CHAPTER 10.0

RESEARCH GAPS EVALUATION AND SUMMARY

This chapter summarizes the initial 13 research gaps identified during the Phase 1 literature search and provides a ranking for those research gap areas determined to be highest priority based upon input from WERF and WERF subscribers. The WERF research team developed gap summaries providing "problem statements" to define each gap along with potential "research approaches" geared to fill each data gap. The research gaps are listed below and discussed in the following pages:

1. Better definition of sewer ventilation so that natural air movement and displacement in collection systems may be better understood.
2. Better definition of the odorous and corrosive compounds other than H_2S found in collection systems.
3. Better definition of the treatment effectiveness for non–hydrogen sulfide odorous compounds by means of available liquid and gas phase treatment systems.
4. Improved predictive relationship between hydrogen sulfide (H_2S) gas concentration and corrosion rates in sewer systems.
5. Improved understanding of the impacts of collection systems chemical dosing on the downstream treatment plants.
6. Characterization of the importance of substrates on sulfide generation rates in collection systems.
7. Definition of the feasibility, practicality, and related costs of using oxygen treatment in gravity sewers.
8. Improved understanding of available biological treatment using enzymes and bacterial cultures.
9. Documentation of the mechanisms for odor and corrosion control using magnesium hydroxide pH adjustment.
10. Development of design guidance for sizing air jumpers and related ventilation systems.(This research gap may become part of the effort associated with Gap 1.)
11. Improved understanding of the relative effectiveness of biotechnology-based odor control systems in cold climates.

12. Better understanding of the unique odor and corrosion impacts from fats, oils, and grease.
13. Clear definition of the odor and corrosion effect of using sewers as reactor vessels to achieve partial wastewater treatment. (This practice is gaining acceptance in Europe and may need to become better understood worldwide.)

Gaps 1 and 2 were initially ranked very closely by the project research team. Based upon initial review with the WERF PSC, the following six research gap areas were identified as high-priority during a meeting with the PSC at the Detroit Collections Systems Conference in August 2006. A WERF subscriber survey requesting that WERF members provide feedback and ranking for the following six gap areas was then completed:

- Improved definition of sewer ventilation to better understand natural air movement and displacement in collection systems.
- Better define the odorous and corrosive compounds found in collection systems. (What are the non–hydrogen sulfide odor- and corrosion-causing compounds? This gap will include evaluation of a representative variety of collection systems including various climates, CSO and non-CSO systems, and those influenced by fat oil and grease impacts.)
- Better definition of the treatment effectiveness for non–hydrogen sulfide odorous compounds.
- Better understanding of the relationship between hydrogen sulfide gas concentrations and corrosion rates.
- Better understanding of the practicality and related costs of using oxygen treatment in gravity sewers.
- Clear definition of the odor and corrosion effect of using sewers as reactor vessels to achieve partial wastewater treatment.

The subscriber ranking survey was issued to WERF subscribers in October 2006 in order to assist in the final ranking of the highest-priority research gaps. On the basis of this survey, the following were identified as the top-ranking research gaps:

1. Improved definition and understanding of natural sewer ventilation is needed to better understand air movement and displacement in collection systems and the related impacts on odor and corrosion.
2. Improved understanding of the effects of hydrogen sulfide gas concentrations and the relationship to concrete corrosion rates in collection systems is needed.
3. Better definition of the non–hydrogen sulfide odor- and corrosion-causing compounds found in collection systems.
4. Better definition of the treatment effectiveness for non–hydrogen sulfide odorous compounds.

These four research gaps are considered to be of the highest priority. It is anticipated that Phase 2 of this research program will be geared towards addressing these research gap areas in as much as possible. Where additional effort and budget beyond the scope of this project is needed, alternative collaborative research opportunities will be pursued.

The remainder of this chapter outlines each of the initially identified 13 research gap areas. The top four include initial budgetary estimates.

10.1 Natural Ventilation of Sewers

The nature and extent of air exchange (ventilation) between the ambient atmosphere and headspace of sewers is perhaps the most important variable affecting the generation and release of odorous and corrosive gases in gravity sewers. Ventilation replenishes the oxygen in the headspace of sewers, affects the degree of condensation on sewer crowns (and hence sewer corrosion), and releases and conveys odorous gases from the sewer system.

10.1.1 Problem Statement

Despite the importance of sewer ventilation, little progress has been made in fundamentally understanding the factors that affect natural ventilation, how those factors can be controlled to optimize ventilation in corrosive and odorous sewer environments, and how to estimate, even by rough approximation, how sewer ventilation rates and patterns will change with modifications to sewer systems. The following is an overview of some research conducted on this topic.

Pescod and Price (1981) performed lab-scale experiments involving a 0.3-m sewer operating at various depths and rates of flow and measured average headspace air velocities. Their work focused primarily on liquid-drag induced natural ventilation. Parker and Ryan (2001) showed how inert tracers such as carbon monoxide can provide information on air flows in specific sewer reaches, but the technique has not been applied to a wide range of reaches thus allowing for more generalized knowledge. Edwina-Bonsu and Steffler (2004) developed a state-of-the-art model of fluid mechanics in gravity sewers, but focused entirely on the effects of wastewater drag and employed a fairly sparse data base in evaluation of the model. Olson et al. (1997a, 1997b) made novel use of the first law of thermodynamics to predict air flow in sewers given competing ventilation mechanisms, and performed small-scale sewer experiments that correlated very well with model predictions. However, their model was never tested with actual field data. Improved knowledge in this area is critical to advancing integrated solutions to sewer odor and corrosion problems.

10.1.2 Proposed Research Gap Evaluation Method

10.1.2.1 Objective

The objective of the proposed research is to (1) develop a database of field tracer data that can be used to evaluate existing and future models related to sewer ventilation; (2) evaluate existing models for the prediction of sewer ventilation; and (3) modify, as appropriate, the existing models or develop new models based on the results of step 2.

10.1.2.2 Proposed Program

This study would consist of the phases described below.

Phase 1—Identification of Sewer Reaches During this phase, sewer components and locations for testing will be identified. In addition, sampling and analytical procedures will be developed. For the purpose of this proposal, it is assumed that up to eight sampling events will be completed. As part of the sampling plan, a list of parameters necessary for applying computational fluid dynamic models (such as Edwina-Bonsu and Steffler [2004]) and thermodynamic models (such as Olson et al. [1997a, b]) for predicting ventilations (rates and directions) and relationships developed by Pescod and Price (1981) will be identified.

