# CHAPTER 6.0

# SEWER VENTILATION

## 6.1 Literature Search Background Summary

Nineteen papers were reviewed for pertinent information on sewer ventilation. The primary screening criterion for determining a paper's relevancy was a significant discussion of or focus on sewer air movement, headspace pressurization, or sewer emissions. Thus, some of the papers discussing treatment of sewer off-gas, chemical treatments in collection systems, or dispersion modeling were screened but not reviewed in detail. Twelve of the 19 papers were significant in that they had data related to characterizing or handling sewer headspace air movement and pressure conditions. Generally, each of the 12 papers fell into one of three categories:

- Case studies related to resolving agencies' collection system odor problems (nine papers)
- Research studies, focusing to various degrees on pilot-scale and full-scale ventilation using tracer gas methods (two papers)
- Doctoral thesis describing sewer ventilation using a computation fluid dynamics model (one paper)

Seven papers briefly touched on sewer ventilation but focused on odor treatment aspects rather than the dynamics of airflow and pressure development within a sewer headspace.

All papers were dated between 1994 and 2005.

## 6.2 Introduction and Background

Wastewater flow in gravity sewers produces a cocurrent flow of air in the headspace above the liquid. In many interceptors, air movement and sewer-headspace pressurization are negligible and warrant minimal analysis or design considerations to avoid interceptor odor emissions. In cases when sewer odor emissions are potentially significant, chemicals can be added to control liquid phase odorants that may otherwise be released to the sewer atmosphere. However, chemical controls are not always totally effective, especially in critical receptor areas, leaving headspace ventilation and treatment as the only practical means of totally controlling sewer pressure and interceptor odor problems. Based on the literature survey of case studies, interceptor systems that are prone to fugitive emission problems are typically long (from 3 miles up to 50 miles), large-diameter (42 inches to 132 inches) trunk sewers. These systems often exhibit headspace air pressures between -0.2 and +0.2 inches of water column (w.c.) In certain situations, pressure that has developed behind full pipes and siphons can exceed +1.0 inch of w.c. In air movement scenarios, these pressures are relatively low; they can, however, produce foul-air outleakage of several hundred cubic feet per minute (cfm) in poorly sealed manhole covers. Serious fugitive emissions problems have been associated with junction structures, siphons, and highly variable liquid flow conditions, which can greatly affect the movement of air through the interceptor system as well as produce greater hydrogen sulfide stripping from the wastewater, due to liquid turbulence.

The nature and extent of air exchange (ventilation) between the ambient atmosphere and sewer headspace has never been adequately characterized. It is clear that the potential for fugitive odors is a direct consequence of headspace air pressurization, which is controlled primarily by airflow resistance and physical interceptor characteristics. Significant pressurization is often associated with constricted headspace, which restricts airflow through the sewer pipe, causing emissions from manhole covers and in upstream lateral sewer connections. Full-pipe or unjumpered siphons are special examples of such restricted airflow conditions. Rapid wastewater flow tends to produce greater air movement due to greater friction drag from the liquid on the headspace air. This results in potentially higher headspace air pressure. However, greater air movement also tends to increase headspace air turnover, thus reducing odorant concentrations and potentially lessening corrosive tendencies in the pipeline.

Since most collection systems are closed systems designed to carry only liquid flow, the engineering effort given to quantifying headspace air movement in designed interceptor systems has been relatively low. In the theoretical analysis and case studies reviewed, there was no case in which a definitive analysis of sewer air movement had been conducted as part of a new interceptor system design. However, there were several case studies in which evaluations directly related to existing interceptors with pressurization or fugitive emissions problems were conducted. Most of the theoretically based papers and analyses focused mostly on developing and quantifying parameters affecting airflow relative to liquid flow. The case studies tended to focus on measured airflow or pressure conditions and either analyzed the efficacy of foul air extraction or developed a basis for determining the amount of sewer foul air extraction needed to resolve odor conditions in site-specific circumstances.

