F/M Ratio and the Operation of an Activated Sludge Process

Gary Lee Mishoe

Any one of a number of factors can affect overall CBOD and TSS removal efficiencies of an activated sludge process. Some factors are the responsibility of the design engineers and are essentially uncontrollable as far as operations go. These include aeration tankage, settling tanks, flow equalization, return activated sludge, aeration supply, waste sludge handing, and digested sludge disposal.

Other factors affecting efficiencies are functions of the connected system, such as daily flow volume and and raw sewage CBOD, and are again uncontrollable by the operator. These factors may vary seasonally, on weekdays, or on weekends.

But there are other factors affecting efficiency that are controllable by the operator. These include the food to microorganism (F/M) ratio (which is controlled by the wasting of biological growth), proper raw sewage flow equalization, return activated sludge rates, digester supernatant return, digested sludge disposal, and control of residual dissolved oxygen in aeration tanks (valving of centrifugal blowers, proper sheaves on positive displacement blowers, turning on or off blowers, time switch operation of blowers).

Of these factors that can be controlled by the operator, the most important is the F/M ratio. The "food" in the ratio is the CBOD entering the process. The "microorganisms" are the activated sludge solids in the aeration tanks, which are measured as ppm or mg/L of MLTSS.

To establish and maintain a consistent CBOD and TSS secondary waste removal from raw sewage, an activated sludge process must maintain the weight of food to weight of microorganisms under aeration within the limits of the type of treatment being provided by the facility design parameters.

Many operators and engineers have never grasped the importance of F/M ratio control. Part of the reason is because of the many different methods of calculating it.

The three main methods of controlling sludge wasting include the F/M ratio, the Sludge Age method {SA}, and the Mean Cell Residence Time method {MCRT}. In reality, these methods all measure the same thing, and, in fact, the F/M ratio is merely the reciprocal of the SA. The MCRT is somewhat more complex. In the final analysis, all three methods do the same thing: measure the ratio of food to microorganisms by weight in the aeration tanks.

I find the F/M ratio to be the easiest to calculate and the easiest to understand. MCRT and SA can be confusing because they are expressed in days, which many people confuse with calendar days; they are really only indexes.

The key to understanding the F/M ratio is that it is not just concentration versus concentration, it is the weight of food (CBOD) compared to the weight of microorganisms (MLTSS).

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Volume Formulas

To calculate an F/M ratio, you must know the volume of water being aerated. The volume of water in a rectangular tank in millions of gallons is:

V = (L x W x H x 7.48)/1,000,000 (Equation 1)

where L = the interior length and width of the tank in feet,
W = the interior length and width of the tank in feet,
H = water depth in feet,
7.48 = the number of gallons in a cubic foot,
1,000,000 = the number of gallons in a million gallons.

The volume of water in a round tank in millions of gallons is:

V = π x (D/2)2 x H x 7.48)/1,000,000 (Equation 2)
Or simplifying, V = (5.87 x D2 x H)/1,000,000

Where π = 3.142
D = interior diameter of the tank in feet,
H = water depth in feet,
7.48 = the number of gallons in a cubic foot,
1,000,000 = the number of gallons in a million gallons.

The Pounds Formula

To calculate the F/M ratio, both the food and the microorganisms must be compared in the form of mass or weight. In the U.S. the measure usually is in weight, i.e., pounds. Realizing that one gallon of water weighs 8.34 pounds, the following formula converts a flowrate in MGD with a concentration in parts per million (which, for our purposes, can be assumed to be the same as mg/L) to a weight in pounds per day:

W = ppm x 8.34 lb/gallon x MGD (Equation 3)

where W = weight in pounds

For example, assume that a complete-mix activated sludge treatment plant has an average daily flow into aeration of 1.0 MGD, a CBOD into aeration of 200 ppm, and aeration volume of 0.25 million gallons, and an MLTSS of 2500 ppm.

The weight of food entering the process, from Equation 3, is 200 x 8.34 x 1.0 = 1670 pounds per day.

The weight of microorganisms under aeration, again from Equation 3, is 2500 x 8.34 x 0.25 = 5210 pounds.

The F/M ratio is then 1670/5210 = 0.32.

Since the standard process F/M ratio (see accompanying table) is from 0.25 to 0.50, the example process is within proper efficient operating parameters.

For another example, assume that the same process during a seasonal low-flow period has an average daily flow into aeration of 0.7 MGD, a CBOD into aeration of 170 ppm, and the same MLTSS as before.

