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Field Demonstration of Condition Assessment Technologies for Wastewater Collection Systems

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Disclaimer

Abstract

Reliable information on pipe condition is needed to accurately estimate the remaining service life of wastewater collection system assets. Although inspections with conventional closed-circuit television (CCTV) have been the mainstay of pipeline condition assessment for decades, other technologies are now commercially available. Five such innovative technologies were selected for field trials: zoom camera, electro-scanning, digital scanning, laser profiling, and sonar. The goal of the field demonstration was to evaluate the technical performance and cost of these technologies. The field demonstration was conducted in August 2010 and was hosted by Kansas City, MO Water Services Department. The innovative technologies were compared to CCTV inspection. Each technology identified maintenance and structural defects by collecting data or images of the pipe condition. The camera technologies (digital scanning, zoom camera, CCTV) and laser scanning provided pipe condition above the water line, whereas sonar assessed conditions below the water line. Electro-scanning detected defects anywhere along the pipe circumference. Costs were compared for different inspection technologies based on actual costs for planning, field work, data analysis, and reporting. Total costs for the multi-sensor inspection were $4.21 per foot of pipeline inspected as compared to $2.95 per foot for electro-scanning, $0.99 per foot zoon camera, and $2.80 to $3.00 for CCTV.

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The technology vendors proved very resourceful in making required adjustments to account for field conditions, including daytime temperatures of 100°F. Each vendor staffed the project with well-qualified and experienced personnel. The project team appreciates the contributions of the following field personnel:

TREKK Design Group:	Mark Calvert, Kris Cook, and James Fisher, P.E.
Burgess & Niple:	Neal Barron, and René Candanoza
Leak Busters, Inc.:	Robert J. Harris
ACE Pipe Cleaning:	Burt Richardson, Dale Jackson, and Tim Osgood
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Other project team members provided technical input. Clayton Carlisle, P.E, of Louis Berger Group managed the logistics of the field work and also served as site inspector for the multi-sensor inspection team. Walter Mahoney, Environmental Engineer of Louis Berger Group, was the site inspector for the zoom camera inspection and electro-scan inspection teams. Kevin Enfinger, P.E. of ADS Environmental Services, LLC was the field observer for the CCTV baseline evaluation team and provided on-site review of CCTV inspection findings. Philip Johns of Redzone, Inc. reviewed the quality assurance plan. James Jolley, P.E., Steve Couture, P.E. and Laura Dufresne, P.E. of The Cadmus Group provided technical support.

Of seven original members of the project stakeholder group, two played an active role throughout the project by providing peer review of key deliverables, including this final report:

- Dr. Yehuda Kleiner, P.E., Group Leader and Senior Research Officer Buried Utilities, National Research Council Institute for Research in Construction, Ottawa, Ontario, Canada.
- Robert Villee, Representative of WEF Collection System Committee and Executive Director of Plainfield Area Regional Sewer Authority, Middlesex, NJ.

In particular, stakeholder comments were very helpful in shaping the field demonstration program such that the findings would be representative and useful to many utilities.

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Acronyms and Abbreviations

2D	Two-dimensional
3D	Three-dimensional
AC	Alternating current
ASTM	American Society for Testing and Materials
AWI	Aging Water Infrastructure
CCTV	Closed-circuit television
CIPP	Cured-in-place pipe
GIS	Geographic information system
HD	High definition
HDPE	High-density polyethylene
HID	High-intensity discharge
hr	Hour
I/I	Infiltration and inflow
KCMO	Kansas City, MO
kHz	Kilohertz
LED	Light-emitting diode
MHz	Megahertz
Min.	Minute
MPRI	Maintenance Pipe Rating Index
NASSCO	National Association of Sewer Service Companies
O&M	Operation and maintenance
ORD	Office of Research and Development
PACP	Pipeline Assessment and Certification Program
POD	Portable on Demand
PVC	Polyvinyl chloride
RCP	Reinforced concrete pipe
SMH	Sanitary manhole
SPRI	Structural pipe rating index
USEPA	United States Environmental Protection Agency
VCP	Vitrified clay pipe

Executive Summary

Condition assessment of wastewater collection systems is a vital part of a utility's asset management program. Reliable information on pipe condition is needed to accurately estimate the remaining service life of each asset and to prioritize rehabilitation and replacement projects. These data needs are especially urgent given the current state of our nation's infrastructure. To help utilities improve their condition assessment programs, the U.S. Environmental Protection Agency (USEPA) is conducting research under the Aging Water Infrastructure program, part of the USEPA Office of Water's Sustainable Infrastructure Initiative. This report presents the results of a field demonstration program conducted as part of a three-year research project titled *Condition Assessment of Wastewater Collection Systems.*

Although inspections with conventional closed-circuit television (CCTV) have been the mainstay of pipeline condition assessment practice for decades, other technologies are now commercially available and may provide complementary information to CCTV. Five such innovative technologies were selected for field trials: zoom camera, electro-scanning, digital scanning, laser profiling, and sonar. The goal of the field demonstration was to evaluate the technical performance and cost of these technologies.

The field demonstration was conducted in August 2010 and was hosted by the Kansas City, MO (KCMO) Water Services Department. Two areas of the collection system were selected for demonstration testing: Gracemor, a residential area with predominantly 8-in. vitrified clay pipe (VCP), and the Line Creek Interceptor, composed of 54-in. to 72-in. reinforced concrete pipe (RCP). Electro-scanning and zoom camera were tested in Gracemor, and the multi-sensor unit (containing digital scanning, laser, and sonar) and zoom camera were tested in Line Creek. Traditional CCTV inspection was performed in both areas, the results of which were used as a baseline from which to compare other findings.

Each technology identified maintenance and structural defects in the pipelines by collecting data or images of the pipe condition. The camera technologies (e.g., digital scanning, zoom camera, CCTV) and laser scanning provided pipe condition information above the water line, whereas sonar assessed conditions below the water line. Electro-scanning detected defects anywhere along the pipe circumference.

Zoom camera inspection did not require pre-cleaning; however, the camera's sight distance was sometimes limited during the testing by objects in the pipe (e.g., spider webs, roots). The camera's sight distance was less than 50 ft in most 8-in. pipes. Although the 81 manholes accessed in Gracemor for zoom camera inspection had more than 22,000-ft of connecting pipelines, zoom camera images were obtained for only 4,595-ft (approximately 21% of the total pipeline length). The zoom camera detected 18% of defects found by CCTV in the same pipelines. Approximately 70% of the total defects were maintenance type defects (e.g., root intrusion, sediment deposition) and 30% were structural defects.

Electro-scanning identified an average of 17 defects per pipe segment, although most were determined to be minor defects. Electro-scanning identified more anomalies than CCTV defects and in some cases, detected different defects than CCTV. Electro-scanning technology did not

detect all line breaks identified by CCTV; therefore, it may not be an appropriate replacement for CCTV technology. It could, however, provide complementary information on leak potential. While CCTV provided visual identification of pipe features, electro-scanning results were used to interpret defect severity and to better understand whether a defect poses a serious infiltration or exfiltration problem.

Digital scanning identified a similar number of O&M defects as CCTV for the 12 pipe segments evaluated by both technologies. However, the two technologies differed in the type(s) of defects identified: digital scanning identified sediment accumulation whereas CCTV identified encrustations and defective taps. For these same pipe segments, digital scanning identified a total of 41 structural defects and CCTV identified none. Subjectively, the digital scanning image quality appeared to be superior to CCTV.

Laser and sonar scans provided information on the location and extent of corrosion loss from interior pipe surfaces. Seven of eighteen pipe segments evaluated showed corrosion greater than 1.0-in with a maximum corrosion depth of 1.5-in. The sonar scan also identified the depth and location of sediment in the pipe. The CCTV inspection did not provide information on corrosion losses or sediment accumulation.

During the field demonstration, the project team evaluated versatility of the technologies in overcoming variable pipe and environmental conditions. Weather conditions, manhole access points, and pipeline flow conditions presented several challenges. Extremely hot temperatures and high humidity during the first week of testing may have contributed to zoom camera equipment problems. Low daytime flow conditions at Gracemor required use of supplemental water to create surcharged flow conditions for the electro-scanning inspection. Turbulent flow conditions in the Line Creek Interceptor created difficulties with the stability of the multi-sensor float assembly. Access to the pipelines was particularly challenging at the Line Creek Interceptor due to dense vegetation and the depth to the pipeline. Although the pole-mounted zoom camera could not be used in manhole structures >30-ft deep, the technology was found to be adaptable in addressing some manhole access issues using alternative mountings (e.g., tripod, truck or hand-held). Narrow manhole structures at this site caused difficulties for inserting and removing the multi-sensor float assembly.

Costs were compared for the different inspection technologies based on actual costs for planning, field work, data analysis, and reporting. Costs of field work were further detailed by costs for equipment set-up and calibration, pipe cleaning, water service, inspection work, equipment troubleshooting, and repair. Total costs for the multi-sensor inspection were $4.21 per ft of pipeline inspected as compared to $2.95 per ft for electro-scanning, $0.99 per ft for zoom camera, and $2.80 to $3.00 per ft for CCTV. Although zoom camera had the lowest total cost per ft, it had limited sight distance and did not provide inspection results for the entire pipeline length between manholes. Data analysis was expensive for the multi-sensor and zoom camera at 42% and 61% of the total inspection costs, respectively, compared to 21% for electro-scanning.

1. Introduction

Our nation's infrastructure is generally in poor condition, and wastewater collection systems are no exception. The American Society of Civil Engineers Infrastructure Report Card gave wastewater infrastructure a D− in 2009 (ASCE, 2009). Aging pipes have not been inspected, replaced, or rehabilitated rapidly enough to prevent deterioration and failure. The frequent occurrence of sanitary system overflows and sewer pipe failures is an additional indication that the infrastructure is in a deteriorated state and needs immediate attention.

In fiscal year 2007, the USEPA Office of Research and Development's (ORD's) National Risk Management Research Laboratory initiated the Aging Water Infrastructure (AWI) Research Program to support the USEPA Office of Water's Sustainable Infrastructure Initiative (USEPA, 2007). Specific objectives of the AWI research are: (1) to evaluate promising innovative technologies and (2) to improve the cost-effectiveness of operation, maintenance, and replacement of aging drinking water and wastewater treatment and conveyance systems.

Condition assessment is an important topic within the infrastructure research area. It provides the key information needed to assess the physical condition of an asset, estimate its remaining useful life, and evaluate long-term performance measures. The USEPA defines condition assessment as "…the collection of data and information through direct inspection, observation and investigation, indirect monitoring and reporting, and the analysis of the data and information to make a determination of the structural, operational and performance status of capital infrastructure assets" (USEPA, 2007). This report is part of a project focused on evaluating technologies designed for condition assessment of wastewater collection systems.

Project Background

In November 2007, USEPA-ORD's National Risk Management Research Laboratory funded a three-year research project entitled *Condition Assessment of Wastewater Collection Systems* in support of the AWI Research Program. The primary goal of this project is to help wastewater utilities better understand their wastewater collection system needs and develop and implement condition assessment programs. The overall project objectives include an evaluation of the state of condition assessment technology and compilation of cost and performance data for innovative assessment technologies. These technologies include innovative camera-based methods, newer non-camera-based methods, and technologies under consideration for adoption from other industries.

As part of this project, several innovative technologies were selected for demonstration testing to obtain technically reliable cost and performance data under field conditions. The field demonstration program was conducted in Kansas City, Missouri in August 2010 and included the following condition assessment technologies:

- Digital scanning;
- Zoom camera;

- Electro-scanning;
- Laser; and
- Sonar.

