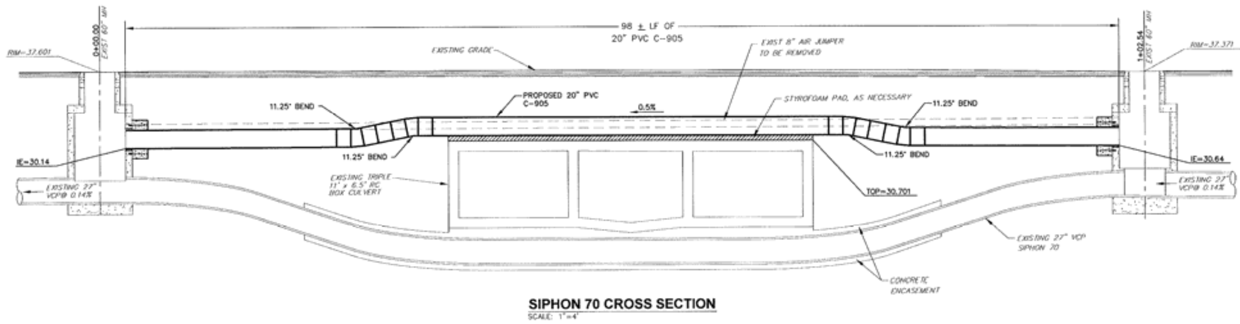


Figure 1
Typical OCSD Sewer Siphon

As is typical for the sewer siphons in OCSD, a "depressed sewer", "inverted siphon", or "siphon", equal in diameter, or slightly smaller, to the inlet sewer, is then routed down and under the intervening obstacle, which is a triple box culvert storm drain in this case. The siphon then rises to the siphon outlet box at the left-hand side of Figure 1. The siphon runs full between the siphon inlet and outlet boxes and returns to open channel flow as it continues downstream from the siphon outlet structure.

The headspace air at the studied siphon locations has hydrogen sulfide concentrations in the range from 10 to 600 parts per million (ppm) and as a result is quite odorous. The headspace air typically flows downstream in the same direction as the wastewater, until it reaches a headspace obstruction, such as siphon. Headspace air cannot pass through a siphon because the hydraulic grade line is higher than the siphon pipe causing the siphon to flow full and thereby not allowing the passage of the headspace air.

As a result of the headspace blockage, the upstream sewer headspace air will pressurize sufficiently to cause an upstream release of odorous headspace air through the path of least resistance. Odorous air outlets may include pick holes in manhole covers, plumbing vents in houses and businesses, and compromised sewer joints. It is this discharge of odorous air to which the public objects.

If all headspace obstructions could be removed, then ultimately in the OCSD system the headspace air would be transported to mechanically ventilated headworks areas at one of the OCSD pump stations or at the two regional wastewater treatment plants, where the air would pass through odor scrubbers before release.

Typically, the headspace air of the downstream siphon outlet structure is under a slight vacuum caused by movement of headspace air away from the outlet box.

In the case of Figure 1, there is an existing 8-inch diameter air jumper connecting the siphon inlet and outlet boxes well above the hydraulic grade line of the inlet and outlet gravity sewers. As a result of the field observations and air jumper design guidelines established in this project, the existing 8-inch diameter siphon air jumper shown in Figure 1 will be removed and replaced with a new larger 24-inch diameter air jumper.

PROJECT APPROACH

OCSD developed a project approach for evaluation of the existing sewer system, siphons, and siphon air jumpers to determine retrofit requirements necessary to prevent sewer headspace pressurization and odorous sewer headspace off-gassing. The project steps taken in this process included:

1. Review literature for sewer siphon and air jumper design
2. Collect pertinent field data
3. Analyze the literature and collected field data
4. Make recommendations in a Preliminary Design Report for air jumper sizing, routing, estimated cost, and recommended air jumper construction schedule

Upon OCSD acceptance of the Preliminary Design Report and Engineer's estimate of construction cost, the project moved into final design with site specific air jumper sizing and routing.

Office Research and Literature Review

Office evaluation of the as-built construction drawings and field data for each of the 17 subject inverted sewer siphons was conducted together with Geographic Information System (GIS) based aerial photographs and wastewater collection system characteristics.

Air Jumper Design. An extensive literature search for sewer siphon air jumper design was conducted. There was very little information available regarding sewer siphon design, and even less available regarding siphon air jumper design. Although the importance of maintaining sewer ventilation was followed back to medieval times in London, only a couple references were found recommending a method of air jumper sizing. Those recommendations were based on "rules of thumb" and empirical criteria not dependent on or adjusted to site specific conditions.

Based on the research and practical experience, there is a net movement of sewer atmosphere along the headspace of a sewer. The quantity and velocity of the air flow, which determines the magnitude of required ventilation, is controlled by several factors, including: liquid drag; barometric pressure differences; temperature differential between sewer headspace and ambient outdoor temperature; wind eduction; and rise and fall of wastewater with diurnal flow pattern. Of these factors, liquid drag has been found to be the only consistent and dominant cause of air flow in sewers under conditions similar to those found at OCSD. Liquid drag causes a movement of the air in the headspace of the sewer in the same direction as the wastewater flow.

The most applicable literature regarding the dynamics of sewer atmosphere was found in references by Richard Corsi, et al, discussing the transport of volatile organic compounds (VOCs) in sewers. The references reported the concept of a Reduction Factor (RF), which is the measured ratio of the headspace airflow rate to wastewater flow rate ranging from near zero up to 0.8 at the air/water interface. The conclusions and points of note in the Corsi reference are as follows:

1. It was concluded that no single mechanism controls sewer ventilation under all situations, but environmental conditions, wastewater flow conditions, and physical characteristics of a collection system were identified as some mechanisms that contribute and control to varying degrees depending on in situ conditions at the time.
2. Given the complexity of most collection systems it is impossible to accurately calculate actual ventilation rates and gas flow patterns for any given system. For a specific sewer reach, release of an inert tracer can be used to estimate gas flow rates.
3. Liquid drag causes gas flow in the same direction as wastewater flow, and is the only ventilation mechanism that acts continuously.
4. Under conditions of low resistance to ambient air inflow and sewer gas exhaust, liquid drag can induce maximum gas mean velocities of up to 0.2 meters per second (m/s) (0.2 m/s = 0.66 feet per second (fps)). Actual velocities in sanitary sewers are expected to be on the order of:
    a. 0.04 to 0.2 m/s (0.13 to 0.66 fps) for small pipes up to 0.25 m diameter (10-inch diameter);
    b. 0.003 to 0.20 m/s (0.010 to 0.66 fps) for mid-sized pipes up to 1.0 m diameter (39-inches); and
    c. 0.005 to 0.18 m/s (0.016 to 0.59 fps) for large pipes up to 2.5 m diameter (98-inches).