The weight of food into the activated sludge process, from Equation 3, is 170 x 8.34 x 0.7 = 992 lb/day.

The weight of microorganisms under aeration, from

Activated Sludge Process Ranges for F/M Ratio Control

Process Range Names	Common SWT ASP Names	F/M Range
Extended Aeration	Extended Aeration Sequencing Batch Reactors Race Track or Orbital Ditch	0.05-0.15 Lb CBOD5/1 Lb MLTSS
Standard Activated Sludge	Conventional Activated Sludge Contact Stabilization Step Aeration Complete (or Homogenous) Mix Others used with nutrient removal	0.25-0.5 Lb CBOD5/1 Lb MLTSS
Hi-Rate Activated Sludge	HRAS based on desired removal {75 to 60% efficiency)	1.0-10 Lb CBOD5/1 Lb MLTSS

Equation 3, is 2500 x 8.34 x 0.25 = 5210 lb.

The F/M ratio is then 992/5210 = 0.19, which is below the standard range of 0.25 to 0.50. The process has too much sludge (weight of micro-organisms) under aeration for the food being provided. The operator should waste sludge to lower the MLTSS in aeration.

Determining Optimal MLTSS

The optimal MLTSS is based on the ratio-proportion formula, R1:R2::P1:P2, where the product of the means is equal to the product, or:

(R1 x P2) = (R2 x P1) (Equation 4)

where R1	= the desired F/M ratio = 0.25 for the above example.
R2	= the MLTSS corresponding to the desired F/M ratio, or 1.0 pounds for an F/M ratio of 0.25.
P2	= optimal MLTSS
P1	= weight of food in aeration from Equation 3, or 992 lb/day in the above example.

Therefore, for the example plant:
(0.25 x P2) = (1.0 x 992)
or, P2 = (1.0 x 992)/0.25 = 3968 lbs MLTSS.

The optimal aeration MLTSS concentration can be found by rewriting Equation 3 as:

ppm = (pounds per day MLTSS)/(8.34 x MG)
ppm = (3968 lb/day)/(8.34 x 0.25 MG) = 1900.

Therefore, 1900 ppm is the maximum concentration of MLTSS to achieve a F/M ratio of 0.25.

A number of years ago when I was a "young buck" in the water and wastewater industry, I wrote some articles on activated sludge operation for the *Overflow Magazine*. I am now an "old-timer," but I still see a need for some emphasis on understanding activated sludge process operation. ■

Editorial Calendar

January	Water Treatment: Membranes. FSAWWA Officers.
February	Water Distribution. FWPCOA Officers
March	Wastewater Collection.
April	Annual Conference Issue. Misc. technical articles.
May	Water Treatment
June	FSAWWA & FWEA Awards. Miscellaneous technical articles.
July	Disinfection.
August	Conservation.
September	Industrial Wastewater/ Residuals Management.
October	Water Resources Management/ FWPCOA Awards. FSAWWA Conference.
November	Reuse.
December	Wastewater Treatment. FWEA Officers.

Implementing Septic Tank Replacement in Florida

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Nearly one million septic tanks were operating in Florida[1] in 1970. Since then, an average of 48,660 new septic tanks have been installed in the state each year. Since 1984, one of three buildings are constructed with septic tanks[2]. An estimated 1.8 million septic tanks are in operation today[3] with more than 80 percent in urbanized counties. Of those 15 counties with more than 50,000 tanks in operation, 11 have more than 70 percent of their soil conditions that significantly limit the ability of on-site septic tank drainfields to function properly[4]. The most common condition is seasonal wetness or shallow groundwater.

Assuming that each septic tank handles an average flow of 250 gpd, the composite discharge into our state's watersheds and groundwaters is 450 MGD of partially-treated wastewater. The closer to surface and groundwater the discharges are, the less soil treatment is available and the greater the impacts are to water quality.

A significant number of tanks are not operating under 1983 state standards, which set certain treatment presumptions with horizontal and vertical setback limits to surface and groundwaters[5]. These setbacks (e.g. two-feet vertical clearance to high groundwater table) allow some removal of nutrients and pathogens. A large number of pre-1983 tanks are installed in coastal communities with high groundwater tables and numerous drainageways, have drainfields that are directly within the groundwater table, and discharge effluent with very minimal treatment.