### 6.2.1 Theoretical Dynamics of Air Movement in Wastewater Conduits

The primary force driving natural air movement in water conduits is friction between the sewer headspace air and flowing wastewater, whereas the natural resistance to flow is friction between the walls and airflow. As one would expect, this results in a theoretical air velocity profile reflecting maximum airflow near the water surface and minimum airflow near the wall surface. One of the earliest and more detailed references for sewer ventilation is work done by Pescod and Price (1981). Their work is referenced in many of the papers that were reviewed. They identify the following five factors influencing sewer ventilation:

- Wind eduction
- Wastewater drag
- Rise and fall of wastewater level
- Temperature differentials
- Barometric pressure differentials

They determined that the wastewater level, temperature, and barometric effects can be dealt with analytically. Wind effects and wastewater drag are not amenable to analytical treatment, and therefore these factors are the focus of their research and testing. A unique aspect of their work is their focusing the majority of their efforts on wind eduction, using carefully crafted stack heads to make maximum use of ambient wind to induce sewer airflow through the stack and headspace. This approach to sewer ventilation is not widely practiced in the United States because of the attendant odor problems that would likely develop from untreated sewer emissions.

The Pescod and Price work included both laboratory-scale tests and full-scale system evaluation. The laboratory tests evaluated wind eduction and liquid drag separately. The wind eduction tests were done with a wind tunnel, and the liquid drag tests were done by operating various liquid velocities and depths in a 300-mm pipe, with airflow measured by thermal anemometers. Their full-scale system evaluations analyzed the combined effects of wind eduction and wastewater drag.

Their wastewater drag findings are shown in Figure 6-1. This represents idealized airflow velocity profiles for one test in which average liquid velocity is 0.8 m/s.