The following activities will be completed during Phase 1:

- Identification of sewer components/operating conditions to be investigated. Potential components might include: (1) inlets to siphons or wet wells; (2) drop structures, both conventional and vortex design; (3) gravity sewers, with and without sidestream connections; and (4) warm and cold climate conditions (where liquid-air thermal gradients may affect out-gassing)
- Identification of potential testing locations. Utility partners to be solicited for support may include Orange County (Calif.) Sanitation District, Los Angeles County Sanitation District, and King County (Wash.)
- Review of candidate location system physical information
- Site visits to finalize ventilation testing locations
- Sampling and analytical plan development

Phase 2—Field Studies Field studies will be completed in the reaches identified in Phase 1 using inert tracer methods similar to those of Parker and Ryan (2001). Data will be collected as additional input to models, such as wastewater and headspace temperatures, and wastewater flow rates during gas tracer experiments. The intent of this testing is to obtain sufficient data to characterize and define various operating conditions or parameters and the resultant natural ventilation rates and to allow assessment of the accuracy of existing ventilation models. Sampling will consist of the following tasks:

- Use inert tracers to quantify ventilation rates
- Monitor wastewater flow and temperature
- Monitor headspace temperature and pressure
- Measure liquid phase sulfide concentration (grab sampled using adsorbent tubes)
- Measure vapor phase hydrogen sulfide concentration (continuous sampling using hydrogen sulfide OdaLogs)

It is expected that each sewer component can be tested in a day. At least two utility partners will be used, one to test during warm conditions, the other during winter conditions:

- Utility Partner A—warm climate testing × 4 component tests = 4 tests
- Utility Partner B—cold climate testing × 4 component tests = 4 tests

Phase 3—Existing Models Evaluation The ability of existing sewer ventilation models to accurately predict ventilation rates will be evaluated using the data collected in Phases 1 and 2. For the purpose of this proposal, it is assumed that up to three models will be compared: for example, the Pescod and Price (1981) air velocity–wastewater velocity relationships, the Edwina-Bonsu and Steffler (2004) computational fluid dynamics–based model, and the Olson et al. (1997a, b) thermodynamic-based model. Where possible, recommendations on improved methods for estimated natural ventilation rates will be suggested.

Phase 4—Report Preparation A draft report will be prepared documenting activities completed during Phases 1 through 3. The report will include:

- Documentation of WCS components and locations selected for testing
- Sampling and analysis plan
- Database of testing results
- Comparison of field-measured versus model-predicted results
- Recommendations on potential improvements to natural ventilation rate algorithms

Comments on the draft report will be used as the basis for revising and completing it. The number, format, and type of final report submitted (electronic, hardcopy) will be consistent with WERF Research Project 04-CTS-1 contract requirements.

10.1.3 Schedule

For the purpose of scheduling, it is assumed that notice to proceed for this research activity will be issued by May 1, 2007.

Table 10-1. Natural Ventilation of Sewers: Schedule

	Start Date	End Date
Phase 1	05/01/2007	05/01/2007
Phase 2	05/01/2007	09/01/2007
Phase 3	09/01/2007	12/01/2007
Phase 4	12/01/2007	02/28/2008

10.1.4 Budget

Table 10-2. Natural Ventilation of Sewers: Budget

	Total ($)
Phase 1	67,595
Phase 2	101,989
Phase 3	21,902
Phase 4	21,245
Total	212,731

10.2 Relationship between Sewer Corrosion and Headspace Hydrogen Sulfide Concentration

Sewer system owners often use modeling to predict sulfide transport within sewers and emissions from sewer headspaces. Some models also predict corrosion and concrete component life based on liquid phase sulfide. Such predictions rely on indirect parametric relationships and provide only order-of-magnitude accuracy.

10.2.1 Problem Statement

Sewer component corrosion is known to be strongly correlated to headspace hydrogen sulfide concentrations, a parameter that is easily measured in the field. Improved knowledge of this relationship would enable more accurate modeling that could be used to better predict pipe life and identify potential corrosion spots. Yet, the relationship between *headspace* hydrogen sulfide and corrosion has not so far been well characterized.

Several studies that characterize the bacterial conversion of hydrogen sulfide to sulfuric acid and subsequent corrosion have been completed. Findings from these studies could be incorporated with an investigation of mass transfer of hydrogen sulfide from the bulk gas phase to the damp film coating unsubmerged pipe walls. The study should track parameters that influence mass transfer, such as headspace ventilation, air temperature, and water level. By combining existing knowledge of bacterial uptake of hydrogen sulfide and subsequent corrosion with new knowledge of mass transfer, a model algorithm could be developed or old algorithms improved.

10.2.2 Proposed Research Gap Evaluation Method

10.2.2.1 Objectives

The objectives of the proposed study are the following:

- Identify the rate of bacterial uptake of hydrogen sulfide on unsubmerged pipe walls and subsequent corrosion in the literature.
- Develop a mathematical model to characterized mass transfer between the bulk headspace air and the un-submerged pipe wall film.
- Determine experimentally the hydrogen sulfide deposition under varying conditions.
- Combine the results into an algorithm that relates corrosion with hydrogen sulfide gas concentration.

10.2.2.2 Program

The program of research would consist of three phases.

Phase 1—Mathematical Model Development Phase 1 will be implemented to describe mathematically the variables, reactions, mass transfer processes present between the bulk hydrogen sulfide gas phase and concrete corrosion of un-submerged pipe walls. Reaction rate constants and mass transfer coefficients will be located in the technical literature, where available. Three months will be budgeted to complete Phase 1.

Phase 2—Experimental Determination of Hydrogen Sulfide Deposition Phase 2 will be completed in a laboratory where important variables can be controlled. It is proposed that experiments be conducted in a horizontal cylindrical chamber partially filled with water. The water need not be flowing. However, the water level should be variable. Also, headspace ventilation and hydrogen sulfide gas concentration should be variable. Five months will be budgeted for the completion of Phase 2.

Phase 3—Algorithm Development During Phase 3 the results of Phases 1 and 2 will be combined into an algorithm that can be used to predict pipe corrosion based on headspace hydrogen sulfide gas concentration. Four months will be budgeted for Phase 3, including documenting Phases 1, 2, and 3 in a final report.

10.2.3 Budget

Table 10-3 summarizes the schedule and budget.

Table 10-3. Relationship between Sewer Corrosion and Headspace Hydrogen Sulfide Concentration: Schedule and Budget

	Schedule	Budget ($)
Phase 1	05/2007–08/2007	25,748
Phase 2	08/07–01/08	128,466
Phase 3	01/08–05/08	42,771
Total	12 months	196,985

The approach outlined above does not include field verification. If an extensive field verification step is added then it is estimated that additional time and cost would be incurred. Total time might increase to as much as 2 years and estimated total costs could approach $379,000.