The "post-1983" systems offer a mixed bag of nutrient removal. An in-depth study sponsored by the Florida Department of Health[6] shows evidence of nitrate impacts and potential breakthrough of phosphorus, even with mounded drainfield systems, after only six months of effluent dosing. Average nutrient levels measured at two feet below the drainfield system in this study were as follows:

Parameter	*Septic Tank Effluent*	*Drainfield Hydraulic Loading Rate*	
		0.75 gpd/ft.²	*1.5 gpd/ft.²*
TKN (mg/l)	47.2	0.78	0.88
Nitrate (mg/l)	0.04	24.4	22.9
Total Phos. (mg/l)	9.6	0.38	1.23

Although organic nitrogen (TKN) is nitrified, denitrification is not provided by unsaturated soils. Nitrate values are more than double the allowance for groundwater discharge systems permitted by DEP, Chapter 62-600, F.A.C.), which has a limit of 10 mg/l. Assuming an average nitrate concentration of 24 mg/l, a release of 45 tons/day is entering Florida waters. Most natural waters have total phosphorous (TP) levels less than 0.05 mg/L.

Environmental and health impacts on estuarine systems such as Sarasota Bay and Tampa Bay have been noted[7, 8]. The U.S. Department of Wildlife demonstrated the impact to Cape Coral waterways as a result of numerous septic tank systems[9]. A recent study conducted for the Department of Health[10] reports the impacts on the state's waters and recommends a minimum of performance standards for septic tanks. However, the most recent update to Chapter 10D-6 (1997) still shows no effluent quality requirements or performance standards for discharge.

Site-specific studies conducted in Charlotte[11] and Sarasota[12] counties report high nutrient and human originated microorganism levels in ground and surface waters adjacent to densely populated septic tank neighborhoods:

Location	*TN*	*TP*
Port Charlotte[11] (at rear lot lines)	7.9 mg/L	14.8 mg/L
Florida Stream W.Q. Background (90 Percentile)[11]	0.6 mg/L	0.02 mg/L

	Clostridium (CFU/100 ml)	*Enterocci (CFU/100 ml)*	*Coliphage (CFU/100 ml)*
Phillippi Creek (unsewered area) Sarasota County[12]	165	950	58
Bowless Creek - (sewered area) Sarasota County[12]	110	385	9

Several local governments throughout the state have implemented septic tank removal programs. Federal funding under the EPA Grants Program for wastewater systems facilitated the majority of such programs, but that funding is no longer available. Currently, the number of septic tank systems in Florida is increasing without environmental assessment, monitoring, or initiative for environmental consequences. There is a need for well-defined and cost-effective improvement programs.

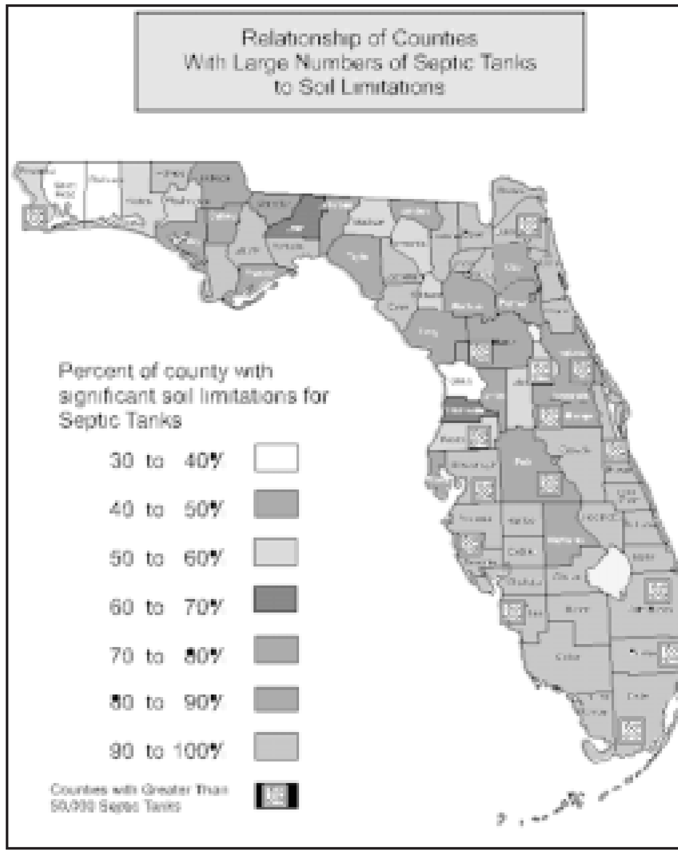
Delineate Site Specific Needs and Priority Areas

Obtaining site specific information to prioritize the most impacted areas within high-density septic tank developments is essential for alternative and cost analyses. County public health and building departments units have existing records that may provide information regarding septic tank densities, number of units, relative age of subdivisions, and water quality information. National Estuary Programs along the coasts have pointed out target areas of problematic septic tanks. Also, shallow drinking water wells in the vicinity of septic tank neighborhoods are good monitoring stations for public health implications. High nitrate or microbial concentrations may help prioritize such neighborhoods for sewers.