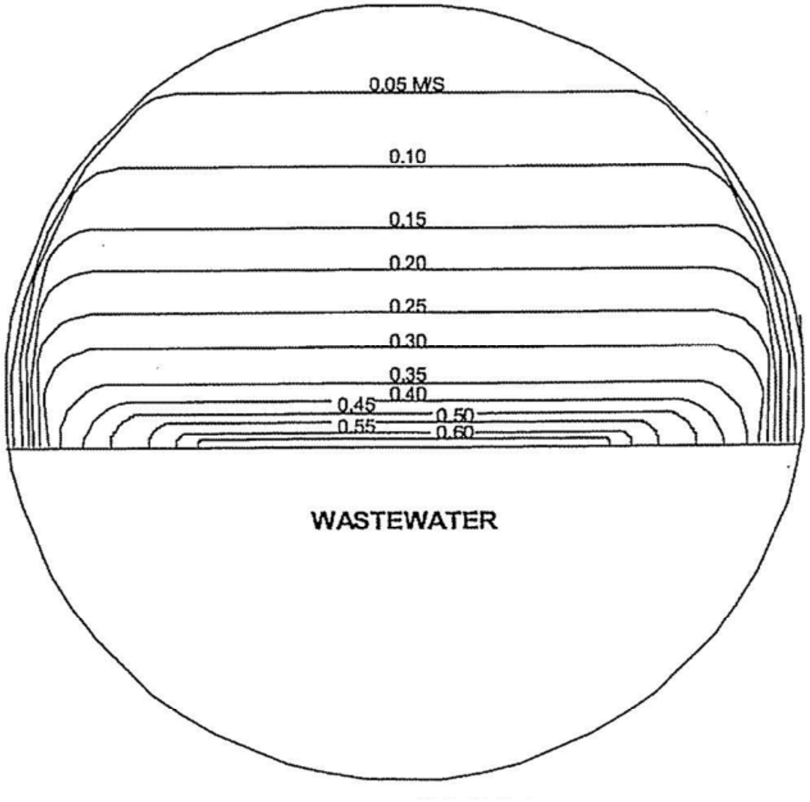

Figure 6-1. Idealized Velocity Contours

Overall, their data covering nine separate drag-induced flow tests showed considerable scatter, making correlations difficult. However, they did relate average air velocity to water surface velocity, and to both air space perimeter and air space “hydraulic” radius. The data reflected an apparent maximum air velocity limit, regardless of liquid velocity and depth considerations. Although the applicability of their research is limited by the small pipe size and modest liquid velocity (less than 0.6 m/s), their work is referenced in many sewer ventilation papers. An often-cited rule of thumb from this work suggests that airflow velocity will be 35 to 50 percent of liquid velocity in a half-full sewer. It is clear from their analysis (which included tests at various flow depths) that airflow above the wastewater can vary significantly depending on the width of the liquid surface, since the liquid surface is the prime liquid drag motive force to move the air along with the wastewater. Their work suggests that the point of maximum airflow is a condition of a half-full sewer, which maximizes the surface exposure to the above headspace.

The primary limitation of the Pescod and Price (1981) work is that it develops data on the basis of a relatively small pipe with a liquid flow at a relatively modest velocity; most collections systems are far more complex. Hydraulic jumps, vertical drops, large junction and diversion structures, inverted siphons, and pump stations add significant complexity to the factors that govern sewer ventilation. If wastewater flow is fast and turbulent or if there are large hydraulic jumps or vertical drops, liquid surface area and velocity increase significantly, greatly increasing drag-induced flow in the surrounding air. Conversely, slow-moving quiescent streams will exert minimal drag on the air and move relatively small volumes of air.

## 6.3 Sewer Ventilation and Pressurization Case Studies

Most published work on sewer ventilation is related to case studies looking at emissions control in specific systems. These papers analyze deep tunnel systems, large-diameter trunk interceptors, and special cases involving industrial sewer volatile organic compound (VOC) emissions. Some studies use laboratory evaluations of sewer ventilation and compare results to full-scale systems.

### 6.3.1 Deep Tunnel Systems

Deep tunnel systems are a special case in sewer ventilation. These systems employ vertical drop structures in which the wastewater falling vertically into the tunnel induces large amounts of airflow. Typically, various energy dissipation structures and air-relief vent pipes are provided with these systems. Three papers in the literature search focused on deep tunnel systems that were evaluated from a ventilation perspective, focusing on mitigating specific fugitive odor emissions.

A deep tunnel system in Columbus, Ohio, was studied by Sorenson et al. (2000). The system that was evaluated consists of six drop structures to a tunnel 72 inches to 84 inches in diameter. Key findings included fairly consistent diurnal pressure variations at a drop structure. Pressures ranged from +0.2 inches to -0.15 inches of water column (w.c.). To provide fugitive emissions control, airflow requirements were estimated from both pressure data and wastewater flow data. Airflow estimates developed from pressure data ranged from a minimum of 1,300 cfm to 10,000 cfm at various points in the system. Airflow developed by correlation to wastewater flow (pipe half full and air velocity equal to half the liquid velocity) produced flow estimates of 2,500 to 5,500 cfm applied to three locations along the system.

A deep tunnel system in the Northeast Ohio Regional Sanitation District was evaluated by Smith and Klunzinger (2001) to assess pressures with and without odor control system fans operating. The diameters of the pipes in this system range from 42 to 132 inches, and five biofilters are installed to treat foul air exhausted from the interceptors. Their paper evaluated the level of “baseline” pressure that exists in this system without any forced ventilation from the biofilter fans. These data were compared with pressures using various combinations of biofilter fans. Ten manholes were tested; data reflect that seven of the 10 locations exhibited negative headspace pressure, even with no fans operating. Pressures ranged from -0.78 inch of w.c. to +0.12. Six of the 10 locations averaged between -0.01 and -0.10 inch of w.c. With the fans on, negative pressures increased; however, one manhole developed positive pressure, and another manhole that had been under positive pressure remained so after the fans had turned on. The study evaluated these data in the context of the system design and locations where restrictions to air movement were likely. At one key pressurization point, an estimated 6,500 cfm of air was flowing from the convergence of three sewers and accounting for pressurization at that point.