10.3 Compounds in Sewer Gas That Lead to Odor Complaints and Corrosion: Non-H_2S Odor- and Corrosion-Causing Compounds

10.3.1 Problem Statement

Odors associated with wastewater collection systems typically are attributed to the presence of hydrogen sulfide. Thus many technologies used to control sewer odors are directed toward suppression of hydrogen sulfide generation (for example nitrate addition to wastewater), or to its destruction/removal following generation (ferrous chloride addition to wastewater or treatment of headspace gases in biofilters). Conditions in sewer systems can produce other compounds of low odor threshold, such as those listed in Table 10-4. The contribution of such compounds to odor nuisance complaints is not well understood, and little has been done to study this odor phenomena. Collection systems may well have locations where effective control and removal of hydrogen sulfide will not lessen an odor problem. A control strategy may need to be developed for other odorous compounds besides hydrogen sulfide to alleviate a collection system odor problem.

Table 10-4. Odorous Compounds Associated with Untreated Wastewater

Class of Compound	Relevant Examples
Inorganic gases	Ammonia, hydrogen sulfide
Mercaptans	(Allyl; amyl; benzyl; crotyl; ethyl; methyl; propyl) mercaptans
Other organic sulfur	Dimethyl sulfide, diphenyl sulfide, thiocresol, thiophenol
Amines	(Dibutyl; diisopropyl; dimethyl; ethyl; methyl; triethyl) amines
Diamines	Cadaverine (1,5-pentanediamine); putrescine (butanediamine)
Other organic nitrogen	Indole, pyridine, skatole
Volatile fatty acids	(Acetic; propionic; butyric; isovaleric) acids

10.3.2 Study Goals and Objectives

The following study goals and objectives for the identification of compounds that may contribute to collection system odors:

- Survey several collection systems throughout the U.S. and in Australia to evaluate locations that may have odors associated with compounds that are not hydrogen sulfide.
- Identify the most significant compounds, in addition to hydrogen sulfide, that contribute to perceived odors in sewer headspace gases. Due to limitations in existing analytical methods

the contribution to odor by amines, organic nitrogen compounds and volatile fatty acids will have limited consideration during this study.

- Evaluate the contribution of odorous compounds to perceived odors relative to the contribution from hydrogen sulfide.
- Develop guidelines or procedures for distinguishing between locations where control of hydrogen sulfide alone is sufficient to minimize odors and locations where odor control must target control of other compounds.

10.3.3 Experimental Approach Proposed Research Gap Evaluation Method

A gas chromatograph mass spectrometer olfactometer (GC/MS/O) will be used. The WERF team has access to two of these systems, one in Australia at the University of South Wales and another in Los Angeles through the partnered labs of Los Angeles County Sanitation District.

In the GC/MS/O, individual odorous compounds in the sample gas are resolved using gas chromatography. A gas sample is introduced into a gas chromatograph and cryo-trapped onto a column. As different compounds are eluted from the gas chromatograph column they pass through a flow splitter. A portion goes to the mass spectrometer, where a spectral signature is generated that enables identification and quantitation of each analyte. Another portion is directed to a sniffing port that presents the gas to a trained chemist. For each compound that registers an olfactory response, the odor is characterized and ranked on an odor intensity scale containing up to seven steps. The GC/MS/O set-up enables the spectral signature produced by each analyte in the mass spectrometer to be correlated to the odor perceived by the human subject. The correlation is dependent on the gas chromatograph methodology, which will impart a slight difference between the mass spectrometer spectra and the odorgram.

The approach to characterizing odors in sewer gas will include the following tasks:

- Establish protocols to ensure consistency in sample collection and proper handling of equipment.
- Screen sampling locations.
- Select sample locations for detailed study.
- Conduct sampling and analysis.
- Conduct data analysis and prepare a report.

10.3.3 Sampling Protocols

Sampling collection Grab samples for GC/MS/O analysis will be collected in either fused-silica-lined stainless steel canisters 6 L in volume or Tedlar bags (whichever is most appropriate). Samples analyzed for odor strength will be collected in commercially produced Tedlar bags that have been condition with high purity air to remove impurities. Sampling depth—All samples to be collected from inside the collection systems below the manhole covers.

Holding times Odor panel samples that are collected in Tedlar bags will be analyzed within 24 hours of collection. Samples that are collect stainless steel canisters can be held for longer periods of time because of the nonreactive nature of the canisters but analyses will typically be made within 24 to 48 hours after collection of sample.

10.3.4 Selection of Sampling Locations

To determine the influences that different wastewater collection systems have on generation of odorous compounds in sewer headspaces, samples will be collected at several different collection systems. The sample locations will be situated in different regions of the U.S. so that regional climatic differences can be compared. In addition, the sample locations will include large and medium collection systems, systems with high and low percentages of industrial waste, systems with and without force mains and will include older combined sewer overflow systems and newer non–combined sewer overflow systems.

The proposed U.S. locations for sampling include the following:

Table 10-5. Collection Sampling Locations and Their Properties

Collection System	Collection System Properties
Los Angeles County Sanitation Districts	Large collection system in a warm climate with significant industrial waste
Orange County (Calif.) Sanitation Districts	Large collection system in a warm climate with little industrial waste
King County (Wash.)	Large system in a cool wet climate, with little industrial waste and a mixture of force mains and gravity sewers
Hampton Roads (Va.) Sanitary District	Medium-sized east coast system with a significant number of force mains
Chicago Metropolitan Water Reclamation District	Large system with a major industrial waste component
Pittsburgh Water Authority	A medium-sized system with combined sewer overflows

Locations are also being identified in Australia. Other collection systems could also be included to try and compare additional field conditions that could influence the generation of odorous compounds. Final selection of collection sites will attempt to balance locations where hydrogen sulfide is the predominant contributor to odor character against locations where other compounds may exist at significant levels. As an initial step, utility partners will be asked to submit a list of candidate locations from their collection systems where odor control has been difficult. As part of the submittal, the utility partner will include basic information for each candidate location such as range of flows, sewer diameter, depth to sewer invert, range of flow depth, type of manhole structure, sewer slope, distance to treatment plant, type of wastewater (for example, mostly residential, mixture of industrial and residential), identification of significant industrial discharger and type of industry, data, odor characteristics, dissolved sulfide, total sulfide, hydrogen sulfide). The utility will also briefly explain why each location is proposed for further evaluation.

Candidate locations will be selected for preliminary evaluation. Gas samples from those locations will be presented to an odor panel for initial odor characterization. Each location could be sampled two times. During sample workup, the gas will be split into two duplicate samples.