These methods are commercially available, but are relatively new and not yet in wide practice. They represent newer developments in camera-based inspection as well as technologies that produce data different from and complementary to visual imagery. Selection of these technologies was made with the input of stakeholders and experts who attended the project's Technology Forum in September 2008.

For additional background information, refer to the following three reports which have been previously published to summarize interim project findings:

(1) *Condition Assessment of Wastewater Collection Systems – State of Technology Review Report,* USEPA Report, EPA/600/R-09/049, May 2009, http://www.epa.gov/nrmrl/pubs/600r09049/600r09049.pdf. This report summarizes the current state of technology for condition assessment of wastewater collection systems. It includes detailed information on a number of technologies, including equipment models and vendors.

(2) *Innovative Internal Camera Inspection and Data Management for Effective Condition Assessment of Collection Systems,* USEPA Report, EPA/600/R-09/082, July 2010, http://www.epa.gov/nrmrl/wswrd/awi/. This report provides information on innovative camera-based technologies and data management practices currently used by more advanced wastewater utilities with the goal of making this information available to utilities at large. Seven utility case studies are used to illustrate key points. The report includes an example of a closed-circuit television (CCTV) inspection report, examples of defect code methods, and technology vendor contact information.

(3) *Report on Condition Assessment of Wastewater Collection Systems,* USEPA Report, EPA/600/R-10/082, August 2010, http://www.epa.gov/nrmrl/pubs/600r10101/600r10101.pdf. This report provides performance and cost information on current, innovative, and emerging technologies for conducting sanitary sewer condition assessments. This information can be used as a resource when selecting the most appropriate technology given a system's characteristics, history, and condition assessment goals.

2. Field Site and Host Utility

The host utility for the field demonstration program was the KCMO Water Services Department. The utility serves approximately 653,000 customers in a 420 square mile area in Kansas City and portions of twenty seven other communities located in Platte, Clay, and Jackson Counties in Missouri and Johnson County in Kansas. The wastewater collection system comprises approximately 2,000 miles of sanitary sewers and 600 miles of combined sewers. The combined sewer portion of the system covers approximately 58 square miles, mostly within the urban core of Kansas City. The collection system currently handles about 96 million gallons of wastewater per day and delivers it to seven wastewater treatment facilities. It includes forty wastewater pumping stations and eighteen flood control pump stations.

The KCMO Water Services Department was selected as the host facility on the basis of several criteria, including:

1. Their willingness to be an active participant in the research;

2. The availability of historical data such as system maps, maintenance records, and inspection reports; and

3. The availability of pipes with the appropriate characteristics for the technologies.

Appendix A provides a more thorough discussion of the steps involved in planning this field demonstration, including selecting the host utility. The appendix also provides guidance for readers who wish to plan their own field demonstration projects.

Within the KCMO system, two areas were chosen: the Gracemor area and the Line Creek Interceptor. The pipelines in these specific areas were chosen in collaboration with utility personnel on the basis of pipe material and diameter, maintenance and operational history, the pipes' physical and hydraulic conditions, accessibility, and worker safety. The team sought pipes with known defects or a high probability of defects. In addition, the two testing areas were chosen to accommodate testing of five condition assessment technologies as shown in Table 2-1.

Table 2-1. Required Site Conditions for Field Testing.

Technology	Pipe Material	Pipe Diameter	Flow Regime
Digital Scanning	Any	6-in. to 60-in.	Technology inspects dry pipe segments. Line must be tested during periods of low flow.
Zoom Camera	Any	>6-in.	Technology inspects dry pipe segments. Line must be tested during periods of low flow.
Electro-scanning	Non-ferrous	3-in. to 60-in.	Surcharged at face. Sliding plug system proposed.
Laser	Any	>4-in.	Technology inspects dry pipe segments. Line must be tested during periods of low flow.
Sonar	Any	$\geq$12-in.	A minimum depth required to submerge the head of sonar unit. Technology inspects pipes below the water surface.

Utility staff provided base maps and geographic information system (GIS) shape files for the two study areas as well as background information on the maintenance issues and concerns for each area. Record drawings were also made available for each service area in preparation for the field work.

The following sections provide details on the two demonstration areas.

Gracemor

Gracemor is a fully built-out residential community in the northeast section of Kansas City, east of US Route 435. The Gracemor residential subdivision (Figure 2-1) is platted with one-quarter acre lots. Utility staff estimated that homes were constructed between the early 1960's and the mid 1970's. The subdivision includes the Gracemor Elementary School and the San Rafael Park. Its streets are primarily through-way streets with occasional cul-de-sacs.

Figure 2-1. Gracemor Subdivision.

The sanitary sewer system in the Gracemor area consists of 8-in. vitrified clay pipe (VCP) connecting to 10-in. and 15-in.VCP. In recent years, limited sections of pipe have been replaced with polyvinyl chloride (PVC) pipe and/or lined with cured-in-place pipe (CIPP). The large collector piping travels through the San Rafael Park in the easterly direction, away from the neighborhood. The 8-in. lines are shallow in some areas (24-in. below grade). The 10-in. line through San Raphael Park is approximately 10-ft to 12-ft deep. Some of the pipelines are more than 40 years old. This area was selected for inspection by electro-scanning and zoom camera because of the small pipe diameters and the lack of ferrous pipe materials. The issues of concern are infiltration and inflow (I/I), and root intrusion, which create the need for regular maintenance to remove roots and debris.

Line Creek Interceptor

The Line Creek Interceptor is located in the cities of Riverside and Northmoor, MO. It runs adjacent to Line Creek through an area protected by the Riverside Levee system (Figure 2-2).

Figure 2-2. Line Creek Interceptor.

The Line Creek Interceptor is composed of various sizes of reinforced concrete pipe (RCP), ranging from 54-in. diameter upstream to 72-in. downstream. Constructed in the late 1960s, the interceptor is fairly deep, typically in the range of 20-ft and greater below grade. The section of the interceptor identified for the demonstration program covers just over 7,000-ft of pipe and includes sixteen manholes, some located as close as 54-ft and as far apart as 750-ft from each other. While most of the manholes are readily accessible, several are located deep into the heavily vegetated brush alongside Line Creek or within the easements behind some of the residential neighborhoods.

Prior to the field demonstration program, the upper portion of the Line Creek Interceptor (i.e., north of I-29) was lined with CIPP due to concrete corrosion from hydrogen sulfide. The interceptor segments included in the demonstration program were inspected by the utility several years ago, prior to the construction of the Riverside Levee and gate system. The area experiences increased flows during wet-weather events.

3. Condition Assessment Technologies

Five technologies were evaluated in the field and compared to a baseline of CCTV inspection. Of the five technologies, two methods are camera-based (digital scanning and zoom camera). Three technologies (laser, sonar, and electro-scanning) operate by different principles and provide quantitative data that can be used to evaluate pipe geometry, sediment buildup, and leak potential. This chapter provides background information on these condition assessment technologies.

3.1 Closed-Circuit Television Inspection (Baseline Evaluation)

CCTV inspection is the industry standard for inspecting wastewater collection systems. The resulting video data provide a visual representation of the interior condition of the pipe above the water line. Because utilities will likely want to evaluate the benefits of innovative technologies against the familiar CCTV inspection data, CCTV was performed to acquire "baseline" data on pipe conditions.

3.1.1 Technology Overview

CCTV allows utilities to identify distress indicators that are manifested on the pipe inner surface. It is used to locate specific defects (i.e., structural deficiencies maintenance needs, and/or construction/installation deficiencies) that may contribute to the infiltration of groundwater into the sewer system, exfiltration of sewage into the soil surrounding the sewer system, impacts on the pipe's hydraulic capacity, and/or structural failure of the pipeline. Because the pipe needs to be relatively free of debris to allow the CCTV camera to move through it, pre-cleaning is often required. CCTV cannot be used to inspect pipe condition below the water line or to quantitatively characterize structural defects. It cannot identify voids in backfill and soil, cracks that have not yet surfaced, or deterioration of the pipe's exterior surface. CCTV is a subjective assessment that is dependent on the technician's expertise and judgment.

Defects and maintenance issues identified by CCTV inspection include:

- Active leaks;
- Pipe cracks;
- Offset joints;
- Pipe sags and deflections; and
- Sediment, debris, and roots.

The project team selected a vendor with extensive experience performing condition assessment, CCTV inspection, and maintenance within the KCMO system (Ace Pipe Cleaning, Inc. Kansas City, MO). To avoid potential bias in demonstration testing, CCTV inspection results were not shared with other equipment vendors during the course of the field demonstration. CCTV inspection results and defect coding were reviewed by a third party technician certified with the National Association of Sewer Service Companies (NASSCO) Pipeline Assessment and Certification Program (PACP) as a quality assurance measure.

3.1.2 Equipment Description

For the CCTV inspection, the vendor used an Optical Zoom II (OZ II) pan and tilt optical zoom camera manufactured by CUES (Orlando, Florida). The camera unit has a 10:1 optical zoom and 4:1 digital zoom for a 40:1 digital/optical zoom. The unit has the following industry standard features: automatic focus, manual focus, iris control, and back light compensation. It also has full pan and tilt capabilities for a 400-degree rotation optical viewing angle and a 331-degree pan viewing angle range. A four-head LED lamp is incorporated into the unit.

The CCTV inspection was conducted by transporting the camera through the pipelines. The camera was mounted on a self-propelled crawler or pontoon depending on pipe conditions (e.g., water level, flow rates, presence of debris). The size of the self-propelled crawler differed as a function of the pipe diameter. For Gracemor, light cleaning and root cutting were necessary to advance the self-propelled crawler. For Line Creek Interceptor, the inspection camera was initially mounted on a large-wheeled self-propelled crawler but a float system was later used due to debris in the pipe (Figure 3-1). The interceptor was not cleaned.

Figure 3-1. Custom Pontoon for Floating CCTV Camera in Large-Diameter Sewer.

Other equipment used for the CCTV inspection included:

- A CCTV inspection truck equipped with CCTV inspection camera, crawler, winch, and computer equipment for camera operation and documentation. The inspection truck also had the required hand tools, air blower for ventilation, and small electrical generator.
- A hydraulic jet truck equipped for sewer cleaning with a high pressure jet nozzle and root cutting blade.
- A roller guide system that was used to control the insertion of the camera cable at the ground surface and to guide the winch without rubbing on the edge of the manhole. A second guide was used at the base to control the cable and prevent abrasion at the crown of the pipe.
- Safety equipment (e.g., harness, tripod with safety winch, gas detector) for compliance with confined space entry requirements.

3.2 Zoom Camera

The zoom camera is promoted as a screening tool that can be used to prioritize an inspection and maintenance program. Unlike conventional CCTV, a zoom camera is affixed to a stationary mount and "looks down" or "zooms" down the pipe rather than traveling through it. It is not designed to replace conventional CCTV systems, but rather to screen and prioritize pipes for further inspection work and/or cleaning.

3.2.1 Technology Overview

Zoom camera inspection produces still imagery and/or video records of the pipe (or manhole) interior that can give a general indication of pipe condition within the camera's sight distance. It can be used for any pipe material. The zoom camera's primary advantages are improved production rate compared to conventional CCTV and potential cost savings. Its stationary mount eliminates the need for cleaning the sewer prior to the inspection. Furthermore, this method avoids the inevitable down-time associated with a crawler-mounted CCTV unit due to pipe obstructions. The zoom camera inspection crew can move rapidly through a service area and highlight segments requiring a more detailed CCTV inspection. Drawbacks of zoom camera inspection are that it does not provide as much visual detail as conventional CCTV and it cannot image below the water line (the same limitation as CCTV). It does not provide accurate measurements of the pipe and the location of defects.