Specific water quality testing in high-density areas should be considered as a means for identifying transport rates of nutrients and other pollutants. Specific viruses, common to the human body, should be sampled to limit the influence of stormwater runoff and animals. Although such studies can be costly and time consuming to evaluate both wet and dry seasons, they are valuable in documenting specific impacts. Such documentation is important for public awareness and potential funding. If the study can be tied to available GIS or other county planning efforts, priority areas for sewer systems can be identified.

Evaluate Alternative Systems for Implementation

Since the end of the EPA wastewater construction grants program in the late 1980s, affordability of septic tank replacement programs has become a major issue and a difficult barrier. Public resistance, and therefore controversy, increases propor-



tionately to cost impacts on users. Recent programs to replace septic tanks with gravity sewers in Florida have resulted in potential assessments on single family dwellings of over $8,500.

Alternative sewer technologies are receiving increased interest and attention as a way to reduce up-front capital costs and to improve the affordability of sewer expansion programs. There are a number of alternative systems currently available in the marketplace, and ongoing research will, no doubt, result in more innovations in the future.

Each alternative to a conventional gravity central sewer system has its own advantages and disadvantages. A detailed, site-specific engineering analysis is needed to develop the best approach to septic tank replacement and to take into account the many variables that apply to each project, such as soil, groundwater, road, and pavement conditions, easements and right-of-ways, existing and projected population densities, lot sizes, and tank locations. It is also important to compare life-cycle costs for alternatives so that operation and maintenance costs are considered along with construction dollars.

Low-pressure sewer systems (LPSS) typically consist of a small grinder pump station at each residence. It pumps wastewater through a pipeline system, either to a master pump station or directly to a treatment plant. Small diameter pipe and shallow installation can result in significant construction cost reductions compared to conventional gravity systems. Issues of pump station ownership, who performs maintenance, and what happens in case of failure must be carefully addressed and resolved, since typically homeowners are not accustomed to operating and maintaining wastewater mechanical equipment.

One variation on the low pressure system is the septic tank effluent pumping (STEP) system. The small individual pump is typically installed at the effluent end, or just downstream, of the septic tank. The existing septic tank remains in service, and still functions to settle out and anaerobically digest solids. The effluent is pumped through a system of small diameter pipes, similar to the low-pressure system. The pumps and piping can be somewhat downsized because a portion of the solids have been removed. STEP systems require regular pumping out of the individual septic tanks to avoid downstream clogging. This, along with the issues of pump ownership, maintenance, and reliability, must be addressed.

Another variation on LPSS and STEP systems has evolved and, in some cases, has successfully addressed the problems associated with having individual pumps installed on each homeowner's private property. It also may result in cost savings. If water consumption is sufficiently low, several homes can be clustered, or served by one pump station. If the pump station can be located on public property or in a utility easement, it becomes much more feasible for the utility to perform maintenance. A recent project in Missouri bid a low pressure clustered system along with conventional gravity sewers, and the low pressure system bid was approximately 50 percent of the gravity system[13].

Vacuum sewer systems are now available from several manufacturers, and the number of operating systems in the U.S. has grown in recent years. A vacuum system consists of a centralized collection station with a network of sewer mains operated under a negative pressure. The collection station contains a collector tank, vacuum pumps, and sewage lift pumps to send the collected wastewater to the treatment plant. The vacuum pumps maintain a constant negative pressure in the collection tank and throughout the system. The vacuum sewer mains are typically 4 to 10 inches in diameter and can be laid at a shallow depth, usually three to five feet from the surface. Gravity lines carry sewage from each home or connection to a valve pit, which releases sewage into the vacuum sewer main when the level in the pit reaches a certain point. The Englewood Water District in southwest Florida recently received bids on vacuum and conventional gravity systems for the same service area. The bid results indicated construction cost savings of 8 to 21 percent for vacuum from the three bids received[14].