10.3.5 Laboratory Methods

10.3.5.1 Odor Measurements

Odor level in sewer headspace gas samples will determined by a certified odor panel at the Los Angeles County Sanitation District Joint Water Pollution Control Plant laboratory. The panel can measure up to about six samples per day. (Above six, fatigue of the senses tends to occur.)

Panel members will rate the odor intensity of the undiluted sample on a seven-point scale and assign descriptors for the odor chosen from a defined list (for example, rotten egg, rancid, fermented cabbage, earthy).

10.3.5.2 GC-MS–O

Samples will be analyzed at both the Los Angeles County Sanitation District and the University of South Wales labs. Each lab will spend roughly 12 weeks running two tests per week. As such, no more than 48 samples are expected.

- Tasks 1: Initial survey for locations and staff training for initial screenings. This task is expected to require the initial 2 months and include set-up and training, survey of utility partners and selection of sampling locations for preliminary screen, and preliminary screening of locations.
- Task 2: Initial sampling and GC/MS/O analysis. This task is expected to require the next 3 months and to comprise collection and analysis of samples for GC/MS/O and data analysis.
- Task 3: Report summary. This task is expected to require months 6 to 9 months.

10.3.6 Schedule

For the purpose of scheduling, it has been assumed that notice to proceed for this research activity will be issued by May 1, 2007.

Table 10-6. Non-H_2S Odor- and Corrosion-Causing Compounds: Schedule

	Start Date	End Date
Task 1	05/01/2007	07/01/2007
Task 2	07/01/2007	10/31/07
Task 3	10/31/07	04/31/08

10.3.7 Budget

Table 10-7. Non-H_2S Odor- and Corrosion-Causing Compounds: Budget

	Total ($)
Task 1	37,904
Task 2	83,448
Task 3	85,096
Total	163,000

10.4 Effectiveness of Treatment Methods for Compounds Other Than Hydrogen Sulfide

Measurement and odor treatment techniques are usually designed for hydrogen sulfide, but numerous, less-well-understood compounds contribute to odor and warrant attention. Since treatment technologies are geared to hydrogen sulfide, other compounds are sometimes less effectively treated and can represent the bulk of odors remaining after treatment.

10.4.1 Problem Statement

Neglecting the spectrum of odor-causing compounds has led in some cases to failure of odor control systems even while hydrogen sulfide is effectively treated. Likewise, the success of many odor control systems may depend on the absence of other compounds in significant concentrations. A study is needed to evaluate how effectively odor compounds, other than hydrogen sulfide, are controlled with existing treatment systems.

10.4.2 Proposed Research Gap Evaluation Method

10.4.2.1 Objective

The objective of the propose study is to determine the effectiveness of existing odor control technologies for removing odor compounds other than hydrogen sulfide.

10.4.2.2 Program

The program of research would consist of the following three phases: (1) facility selection, (2) facility sampling, and (3) results documentation.

Phase 1—Facility Selection During Phase 1, up to 20 wastewater collection facilities where odor control technologies are in place will be identified. The facilities where permission can be obtained to carry out sampling should be selected. Also, a range of odor control technologies should be represented among the 20. Three months will be allocated for Phase 1.

Phase 2—Facility Sampling Air samples will be collected at each facility upstream and downstream of the control technology. GC-MS will be used to identify VOCs. Additionally, reduced sulfur compound analysis will be used to identify the dominant reduced sulfur compounds in each sample, hydrogen sulfide among them. Odor panel analyses will be used to determine the character and concentration change from upstream to downstream each treatment facility. Six months will be budgeted for Phase 2.

Phase 3—Results Documentation During Phase 3 results measured during Phase 2 will be documented. A report will be produced that provides guidance on the effectiveness of existing treatment technologies for controlling odor compounds. Three months will be provided to complete Phase 3.

10.4.3 Schedule and Budget

The cost of Phase 1 should consist mostly of labor required to research facilities that would best lend themselves to this project and to contact those utilities. Table 10-8 summarizes the schedule and budget.

Table 10-8. Effectiveness of Treatment Methods for Compounds Other Than Hydrogen Sulfide: Schedule and Budget

	Schedule	Budget ($)
Phase 1	05//07–08/07	17,500
Phase 2	08/07–02/08	97,000
Phase 3	02/08–05/08	37,400
Total	12 months	151,900

10.5 Life-Cycle Analysis of Chemical Addition on Downstream Processes

Liquid phase treatment of wastewater to remove dissolved sulfides usually involves adding significant quantities of chemicals. Several classes of chemical are used. Chemical oxidants (hydrogen peroxide, sodium hypochlorite) are used to oxidize sulfide to sulfate or sulfur. Iron salts are used to precipitate sulfide to an insoluble solid form. Nitrate is added to prevent sulfide from forming. pH adjustors such as magnesium hydroxide are used to prevent sulfide from entering the gas phase.

Many the chemicals used in liquid phase treatment may have side effects on the downstream treatment plant. For example, chlorine used to oxidize sulfide may have a residual disinfectant effect on activated sludge processes. Iron salts can cause increased sludge production. Nitrate addition may increase the nitrogen load on the plant. Some chemical suppliers claim that their products have beneficial side effects on downstream processes. For example, a supplier of magnesium hydroxide claims that its product improves flocculation in the primary clarifier.

10.5.1 Problem Statement

Although effects of chemical addition on downstream processes have been reported anecdotally, little quantitative information is available on these effects. In particular, the life-cycle analysis (LCA) of protecting infrastructure and preventing emissions verses downstream wastewater treatment impacts are unknown. A study is needed to quantify the downstream effects of chemical addition to the collection system and compare their performance using an LCA framework that calculates technical options based on economic, social, and environmental parameters. LCA is an ISO-standardized framework for the comparison of alternative products or services from an environmental perspective. The fundamental idea behind LCA is much broader than life-cycle costing (LCC) and consists of an assessment of all the physical and energetic flows that occur as a consequence of the selection of a particular process (see Figure 10-1).

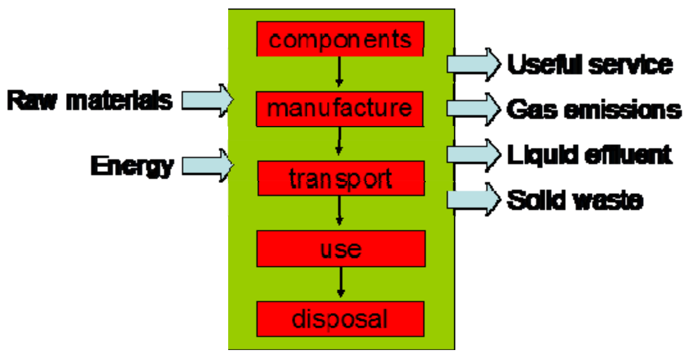

Figure 10-1. Example Process upon Which LCA Can Be Based

10.5.2 Proposed Research Gap Evaluation Method

10.5.2.1 Objectives

The proposed study has the following objectives: (1) Identify effects of chemicals commonly added to collection systems on downstream processes, (2) develop LCA framework, and (3) quantify effects of chemical dosing on wastewater treatment using LCA.