The effectiveness of zoom cameras is often limited by their sight distance (the distance from which a defect remains visible) due to several factors such as the pipe diameter, pipe environment (e.g. presence of debris, moisture, available light), and the pipe configuration (i.e. presence of bends and obstructions). Historically, zoom cameras have been used to perform manhole inspections and to inspect a few feet down the pipe. Newer zoom cameras can pan 360° and zoom farther down pipes. For example, Envirosight claims that the QuickView camera has the ability to record imagery up to 100-ft in a straight, clean pipe segment, and up to 350-ft for a 60-in. diameter line.

The field demonstration was focused on investigating various aspects of zoom camera performance by comparing the results with data from conventional CCTV. Specific questions evaluated during the field demonstration included:

1. How much does the limited sight distance inhibit use of zoom camera in condition assessment?

2. How does image quality compare to images from conventional CCTV inspection?

3. Is zoom camera cost-effective for prioritizing inspections?

4. How does the inspection rate and sight distance compare to vendor claims?

3.2.2 Equipment Description

The subcontractor (TREKK Design Group, LLC, Kansas City, Missouri) used the QuickView camera system, manufactured by Envirosight of Randolph, New Jersey (http://www.envirosight.com/index.php/news/133-081101qv35.html). The system is equipped with a 432:1 zoom camera (36:1 optical zoom, 12:1 digital zoom) and twin 14-watt high intensity discharge (HID) lights. The lights are contained within a waterproof camera/light assembly mounted to a telescoping, carbon fiber pole extendable to 24-ft (Figure 3-2). Pole assemblies are available at different lengths; a 30-ft mast arm is the longest available.

Figure 3-2. Zoom Camera with HID Lights.

Camera system accessories included a tripod, stabilizing rod, camera control head, rechargeable battery pack, laptop computer, and cables/connectors. The control head adjusts the focus and focal length (zoom) of the camera. A separate carbon dioxide purge/pressurization device was used to maintain positive pressure inside the camera housing to prevent water infiltration.

A ¾-ton inspection truck was used to transport the zoom camera system and appurtenant equipment. The pickup bed was used to store miscellaneous tools commonly used for sewer work such as a manhole cover hook, sledgehammer, survey rod, and lights. Confined-space entry equipment was not required for camera operation.

3.3 Electro-scanning

Electro-scanning technology uses electrical current to identify pipe defects that are potential leaks in non-ferrous pipes (e.g., clay, plastic, concrete, reinforced concrete and brick). It can be used to estimate the magnitude and location of potential leaks, helping utilities to better understand and control sources of infiltration and exfiltration. Drawbacks to applying this technology include its inability to directly determine the cause of a pipe defect (e.g., misaligned joints, pipe cracks, defective service connections) or the defect's position around the pipe circumference. However, with the assistance of computer processing, the output can reliably discriminate between defects that are due to faulty joints, service connections, manhole connections and structural defects such as pipe cracks. The computer processing also provides information on defect size.

The broad goal of this demonstration was to compare information from electro-scanning to that generated by conventional CCTV inspection and PACP defect coding. Specific objectives were to evaluate the capability of electro-scanning to discriminate among types of defects that can leak and to determine whether the amplitude of the electro-scan anomaly can be interpreted qualitatively for use in defect coding.

3.3.1 Technology Overview

Electro-scanning is performed using a standardized testing protocol that meets American Society for Testing and Materials (ASTM) standard F2550-06 (ASTM, 2006). The electro-scan is carried out by applying an electric voltage between an electrode in the pipe, called a sonde (Figure 3-3), and an electrode on the surface, which is usually a metal stake pushed into the ground. The high electrical resistance of the pipe wall inhibits electrical current from flowing between the two electrodes unless there is a defect in the pipe, such as a crack, defective joint or faulty service connection.

Figure 3-3. Sonde for Electro-scanning Unit.

Electro-scanning registers only those defects that are covered by water. If the pipe is partially filled, then the data represent the portion of the pipe circumference that is under water. To inspect the entire circumference of pipes that are typically not surcharged (e.g., gravity sewers), the pipe must first be filled with water at the location of the sonde using one of two methods. The more common method for pipe diameters of 12-in. or less, which was used in this project, employs a sliding pipe plug (Figure 3-4). The sonde is attached to the upstream side of the plug, which is pulled a short distance down the pipe. The upstream portion of the pipe (i.e., behind the plug) is filled with water so that the sonde is submerged and the pipe surcharged. Then the plug and attached sonde are pulled through the pipe. Output from a pressure gauge in the sonde is monitored at the recording computer to ensure that the pipe remains surcharged at a level of 20% to 100% of the pipe diameter at the location of the sonde. The second method involves plugging the downstream manhole and filling the pipe with enough water such that the pipe is covered at the upstream manhole. This method can increase the set-up time by 20% to 50% and care must be taken to ensure that sewage does not back up to a hazardous degree into service laterals. Consequently, pipe plugging is usually only used in pipe diameters greater than 12-in. These larger diameter pipes usually have greater natural flow, reducing the time required to surcharge the pipe. They are also usually significantly deeper and the likelihood of sewage backup into a connected service is minimal.

Figure 3-4. Sliding Plug for Electro-scanning Equipment.

An electro-scan is carried out by pulling the sonde through a pipe at a speed of 30 ft per min. Other than monitoring the water level in the pipe at the sonde location, no other action is required by the field operator while carrying out an electro-scan.

The current flow between the surface electrode and the sonde is recorded at approximately 0.5-in intervals along the pipe. For sewer pipe materials that have high resistance to electrical current, there is only a small current flow except where there is a pipe defect. As the center of the sonde approaches within about an inch of a pipe defect, the current from the focused electrode increases, reaching a maximum when the center of the sonde is radially aligned with a defect.

Results of electro-scanning are typically graphed to show spikes or elevated levels of the measured electrical current that indicate the location of potential leaks, pipe defects (e.g., cracks, defective joints), or pipe features (e.g., joints, service connections). The shape and amplitude of these anomalies are interpreted to define the type and severity of each defect. Operator experience and previous studies (e.g., Harris and Tasello, 2004) are used to distinguish between electrical currents that represent normal conditions (i.e., no defect) versus an anomaly (i.e., a potential pipe defect or leak). The magnitude of the anomaly (e.g., small, medium, large) is estimated based on a comparison of electro-scanning results with pressure testing results for pipe joints (Harris and Tasello, 2004).

3.3.2 Equipment Description

The contractor (Burgess and Niple, Inc. (B&N), Dallas Texas) used two electro-scanning models for this project: Focused Electrode Leak Locator (FELL-41) manufactured by Metrotech Corporation of Santa Clara, California (http://www.fell41.com/) and the MSI-1620 unit manufactured by Mount Sopris Instruments of Denver, Colorado. Both models performed electro-scanning inspection in accordance with ASTM Standard F2550-06 (ASTM, 2006). The FELL-41 was the primary electro-scanning equipment being evaluated. The MSI-1620, a prototype instrument provided by Mount Sopris Instruments, was used in three pipe segments to compare results with the FELL-41.

Primary components of electro-scanning systems are a sonde, a surface electrode, a motorized cable drum, a sliding plug, and power supply and supporting electronics. Each component is described below.

The **sonde** is a torpedo-shaped stainless steel electrode assembly incorporating three separate electrodes: a 0.75-in long center electrode and two 10-in long guard electrodes, one located at each end. The guard electrodes prevent current produced by the center electrode from flowing along the length of the pipe. A pressure transducer mounted inside the sonde at one end provides data to the operator to ensure that the pipe remains surcharged at 20% to 100% of the pipe diameter at the sonde location as the sonde is advanced through the pipe segment.

The **surface electrode** is generally a stake pushed into the ground.

A cable deployed from the **cable drum** carries electric power to the sonde, completes the electric circuit between the sonde electrodes and the ground stake, transmits digital data from the sonde to the recording computer, and serves as a means of retrieving the sonde from the downstream manhole. The distance of the sonde from the upstream manhole is determined via a shaft encoder pulley on the cable.

The **sliding plug** is a rubber cone that fits snugly inside the sewer line. It travels with the sonde to keep the pipe full of water in the area being scanned.

Power supply and electronics: A constant-voltage power supply provides operating current to the sonde. The voltage impressed on the three electrodes of the sonde is an alternating current (AC) voltage at a frequency of 982 Hz. The operating current is very low (roughly 40mA or less). The power supply holds the potential of all the electrodes at the same level regardless of the current flow. This results in the current flow being "focused" from the center electrode onto the circumference of the pipe in a 1-in. disk, allowing precise identification of leaks. The system is powered by a 12 volt 45 amp hour deep cycle battery. A 12 VDC to 120 VAC inverter provides power for the laptop computer that is used to record system data.

Figures 3-5 and 3-6 show a schematic and photo of the electro-scanning components, respectively. Figures 3-7 and 3-8 illustrate the cable guides and down-hole arrangement of the sonde, respectively.

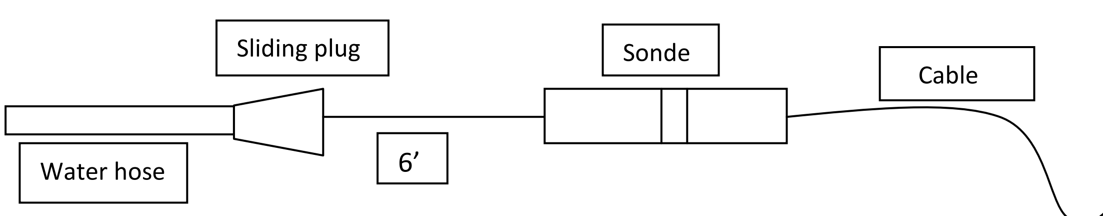


Figure 3-5. Schematic of Electro-scanning Equipment.

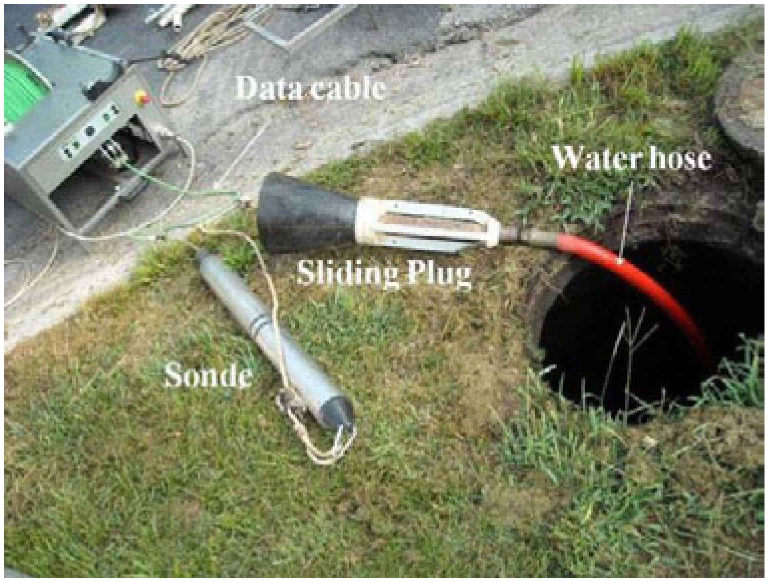


Figure 3-6. Photo of Electro-scanning Components.