In comparison to Corsi, the headspace air velocity measured for OCSD ranged between 0.11 fps to 2.3 fps with an average field result of 0.55 fps for OCSD over 30 flow rate data points converted to headspace air velocity for the depth of flow at the time of the measurement.

For purposes of the OCSD air jumper sizing calculations, it was decided to evaluate field measured wastewater depth and flow rate and headspace air flow rates to calculate a field Reduction Factor for each studied siphon. Use of a reduction factor applied to headspace cross-sectional area and wastewater flow rates allowed calculation of estimated headspace air flow rates.

In the literature, there was a limited discussion of sewer headspace vacuum and pressure having been measured in other odorous sewers, ranging from -0.10 inches of water (vacuum) to +0.25 inches of water (pressure). It was decided to also include field measurement of headspace pressure or vacuum at each of the subject siphon inlet and outlet structures.

Sewer Hydraulics. The theoretical relationships between sewer slope, Mannings “n” factor, actual depth of wastewater flow, and wastewater velocity were studied for open channel sewers. It was determined that the theoretical maximum cubic feet per minute (cfm) of foul air movement per headspace cross-sectional area in square feet multiplied by predicted wastewater velocity in feet per minute for any given slope sewer based on Mannings Equation occurs at a d/D = 0.3.

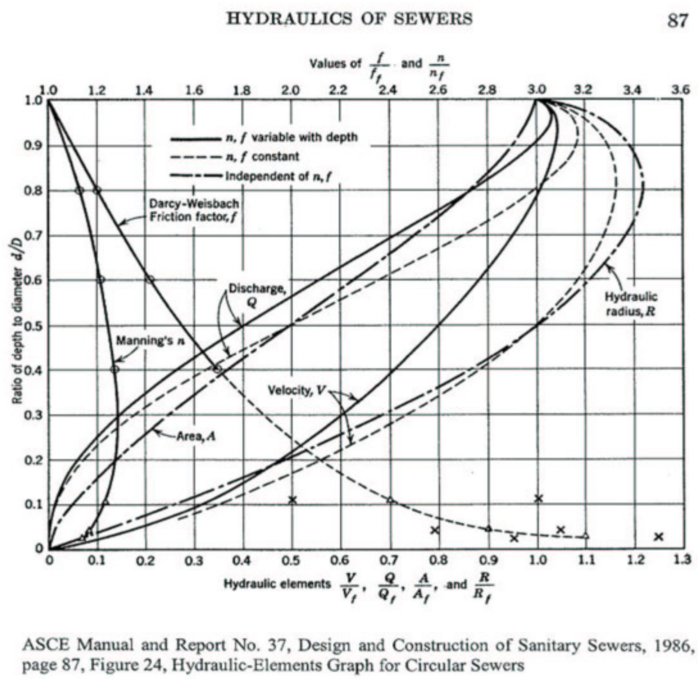


Figure 2 – ASCE Hydraulic Elements Graph for Circular Sewers

Gravity sewers are designed to flow partially full; this type of flow regime is known as “open channel” flow. Gravity sewers are also typically designed for projected peak diurnal flow for a minimum velocity exceeding 2.2 feet per second at a flow depth (d) to sewer diameter (D) ratio (d/D) of 0.5 to 0.75, depending on sewer size. Maintaining a minimum wastewater velocity prevents deposition of suspended solids from the wastewater, and promotes entrainment of fresh air and oxygen into the wastewater.

Over a number of years and review of numerous wastewater collection systems, the authors have noted that sewers are often sized larger than optimum under present day conditions. To avoid sewer surcharging and spills, it is the nature of the sewer design process to be generous with unit flow factors per person or per connection and to be conservative with selection of peak to average ratios. Additionally, development does not always proceed to the ultimate density allowed by zoning, or the zoning may be changed to lesser density allowed. Some or all of these factors can lead to a sewer that is larger than necessary and a sewer that flows with less velocity than originally anticipated. This may result in excessive deposition of solids, increased potential for odor release, and a need for increased frequency of sewer cleaning and maintenance.

A well mixed and oxygenated wastewater remains aerobic and discourages anaerobic liquid phase hydrogen sulfide (H_2S) generation. Due to typically conservative planning and hydraulic design, pipelines are often oversized and wastewater is often not conveyed at sufficient velocity or with sufficient oxygenation to maintain aerobic conditions, resulting in anaerobic generation of dissolved H_2S. Hydraulic turbulence of wastewater rich in dissolved H_2S results in release of H_2S gas to the sewer atmosphere above the open channel flow in sewers. In contrast to open channel sewers, inverted sewer siphons are designed to flow full and under pressure as they pass under obstacles. Sewer siphon diameter is often reduced, compared to the upstream and downstream sewer, to maintain equal or greater velocity in the full-pipe sewer siphon versus the open channel sewer. Sewer siphons often include two or three parallel "barrels" with hydraulically stepped use to maintain higher wastewater velocity in each barrel. This increased wastewater velocity improves suspension and carry-through of settleable solids and grit, reducing the need for cleaning. This increased velocity, however, comes at the price of increased headloss, partially offsetting the original purpose of the siphon.

FIELD EVALUATIONS

The literature review confirmed the proposed field data collection approach for the OCSD Siphon Rehabilitation Project. The data collection from extensive field evaluations at the project's 17 inverted sewer siphon sites included:

- Ambient H_2S air testing in the vicinity of the siphons was conducted using Odor Logger continuous monitoring, with measured H_2S results ranging from 0.0 ppm to 0.7 ppm. Short-term human monitoring assisted by Nasal Ranger Olfactometer analysis was also conducted.

Photo 1 – Ambient H_2S - App-tek OdaLog

- Physical inspections of the siphon inlet and outlet manholes; cleaning and CCTV inspection of air jumpers (if existing); and cleaning and sonar inspection of the inverted siphons were conducted.
- Wastewater flow was measured and recorded for a minimum 13-days for each siphon
- Instantaneous wastewater dissolved hydrogen sulfide (H_2S), dissolved oxygen (DO); temperature; and pH measurements were made and recorded. The pH of the sewer crown and manhole interior surface were measured

- Sewer headspace atmospheric H_2S measurements were made over a minimum three day period, with H_2S Odor Loggers suspended in manhole headspace. H_2S concentrations as high as 500 parts per million (ppm) were detected
- Airflow rates into, or out of, siphon inlet and outlet manholes were measured up to 600 cubic feet per minute (cfm)

Photo 2 – Alnor LoFLo Balometer

- Sewer headspace vacuum or pressure was measured at siphon inlet and outlet manholes, with any existing air jumpers both plugged and unplugged. The measured instantaneous upstream unplugged range of vacuum/pressure was from .04 inches water column (in. WC) vacuum to 0.20 in. WC pressure with an average pressure of 0.019 in. WC. The measured instantaneous downstream unplugged range of vacuum /pressure was from 0.05 in. WC vacuum to +0.02 in. WC pressure. For the few downstream locations with pressure, there are other likely downstream obstructions to flow other than the adjacent siphon.