10.5.2.2 Program

The program of research would consist of the following three phases: (1) Utility survey, (2) utility records analysis, and (3) LCA analysis.

Phase 1—Utility Survey In Phase 1, a survey will be conducted of utilities where collection system chemical addition is used. The observations of plant operators of downstream effects due to upstream chemical addition will be recorded. Plant records, where available, will be compiled for a period of at least 1 year before chemical addition was implemented until at least 1 year after. Four months will be budgeted to complete Phase 1.

Phase 2—Utility Records Analysis During Phase 2, records will systematized into a form whereby relevant treatment plant operating parameters can be compared before and after the start of upstream chemical addition. Before/after differences in operating parameters (such as aeration rate and sludge production) will be tracked and normalized for external conditions parameters (such as wastewater temperature and flow rate). Trends in operation parameter changes will be identified for each upstream chemical addition method. Trends will be analyzed to determine whether they can be attributed to upstream chemical addition. Where strong evidences suggest a relationship between upstream chemical additions and a downstream effect, LCA analysis will be used to compare performance (Phase 3). Four months will be budgeted to complete Phase 2.

Phase 3—LCA Analysis In Phase 3, an LCA framework will be developed to compare the performance of chemical dosing on collection system operation and wastewater treatment. This will involve dialogue with a Reference Panel of industry stakeholders to help define the sustainability criteria and relative significance of different key performance indicators. These quantitative key performance indicators will be used for the technology assessment. As a minimum, LCA requires (1) a clear definition the process being examined; (2) the compilation of an inventory of the flows in and out of the process and the product or products it yields; (3) characterisation and aggregation of these flows into environmental themes and impact assessment using models suitable for assessment of global and regional environmental impacts. This process will take into account financial and social analyses, and enable decision makers to determine the relative sustainability of alternative options. Data collected during Phase 2 will be evaluated and reported. Eight months will be budgeted to complete Phase 3.

10.5.3 Budget

Table 10-9 summarizes the schedule and budget.

Table 10-9. Life-Cycle Analysis of Chemical Addition on Downstream Processes: Schedule and Budget

	Schedule	Budget ($)
Phase 1	4 months	TBD
Phase 2	4 months	TBD
Phase 3	4 months	TBD
Total	12 months	TBD

10.6 Sulfide Generation Rates in Wastewater Collection Systems: Relative Importance of Substrates

10.6.1 Objective

The objective of this research is to gain a better understanding of the biochemical and ecological factors that influence the rate at which aqueous sulfide is generated in collection systems. This would lead to a better understanding of the variation of sulfide levels in different sewers and enable improvements in existing models for predicting sulfide accumulation in sewer networks. The results of the proposed experiments may enable more judicious application of sulfide suppressing treatments such as calcium nitrate and liquid oxygen.

10.6.2 Rationale

Models to predict sulfide generation rates in wastewater collection systems have been proposed by Pomeroy and Hvitved-Jacobsen. In both models, the sulfide generation rate has been correlated to a general measure of the wastewater's organic strength. In the Pomeroy model, the sulfide generation rate is described as a function of BOD. Hvitved-Jacobsen bases the generation rate on the square root of the quantity (COD-50). Although the literature identifies a broad range of substrates that support the metabolism of sulfate-reducing bacteria, it also suggests that the primary substrates are restricted to a group of short-chain fatty acids and alcohols. Sulfate reducers appear to occupy a niche near the end of the metabolic food chain and, as such, depend upon other organisms to break down larger organic molecules. If this hypothesis is correct, then the two models describing sulfide generation are incomplete.

The above hypothesis makes the following predictions that are not considered by either the Pomeroy or Hvitved-Jacobsen formulations:

- Sulfide generation rates will be low in upstream sewer reaches because the substrates that have the strongest sulfidogenic potential will be present at only low levels.
- Sulfide generation rates will tend to increase as the wastewater flow moves down the collection system. The increase is a consequence of the degradation of poorly sulfidogenic substrates to metabolic intermediates preferred by sulfate-reducing bacteria. This assumes that the dissolved oxygen level in the wastewater remains at low concentrations that do not allow strongly sulfidogenic substrates to be cleared by biological oxidation, and that the flow has not been subject to significant dilution from other streams.
- The presence of dissolved oxygen in the upstream sewer reaches will delay the onset of sulfidogenesis. Dissolved oxygen will suppress the net production rate by the non-sulfate-reducing bacteria of relevant sulfidogenic substrates. Dissolved oxygen will also allow non-sulfate-reducing bacteria to compete for and clear the sulfidogenic substrates that are produced.
- The effect of an increase of dissolved oxygen in a wastewater stream already supporting sulfide generation will depend upon the level of sulfidogenic substrates at the point of increase the length of the reach over which dissolved oxygen remains elevated. When the wastewater in enriched in sulfidogenic materials, the effect of the dissolved oxygen increase may be minimal. If the dissolved oxygen increase occurs where sulfidogenic substrate is scarce, the available substrates may be cleared by biological oxidation. In this case, the dissolved oxygen increase may have effects that last a significant distance downstream.

Verification of these hypotheses would improve our understanding of the processes underlying the accumulation of sulfide in wastewater collection system. The accumulation of sulfide has direct impacts on the potential for odors to be emitted from sewers and on the corrosion of sewer crowns. Corrosion is a problem that plagues certain collection systems. The knowledge could be applied to target sulfide suppressing technologies to reaches where they will have maximal effect.

The following is proposed to assess the validity of these hypotheses on sulfidogenic substrates and oxygen levels and to identify most significant substrates with regard to sulfide generation:

- In conjunction with our utility partners, surveys of a sewer system will be conducted to identify areas where sulfide generation rates are low, intermediate, and high. Concrete coupons will be incubated at selected locations for the purpose of developing biofilms that have a microbial ecology representative of the various sulfidogenic conditions.