Figure 3-7. Cable and Cable Guides for Electro-scanning Inspection.

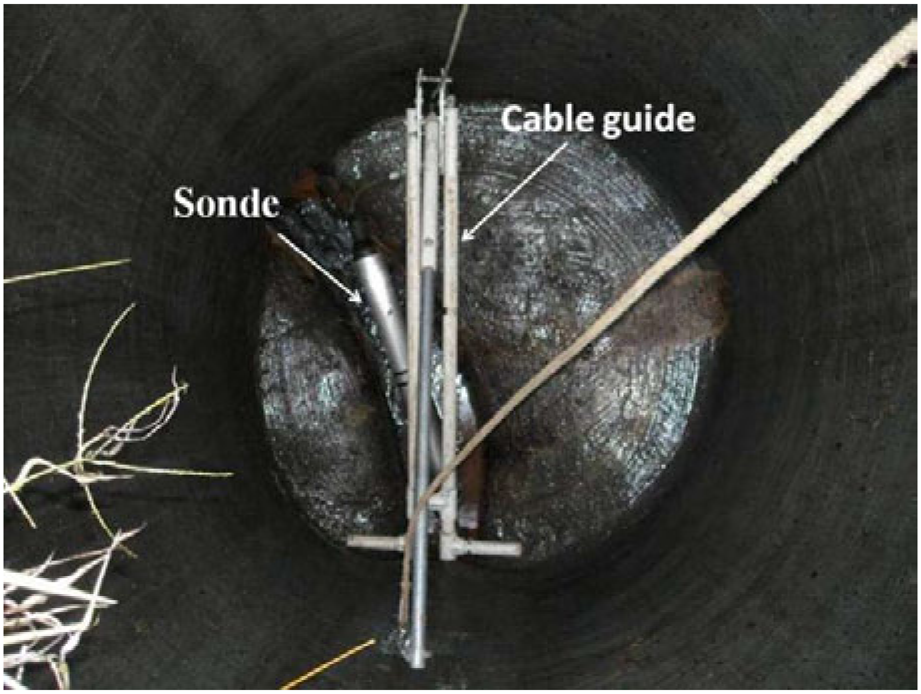


Figure 3-8. Sonde Centered in the Manhole Prior to Charging Structure with Water.

The inspection truck (Figure 3-9) was equipped with safety equipment (e.g., harness, tripod with safety winch, gas detector) for compliance with confined space entry requirements, hand tools, an air blower for ventilation, and a small generator. Generally manhole entry is not required for electro-scanning. Of the 35 pipe segments scanned, manhole entry was only required on three occasions.

Figure 3-9. Inspection Truck with Laptop and Cable Spool/Winch.

A hydraulic jet truck equipped with a high pressure jet nozzle was used to jet the hose from the downstream to the upstream manhole. The jet nozzle was then replaced with a sliding pipe plug and water from the jet truck was used to surcharge the line behind the sliding plug. A roller guide was used to control insertion of the sonde cable at the ground surface and to guide the winch without rubbing the line on the edge of the manhole. A second guide was used at the base to control the cable and prevent abrasion at the crown of the pipe.

3.4 Digital Scanning

Digital scanning uses high definition (HD) imaging to provide a detailed visual assessment of pipe condition above the water line. It has been commonly used in Europe and Asia for a number of years, but has a limited history of use in North America. Therefore, performance and cost information for digital scanning are limited in the context of the U.S.

3.4.1 Technology Overview

Similar to conventional CCTV, digital cameras are transported through sewer lines using self-propelled crawlers or floating platforms. Unlike conventional CCTV systems, digital scanning uses one or two high-resolution digital cameras with wide-angle lenses in the front, or front and rear, section of the housing to collect HD video and still images. During pipe inspections, parallel mounted lights are triggered at the same position in the pipe.

Defect coding is performed in the office with post-processing software that permits the user to virtually pan, tilt, zoom, and stop the image at any point to capture video clips and images of pipe condition and features. Because the data can be assessed at any time, it provides the opportunity for a second level of quality control in the review process and allows other individual(s) involved in the process to gain insight into the pipe condition (e.g., designers, rehabilitation contractors, and utility owners).

Performance issues for digital scanning include its ability to provide reliable images for different diameter pipes (larger pipes in particular), issues of appropriate lighting and resolution, production rate, and comparison of image quality with that of conventional in-line CCTV. As with other camera technologies, one of the limiting factors for digital scanning is camera resolution. In general, the resolution for digital scanning decreases as pipe diameter increases, although better lighting can help offset this limitation to some extent.

The subcontractor for this technology was Hydromax USA (Louisville, KY).

3.4.2 Equipment Description

The digital scanning unit used for this study was the HD digital camera on the Cleanflow multi-sensor platform used for sewers 30-in. to 120-in. in diameter (http://hydromaxusa.com/large-pipe-cleanflow.html). The HD camera has a resolution of three megapixels and is equipped with LED lighting to provide high quality visual imaging (Figure 3-10). It has a full 180° view and collects images 6 times per second. The data processing for Cleanflow's HD camera does not currently produce an unwrapped side view of the pipe wall, but it does enable coding to be completed in the office using virtual panning, tilting and zoom features.

Figure 3-10. HD Camera and Twin LED Lights at Front of Float.

In addition to the HD digital camera, the multi-sensor float system is equipped with a laser Fly-Eye system with a four camera array and a sonar head mounted on the underside of the float. Each sensor has its own control module, portable on-demand (POD) data storage, and four separate POD batteries.

The float system includes two integral pontoons and two pontoon outriggers that are attached to the float after it is lowered through a manhole. The float assembly is controlled by a tether, which is attached to the tail end of the float. A hydraulically-operated winch controls the amount of rope extended and the speed at which the float moves down the sewer pipe. A roller guide system is used to control insertion of the tether line at the ground surface and to guide the winch without rubbing on the edge of the manhole. A nylon drift sock is attached to the float and suspended downstream approximately 10-ft ahead of the float. The drift sock fills with water and helps smooth the flow for the float. An orange or yellow highly visible ball float is attached downstream approximately 10-ft ahead of the drift sock to enable the crew to look down each manhole and verify that the float is travelling successfully.

The inspection truck is equipped with the required hand tools, safety equipment, an air blower for ventilation, and a small generator. Safety equipment for confined space entry includes a harness, a tripod with safety winch, and a gas detector.

3.5 Laser

Laser scanning is generally used in conjunction with standard in-line CCTV inspection to provide additional information on pipe condition. Specifically, this technology provides information on pipe wall geometry and can be used to evaluate corrosion, deflection, and other defects. Laser scanning does not rely on the subjectivity of visual observation.

3.5.1 Technology Overview

Laser scanning generates a two-dimensional image of the interior contour of the pipe. Results are compared to a reference shape to identify pipe defects and maintenance needs. If the scan shows that the interior shape of the pipe deviates outside the reference shape, the pipe has likely corroded. If the scan shows deviations inside the reference shape, it is likely that debris has accumulated in the pipe invert. Measurements can be made on any pipe material, but only above the water line. Data are presented as internal diameter and deflection graphs. These graphs are used to quantify internal pipe wall material loss/gain or deformation at a given location.

Currently, laser data analysis does not rely on a standard defect coding system. Testing objectives for this technology focus on merging the results of laser testing with those from camera inspection. Questions include whether laser data can be integrated with PACP coding standards and whether the laser profiling provides tangible benefits to a condition assessment program in terms of enhanced information.

3.5.2 Equipment Description

The laser unit for this demonstration was the Fly-Eye system (Figure 3-11), which is part of the Cleanflow multi-sensor platform used by Hydromax USA (http://hydromaxusa.com/large-pipe-cleanflow.html). The laser system is suitable for pipes 24-in. to 100-in. in diameter. The Fly-Eye unit uses a 360°, high resolution, four-camera array to produce a processed digital profile image (2048 x 1536 pixels) of the ring of light produced by the laser. Images are taken 12 times per second. The laser scanning system records all measurements for post-inspection reporting.

Figure 3-11. Fly-Eye Array of Four Cameras for Laser Profiling Imaging.

3.6 Sonar

Sonar is used to inspect pipe surfaces below the water line and to estimate the accumulation of debris and sediment. It complements laser technology which inspects pipe condition above the water line. Sonar can also provide information on pipe geometry, pipe wall deflections and the presence of pits, voids and cracks. The detection of voids and cracks may be limited depending on the amount of sediment. The technology can be applied to gravity sewers and sewage force mains made of any pipe material, and it can be deployed in pipes with diameters greater than 4 in. One benefit of this technology is that it can be deployed in pressurized force mains without taking the main out of service. A number of units are commercially available for wastewater applications.

3.6.1 Technology Overview

Sonar inspection is accomplished by passing a sonar unit through a sewer pipe. Depending on the pipe's size and flow conditions, the sonar head is deployed on a raft, skid, or robotic tractor. As the sonar head moves through the pipe, it sends out high frequency sound waves, which are reflected by pipe walls and debris and received by the sonar head. The reflection of the signals varies with changes in the reflecting material, allowing the detection of defects such as pipe wall deflection, corrosion, pits, voids, and cracks, as well as the quantification of debris and silt. The time between signal transmission and receipt is used to determine the distance between the sonar head and the pipe wall, as well as to determine the internal shape/circumference of the pipe.

Two important criteria for sonar are the acoustic frequency and the device's travel rate through the sewer. Acoustic frequency affects image sensitivity and power requirements (Andrews, 1998). Andrews (1998) found that a 2 megahertz (MHz) frequency is suitably accurate to provide information on a sewer's interior shape but lower frequency units are used to obtain structural information because they have greater penetrating power. Andrews (1998) found that a travel rate of 3.94-in. per second (i.e., 1,182-ft per hour) allows for the optimal identification of critical defects, but, at the same time, prevents the detection of very small defects.

Sonar inspection provides data on the amount of debris and gross defects below the water line. Therefore, the results cannot be compared directly to results of CCTV inspection, which only images the portions of the pipe above the water line. However, use of the multi-sensor platform allows the data to be seamlessly tied to the laser data to provide information on the entire circumference of the pipe. As with laser, sonar data analysis does not use a standard defect coding system; it relies on engineering judgment to assess the magnitude and/or severity of a defect and make a determination on the need for subsequent maintenance.

Demonstration of this technology was focused on the added value of including sonar in a condition assessment program. Questions include whether sonar can map defects as effectively as it can quantify sediment accumulation and whether sonar data can be coded in accordance with the PACP system. Generally, vendors of sonar scanners claim that sonar inspection can detect defects greater than 1/8 in. in size, including pits, cracks, corrosion, and debris accumulation.

3.6.2 Equipment Description

The sonar unit used by Hydromax USA for this study was the Marine Electronics Model 1512USB Pipe Profiling Sonar (www.marine-electronics.co.uk) that uses a 2 MHz acoustic signal. It was an integral component of the Cleanflow multi-sensor platform described above

(Figure 3-12) (http://hydromaxusa.com/large-pipe-cleanflow.html) mounted to the underside of the float assembly. It collects a 360-degree profile of a surcharged pipe surface once per second.

Figure 3-12. Sonar Head on Multi-sensor Float Assembly.