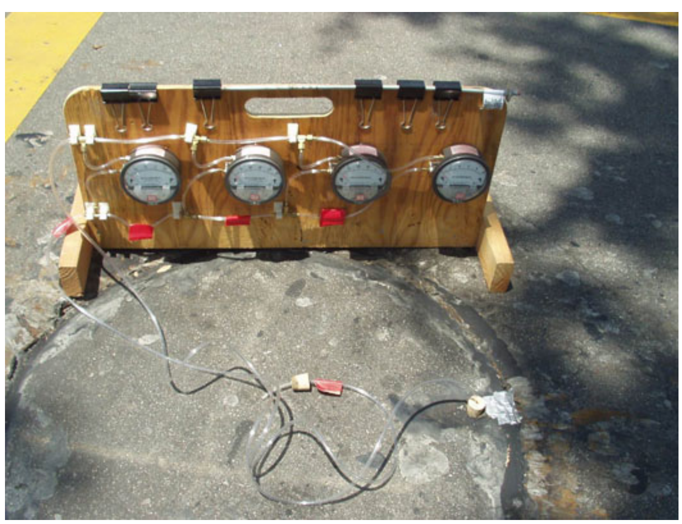


Photo 3 – Dwyer Instruments, Magnehelic Pressure/Vacuum Gauges

Correlations between measured wastewater flow rate and measured sewer headspace airflow rate and vacuum or pressure were determined.

Air Jumper Sizing Procedure

Wastewater Flows and Velocities. Wastewater depth and velocity profile data were collected continuously for a two week period at each of the 17 siphon sites. From the depth and velocity profile data, wastewater flow rates were calculated through the siphon using the following equation:

$$Q = A \times V \qquad \text{(Equation 1)}$$

Where:

Q = Flowrate, cubic feet per second
A = Cross-sectional area of flow, square feet
V = Velocity, feet per second

Some of the wastewater flow meters were located on the downstream side of the siphons if upstream installations were impractical. There was a considerable difference in flow characteristics for those locations. Downstream of the siphon, wastewater velocities were generally lower and depth of flow was greater compared to the calculated, normal flow expected from Manning's Equation. This could reflect some other downstream hydraulic control influencing the depth of flow at the siphon outlet.

Manning's Equation. Manning's Equation was used with Equation 1 for both open channel and siphon hydraulic calculations (pg. 7-26, King Handbook of Hydraulics, 4th Edition) to calculate the flowrate.

$$Q = \frac{1.486}{n} ar^{2/3}s^{1/2} \qquad \text{(Equation 2)}$$

Where:

n = coefficient of roughness in Manning's Equation
a = area of cross section of water in channel
p = wetted perimeter, square feet
r = a/p = mean hydraulic radius
s = H/l = average loss of head per foot
H = loss of head due to friction in reach
l = length of reach, feet

For similar sections, the value of the expression $ar^{2/3} = a^{5/3} / p^{2/3}$ varies as the eight-thirds power of corresponding linear dimensions. Equation 2 can therefore be written in the equivalent form to solve for flow rate or velocity at a given depth and slope.

$$Q = \frac{K}{n} d^{8/3} s^{1/2} \quad \text{(Equation 3)}$$

Where:

K = discharge factor of 1.486

d = maximum depth of water

Manning's Friction Factor (n). The slope and diameter of the sewer upstream of the siphons was found on either the AS-BUILT drawings provided by OCSD or from the OCSD geographic information system (GIS) database. All of the AS-BUILT drawings except for two showed the original sewer design criteria on the plans. All design criteria had the same nomenclature including the coefficient of roughness, n; diameter, d; maximum depth of flow, D; mean velocity, v; and flow rate, Q.

A common assumption for sewer hydraulic calculations is to use the value of 0.013 for the roughness coefficient. The same roughness coefficient was used for the design criteria on every siphon included in this project, regardless of the type of pipe. Existing sewer pipe materials found include Vitrified Clay Pipe (VCP) and Polyvinyl Chloride/Plastic Lined Reinforced Concrete Pipe (PLRCP).

In reality, the roughness coefficient varies with pipe material. Some of the concrete pipe sewers were originally unlined. The unprotected concrete lining will deteriorate in the corrosive environment common to sanitary sewer. Lining concrete sewers therefore became necessary to extend the service life of the sewer system. Once a sewer becomes lined it changes the hydraulic properties of that sewer. For instance, after a concrete sewer is lined with PVC, it will flow at a higher velocity and a lower depth with the same flow rate. Age also changes the hydraulics of a sewer. When pipe is initially installed, it has a lower roughness coefficient than an older sewer which may have a roughened interior surface. Roughness coefficient sometimes varies with depth of flow. For the purpose of this study and for most sewer designs, the typical value of the roughness coefficient is considered constant as depth of flow changes and varies for different pipe materials.

Pipe Material	n
Plastic (PVC)	0.009
Concrete, average value used	0.013
Concrete, with rough joints	0.016-0.017
Concrete, very smooth or PVC lined	0.011-0.012
Clay	0.011-0.015

Table 1 - Roughness Coefficient Values

A roughness coefficient value of 0.013 is not suitable for all types of pipe materials. A roughness coefficient was calculated for the upstream sewer of each siphon in order to predict wastewater velocity in the pipe. The roughness coefficient was calibrated using the depth of flow and velocity measured in the field. Once a roughness coefficient was assigned for each siphon, the upstream sewer velocity can be predicted at any depth of flow using Equations 1 through 4. The velocity is used later to determine the Reduction Factor (RF), as discussed below.

In most cases the flow meters were installed just upstream of the siphons. When the flow meter was on the downstream side of the siphon and there appeared to be a downstream hydraulic control, the "n" value was not adjusted based on field data to match the flow depth. Instead, the Manning's Equation was used to match the measured flowrate and corresponding wastewater velocity with theoretical normal depth conditions.

Reduction Factor. The Reduction Factor (RF) is the ratio of the air velocity to the wastewater velocity. It is the proportionality constant between the wastewater velocity and the air velocity occurring at the boundary layer.

$$RF = \frac{V_{air}}{V_{wastewater}} \qquad \text{(Equation 4)}$$

Air jumper sizing is based on the fluid dynamics of open channel flow. Friction imparted on the air as the wastewater travels down the sewer creates an air flow rate and air velocity in the headspace within the pipe. The wastewater stream in the sewer has two coefficients of friction, one with the pipe surface and one with the air above the wastewater surface.