If one considers the spectrum with individual septic systems at one end, and regional gravity sewer systems at the other, then some communities may lend themselves to a solution somewhere in between. This concept involves treatment of septic tank effluent at multiple locations close to the source and close to effluent disposal sites. Cost savings are realized by eliminating a portion of collection system infrastructure. While this concept is similar to a conventional approach with decentralized package treatment plants (and therefore subject to concerns about reliability and level of treatment), simple and relatively failsafe processes that could minimize the operation and maintenance liabilities while meeting water quality standards are being studied. Examples of such treatment technologies include the intermittent sand filter, and upflow anaerobic filter[16, 17]. Effluent water quality has been achieved which approaches advanced wastewater treatment standards, including total nitrogen.

One of the biggest concerns about the impacts of septic tank effluent on Florida's water resources is the level of nutrient. The required two feet of unsaturated soil separating the drainfield from the groundwater surface is not adequate to reduce total nitrogen and phosphorous, and in densely developed areas with too many septic tanks, this can lead to water quality degradation. The Department of Health's On-Site Sewage Program is conducting the Florida Keys AWT Demonstration Project[18] that is testing five on-site treatment processes. Such systems have demonstrated that biological nitrification/denitrification is possible and that low nutrient effluent is attainable. Disinfection is also necessary for pathogen reduction, especially in such highly permeable soils.

Studies[19] conducted for the Town of Washington, Wisconsin, indicate that disposal field design and management practices may improve nutrient removal. Such practices include low loading rates, uniform distribution, and dosing cycles. There is great concern, however, about homeowners and individual property owners being responsible for operating and maintaining such complex processes and equipment. Americans are so accustomed to "flushing and forgetting" that it may be unreasonable to expect homeowners to perform regular maintenance on an AWT system. These same technologies, however, may very well prove to be candidates for neighborhood decentralized treatment systems, as described above.

Develop Public Understanding of Needs.

Developing public understanding of needs is the pivotal point in many of these large, relatively expensive projects. Communities targeted for septic tank removal or alternative systems must be made aware of the needs and benefits of the overall program. It is important that residents are brought into the early planning of the program to begin developing an appreciation for the long-term importance of the effort. Developing such early understanding can gain appreciation for the program's needs, which should benefit all residents.

Program elements which may prove useful, depending on the community, are:

- Establish lead government agency to conduct program.
- Identify key issues and problem areas.
- Provide resources to allow involvement.
- Find success stories to share.
- Get public involved early and build consensus.
- Demonstrate community benefits.
- Establish community goals for dealing with wastewater.
- Demonstrate commitment to cost-effective solutions.

Demonstrating positive elements of a sewer program to share with the public is important in developing understanding of the needs. Showing case studies of similar programs can be useful. Showing results of water quality improvements in popular water bodies, lowered health risks, higher property values, better recycling of water supply, and potentially new road surfaces in septic tank removal areas can help to gain program support. It is important to get younger families, who have a long-term vested interest in their communities, to understand the benefits.

Develop Equitable, Cost-Competitive Pricing and Financing

When policy decisions are made at a local level to sewer a given area, the challenge focuses on financing. How are the costs most equitably assessed across the community? Who should pay? Communities need to develop consistent and equitable means of distributing costs to the relative benefit of those who live in or visit the state. Local governments and septic tank users must also realize the ongoing costs already being paid by those on central sewers. Tourist taxes and local one-cent sales taxes (e.g., Sarasota County, 1997) are methods for collecting countywide revenue.

Financing programs should consider obtaining low interest loans from EPA/DEP's State Revolving Fund (SRF) program. SRF loans avoid conventional borrowing costs and have interest rates 2-3% lower than revenue bonds, which leads to significant annual savings in debt service payments. Grant monies from water management districts and other sources should also be considered. Treatment and reuse of septic tank effluent should qualify for grants as alternate water supplies. Some communities may qualify for HUD's Community Development Block Grant (CDBG) program.

Program phasing may be important in communities with resources available to conduct only limited improvements. Priority phasing plans can be developed to limit debt service, yet get the program moving forward.

Consistent State Policy For Water Quality Improvements

Florida's existing policies are inconsistent when dealing with water quality from sewered systems versus onsite systems. The DEP rules under Florida Statutes 403[19] require high water quality standards for public and private treatment systems. However, Department of Health rules, under Florida Statutes 381[20], allow systems that negatively impact receiving waters. Inconsistencies are highlighted when the Florida Water Plan[21] is considered. This state policy targets the need for water resource conservation and environmental protection. Septic tank systems in high density or coastal areas are contrary to both these goals.

Also, comprehensive plans for communities may require existing septic tank areas to be sewered, yet thousands of new septic tanks are being permitted each year. This is partially a result of the comprehensive planning process not being able to withstand challenges to such plans, since the state regulations continue to allow for the status quo. It is recommended that consistent state policy be developed to assist local communities in dealing with this statewide problem.