- The metabolic preferences of the sulfate-reducing population will be assessed in the laboratory. Coupons will be retrieved from the sewer and carefully washed to deplete them of substrates of sewer origin. The coupons will then be incubated in a mineral media containing one or more of the substrates preferred by sulfate-reducing bacteria. The substrates will include acetate, propionate, formate, fumarate, malate, lactate, ethanol, mixtures of fatty acids up to 16 carbons long, and perhaps others. The rate of sulfide generation at various concentrations of substrate will be measured.
- Biofilms will be incubated in a media consisting of important biomolecules such as simple sugars, amino acids, short polypeptides, polysaccharides, and mono-, di-, and triglycerides. The media, however, will be void of substrates known to be strongly sulfidogenic. The object of this experiment is to assess the hypothesis that larger biomolecules support sulfidogenesis only weakly. To supplement data collected when incubating biofilms in a well-defined media, the biofilms will also be incubated in wastewater collected from locations where sulfide generation is negligible and vigorous.
- The activity of sulfate-reducing bacteria is inhibited in the presence of dissolved oxygen. Oxygen concentrations in wastewater reflect the dynamic balance between reaeration processes and uptake by the biofilm. Increases in dissolved oxygen concentration along a sewer can be induced by changes in slope. The effect of dissolved oxygen changes on sulfide generation rates may be influenced by the time history of the wastewater before it enters the more oxygenated reach. The longer the wastewater has been in an anaerobic or microaerobic condition, the greater the buildup of sulfidogenic substrates, and the longer the time necessary to clear them out by biological oxidation. High concentration of sulfidogenic substrate may mitigate the inhibitory affects of the oxygen. It may also affect the time required for strongly sulfidogenic conditions to reestablish themselves following a sewer transition that results in a slowing of the reaeration rate. These hypothesized effects of dissolved oxygen can be evaluated using the coupon-grown biofilms.
- Should the proposed hypotheses correlating sulfide generation rates to the concentration be supported by the in-vitro studies proposed above, a follow-up study would be conducted to analyze for these substrates in wastewater collected from various locations. The object of this effort would be to obtain further confirmation of the mechanisms proposed above to explain variations in sulfide generation rates.

10.6.3 Duration and Budget

Total budget:	To be determined
In-kind contribution:	To be determined
WERF cost:	To be determined

10.7 Pure Oxygen Treatment of Gravity Sewers

Pure oxygen injection has been employed to prevent sulfide generation in force mains. Pressurized pipes flowing full allow much higher oxygen concentrations (and fewer injection stations) than can be applied in gravity sewers. Because of the high unit cost to transport oxygen and high capital costs to generate oxygen onsite, oxygen injection into gravity sewers is usually ruled out. However, small-scale pressure swing adsorption (PSA) could enable oxygen injection spaced frequently enough along gravity sewers to prevent anaerobic conditions from developing between injection points.

10.7.1 Problem Statement

If oxygen-generating equipment could be made small enough, oxygen injection could save costs by replacing chemical addition in gravity sewers. The feasibility of developing small PSA units for frequent spacing along gravity sewers should be studied.

10.7.2 Proposed Research Gap Evaluation Method

10.7.2.1 Objectives

The objectives of the proposed study are the following:

- Calculate the range of oxygen generation capacity appropriate for controlling sulfide generation in 0.5-mgd and larger gravity sewers.
- Identify technical and market obstacles preventing PSA manufacturers from developing small-scale PSA systems.
- Determine the feasibility of introducing a small-scale PSA system to the odor control market.

10.7.2.2 Program

The program of research will consist of a feasibility study to achieve the research objectives.

- **Task 1—**Determine the most appropriate sizes for an onsite oxygen generator to be used for injecting oxygen into gravity sewers.
- **Task 2—**Determine the capital cost, above which oxygen injection would not compare favorably to chemical addition.
- **Task 3—**Seek a partnership with a manufacturer of PSA systems, and determine the feasibility of developing a system of the size and cost needed to compete with chemical addition.
- **Task 4—**Develop a market analysis for presentation to manufacturers should Tasks 1 through 3 indicate a favorable market opportunity for small-scale PSA.

The intention is that demonstrating a favorable opportunity for oxygen generation manufacturers would foster the development of systems that could save a lot of money for utilities. For example, Orange County (Calif.) Sanitation District already spends $3 million per year on chemical addition and has calculated that oxygen would cost one-fifteenth of that if it could be delivered with the right equipment. At least 8 months should be budgeted for this project.

10.7.3 Budget

Total budget:	To be determined
In-kind contribution:	To be determined
WERF cost:	To be determined

10.8 Liquid Phase Biological Treatment

Methods that seek to modify microbial metabolism, change microbial populations, or otherwise affect the microbes responsible for generating odors in wastewater collection systems are broadly classified as liquid phase biological treatment methods. These methods are distinct from liquid phase chemical treatment methods, which seek to chemically react with odor-causing compounds and convert them to nonodorous species.

Three main types of biological treatment methods have been marketed and applied with varying degrees of success. One method, bioaugmentation, seeks to deluge a collection system with bacteria specially bred to oxidize sulfide as it is generated, thereby reversing the natural anaerobic conversion of sulfate to sulfide. Another method, enzyme blocking, uses substances to interrupt the bacterial metabolic process that converts sulfate to sulfide. The third method, nitrate addition, seeks to supply sulfate-reducing bacteria with an alternate electron acceptor, whereby bacteria convert nitrate to nitrogen gas instead of converting sulfate to sulfide.

10.8.1 Problem Statement

The effectiveness of nitrate addition is well documented both in practice and in the technical literature, but the effectiveness of the other two biological treatment methods has not been sufficiently verified or documented. In some reports, the effectiveness of biological methods (other than nitrate) was inconclusive (Onondaga County Department of Drainage and Sanitation, 2001). In others, biological treatment methods were tested concurrently with nitrate or chemical methods, and the contribution of bioaugmentation or enzyme blocking could not be determined (Arthur and Anker, 2000; Kim et al., 2005). In some studies, anecdotal reports of the effectiveness of biological treatment methods are provided without showing data or system characteristics (Sercombe, 1995).

Because of prolific patenting and marketing of bioaugmentation and enzyme-blocking products, there is need for systematic research verifying the effectiveness of these biological methods. An independent study is needed to test leading biological methods under realistic conditions, without the influence of other methods. All relevant parameters should be reported, and the duration of the study should allow sufficient time to arrive at conclusive results.

10.8.2 Proposed Research Gap Evaluation Method

10.8.2.1 Objectives

The objectives of the proposed study are the following:

- Identify leading biological treatment methods (excluding nitrate addition, which has been sufficiently tested).
- Determine conclusively the level of effectiveness of each leading product.
- Determine the applications and doses for products determined to be effective.

10.8.2.2 Program

The program of research would consist of the following three phases: (1) study design, (2) pilot-scale testing, and (3) results documentation.