Odor problems from a deep tunnel system in Austin, Texas, were evaluated by Pope et al. (1998). The essence of their work is that the tunnel ventilation problems and fugitive odor emissions were influenced almost entirely by a downstream pumping station's wet well odor control system. The findings were that influent pumping required liquid levels that submerged or nearly submerged the inlet pipe. This process sealed the air space in the influent pipe, thereby limiting airflow to the pump station odor control system and stopping the natural draft and ventilation through the tunnel system.

### 6.3.2 Large-Trunk Sewer Evaluations

Ventilation and headspace pressure conditions were studied in papers covering three large-trunk interceptor systems. These systems tend to have large-diameter pipes with large available headspace for airflow.

The Potomac Interceptor, which links jurisdictions in northern Virginia with a wastewater treatment plant in Washington, D.C., was evaluated to determine feasible approaches to odor control, including both chemical treatment and foul air extraction (Trypus et al., 2001). This interceptor is a 50-mile-long regional gravity interceptor that is vented along most of its routing to promote the exhausting of sewer gases and their replacement with fresh air. Trypus et al. evaluated forced air exhaust from the headspace using a 5,000-cfm blower. On the basis of pressure measurements from the field pilot study, it was determined that at a 7,300-cfm air exhaust rate would produce pressure influence approximately 3 miles upstream and 1,000 feet downstream of the exhaust point. The 7,300-cfm exhaust rate was developed by applying a 0.7 factor to the liquid velocity to determine air velocity. The 0.7 factor is an average of data from Thistlewaite (1972) and Joyce (2000). In the 84-inch pipe being evaluated, this resulted in a 6,000-cfm airflow, which was then adjusted upward based on pressure observations from the blower air extraction test.

A Phoenix, Arizona, study on the Southern Avenue Interceptor trunk sewer (diameters of 42 to 72 inches) and Salt River Outfall sewer (90-inch section) examined forced air extraction to evaluate depressurizing the sewer headspace (Davidson et al., 2002). Figure 6-2 shows a portable fan skid and temporary flexible duct used to conduct this evaluation hooked up to a manhole. A variety of tests was conducted, with flow rates varying between 2,700 and 5,400 cfm. Table 6-1 summarizes pressure data, showing the sewer headspace shift from positive to negative pressure and pressure influence of several miles. The work in Phoenix evaluated headspace $H_2S$ concentrations but was unable to correlate these values to sewer ventilation rate. The work also confirmed that headspace pressure follows a diurnal pattern, a fact mentioned elsewhere in the literature.

Figure 6-2. Air Extraction Skid for Sewer Ventilation Testing (Phoenix, Arizona)

Table 6-1. Phoenix, Arizona, Area Sewer Pressure Variation with Forced Ventilation

| Location | Sewer Diameter (inches) | Airflow (cfm) | Normal Pressure[a] | Pressure with Air Extraction | Distance of Pressure Influence on Sewer (miles) |
|---|---|---|---|---|---|
| Tempe, SAI | 42 | 2,700 | +0.10 | -0.80 | 4 |
| Phoenix, 51st Avenue Siphon, SAI | 72 | 4,000 | +0.50 | -0.50 | 5 |
| Phoenix Airport Parking Facility, SRO | 90 | 5,200 | +0.02 | -0.13 | 4.5 |

[a] Average pressure experienced in sewer headspace in unventilated conditions.
SAI, Southern Avenue Interceptor.
SRO, Salt River Outfall.