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Holly Lakes I/I Reduction: The Extra Step in Sewer Rehabilitation

Jens Peter Larsen, Hong Guo, and Gordon Keibler

To comply with EPA Administrative Order No. 90-083, the city of Pembroke Pines, along with other large users of the Hollywood Southern Regional Wastewater Treatment Plant, has gone through an extensive infiltration/inflow (I/I) reduction program during the past five years. I/I analysis, sewer system evaluation surveys (SSES), and rehabilitation have been implemented for the collection areas that were cost effective for sewer system repair. A total of 96 manholes and 9,800 feet of sewer lines were repaired in Pembroke Pines, and point repairs and lateral repairs were completed at 99 locations. However, approximately 1.2 million gallons per day of I/I still remain in the system. Continuous deterioration of other portions of the collection sewer may create new I/I sources. Therefore, Pembroke Pines is implementing its continued I/I program to further reduce and keep I/I under control. One of the tasks was to perform an SSES and rehabilitation throughout the Holly Lakes system.

The Holly Lakes wastewater collection system, serving a 130-acre community in southwest Broward County, consists of 84 manholes, 18,890 linear feet of 8-inch diameter collection sewer, three lift stations, and one re-pump lift station. It is a mixed system in which 4,330 feet are clay lines and the remainder PVC lines.

SSES

An SSES is a systematic examination of a sewer system to determine the specific location, flow rate, and rehabilitation costs of each I/I source. It will confirm the presence, location, and degree of I/I, and it will determine what I/I source is excessive or non-excessive. The findings of the survey determine the nature of corrective actions and their cost, the means by which I/I will be controlled, and the extent of sewer rehabilitation. Definitive cost effectiveness analysis supported by the actual findings of the evaluations survey are used to estimate the amount of I/I that could be eliminated as compared to the cost of the transportation and treatment of the I/I flows. Based on the Holly Lakes SSES results, it was estimated that approximately 320,000 gpd of I/I could be eliminated through rehabilitation.

Sewer system evaluation survey procedures usually include manhole and pipeline visual inspection, smoke testing, night flow isolation, pipeline cleaning and television inspection, and dye-water flooding. In this project, dye-water flooding was not conducted since smoke testing found no storm sewer cross-connections.

The purpose of manhole inspections was to determine the physical condition in and around each manhole, the presence and degree of infiltration and inflow, and the accuracy of system mapping. All but one of the 84 manholes were physically inspected; one could not be located. It was found that one manhole had poor casting fit, five had pipe-to-manhole connections in poor condition, and six were generally in poor condition with leaks throughout the walls.

Smoke testing, a relatively inexpensive and quick method of detecting I/I sources in sewer systems, is best used to detect inflow such as storm sewer cross connections and point source inflow leaks in drainage paths or ponding areas, roof leaders, cellar, yard and area drains, foundation drains, abandoned building sewers, and faulty service connections. All of the sewer lines in the Holly Lakes area were smoke tested. It was found that two cleanout risers were broken and one was missing a cap, and one service lateral was broken. No storm sewer cross connections were identified.

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Flow isolation is used to screen and identify collection lines or groups of collection lines (micro-systems) that have excessive groundwater infiltration and that should be further inspected with closed circuit television equipment. In the Holly Lakes drainage areas, micro-systems of from 300 to 600 feet (approximately one to three manhole reaches) were delineated. Infiltration was then measured at micro-system key manholes by taking "instantaneous" flow measurements during the early morning hours. Where practical, hand weirs were used to measure the flows. Where the usage of weirs was not practical, the flow was measured by dipstick depth of flow measurement and velocity measurements via portable magnetic meter probes. A total of 9,440 feet of sewer, including all vitrified clay pipe sewer lines, was recommended for television inspection.

Television inspection involved the pulling a color video camera through each of the manhole reaches. The picture was transmitted by cable to an above-ground monitoring station where it was videotaped for an inspection record.

Because part of the success of television inspection depends on the cleanliness of the lines, the sewer line was cleaned prior to videotaping to allow clear viewing of the interior surface of the pipe and to restore the sewer to near original carrying capacity.

During the main sewer line televising phase, a total of 46 laterals were identified as having clear water or root intrusion. As a special project, 31 of the laterals were televised using a recently developed German camera system that is specifically designed for inspection of sewer laterals. The remaining 15 laterals, which could not be televised with the specialty camera, were recommended to be televised during the rehabilitation phase.