4. Field Methodology and Observations

The field demonstrations took place over a 3-week period, from August 9 through August 27, 2010. The testing schedules for the various technologies were intentionally staggered to avoid contact between contractors for the different technologies. As noted earlier, the results of the baseline evaluation and the demonstrations of the other technologies were not shared among the vendors, preventing the field crews from having preset knowledge of the pipe condition. The demonstration schedule was as follows:

- Week 1 (August 9th to August 14th): Multi-sensor inspection of Line Creek Interceptor and zoom camera inspection of Gracemor and Line Creek Interceptor (zoom and multi-sensor vendors did not overlap at Line Creek).
- Week 2 (August 16th to August 20th): Cleaning and baseline CCTV inspection of Line Creek Interceptor and Gracemor.
- Week 3 (August 23rd to August 27th): Electro-scanning inspection of Gracemor and completion of zoom camera inspection at Gracemor.

Prior to the inspections, project team members met with utility staff to finalize the selection of pipe segments. This included walking the alignments of both the Line Creek Interceptor and the Gracemor pipelines to locate manholes and to determine if access and traffic control would be a concern. Utility staff, with the assistance of Ace Pipe, was able to locate several key structures. The Gracemor pipelines were easily identifiable, with the majority of access points (i.e., manholes) in the public right-of-way; only one manhole was inaccessible.

Sewer cleaning was completed in the Gracemor area to remove debris that prevented advancement of the CCTV crawler. A high-pressure hose was used to flush debris to a downstream manhole where it was removed by a vacuum truck. Water was obtained from the nearest fire hydrant using an approved water meter from KCMO Water Services Department. Because cleaning was not required for the zoom camera or multi-sensor technologies, it was scheduled just prior to CCTV inspection during Week 2. Cleaning of the Line Creek Interceptor was not required for the multi-sensor technology or CCTV because its diameter is large enough to allow the equipment to be transported through the sewer. The results of the multi-sensor inspection during the week prior to the CCTV inspection showed that the line contained debris but it was deemed passable with the CCTV camera.

Weather conditions during the first week of testing were extremely hot, with temperatures of approximately 100ºF and high humidity. Conditions during the second week were slightly cooler, with afternoon temperatures between 80 ºF and 90 ºF. During the third week, temperatures ranged from 70ºF to about 95ºF.

Traffic was generally light in both areas, and work did not entail major traffic disruptions. Orange cones were set up around the inspection vehicles.

The depth of sewage flow in the Line Creek Interceptor was 12-in. to 15-in. The pipelines at Gracemor had low flow rates typical of a residential area during the day with a sewage depth of approximately 1-in. or less.

Throughout the demonstrations, equipment set-up was consistent with the manufacturers' procedures and included calibration where needed. All work was observed by project personnel and documented on a daily basis in written field reports.

4.1 CCTV Baseline Evaluation

During the CCTV baseline evaluation, approximately 7,000-ft of pipe was inspected in the Gracemor area, and 5,000-ft was inspected in the Line Creek Interceptor. Figures 4-1 and 4-2 show the pipe segments inspected in Gracemor and Line Creek Interceptor, respectively.

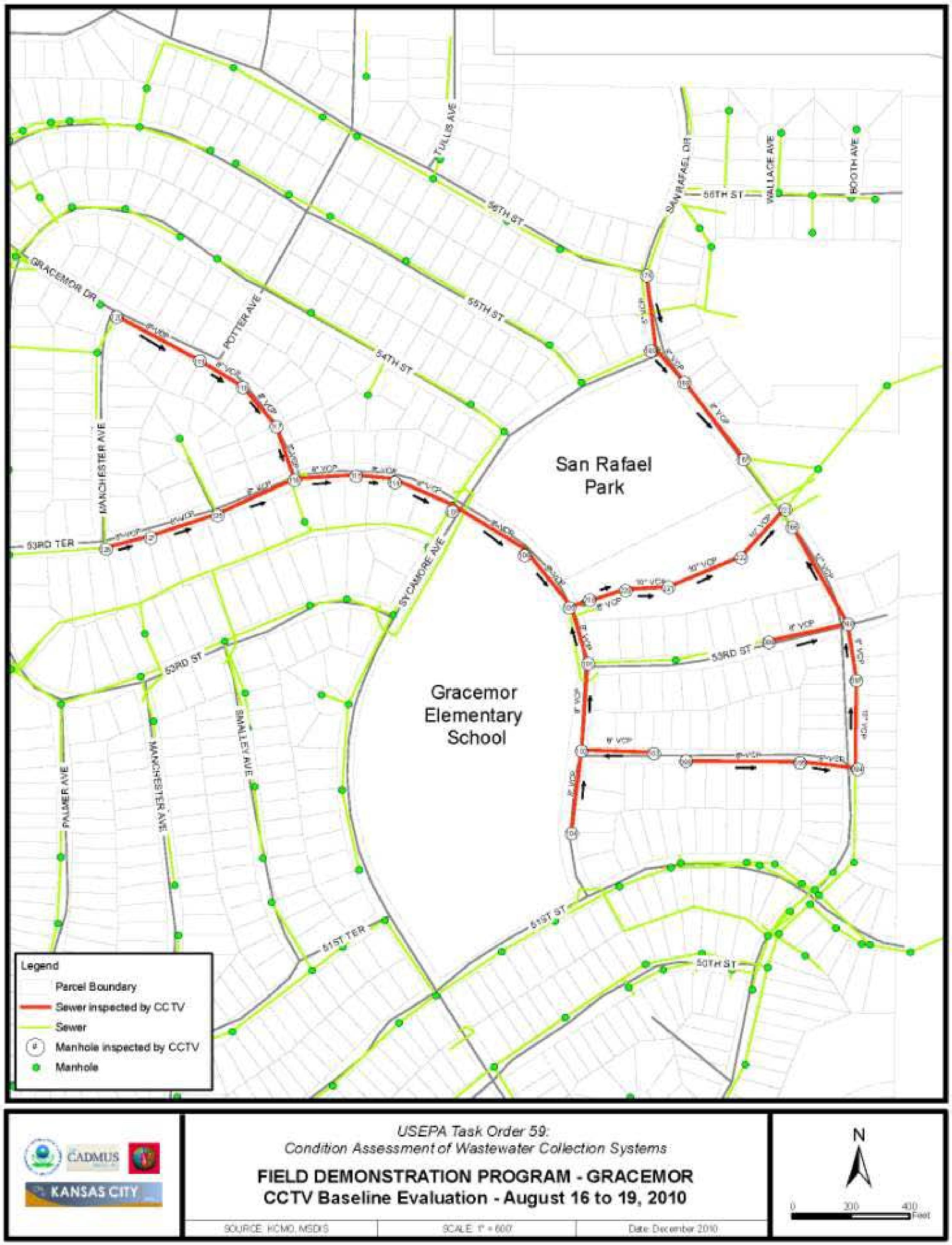


Figure 4-1. Pipe Segments Inspected by CCTV in the Gracemor Area.

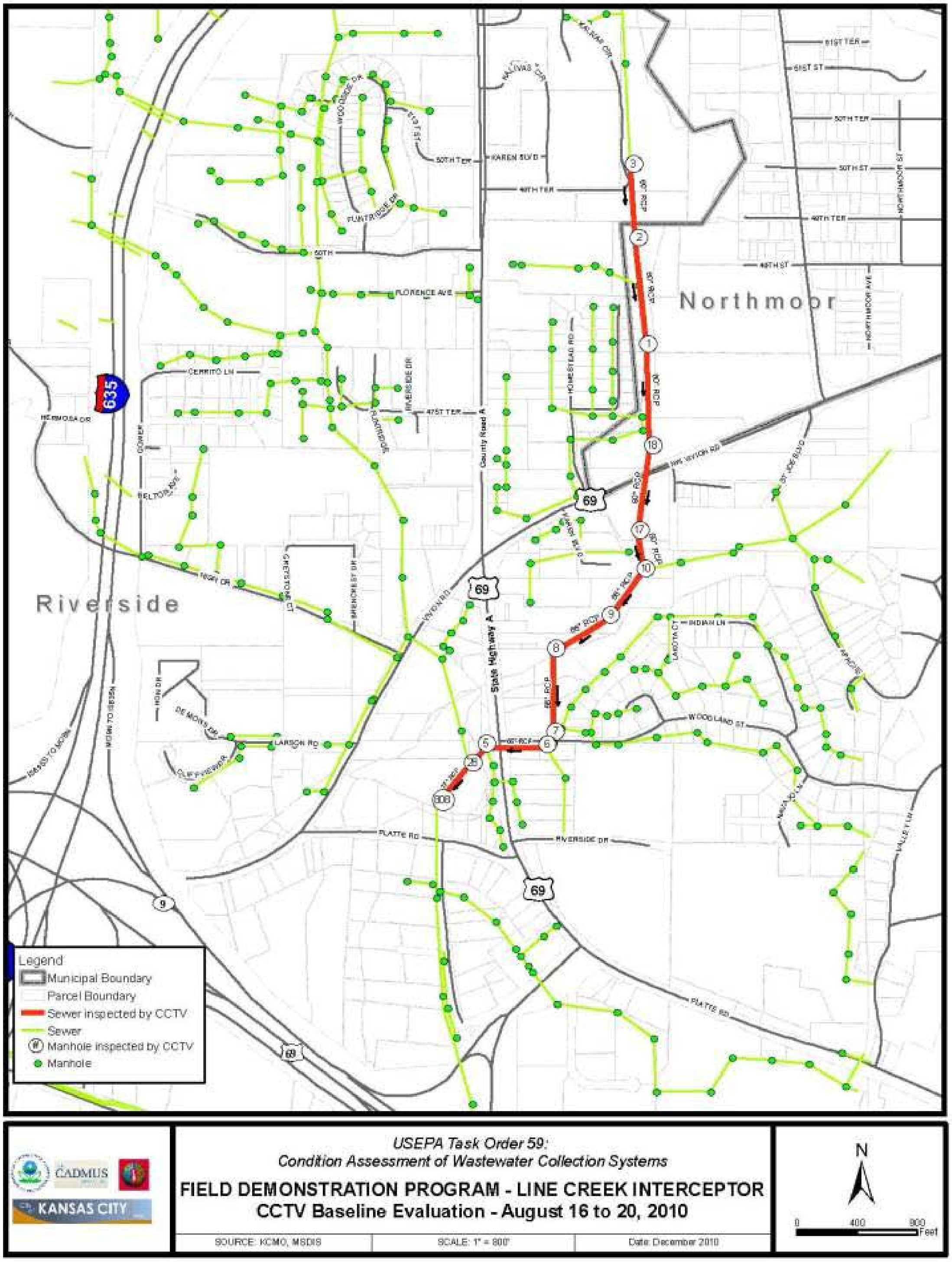


Figure 4-2. Pipe Segments Inspected by CCTV in the Line Creek Interceptor.

4.1.1 Equipment Set-up and Deployment

Set-up time at each manhole in the Gracemor area was minimal. The lines were cleaned ahead of time as the flushing truck was able to stay ahead of the camera crew. Each camera crew had two inspection technicians. At the Line Creek Interceptor, set-up time at each structure was longer because access to the manholes was more difficult and the equipment needed to conduct a large diameter inspection generally took longer to set up.

4.1.2 Overview of Inspection Activities and Issues Encountered

In Gracemor, the crew initially attempted to inspect without cleaning the lines. However, debris and obstructions prevented the self-propelled crawler from advancing. The pipe segments were then cleaned as described previously to remove sediment and debris. A cutting head was needed in some segments to remove roots. The line remained in service at all times, and the inspection proceeded with no major difficulties.