Air Velocity. Air velocity is calculated to determine the Reduction Factor. Instantaneous air flow rate measurements were taken at all siphons locations.

$$V_{air} = \frac{Q_{air}}{A_{air}} \qquad \text{(Equation 5)}$$

Air area is calculated by subtracting the area of the wastewater by the area of the full pipe. The equation can be written as:

$$A_{air} = \frac{\pi d^2}{4} - \frac{Q_{wastewater}}{V_{wastewater}} \qquad \text{(Equation 6)}$$

Where:

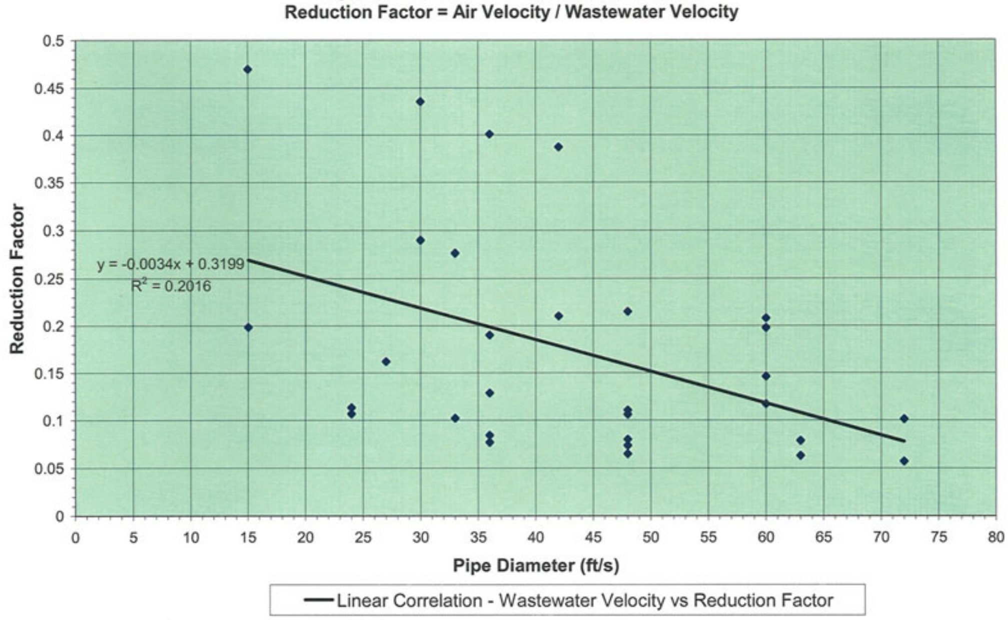
A_{air} = the headspace area within the sewer pipe
d = diameter of the pipe

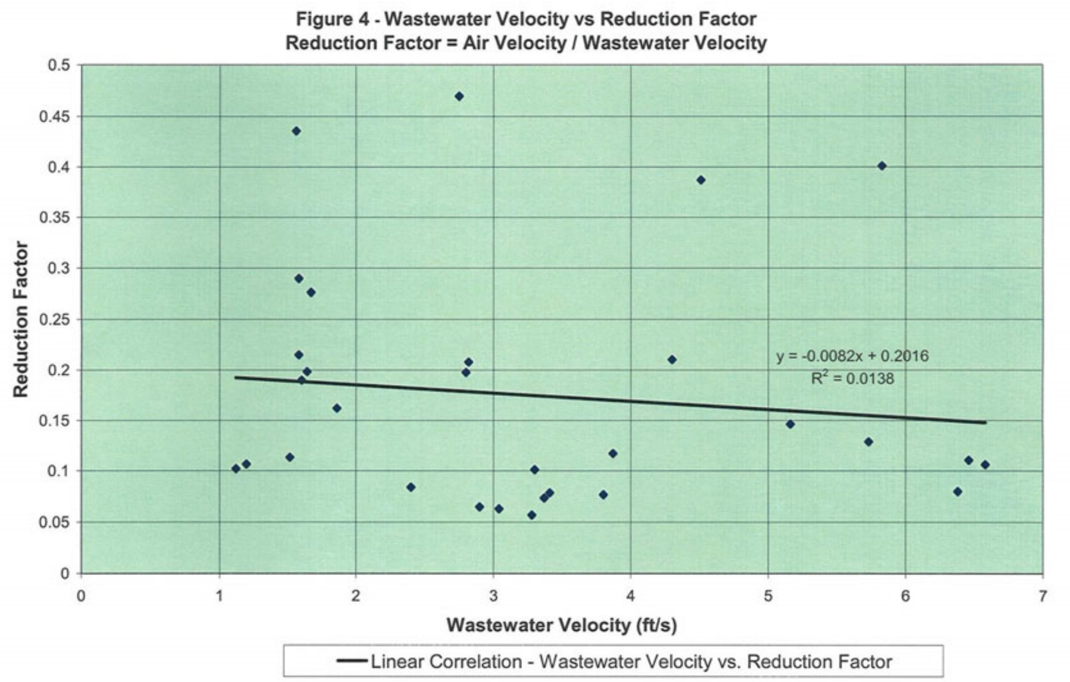
Wastewater Velocity. The wastewater flow rate, depth, and velocity were reported by MGD in the flow metering report. Because air flow rates were measured prior to installation of the wastewater flow meters, the wastewater velocity and flow rate used to determine the headspace area was approximated. Data taken at the same time of day and day of the week, rounded to the nearest half hour, was used in the calculation. To calculate a more accurate reduction factor for existing siphons in the future, it is recommended that the wastewater flow meters be installed and operating during the entire data collection process.