Of the 41 collection lines (manhole reaches) televised, 22 had defects. Ten lines with multiple longitudinal and radial cracks, holes in pipe, shattered pipe, and leaking joints were considered to be severely deteriorated. Total estimated infiltration into each line varied from 2.5 to 28 gpm. Ten lines had essentially sound pipe with leaking joints, root intrusion, and minor amounts of cracks and were considered to have medium deterioration. Infiltration into each line segment varied from 1 to 5.5 gpm. Two collection lines, with either a cracked pipe or a hole in the line, had less than 1 gpm infiltration each. These lines were considered to be lightly deteriorated.

Seventeen of the 31 televised laterals had leaking joints, root intrusion, and holes. Infiltration varied from 1 to 10 gpm at each lateral.

The next step after the SSES phase was to determine the best rehabilitative technologies, including trenchless technologies, to repair the identified defects.

Rehabilitation Alternatives and Evaluation

Defect	No.	Alternate I Standard Approach	Alternate 2 Fold-and-Formed	Alternate 3 Cured-in-Place	Alternate 4 Pipe Bursting	Alternate 5 Replacement
I . Pipe Connection at MH	5	Repair Connection Liner	Cementitious Spray	Polyurethane Liner	Cementitious	Replace
2. Manhole Walls	6	Cementitious Liner	Cementitious Liner	Polyurethane Spray	Cementitious Liner	Replace
3. Severe Line Segments						
a. High infiltration	2	CIP Liner	FAF Liner	CIP Liner	Pipe Burst	Replace
b. Medium infiltration	8	FAF Liner	FAF Liner	CIP Liner	Pipe Burst	Replace
4. Medium Line Segments						
a. Line repair	7	Test & Seal (Grouting)	FAF Liner	CIP Liner	Pipe Burst	Replace
b. Point repair	3	Excavated Repair	Excavated Repair	Excavated Repair	Excavated Repair	Replace
5. Light Line Segments	2	Sectional Liner	Sectional Liner	CIP Liner	Sectional Liner	Replace
6. Service Laterals	32	Grouting and Excavated Repairs	Replace	CIP Liner	Pipe Burst	Replace
Evaluation Criteria						
I . Cost		$375,000	$520,000	$545,000	$665,000	$860.000
2. Cost-Effective		Yes	Yes	Yes	Yes	Yes
3. Available		Yes	Yes	Yes	Yes	Yes
4. Durability		Medium	High	High	High	Very High
5. Social Cost		Moderate	Moderate	Low	High	Very High
6. Procurement		Bid	Piggyback	Piggyback	Bid	Bid
7. No. of Contracts		Several	One	One	One	One

Rehabilitation Alternatives

Pipelines can generally be repaired by internal and external methods, although internal methods are more effective for most problems. Several internal rehabilitation methods (trenchless technologies) are available to restore use to a pipeline without excavating and replacing large portions of the system. Small pipeline repair alternatives include chemical grouting, point repairs/excavation and replacement, cured-in-place sectional liners, inversion lining, fold and formed liners, and pipe bursting.

Chemical grout is used to seal leaking joints and circumferential cracks in sewer lines. The grout material (e.g., acrylamide, acrylic, acrylate, or urethane gel, or polyurethane foam) can be applied to pipeline joints by injecting it under pressure using special tools and techniques. Chemical grouting adds no external structural properties to the pipe where joints or circumferential cracking problems are due to ongoing settlement or shifting of the pipelines. Consequently, it is not effective to seal longitudinal cracks or to seal joints where the pipe near the joints is longitudinally cracked and should not be considered when the pipeline is severely cracked, crushed, or badly broken.

Point repairs utilize standard repair technologies that require the excavation and repair of the defect. Point repairs are done where there is an isolated major structural pipe defect, such as a broken, severely cracked, or corroded sewer pipe, or a misaligned joint, and where other repair alternatives are less cost effective.

Cured-in-place sectional liners are generally limited in lengths from 3 to 15 feet and are utilized to reline segments of pipe that are cracked and/or leaking. Sectional liners are most practical when the pipe is still in a "rounded" condition. It is used where depth or location of the sewer makes a point repair difficult and expensive.