At the Line Creek Interceptor, the crew experienced difficulties on the first two days. The inspection camera was initially mounted on a large-wheeled self-propelled crawler designed for use in large-diameter sewers. In the 60-in. interceptor from sanitary manhole (SMH)-3 to SMH-2, the crawler encountered debris below the flow line near the upstream manhole and could not maneuver around it. The inspection camera was then mounted on a custom-made pontoon and the crew attempted to float the camera downstream. To guide the pontoon, a nylon lead rope with floats was first sent downstream and retrieved from the next manhole where it was tethered to the CCTV inspection truck by a cable and winch. The other end of the rope was connected to the pontoon and an attempt was made to guide the pontoon through the pipeline. However, the rope did not create enough tension to move the float past the debris.

On the third day, a hydraulic jet truck was positioned at the downstream manhole so that the hose reel could be used as a winch. A nylon lead rope was floated between the upstream and downstream manholes and tied to the hose reel on the jet truck. With jet truck and CCTV truck operators communicating by radio, the pontoon was then pulled through the sewer. This method was used to inspect each manhole-to-manhole segment individually. These issues provide an example of the difficulties that can be encountered when conducting an inspection of a large-diameter line.

4.2 Zoom Camera

Zoom camera inspection was carried out in the Gracemor subdivision primarily during the week of August 9-14, 2010. The crew also inspected manholes and pipe segments in the Line Creek interceptor with limited success; the depth of some manhole structures in Line Creek exceeded the length of the zoom camera pole (24-ft). The inspection work was completed two weeks later on August 26th. Figures 4-3 and 4-4 show the manholes accessed for inspection at Gracemor and Line Creek, respectively. The total length of pipe to be inspected was not established prior to start of the work; the vendor inspected as much as possible during the allotted time.

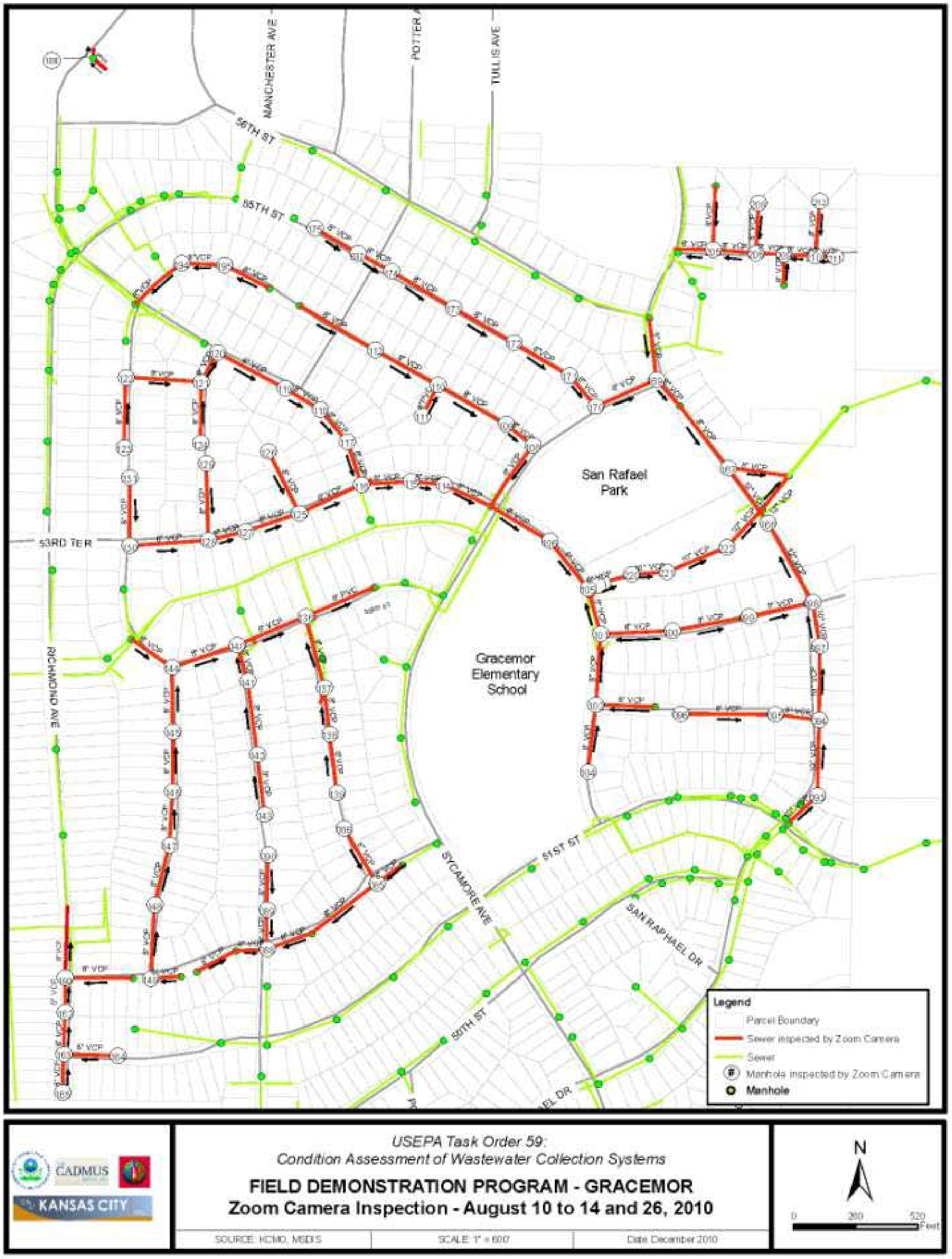


Figure 4-3. Pipe Segments Inspected by Zoom Camera in the Gracemor Area.

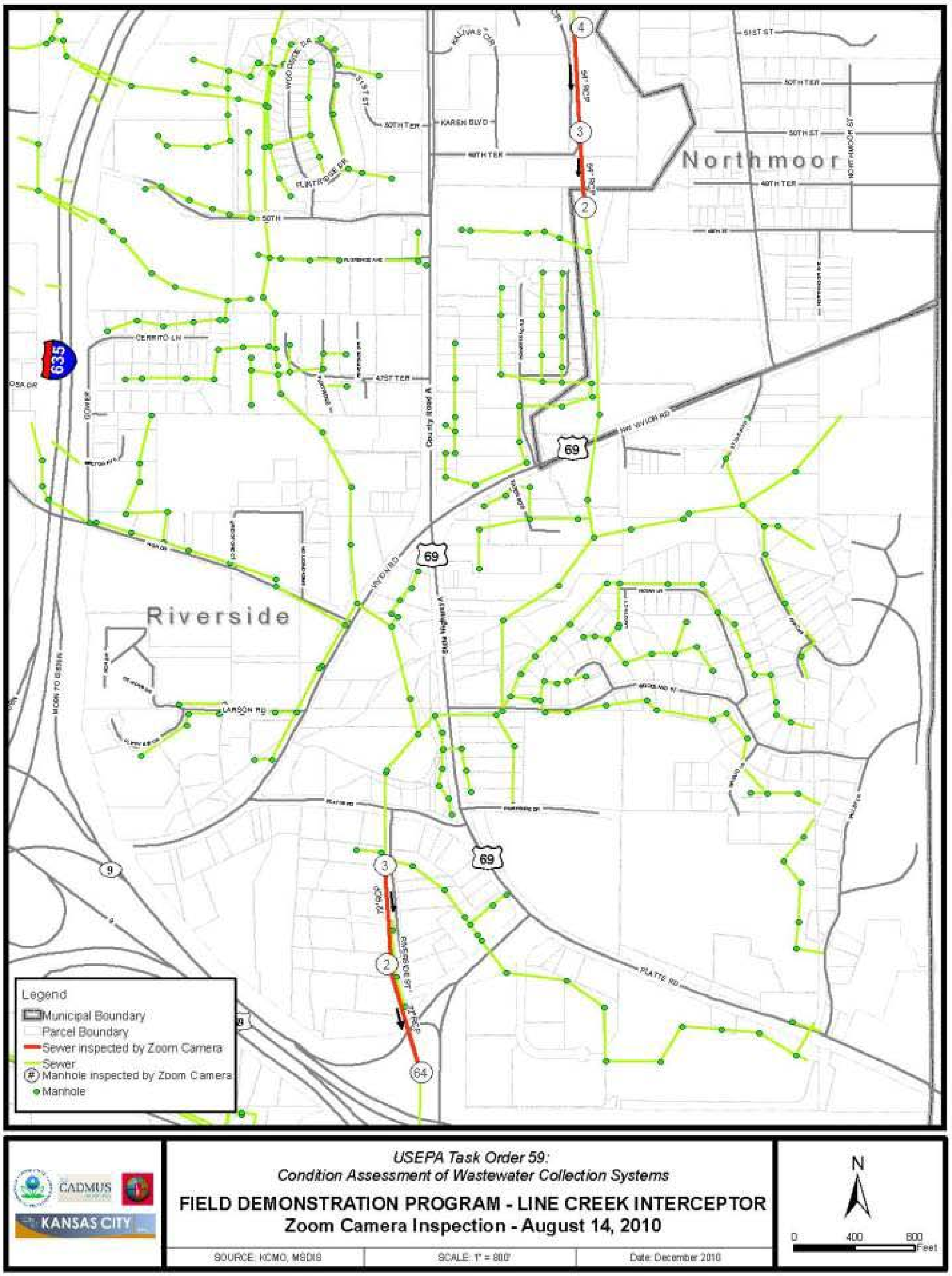


Figure 4-4. Pipe Segments Inspected by Zoom Camera in the Line Creek Interceptor.

4.2.1 Equipment Set-up and Deployment

To prepare for zoom camera inspection, the work area was first protected with traffic cones. Open manholes were always attended. Equipment assembly involved connecting the zoom camera cable to the control head/battery pack assembly and the control head cable to a laptop computer. The laptop computer was placed in the bed of the inspection truck with an improvised sun screen. Camera housing pressurization was verified using a separate carbon dioxide cylinder and regulator assembly.

The camera was calibrated at the start of each day by focusing the camera on an object (e.g., a curbstone) at a measured distance of 20-ft from the camera lens (Figure 4-5). The camera image was manually brought into sharp focus, and the 20-ft distance was set via the system software. No other calibration was needed.

Figure 4-5. Calibration of Zoom Camera to Measure Distance.

At each manhole, a tripod was placed over the manhole opening, and the telescoping pole was clamped to the tripod (Figure 4-6). The camera was lowered into the manhole and aligned with the pipe. Ideally, the centerline of the camera was brought into alignment with the centerline of the pipe. However, exact alignment was not necessary. The camera was mounted to the pole which is adjustable for elevation. This adjustment was made manually using a survey rod to move the camera. Windage (i.e., camera alignment in the horizontal plane) was adjustable. If the terrain around the manhole was not flat, the zoom camera was hand-held during inspection (Figure 4-7).

a) Lowering zoom camera into manhole. b) Use of stabilizing rod in shallow manhole.

c) Lowering tripod at deep manhole.

Figure 4-6. Zoom Camera Set-up at Manhole.

Figure 4-7. Hand-held Use of Zoom Camera.

4.2.2 Overview of Inspection Activities and Issues Encountered

The camera's electrical system malfunctioned during the early part of the week, resulting in significant slowdown and stoppage of inspection work. The field operational problems were resolved by using a replacement camera (same make and model) starting on Wednesday August 12th. After this change, the pace of the work increased to the anticipated production rate.