Phase 1—Study Design Phase 1 will be implemented in order to plan a study that can produce successful and conclusive results. During Phase 1, 3 months will be budgeted to complete the following three tasks:

- **Task 1—**A survey will be conducted to identify the biological treatment methods most commonly used and most likely to prove effective. Two bioaugmentation products and two enzyme-blocking products will be selected for testing.

- **Task 2—**A representative sewer system will be identified that can provide conditions for successful trials of the products to be tested. The sewer system should convey municipal wastewater, have long gravity sewers and force mains, generate significant concentrations of hydrogen sulfide and other odors, and have no existing liquid phase treatment program.
- **Task 3—**A pilot-scale testing regime will be designed. Appropriate doses of each of the four products will be selected; a feed system will be designed; feed durations will be selected; measurement methods will be selected; parameter variations will be selected; and a quality control program will be developed.

Phase 2—Pilot-Scale Testing During Phase 2 the products identified in Task 1 will be tested sequentially according to the protocol developed in Task 2. Phase 2 will consist of one task for each of the four products (Tasks 4 through 8). Eight months (two for each product) will be budgeted to complete Phase 2. The 8 months will be divided between two warm seasons. One bioaugmentation method and one enzyme blocker will be tested during the first warm season; the other two methods will be tested during the following warm season. In this way, enough time will be allowed that the effects of the first method do not interfere with the following methods. Also, each method will be tested under comparable conditions.

Phase 3—Results Documentation During Phase 3, results measured during Phase 2 will be documented. In Task 9, a report will be generated that presents testing methods, parameter measurements, results, and conclusions. In Task 10 publication will be sought for the Task 9 report. Three months will be budgeted for Phase 3. The project will be considered complete upon the submission of an article to a major technical journal.

10.8.3 Budget

Table 10-10 summarizes the schedule and budget.

Table 10-10. Liquid Phase Biological Treatment: Schedule and Budget

	Schedule	Budget
Phase 1	3 months	TBD
Phase 2	8 months	TBD
Phase 3	3 months	TBD
Total	14 months	TBD

10.9 Magnesium Hydroxide Odor Control Mechanisms Other Than pH Adjustment

Magnesium hydroxide ($Mg(OH)_2$) is a common chemical used prevent sulfide release in sewers. It works primarily as a pH adjuster, raising wastewater pH to between 8.5 and 9. In this pH range sulfide tends to remain in solution, where it does not cause odor and corrosion problems. Magnesium hydroxide is less soluble than other pH adjusters, such as caustic soda and lime. As such, it buffers the pH rather than reacting quickly, a favorable characteristic.

The pH adjustment effects of magnesium hydroxide are generally accepted in engineering practice, but other less understood benefits have been observed and attributed to the chemical. Premier Chemical, a supplier of magnesium hydroxide, claims that sulfide complexes with Mg^{2+} ions, forming a suspension that keeps its form during treatment processes. This action purportedly is similar to sulfur precipitation by iron salts and results in sulfide removal and pH adjustment. Premier also claims that Mg^{2+} catalyzes the oxidation of dissolved sulfides. The rate of sulfide oxidation is believed to increase two to three times in the presence of magnesium ion.

10.9.1 Problem Statement

Although there is anecdotal evidence of sulfide removal by magnesium hydroxide, independent research has not been carried out to verify the claims of chemical suppliers. An independent study is needed to establish the mechanisms responsible for sulfide removal by magnesium hydroxide and to quantify dosages that can be used to design chemical treatment systems.

10.9.2 Proposed Research Gap Evaluation Method

10.9.2.1 Objectives

The objectives of the proposed study are the following:

- Determine experimentally chemical mechanisms responsible for sulfide removal by magnesium hydroxide.
- Verify or debunk existing theories for sulfide removal mechanisms.
- Quantify dosage rates for sulfide removal by magnesium hydroxide.

10.9.2.2 Program

The program of research would consist of the following three phases: (1) study design, (2) experimentation, (3) results documentation.

Phase 1—Study Design Phase 1 will be implemented in order to plan a study that can produce successful and conclusive results. During Phase 1, existing mechanisms will be evaluated and experiments designed that can demonstrate whether or not the mechanisms are valid. Three months will be budgeted to complete Phase 1.

Phase 2—Experimentation An experimentation phase will be carried out during Phase 2. The program will depend on methods determined in Phase 1. Six months will be budgeted to complete this phase.

Phase 3—Results Documentation During Phase 3 results measured during Phase 2 will be documented. A report will be generated that presents testing methods, parameter measurements, results, and conclusions. Three months will be budgeted for Phase 3.

10.9.3 Budget

Table 10-11 summarizes the schedule and budget.

Table 10-11. Magnesium Hydroxide Odor Control Mechanisms Other Than pH Adjustment: Schedule and Budget

	Schedule	Budget
Phase 1	3 months	TBD
Phase 2	6 months	TBD
Phase 3	3 months	TBD
Total	12 months	TBD

10.10 Design Basis and Standards for Air Jumpers

Air jumpers are used to convey foul air from sewer line headspace at siphons and other sewer headspace bottlenecks. Pressurization, and thus off-gassing, occurs without them or with them if they are undersized. Air jumpers usually are designed by estimating the volume of air needed to maintain negative pressure on the upstream end.

10.10.1 Problem Statement

Orange County (Calif.) Sanitation District has encountered odor issues associated with inadequately sized air jumpers. There is a general lack of technical literature on design standards and guidelines for sizing air jumpers, and thus a study is needed to develop a set of industry guidelines for designing air jumpers.

10.10.2 Proposed Research Gap Evaluation Method

10.10.2.1 Objective

The objective of the proposed study is to develop a document that will serve as a guideline for application of sewer air jumpers.

10.10.2.2 Program

The research program will consist of establishing the basis for air jumpers. The end product will be a comprehensive document outlining the theory and methodology for sizing air jumpers.

10.10.3 Budget

Table 10-12 summarizes the schedule and budget.

Table 10-12. Design Basis and Standards for Air Jumpers: Schedule and Budget

Schedule	Budget
6 months	TBD

10.11 Effectiveness of Biotechnology in Cold Climates

The effectiveness of biotechnology is temperature dependent within the normal range of operating temperatures. Below that range, odor compound removal efficiency can be quite sensitive to temperature. Shareefdeen et al. (2004) studied biofilter removal of hydrogen sulfide at low temperatures in a laboratory and found that removal began to decrease precipitously below 5°C. Moreover, cold weather can cause inlet air to lose humidity, because of condensation, before entering the media. This hampers the effectiveness of biofilters.