A collection system odor and corrosion study in Los Angeles by Hagekhalil et al. (1994) identified a number of factors typically contributing to sewer odor emissions and odor complaints (unvented siphons, wastewater turbulence, etc.). As part of the study, the authors measured sewer headspace velocity with a vane anemometer in a 78-inch pipe. Their data indicated an air-to-liquid velocity ratio of 0.04, with no measurable velocity at 8 inches from the liquid–air interface. Liquid velocity was estimated at 5 fps. These results suggest previous work by Pescod and Price (1981) would estimate air velocity a factor of 10 too high, if applied to a larger diameter sewer.

A study of a large-diameter trunk sewer in Clark County (Las Vegas area) evaluated hydraulic conditions in a steeply sloped sewer with several hydraulic jumps (Pai et al., 2000). The evaluation concluded that hydraulic jumps would produce significant pressurization in upstream sections of the interceptor. This analysis led to a system requiring an external odor control duct running in parallel for 3 miles to the main treatment plant. A 5,000-cfm booster fan system was installed to convey foul air through a 36-inch duct running parallel to the interceptor.

### 6.3.3 VOC Emissions Evaluations

Two papers included a discussion of sewer ventilation with respect to VOC emissions. In these evaluations, sewer ventilation estimates were made to establish VOC emission quantities, and sewer pressurization was not the major issue.

One VOC emissions study evaluated out-gassing through four perforated manhole covers within the lower part of a 1.6-km sewer reach (Corsi et al., 1995). Pipe diameters ranged from 0.9 to 1.2 m, and pipe slopes varied from 1.0 percent in the upper part of the reach to 0.25 percent in the lower part. Thermal anemometers were used to estimate sewer out-gassing velocities. The combined out-gassing flow rate ranged from 1,300 to 2,300 $m^3$/hr during three different testing events. During a fourth testing event, the furthest downstream manhole exhibited flows ranging from a low of 140 $m^3$/hr to a high of 590 $m^3$/hr.

Melcer et al.(1994), in a study evaluating ventilation and its impact on VOC emissions in collection systems, modeled conditions needed to maintain a sewer headspace at less than 10 percent of the low explosive limit (LEL) at given liquid phase concentrations of VOCs. In other words, this study modeled the highest potential liquid phase VOC concentration that could be tolerated to maintain the sewer atmosphere below 10 percent of LEL. This study confirmed through modeling (with Toxchem+) that an order-of-magnitude increase in ventilation (air velocity ranging from 0.5 to 5 times the liquid velocity) allowed liquid phase VOC concentrations to be six to eight times higher for the compounds under study (the benzene, ethylbenzene, toluene, and xylene family) without exceeding a 10 percent LEL condition.

### 6.3.4 Theoretical Analysis and Pilot-Scale Tracer Evaluations

Three papers offered pilot testing and theoretical perspectives on sewer ventilation rates that were subsequently compared to full-scale sewer segments. Sewer airflow algorithms were analyzed in these studies and applied to full-scale studies.

Monteith et al. (1997) conducted pilot tracer gas ventilation testing and followed this with full-scale tracer testing. Many of the parameters in their study were those known to influence airflow and were originally investigated by Pescod and Price. These included water flow, water temperature, and wind velocity over sewer openings. They attempted to fit their data to an empirical model:

$$v_g = a v_w^{b} + c w^{d} \tag{6.3.4-1}$$

where

$v_g$ = headspace gas velocity

$v_w$ = water velocity in the reach

$w$ = surface wind velocity over reach opening

Their optimized solution to the model that was developed from pilot plant tests utilizing tracer gases is

$$v_g = 0.236 v_w^{1.12} + 0.0288 w^{0.88} \tag{6.3.4-2}$$

Comparing these models with tracer test results on a full-scale system indicated the model had overpredicted gas velocities by a factor of 3 to 5.