A number of issues were observed during the early part of the week. Objects in the pipe segments (e.g., spider webs, roots, and debris) caused the camera's autofocus feature to focus on them rather than the pipe wall. The camera's manual focus was inconsistent in its ability to sharpen the focus any further. The high temperature (approximately 100°F) likely contributed to equipment problems, including possible overheating of an electrical connection at the control head. A notable factor limiting the camera's sight distance was condensation inside the pipe ("headlights in fog" effect). This is a result of significant disparity between surface temperature and the temperature at the bottom of the manhole and is a function of the weather. The replacement camera eliminated the electrical and general performance issues encountered during the first two days of work. It did not eliminate the problem with condensation.

4.3 Electro-scanning

The electro-scanning inspection was performed in the Gracemor area during the week of August 23 - August 27. Figure 4-8 shows the pipe segments that were inspected.

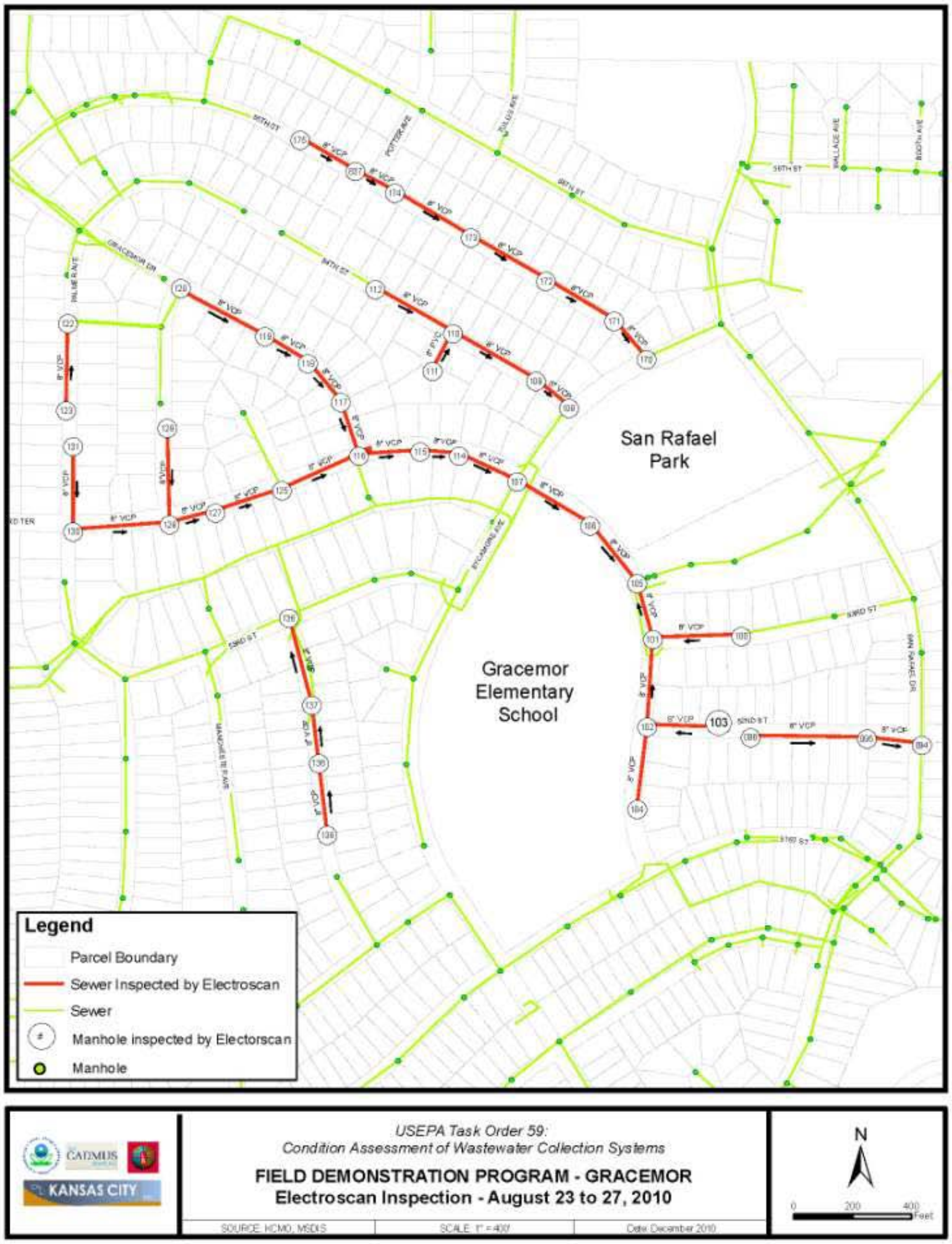


Figure 4-8. Pipe Segments Inspected by Electro-scanning in the Gracemor Area.

4.3.1 Equipment Set-up and Deployment

The only equipment calibration required was daily setting of the atmospheric pressure to ensure accuracy of the sonde's pressure transducer. The distance between the manholes of the pipe segment being scanned was measured using a measuring wheel.

When there was no pipe direction change at a manhole, it was often possible to pull the sonde from an upstream manhole, through an intermediate manhole, and into the downstream manhole. The maximum distance of such a pull was approximately 500-ft as determined by the amount of cable stored on the drum and/or the length of hose on the jet truck and the grade of the pipe. For any given section of sewer line, the sewer cleaning truck was set up at the downstream manhole. The sewer cleaning hose was propelled upstream and stopped at the upstream manhole. The hose was retrieved from the upstream manhole and the jet detached.

The jet hose used for this particular project did not have the 10-ft long steel mesh reinforced leader hose that is usually attached to the end of the jet hose. As a consequence, the hose was too flexible for the usual manhole retrieval method and for manholes greater than 10-ft deep, hose retrieval was laborious and generally required two people (Figure 4-9). At two manholes greater than 18-ft deep, a third person was needed to manhandle the jet hose out of the manhole.

Figure 4-9. Retrieval of the Sewer Cleaning Hose During Electro-scanning Inspection.

The cone-shaped traveling plug was then attached to the hose in place of the jet. A 6-ft long lanyard was attached between the plug and the sonde. The sonde was tethered to the cable drum by its electric cable. The jet truck operator was signaled to spool back the hose, and the traveling plug was drawn approximately 3-ft into the downstream pipe. The sonde was placed into the center of the manhole, and water from the sewer cleaning truck was pumped into the manhole. Sufficient water was introduced to fill the manhole to 3-in. to 4-in. above the crown of the upstream pipe. As the manhole structure filled, a lightweight roller guide was positioned inside the manhole to center the cable in the bore of the pipe to prevent fouling or cable abrasion by the pipe wall. A second cable guide was used to direct the cable at the manhole opening (Figure 4-10). A plug was also installed at the outlet of the downstream manhole.

When surcharged conditions were achieved as indicated visually and by the sonde pressure transducer reading, the sewer cleaning truck was signaled to pull the sonde downstream, advancing at a rate of approximately 30 ft per min. In this demonstration, travel rates varied from 13 ft per min. to 50 ft per min. based on pipe segment lengths of 200-ft to 500-ft. Pressure, leakage current, and sonde travel distance were displayed and recorded by the laptop computer. The sonde was halted as it approached the center of the downstream manhole. The previously installed plug retained water in the structure, preserving surcharged conditions as the traveling plug exited the pipe ahead of the sonde. In this way, a complete record was made of the entire length of pipe. The sonde was detached from the plug assembly and was drawn back to the upstream manhole by the motorized cable drum.

Figure 4-10. Electro-scanning Cable Guide Set-up at Manhole Opening.

4.3.2 Overview of Inspection Activities and Issues Encountered

The electro-scanning inspection progressed as planned without any significant problems except for the unavailability of a jetting truck or other supplemental water supply on the fifth day. This restricted the amount of scanning of 10-in. pipes.

The most effective method of electro-scanning 8-in. pipes was to use a jet truck. Most 8-in. pipes had flows of less than 10% and the jet hose was the quickest way to “string a line” from one manhole to the next. For pipes with low flows, the jet truck was also the most convenient method of surcharging the pipe in the region of the sonde. For the manholes greater than 12-ft deep, it was often difficult to retrieve the jet due to the lack of the steel reinforced hose leader. One minor equipment problem arose. On one occasion the cable became caught on the bottom manhole pulley causing damage to the cable and connector. This damage was repaired in the field in less than 30 min. At one location, according to the resident, a small puddle of water entered a basement through a floor drain. This may have been due to the use of the jet hose or an unusual drain configuration. Since the water level in the pipe did not exceed more than 8-in. above the top of the pipe, it is unlikely that this was caused by surcharging the pipe. Pressure was continually monitored to maintain the water head below the anticipated building invert elevations.

4.4 Multi-sensor Technology (Laser, Digital Scan, Sonar)

Inspection with the multi-sensor unit was conducted over the course of two days at the Line Creek Interceptor. Approximately 7,100-ft of 66-in. and 72-in. pipelines was inspected. Figure 4-11 shows the pipe segments inspected. The multi-sensor float was run from SMH-3 (starting point) to SMH-64 (ending point), which is located upstream of the Line Creek pump station.

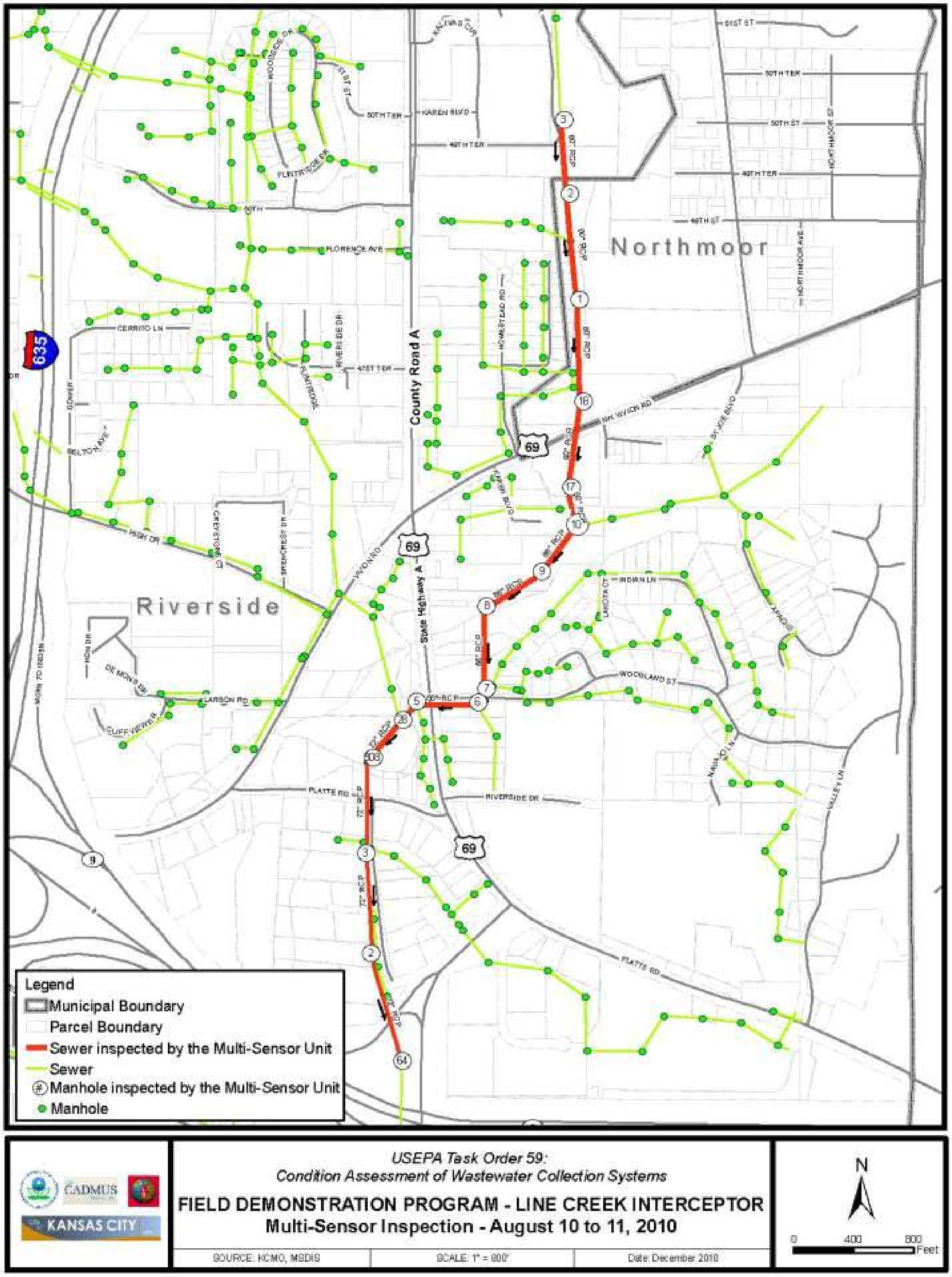


Figure 4-11. Pipe Segments Inspected by Multi-sensor Unit in the Line Creek Interceptor.