10.11.1 Problem Statement

Since cold temperatures hamper biotechnology effectiveness, full-scale biotechnology systems should be evaluated for their effectiveness in cold weather environments. The study should identify locations where odor control functions properly during warm weather but fails during the winter. These cases should be compared to similar cases where the systems do not fail. Also, the effectiveness of modifications such as insulation and steam addition should be evaluated.

10.11.2 Proposed Research Gap Evaluation Method

10.11.2.1 Objectives

The objectives of the proposed study are the following:

- Determine the effectiveness of biotechnology during cold weather in the field.

- Identify design characteristics that permit successful cold weather operation
- Identify system changes that can improve cold weather operation

10.11.2.2 Program

The program of research will consist of the following three phases: (1) facility identification, (2) facility testing, and (3) results documentation.

Phase 1—Facility Identification Phase 1 will be implemented in order to locate cold weather facilities that use biotechnology for odor control. Four facilities that function poorly during cold weather but well the rest of the time will be sought. Another four facilities that function well during cold *and* warm weather will be sought. Permission must be obtained to study the odor control systems and to make temporary process changes. Three months will be budgeted for Phase 1.

Phase 2—Facility Testing During Phase 2, the eight facilities will be tested during two seasons. Warm weather testing will be carried out to verify that each facility operates well during the warm months. Cold weather testing will be carried out to evaluate each system's performance during cold weather. Differences between well-functioning and poorly functioning systems will be evaluated. The most promising system changes will be tried on the poorly functioning systems. Two months will be budgeted for warm weather testing and 4 for cold weather testing.

Phase 3—Results Documentation During Phase 3 a report will be produced documenting the results of Phases 1 and 2. The report will contain guidance for designing biotechnology systems for cold weather odor control. Three months will be budgeted for Phase 3.

10.11.3 Budget

Table 10-13 summarizes the schedule and budget.

Table 10-13. Effectiveness of Biotechnology in Cold Climates: Schedule and Budget

	Schedule	Budget
Phase 1	3 months	TBD
Phase 2	6 months	TBD
Phase 3	3 months	TBD
Total	12 months	TBD

10.12 Fat, Oil, and Grease Odors in Sewers

Fats, oils, and grease (FOG) in wastewater are known to cause odor problems in sewers. However, most research on odors in sewers has focused on sulfur compounds and nitrogenous compounds. FOG forms a separate phase on the wastewater surface and may require control measures different than those for other odor-causing constituents.

10.12.1 Problem Statement

Research is needed to determine which liquid phase treatment methods are effective in treating odors associated with FOG. The study should use existing literature as a starting point and provide a practical basis for addressing odor problems associated with FOG.

10.12.2 Research Proposal

10.12.2.1 Objective

The objective of the proposed research is to determine the effectiveness of various liquid phase chemical and biological treatment methods for removing or preventing odors associated with FOG.

10.12.2.2 Program

The program of research will consist of three phases: (1) Identify FOG odor locations, (2) conduct bench-scale testing, and (3) prepare practical guidance manual.

Phase 1—Identify FOG Odor Locations Phase 1 will consist of a survey of collection systems known to emit odors caused by FOG. Wastewater from locations with severe FOG odors will be selected for bench-scale studies.

Phase 2—Conduct Bench-Scale Testing In Phase 2, wastewater samples from the four most severe FOG odor locations determined in Phase 1 will be tested using liquid phase odor control technologies. Bench-scale testing of the wastewater will be conducted using the most likely control chemicals, as found in the technical literature. Four months will be budgeted for Phase 2.

Phase 3—Prepare Practical Guidance Manual In Phase 3, a practical guidance manual will be prepared. The manual will contain the information gained in Phases 1 and 2. Phase 3 will be budgeted for 2 months.

10.12.3 Budget

Table 10-14 summarizes the schedule and budget.

Table 10-14. Fat, Oil, and Grease Odors in Sewers: Schedule and Budget

	Schedule	Budget
Phase 1	3 months	TBD
Phase 2	4 months	TBD
Phase 3	3 Months	TBD
Total	10 months	TBD

10.13 Sewers as Process Reactors

Wastewater collection systems are designed and operated to serve as conveyance networks only, but sewers actually function as reactors, where numerous chemical and biological transformations occur within wastewater during transport. There appears to be great potential to harness those reactions to serve as part of the overall wastewater treatment process. The dual use of sewers for conveyance and pretreatment could add capacity or reduce costs of downstream wastewater treatment.

10.13.1 Problem Statement

Though research has been conducted to understand transformation reactions within sewers, they have not been harnessed to achieve specific treatment goals or to alter the nature of odorous and corrosive gas generation in sewers. A study is needed that attempts to design a dual-purpose wastewater conveyance/treatment system. Successful implementation of such a design could pave the way for a paradigm shift from the view that sewers are conveyance systems containing problematic reactions to the view that sewers are pretreatment process reactors.

10.13.2 Proposed Research Gap Evaluation Method

10.13.2.1 Objectives

The proposed research has the following objectives: (1) Identify wastewater treatment goals that could most feasibly be achieved; (2) create a retrofit design for a generic sewer system; and (3) offer the design for implementation in an existing system.

10.13.2.2 Program

The program of research would consist of three phases corresponding to objectives listed above: (1) Identify treatment goals, (2) retrofit design, and (3) design implementation.

Phase 1—Identify Treatment Goals In Phase 1 a study of the existing literature will be carried out to identify treatment processes that either benefit or decrease load on downstream treatment processes and that can be achieved within a sewer. Relevant potential design information will then be compiled from the technical literature for use in Phase 2. Three months will be budgeted for Phase 1.

Phase 2—Retrofit Design In Phase 2, a design will be created to retrofit a sewer system with typical or generic characteristics to add changes or equipment that will enable the system to function as a treatment reactor. The retrofit will be designed to meet the treatment goals determined in Phase 1. Parameters for the generic system will be selected with existing systems in mind. Five months will be allotted to complete Phase 2.

Phase 3—Design Implementation In Phase 3 the design and rationale developed in Phases 1 and 2 will be presented to selected owners in an attempt to sell the retrofit design. The design could be provided free of charge in exchange for the opportunity to have it implemented in a real system. Efforts will be made to generate interest in the project among prospective owners before starting. Phase 3 will be ongoing until agreement is reached with a collection system owner.

10.13.3 Budget

Table 10-15 summarizes the schedule and budget.

Table 10-15. Sewers as Process Reactors:
Schedule and Budget

	Schedule	Budget
Phase 1	3 months	TBD
Phase 2	5 months	TBD
Phase 3	TBD	TBD
Total	8+ months	TBD