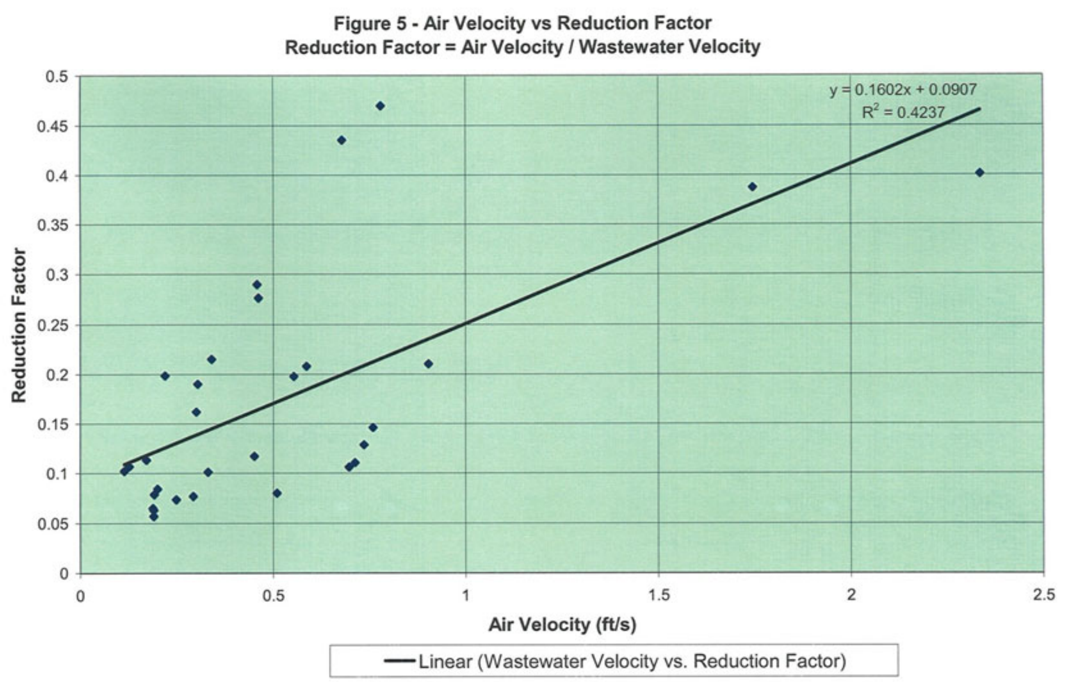
Field Measured Reduction Factors. RF values calculated based on the field data for the evaluated siphons varied between 0.05 and nearly 0.5. The air flow rate measured at Siphon 48 was varying up and down by a factor of 10:1. The cause of this anomaly has not been determined. Possible reasons may include influence from changes in wastewater flow rate due to downstream partial pipeline blockage, transient hydraulic surcharging due to sewer design, grit settlement, grease, mechanical ventilation at pump stations or treatment plants, or other causes.

While a mathematical relationship to calculate RF without field data has yet to be developed, trends are visible in the following graphs. **Figure 3** shows that generally the RF decreases with pipe diameter. **Figure 4** shows that generally the RF decreases with wastewater velocity. Note that in all field measured / calculated cases, the RF does not exceed 0.5. **Figure 5** shows that RF increases with increasing air velocity, however, whereas wastewater velocity can be calculated in the hydraulic design of a pipeline, air velocity can be affected by numerous undefined factors and does not behave consistently. There is poor correlation in all three graphs. Therefore, the calculation procedure described below utilizes a site specific measured and calculated RF with a safety factor applied.

Figure 3 - Pipe Diameter vs Reduction Factor
Reduction Factor = Air Velocity / Wastewater Velocity







Selecting the Reduction Factor. A default RF of 0.5 was selected as the design basis for sizing the proposed air jumpers. This value exceeds every field measured value and is at the upper limit of values found in the literature review. The highest reported RF found in the literature review was 0.6.

To size the air jumpers conservatively, a safety factor was included in the sizing calculation. A minimum safety factor of two was used. Due to the wide variation in RF values, some air jumpers would be oversized with the default RF of 0.5, and for these locations a maximum safety factor of five was selected. This was done to account for found sewer headspace conditions that may have been affected by secondary controls, such as headspace blockage downstream from the siphon area.

The following procedure was followed when adding a safety factor to air jumper sizing. Only three scenarios are possible. The RF is initially multiplied by the minimum safety factor of 2. If the product is greater than 0.5 go to CASE 1. If the product is less than 0.5, do not use that value. Instead, multiply the calculated RF by a safety factor of five and go to CASE 2.

- CASE 1: When the default RF value of 0.5 results in a safety factor less than two, the default value is not used. Instead, a safety factor of two is used and the resulting RF value will exceed 0.5. Siphon 22 is an example of this scenario.
- CASE 2: When the default RF value of 0.5 results in a safety factor greater than five, the default value is not used. Instead, a safety factor of five is used and the resulting RF value is less than 0.5. Siphon 17 is an example of this scenario.
- If CASE 1 or CASE 2 does not apply, use the default value of 0.5.

When calculated this way, the upper limit to the selected RF is 1.0. If a maximum calculated RF greater than 0.5 occurs, other variables besides wastewater velocity must be considered. Such a situation might occur in the vicinity of a large mechanical ventilation and odor control system, where the dominant forces for air flow are not frictional drag from wastewater. If this occurs, the proposed air jumper should be sized based on the flowrate of the mechanical ventilation system.

Calculate Maximum Air Flowrate. The air flowrate within the sewer pipe varies throughout the day with the daily diurnal fluctuations in wastewater flow. The highest potential air flowrate must be calculated in order to size the air jumpers. The typical geometry at the entrance and exit manhole of each siphon, as shown by **Figure 1**, is used to illustrate the variables of the air and wastewater balance. The maximum air flowrate used to size the air jumper is calculated with the following equation:

$$Q_{air} = RF \ x \ V \ x \ A \ x \ 60 \qquad \text{(Equation 8)}$$

Where:

Q_{air} = Air Flowrate in cubic feet per minute
RF = Selected Reduction Factor
V = Wastewater Velocity (at d/D = 0.3) in feet per second
A = Headspace Area (at d/D = 0.3) in square feet
60 = conversion factor from cfm to cfs

The maximum calculated reduction factor is multiplied by the wastewater velocity to get an average air velocity. This is then applied to the cross sectional area (headspace) in the sewer pipe that is over the wastewater to determine the maximum potential air flowrate. As explained and shown by example in TM1, the maximum air flowrate is predicted to occur at d/D = 0.3. This is true since the maximum product of headspace cross-sectional area and wastewater velocity occurs for any sewer at this value.

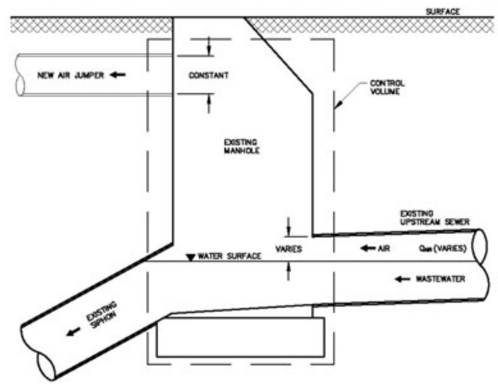


Figure 6: Typical Geometry at Entrance to Siphon

Allowable Air Jumper Headloss. Pressure differentials were measured in the field at the upstream and downstream manhole of each siphon. The allowable headloss through the proposed air jumper is based on the pressure differential measured in the field while the existing air jumpers were blocked. The headloss across the proposed air jumper is calculated using the maximum air flow rate calculated in the previous section. The air jumper diameter is initially chosen with a headloss rate of 0.01 inches of water per 100 feet of air pipe per Figure 7. The maximum pressure differential observed was 0.1 inches of water column. Since most sites have short air jumpers, they will have a total headloss much less than 0.1 inches of water column.