The second paper (Parker et al., 2001), a tracer study for the Regional Municipality of Ottawa-Carleton, employed both pilot- and full-scale tests to assess the impact of wastewater drag and wind on sewer ventilation. In the pilot study, average air velocity was found to increase with the product of the water surface width and the liquid velocity divided by the hydraulic radius of the headspace. The full-scale tests reflected highly variable headspace velocity (3.8 to 31.5 $m^3$/min). Air velocity developed from the field data correlated poorly with the above formulas—ranging from 3 to 30 m/min for one specific value of surface width, liquid velocity, and hydraulic radius.

The third paper was developed primarily from the doctoral thesis of Edwini-Bonsu (2004). This work addressed sewer ventilation from a computational fluid dynamics (CFD) approach and used much of Pescod and Price’s original data for evaluation purposes. It partitioned the algorithms representing flow by wastewater drag into both turbulent and laminar flow regimes. The doctoral thesis also included modeling a portion of the City of Edmonton’s interceptors to validate flow conditions in that system. The system in question has several drop structures and is ventilated with a foul-air treatment system.

The validity of the CFD model was limited owing to very little available input data for the City of Edmonton system under study. Physical verification of the model predictions was also limited. Additionally, another limitation of the model is that it assumes an average flow condition, which is not representative of a typical sewer system, in which flow and depth varies hour to hour. The potential advantage of the CFD approach is that it appears to use a more sophisticated and potentially more accurate, parameter to estimate liquid-induced friction drag from the liquid interface to the air space. Application of the model has produced estimated airflows that are slightly lower than the simpler correlations that were developed from Pescod and Price.

## 6.4 Engineering Perspectives of Sewer Ventilation and Odor Control

Although many of the case histories and much of the research provided unique perspectives on sewer ventilation and pressurization, few of the studies developed a logical discussion of obvious cause-and-effect problems relating to this subject and, more importantly, the significant design issues that follow from an analysis of sewer ventilation. The following summarizes issues whose discussion in the research papers reviewed was limited.

A key factor relating to pressure development is the physical structure of the sewer and the available headspace area under various flow conditions. If adequate headspace is available to accommodate the induced airflow, pressurization may be minimal. However, if the headspace is constricted, greater air pressure develops. In cases where the sewer is completely full (surcharged areas, unjumpered siphons, etc.), all available energy imparted to the headspace is reflected as pressure rather than air movement. In these cases, it is highly likely that foul air will migrate up through manhole covers and laterals—and even through side sewers into customers’ buildings—to find relief points. In many cases, the odors that are escaping in upstream laterals are addressed by sealing manhole covers. However, since foul air can no longer be relieved at these points, the pressurization tendency actually increases. A secondary problem arises because with less airflow in the headspace, $H_2S$ concentrations increase, so that fugitive emissions contain higher concentrations of $H_2S$ with much greater odor and corrosion potential over a larger area.

The only effective solution to resolve pressure conditions is to mechanically extract air from the headspace and treat it. This approach raises a number of technical design questions concerning how much flow capacity is required and at what point in the system the headspace air should be extracted to achieve maximum pressure reduction benefits. In larger interceptors, the airflow question has been addressed by using the Pescod and Price rule of thumb on air movement (airflow velocity of one-third to one-half the liquid velocity). However, some data suggest that Pescod and Price's airflows overstate actual conditions. A second major parameter relates to how much pressure reduction can be achieved in a given section of interceptor system. This parameter is significantly influenced by the interceptor system construction, including location and size of junction structures, leak-tightness of manhole covers, vertical drop of wastewater from laterals, and the presence of siphons. The Phoenix gas extraction tests described earlier (Davidson et al., 2002) demonstrated headspace pressure reduction up to 5 miles on one interceptor that had relatively well sealed manholes and no major lateral connections. However, gas extraction tests on another section of interceptor demonstrated very little pressure reduction at a major junction structure less than 1 mile from the extraction point. The study for Northeast Ohio Regional Sanitation District tunnel system described above (Smith et al., 2001) found considerable pressure variances that depended on how many biofilter treatment systems were operating. This project also pointed out that the hydraulic design, size, and configuration of junction structures can effectively block the pressure influence of downstream biofilters on upstream interceptor segments.