Inversion lining is formed by inserting a resin-impregnated felt tube into a pipe, which is then inverted against the inner wall of the pipe and allowed to cure. A special cutting device is then used with a closed-circuit television camera to reopen service lateral connections, which are located with the camera prior to installation of the liner. The pliable nature of the resin-saturated felt allows its installation around curves, the filling of cracks, the bridging of gaps, and the maneuvering through pipe defects. After installation, the fabric cures to form a new rigid pipe of slightly smaller diameter but of the same shape as the original pipe. The new pipe has no joints or seams and has a very smooth interior surface that may actually improve the flow capacity despite the slight decrease in diameter.

Fold and formed liners involve a folded thermoplastic pipe that is pulled into place and then rounded by pressurized steam to conform to the internal diameter of the existing pipe. As with cured-in-place liners, excavation is not required for installation, and lateral reinstatement is accomplished internally. The finished pipe has no joints and produces a moderately tight fit to the existing pipe wall. This method of pipe rehabilitation is less versatile than cured-in-place liner methods in regards to range of diameter selection and installation length. Fold and formed liners are typically suitable for pipe diameters of 4 to 16-inches with lengths of installation from 300 to 600 feet. The fold and formed method of rehabilitation does not require a long curing process for installation.

Pipe bursting, used for the replacement of existing sewer mainlines or service laterals, involves the insertion of a new pipe of equal or larger diameter into the existing pipe by fragmenting the existing pipe and forcing it into the surrounding sod. The new pipe is attached to and pulled along behind the pneumatic or hydraulic burster and thus inserted into the newly expanded hole. The replacement pipe, usually made of polyethylene, is assembled on-site while work is in progress using an end-to-end butt fusion process. Depending on the system, the pipe is either towed or jacked immediately behind the burster. Excavated entrance and exit pits are required at either end of the line to facilitate the installation of the pipe-bursting equipment and the new pipe. Pipe bursting is suitable for replacing pipe made of brittle material, such as vitrified clay, unreinforced concrete, asbestos cement, and cast iron. It is not appropriate for the replacing steel, ductile iron, or polyethylene pipes.

By matching the defects found during the SSES with rehabilitation technologies, five alternative packages were developed:
1. Standard Approach: The objective of this package was to

match the cheapest rehabilitation technologies available with the corresponding defects.
2. Fold-and-formed: More durable technologies were selected for all line repairs. Manholes were addressed as full repairs and all defective laterals were replaced.
3. Cured-in-Place: Again, durable technologies were selected. Full manhole repairs were addressed, and laterals and mains would be lined with cured-in-place liners.
4. Pipe Bursting: Main lines and defective laterals would be replaced with polvethylene lines, and manholes were addressed as full repairs.
5. Replacement: This alternative would replace all defective manholes, lines, and service laterals with new components.

Criteria used to evaluate each of the packages were cost and cost-effectiveness, availability, durability, social cost, procurement, and number of contracts required to accomplish all work within the package.

The present worth cost to the city for transporting and treating the 0.320 MGD of I/I over a 20-year period was estimated to be $1,989.000. Packages with rehabilitation costs less than that amount would be cost-effective.

Social cost, i.e., the degree of disruption a particular rehabilitation would cause, was an important consideration. Obviously, trenchless technologies are the least disruptive.

Regarding procurement and contracting, piggybacking existing contract unit prices is preferable to bidding in that it saves time and it allows the city to choose known and reputable contractors, and dealing with one rather than several contracts is more desirable.

Although costlier than the standard approach package, the city chose to proceed with the fold-and-formed package because of better durability. Also, the contractor for this package was ready to start immediately, while the contractor for the very similar cured-in-place package would not be available for several months.

Construction Phase

One of the challenges faced during the initial stages of rehabilitation was the large quantity of I/I entering the system. The existing lift station could not handle the flows, and the system remained surcharged at all times. The contractor placed an additional pump and temporary piping to pump the system down and keep it down during the rehabilitation work.

The original design called for the connection of the new (repaired) service lateral to the fold-and-formed liner to be accomplished by means of a compression-fit service connection (Inserta-Tee). After completing the first connection. it was realized that the protrusion by the connection into the liner (approximately 3/4 inch) restricts the capability of using cameras and grouting equipment within the 8-inch diameter lined main. Although less desirable because of the long-term possibility of leakage, the usage of conventional saddles was considered and discarded. Since the fold-and formed liner material is polythylene, the contractor and the engineer agreed that the option of electrofused sewer saddles was the best.

Conclusions

Lessons learned from the construction phase include the importance of daily coordination between the owner, contractor, and engineer, and that a good public awareness program to decrease complaints from the public is essential. It was also learned that innovative technologies (InsertaTee) do not work in all cases.

By completing this project, the city stands to realize savings of over $1 million within the next 20 years. ■