Pipe Diameter Selection

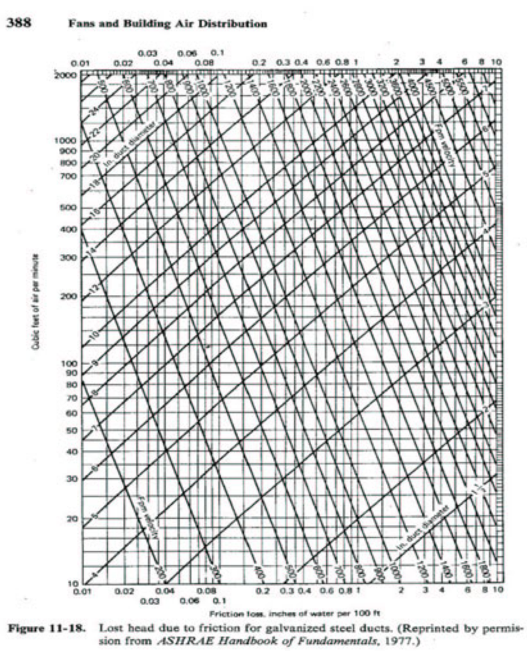


Figure 7 – ASHRAE Handbook of Fundamentals

Once the maximum air flowrate is calculated, a maximum headloss criteria of 0.01 inches of water per 100 feet is selected in the nomograph to the left for preliminary air jumper sizing selection. The final air jumper size is selected to include the total headloss for the jumper, including the main duct and all minor losses, to result in a total headloss for the air jumper not more than 0.1 inches of water headloss. These headloss limitations are guidelines selected to keep headspace air pressure to a minimum on the upstream end of the recommended air jumper sizes.

Lost Head Due to Friction for Galvanized Steel Ducts

Once the pipe diameter is chosen, the as-built drawings were checked to determine if there is enough vertical clearance to install an air jumper of that diameter. At some sites, there is not enough vertical clearance to install one air jumper of the recommended diameter. If multiple air jumpers must be used instead of a single air jumper, then than the total system headloss should be limited to 0.1 inches of WC for the multi-barrel approach.

AIR JUMPER SIZING SUMMARY

The following procedure is recommended for sizing siphon air jumpers at existing siphons. For new siphon and air jumper installations, a Reduction Factor (RF) of 0.5 should be used as a default value when field data is unavailable.

1. Install flow meters to measure wastewater flow rates and depths until all air flow rate measurements have been completed. Usually two weeks of wastewater flow monitoring is sufficient, provided all other field data is completed within that timeframe.
2. Measure air flow rates and take pressure readings at the upstream and downstream siphon access manholes.
3. Calibrate a wastewater conduit roughness coefficient based on flow meter data to determine the wastewater velocity at a depth-to-diameter value ratio of 0.3.
4. Calculate site specific RF values using air flow rate, water velocity and depth of flow (to get area). Unless a greater RF value is calculated, use the default RF to compare to the default value.
5. Use the default RF of 0.5 to determine the theoretical air flow rate at a depth-to-diameter ratio of 0.3.
6. Check the maximum calculated RF with the default of 0.5. This is done by dividing the maximum calculated value by 0.5, if the result is less than 2, then multiply the maximum calculated value by 2 and use this new value for the selected RF. If the result is greater than 5, then multiply the maximum calculated value by 5 and use this new value for the selected RF.
7. Determine the maximum air flow rate with the selected RF at a depth-to-diameter value of 0.3.
8. The air jumper diameter should then be selected from the nomograph using a headloss rate of 0.01 feet per 100 feet.
9. Verify that the site has enough vertical clearance to allow the installation of the air jumper. If not, use multiple smaller diameter air jumpers.
10. Headloss within the overall air jumper system (pipe friction plus minor losses) should then be analyzed to confirm total headloss does not exceed 0.10 inches of water column.

CONCLUSIONS

The following siphon and air jumper conclusions are made:

- If the continuity of the sewer headspace is interrupted by an inverted siphon, then the sewer headspace pressurizes and releases malodorous air.
- There was a positive correlation between wastewater velocity and sewer headspace air flowrate in the open channel sewers upstream and downstream of the siphons. Field interpreted Reduction Factors (RF) in the range from 0.1 to 0.5 were derived from field measurements.
- Sewer headspace was typically under pressure upstream of the siphons in the range up to +0.1 inches of water column. Sewer headspace was typically under vacuum downstream of the siphons in the range down to -0.1 inches of water column.

RECOMMENDATIONS

A procedure for calculating the air flowrate for new siphon air jumpers is recommended by applying a 0.5 Reduction Factor for theoretical wastewater flowrate for a given sewer size and slope at d/D = 0.30. For existing siphons, the recommended airflow rate sizing should be field verified to result in a safety factor not less than 2:1 or greater than 5:1. Air jumpers should then be sized to carry the recommended air flowrate at a duct headloss not exceeding 0.01 inches water column per 100 feet of duct and with a total air jumper headloss not exceeding 0.1 inches water column including minor headloss.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the dedication of the OCSD field operations personnel in maintaining the OCSD wastewater transmission system, including the project siphons, in excellent condition.

Steve Deering and Steve Jepsen would like to acknowledge the Project Management and assistance provided to the consultant team for this project by Alberto Acevedo and Mandy Taylor, OCSD.

The Dudek Project Team would like to acknowledge the assistance of all of our subconsultants and service providers on this project including: MGD Technologies for flow measurement and manhole inspection work; Coastal Traffic Systems for field activity traffic control; Ninyo & Moore Geotechnical, National Plant Services for CCTV and sonar inspections; HMS Construction for potholing; Forkert Surveying; and Traffic Management, Inc. for construction traffic control plans.

REFERENCES AND LITERATURE REVIEW

American Society of Civil Engineers, ASCE Manual of Practice No. 60, Gravity Sanitary Sewer Design and Construction*, New York, 1982.*

Air Jumpers, page 144, paragraph 3. "To overcome this difficulty, a number of siphons built in recent years have used air jumpers; that is pipes that take the air off the top of the inlet structure and return it at the end of the siphon. Usually, the jumper pipe is a third to a half the diameter of the siphon."

McQuiston, F.C. & Parker, J.D., *Heating, Ventilating, and Air Conditioning, Analysis and Design*, John Wiley & Sons, New York, 2nd Edition, 1982.

11-7 Air Flow In Ducts", page 385 (friction loss charts for straight, constant area ducts), 11-8 Air Flow In Fittings", page 392 (friction loss in fittings)

U.S. Environmental Protection Agency, Office of Research and Development, *Handbook, Sewer System Infrastructure Analysis and Rehabilitation,* EPA/625/6-91/030, Cincinnati, OH, October 1991.

No direct references to the design or use of air jumpers.

U.S. Environmental Protection Agency, Office of Research and Development, *Design Manual, Odor and Corrosion Control in Sanitary Sewerage Systems and Treatment Plants*, EPA/625/1-85/018, Cincinnati, OH, October 1985.