Mechanical air extraction and treatment raises other issues relative to how and where replacement air is inspirated in the interceptor system. Since a typical goal of mechanical air extraction is to draw a large section of pipe headspace to negative pressure, points near the draw location where air can enter the sewer should be sealed to minimize air "short-circuiting" close to the treatment system. This raises further issues concerning sealing the system or perhaps installing air baffles to partially restrict air movement in various interceptor segments.

## 6.5 Summary of the Knowledge Base

Several broad conclusions can be drawn from this review of sewer ventilation literature:

- That conceptual factors, such as wastewater drag, influence sewer ventilation is generally agreed upon by most researchers. However, the success in quantifying these factors to yield useful guidelines that agree with field data or full-scale tracer studies has been very limited.
- Pressurization and foul-air fugitive emissions are critical problems in several systems, and several papers reflect case studies of these systems. However, systematic design approaches for dealing with sewer pressurization are notably absent, and many foul-air extraction systems seem to be designed by arbitrary rough estimates and airflow approximations. There is very little empirical methodology employed with these foul-air extraction systems.
- Sewer airflow algorithms are studied in some of the papers. However, the value of these algorithms is questionable because both airflow and pressure will be significantly influenced by the physical characteristics of a particular system. Therefore, interceptor system characteristics play as much of a role in sewer ventilation as the factors that impart airflow in the headspace.

- Data from field studies are very difficult to interpret and often widely scattered. It is likely that continually changing flow conditions, common in any interceptor network, produce greatly differing airflow conditions depending on time of day. Diurnal variances in flow make it difficult to obtain consistent and repeatable data. This problem is aggravated by the rather short duration of most field evaluations that were cited.
- None of the research has produced data showing the relationship between sewer ventilation and odorant concentration. One paper (Davidson et al., 2002) attempted to evaluate this relationship, but the data were inconclusive.
- One paper (Hagekhalil et al., 1994) touched upon the issue of "microdispersion" modeling from manhole odor leaks. Dispersion is not a factor relating to sewer air movement and pressurization, but as a practical matter, the dispersion of odors as they migrate from manhole leaks is an important determinate in whether odors will be objectionable—particularly for systems with lower flows and minimal pressurization tendencies. The dispersion element provides perspective on when an odor emission point becomes a source of complaints.

## 6.6 Research Gaps

Despite the obvious importance of sewer ventilation to collection system odor and corrosion problems, there has been little progress made toward fundamentally understanding the competing factors that affect ventilation. Factors required to determine sewer ventilation rates and relate them to changes in wastewater flow, headspace above the liquid, or physical structure of sewer systems are needed. Improved knowledge in this area is critical to advancing integrated solutions to sewer odor and corrosion problems. Research has tended to evaluate specific collection systems and focus on solving site-specific odor problems. Full-scale field data often vary considerably from predicted values developed from laboratory pilot tests. None of the previous work attempts to define sewer headspace ventilation in terms similar to airflow in a duct and then relate those parameters to wastewater flow and interceptor characteristics. Furthermore, collection system leak-tightness, while being a critical ventilation parameter, has not been assessed in any of the work thus far.

The objectives of the proposed research are to accomplish the following:

- Develop a database that can be used to evaluate existing and future models related to sewer ventilation.
- Evaluate existing models for the prediction of sewer ventilation.
- Investigate relationships among sewer headspace pressure, airflow, wastewater flow, and geometry of the headspace.
- Modify, as appropriate, the models described in the research literature or develop new models on the basis of the results of further testing and investigations.

Within the context of the various ventilation parameters, project goals should include evaluating the implications for interceptor system fugitive emissions, odor concentrations, corrosion potential, and control method approach.