5.2.6 Siphons, page 110, paragraph 4. "One technique that has been successfully used to minimize odor release at siphons is the use of air jumpers." "Usually, the diameter of the air jumper pipe is approximately one-half that of the siphon."
5.3.2.1 Natural Ventilation, page 111, paragraph 2
"Natural ventilation occurs from the following forces.

1. Change in barometric pressure along the sewer.
2. Wind velocities past vents.
3. Fractional drag of wastewater on sewer air.
4. Rise and fall of the wastewater level in the sewer.
5. Relative density differences of sewer air and outside air.
   The degree of natural ventilation which occurs in a sewer is difficult to predict, since fluctuations in the above variables may change both the direction of movement and velocity of the air contained in the sewer."

U.S. Environmental Protection Agency, Office of Wastewater Enforcement and Compliance, Detection, Control, and Correction of Hydrogen Sulfide Corrosion in Existing Wastewater Systems, EPA 832 R-92-001, Washington, D.C., September 1992.

Focus is on corrosion control. Page 5-10: "The extent of natural ventilation available within a given sewer is difficult to predict and highly variable due to the number of factors which can affect it." Discussions of natural and mechanical ventilation to control humidity in the sewer. Many case studies. No comments on air jumpers.

U.S. Environmental Protection Agency, Office of Water, Hydrogen Sulfide Corrosion: Its Consequences, Detection and Control, (WH-595), 832-S-91-100, Washington, D.C., September 1991.

No discussion of air jumpers.

U.S. Environmental Protection Agency, Office of Water, Collection Systems O&M Fact Sheet, Sewer Cleaning and Inspection, EPA 832-F-99-031, Washington, D.C., September 1999.

No reference to air jumpers.

U.S. Environmental Protection Agency, Office of Water, Technical Report, Hydrogen Sulfide Corrosion in Wastewater Collection and Treatment Systems, (WH-595), 430/09-91-010, Washington, D.C., September 1991.

No mention of air jumpers. 4.3.4 Sewer Ventilation, page 4-10. "Sewers are naturally ventilated through building vents and manholes, occurring from factors such as changes in barometric pressure, wind, air density differences, and flow conditions."

U.S. Environmental Protection Agency, Office of Water, Report to Congress, Hydrogen Sulfide Corrosion in Wastewater Collection and Treatment Systems, (WH-595), 430/09-91-009, Washington, D.C., September 1991.

No mention of air jumpers.

Great Lakes-Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers, Recommended Standards for Wastewater Facilities, 1997 Edition, Health Research, Inc., Albany, N.Y., 1997.

Inverted siphon design criteria, no mention of air jumpers.)

Blanda, T., *Medium to Large Diameter Sewer Siphon Cleaning*, Orange County Sanitation District, CWEA Annual Conference, Palm Springs, CA, April 2005.

Describes siphon cleaning at the Orange County Sanitation District. Included is the use of a tire with the pull rig to remove heavy debris from the sewer invert.

Water Environment Federation, *Identifying and Controlling Municipal Wastewater Odor, Phase 1*: Literature Search and Review, WEF, Alexandria, VA, 2003**.**

Extensive review of literature from 1990 to 2000; reviewed 669 published articles and 155 unpublished (gray) articles.

2.5.2.6 Control of Ventilation, page 2-17. "During the past 10 years, there has been little published or gray literature related to the ventilation of municipal sewers. In fact, odor complaints are often acted upon by simply 'sealing' a portion of the sewer, such as sealing manhole cover pick-holes with tar or replacing the cover with one that does not have holes. This practice often leads to emissions of odorous gases at another location in the system."

2.7.3 Odor Control Technology - Research Agenda Items, page 2-22. This section discussed the importance of developing ventilation "models" to predict the emission of odorous gases from sewers. "...such models are ultimately limited by a lack of ability to predict natural ventilation rates." The proposed project would fund academic researchers to study this problem.

Water Environment Federation Manual of Practice No. 25, Control of Odors and Emissions from Wastewater Treatment Plants, WEF, Alexandria, VA, 2004.

Includes a detailed information on analysis and treatment of odors with an emphasis on treatment plants. Some general comments on collection system odors and sewer design including using air jumpers.
Page 163-166. Discussion of effect of liquid and vapor phase mass-transfer on odors. Review of factors in sewer ventilation and some data from studies. Summary states that it is necessary to understand both the physicochemical properties of the odorous compounds and the collection system configuration to predict VOC emissions.
Page 253. Comment that air jumpers maybe included in siphon design.

Water Environment Federation, Odor and Corrosion Prediction and Control in Collection Systems and Wastewater Treatment Plants, compendium of papers presented at WEFTEC 2000 workshop, WEF, Alexandria, VA, 2001.

City of San Diego, Clean Water Program Guidelines, Guidelines for Design Consultant, Volume VIII, San Diego, CA, February 1992.

SIPHONS Appendix D, page D9-11. "In general, at least two pipes shall be used in a siphon so that self-cleaning velocities occur over the full range of flow conditions." For the smallest barrel, design for a velocity of 4 to 6 fps at minimum flow. Calculate

friction loss using the Hazen-Williams formula with a C of 100. There is no comment on air jumpers.

Koziel, J.A. & Corsi, R.L., VOC Emissions from Municipal Sewers: Hot Spots, Air & Waste Management Association, 91st Annual Meeting, San Diego, CA, June 1998.

Liquid phase mass transfer coefficients for volatile compounds. A 60 meter long pilot sewer was used in experiments.

Olson, D.A., Varma, S. & Corsi, R.L., *A New Approach For Estimating Volatile Organic Compound Emissions From Sewers: Methodology and Associated Errors*, Water Environment Research, Vol. 70, No. 3, May/June 1998.

Describes interrelationship of mass transfer of VOC from liquid phase to gas phase and sewer ventilation rate on odorous emissions from a sewer.

Corsi, R.L. & Quigley, C.J., VOC Emissions from Sewer Junction Boxes and Drop Structures: Estimation Methods and Experimental Results, Air & Waste Management Association, 88th Annual Meeting, San Antonio, TX, June 1995.

Describes seventeen pilot experiments of VOC stripping at junction boxes and drop structures.

Koziel, J.A. & Corsi, R.L., A Novel Approach for Estimating VOC Emissions from Municipal Sewers: Methodology, Applications, and Implications, Air & Waste Management Association, 89th Annual Meeting, Nashville TN, June 1996.

No discussion of air velocities in sewer or air jumpers

Corsi, R.L. & Quigley, C.J., Design of Low Emission Sewers, Air & Waste Management Association, 87th Annual Meeting, Cincinnati, OH, June 1994.

Review of concepts developed for the analysis of discharge of volatile organic compounds from sewers carrying industrial wastewater. No description of the relationship of wastewater velocity and air flow.

Olson, D., Corsi, R.L. & Rajagopalan, S., Buoyancy-Induced Ventilation between Industrial Sewers and the Ambient Atmosphere, Air & Waste Management Association, 89th Annual Meeting, Nashville, TN, June 1996.

Concerns the discharge of volatile organic hazardous air pollutants.

Corsi, R.L., Volatile Organic Compound Emissions from Wastewater Collection Systems, Doctor of Philosophy Dissertation, University of California, Davis, CA, December 1989.

The thesis did not specifically study siphons or air jumpers.
Abstract. "It was concluded that no single mechanism dominates sewer ventilation under all situations, but environmental conditions, wastewater flow conditions, and physical characteristics of a collection system were identified under which some mechanisms become dominate."
8.1 CONCLUSIONS, Ventilation. 1. "Given the complexity of most collection systems it is impossible to accurately calculate actual ventilation rates and gas flow

patterns for any given system. For a specific sewer reach, release of an inert tracer can be used to estimate gas flow rates."
3. "Liquid drag causes gas flow in the same direction as wastewater flow, and is the only ventilation mechanism that acts continuously."
4. "Under conditions of low resistance to ambient air inflow and sewer gas exhaust, liquid drag can induce maximum gas mean velocities of up to 0.2 m/s. Actual velocities in sanitary sewers are expected to be on the order of 0.04 to 0.2 m/s for small pipes (0.25 m diameter); 0.003 to 0.20 m/s for mid-sized pipes (1.0 m diameter); and 0.005 to 0.18 m/s for large pipes (2.5 m diameter)."

Molseed, A.C., Wolstenholme, P.L., Newman, G.R., Yee, S. & Hiraki, G., Odor and Corrosion Control in a Large Diameter Sewer Upstream of a Low-Head Structure, Odors and Toxic Air Emissions 2002, WEF, Alexandria, VA, 2002.

An inverted siphon in an 108-inch sewer caused a stagnant air pocket to form upstream of the siphon when flows were high. It was decided to treat the resulting foul air with a biofiltration system. An air jumper was analyzed as an alternative.

Dechant, D., Catlin, C. & Huttes, R., Odor Control Study in a Deep Sewer System with Multiple Drop Structures, WEFTEC 2000, WEF, Alexandria, VA, 2000.

An 8-mile reach of interceptor sewer was monitored for air flow, sewage flow, air pressure and hydrogen sulfide. The diameter ranged from three to nine feet. "The collective experience of the project team indicated that.....wastewater flow in the interceptors can produce 25 to 250 cfm of air flow per mgd of wastewater flow." The following general comments were in the Analysis section. "The primary motive force for air movement in sewers is friction between the headspace air and the moving wastewater. The resistance to air movement in a sewer pipe is friction between the air and the water surface and the stationary walls of the sewer. The velocity of the air is at a maximum approaching 0.8 times the wastewater velocity near the surface of the water and decreases rapidly with increasing distance approaching zero at the pipe wall."

Davidson, S., Green, J., Mann, J. & Lamb, E., Design Challenges in Sewer Foul Air Extraction and Treatment, WEF/A & WMA Odors and Air Emissions 2004, WEF, Alexandria, VA, 2004.

This paper focuses on removing odorous air and treating it. Some typical headspace pressures are given.

Davidson, S., Green, J., Mann, J. & Lamb, E., Assessing the Effectiveness of Sewer Headspace Foul Air Extraction, WEFTEC 2002, WEF, Alexandria, VA, 2002.

Tests on Phoenix area sewer 42-inch to 90-inch in diameter exhibited pressures of +0.10 to +0.25 inches water column. Extraction tests with a mobile trailer-mounted fan reduced pressures to -0.03 to -0.80 inches water column. The influence distance of lowered pressure was typically about 5 miles.

Parker, W.J., & Ryan, H., *An Evaluation of Ventilation Patterns in a Regional Collector Sewer*, Odors and VOC Emissions 2000, WEF, Alexandria, VA, 2000.

Report of field tests of the velocities of headspace gas in an 11 km sewer (24”-84” dia.) using carbon monoxide gas as the tracer. The air velocities ranged from 3.8 m/min (0.21 fps) to 31.5 m/min (1.72 fps). The velocities of the sewage flow were not reported. “The velocities (of air flow) observed varied substantially with time and location in the collector.”

Sorensen, H., Joyce, J., Day, D., & Fallara, C.T., Odor Control for Large Diameter Deep Sewer Tunnels - The City of Columbus Ohio, Odors and VOC Emissions 2000, WEF, Alexandria, VA, 2000.

This paper reviewed various computer simulations of HVAC systems. It concluded: “There are no existing mathematical models that accurately describe and predict air movement in sewer under the influence of moving wastewater. There is a very large number of variables and the relationships are too complex to readily assemble any sort of reliable mathematical relationships which could even loosely be called a model.” For design purposes this project assumed the air flow velocity was equal to one-half the wastewater velocity.

Pai, P., Joyce, J. & Sorensen, H., *Large Diameter Sewer Ventilation Dynamics Require a Three Mile-Long Odor Control Duct in Las Vegas*, Odors and VOC Emissions 2000, WEF, Alexandria, VA, 2000.

Analysis of points on a large sewer to withdraw air for treatment. Details of the calculations were not included in the paper.

McConico, W.E., Wooten, K.G., DuVal, G.A., Bizzarri, R.E., Maisch, F.E. & Guhse, G.L., *Hydraulic Energy Flushing of Inverted Siphons*, WEFTEC 2001, WEF, Alexandria, VA, 2001.

No air jumper with these siphons.

Quigley, C.J. & Corsi, R.L., *Emissions of VOCs from a Municipal Sewer*, Journal of the Air & Waste Management Association, Volume 45, Page 395-403, May 1995.

Field tests on an interceptor sewer in metropolitan Toronto, ON. High ventilation rates were observed on this sewer resulting in large quantities of VOC emissions. They studied a 1.6 km reach of a sewer 0.9 to 1.2 m diameter.

City of Los Angeles, *F200 Projection of Flows and Hydraulics of Sewers, Sewer Design Manual - Part F,* Bureau of Engineering, City of Los Angeles, June 1992.

Twelve sub-sections of the manual covering various aspects of inverted siphon and air jumper design. A minimum of two barrels shall be provided for the inverted siphon and the minimum velocity at PDWF shall be 4 fps at least once per day. The recommended “n” is 0.014.
The manual states empirical design of air jumpers is the method of choice. The empirical method determines the cross sectional area (head space) available for gas

flow in the sewer approaching the siphon. The cross sectional area of the air jumper shall be two times the cross sectional area for gas flow.

Pescod, M.B. & Price, A.C., *Fundamentals of Sewer Ventilation as Applied to the Tyneside Sewerage Scheme*, Water Pollution Control, 17, 1981.

Pescod, M.B. & Price, A.C., *Major Factors in Sewer Ventilation*, Journal of the Water Pollution Control Federation, 54, 4, 1982.