4.4.1 Equipment Set-up and Deployment

The set-up work involved establishing the base position for the project trailer and removing all the necessary equipment from the trailer and pickup bed to start assembling the float. The fully charged battery pods were installed on the float and connected to all components via the junction box.

The laser was calibrated at the start of each day to assure accurate measurement of the distance of the pipe wall from the laser. A 30-cm ruler was temporarily attached to the unit at a fixed distance from the laser to calibrate distance (Figure 4-12).

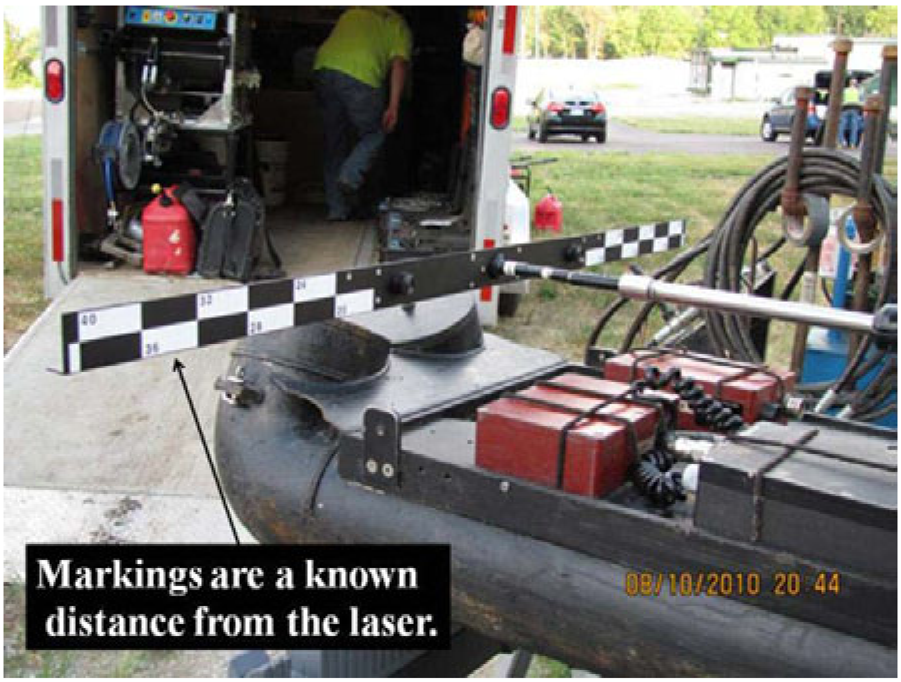


Figure 4-12. Calibration Device for the Laser.

Deployment of the multi-sensor unit requires human entry to orient the float at the bottom of the manhole and launch it. Standard procedures for confined space entry were followed. A safety tripod winch was placed over the starting manhole opening. A safety harness worn by the person entering the sewer was clipped onto the tripod winch with personnel staying above ground at the manhole to operate the winch and meet operational safety requirements. Figure 4-13 shows the float being lowered into the manhole, and Figure 4-14 shows the float after removal.

Figure 4-13. Lowering Multi-sensor Float into SMH 3 at Start of Work.

Figure 4-14. Float Set on Ground after Completion of Sewer Inspection Work.

The connections were verified for all electronic components via the stationary office inside the trailer. A portable laptop computer was connected to the nylon rope counter on the winch to indicate travel speed in real time (Figure 4-15). A travel speed of 15 ft per min. was achieved during the field demonstration.

Figure 4-15. Portable Laptop Computer Used for Multi-sensor Inspection.

4.4.2 Overview of Inspection Activities and Issues Encountered

The crew experienced difficulties common to large diameter sewer inspection. Many issues were related to the stability of the float assembly under turbulent flow conditions. The crew had difficulty inserting and removing the float assembly in the narrow manholes (24-in. diameter). The crew also experienced difficulties at manholes that had sudden changes in geometry (i.e., increase in slope, increase in velocity).

On the first day of inspection, the tether line for the drift sock (described in Section 3.4.2) became tangled with the wiring of the LED head. This damaged the wire connections to the light assembly. On day two, the float assembly flipped, damaging the lights and the sonar POD, causing a six-hour delay. All problems were resolved by the field crew except for the sonar control module. It was not immediately apparent when the unit stopped collecting data, and the crew had limited ability to review data in the field. The crew could only approximate the functionality of the sensors by the amount of data stored on the POD.

Another challenge specific to the multi-sensor unit was battery life. The battery packs lasted for approximately three hours, at the end of which the crew needed to remove the float assembly to replace the battery packs.

5. Summary of Field Results

This chapter presents field results for each of five condition assessment technologies plus the CCTV baseline. Results include the identification of defects, production rate, cost, and a comparison of duplicate runs. For the zoom camera, sight distance results are also presented. In Chapter 6, results for each technology are compared against the CCTV baseline and other technologies.

5.1 CCTV Baseline Evaluation

CCTV inspection was conducted on approximately 7,000-ft of pipelines at Gracemor and about 5,000-ft at Line Creek Interceptor. Defects were identified from CCTV images and coded using the PACP method (NASSCO, 2001). The PACP method grades defects using a scale of 1 to 5, where 1 represents the best condition and 5 represents the most severe defect. "PACP grades are as follows:

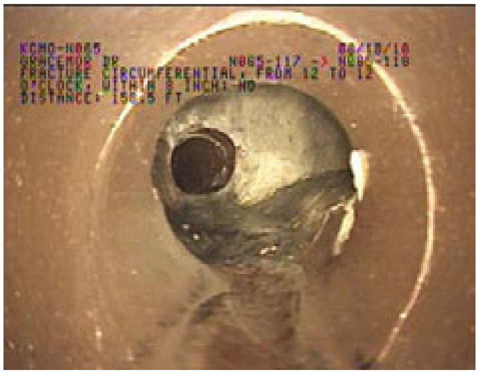
- Grade 5 – Immediate Attention. Defects requiring immediate attention.
- Grade 4 – Poor. Severe defects that will become Grade 5 defects in the foreseeable future.
- Grade 3 – Fair. Moderate defects that will continue to deteriorate.
- Grade 2 – Good. Defects that have not begun to deteriorate.
- Grade 1 – Excellent. Minor defects. (NASSCO, 2001)

5.1.1 Summary of Defects

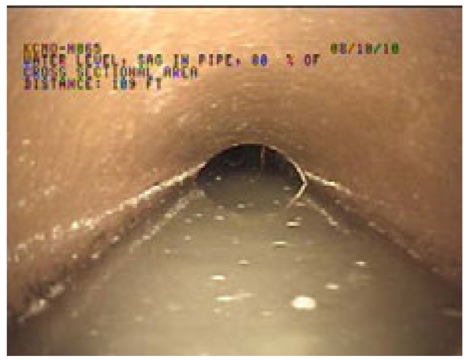
This section summarizes defects identified by the CCTV inspection and provides a discussion of production rates and costs.

Gracemor

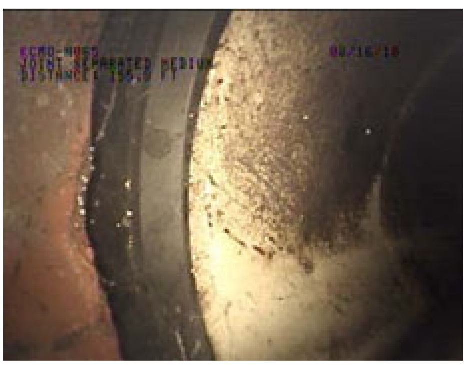
In the Gracemor area, the CCTV inspection identified structural and O&M defects and documented the location of service taps. Cracks, fractures, and broken pipe were the most common structural defects observed. Several minor pipe sags were also seen. These are common findings for established residential areas. Examples of structural defects observed at Gracemor in this demonstration are shown in Figure 5-1.



(a) Circumferential Fracture, Grade 2 Defect (b) Broken Pipe, Grade 5 Defect



(c) Longitudinal Crack, Grade 2 Defect (d) Pipe Sag, Grade 5 Defect

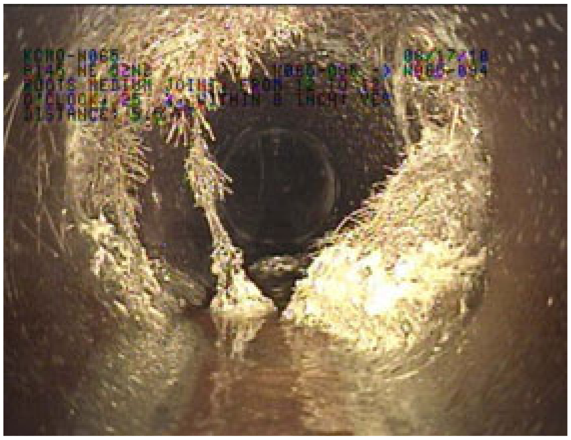


(e) Separated Joint, Grade 1 Defect

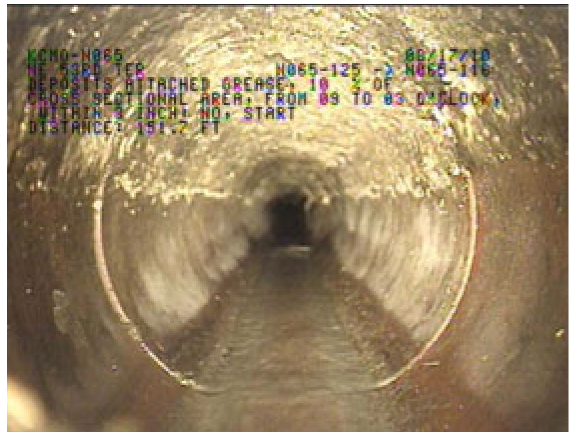
Figure 5-1. Examples of Structural Defects Identified From CCTV Images for the Gracemor Area.

Photos Courtesy of Ace Pipe Cleaning, Inc.

The CCTV inspection findings were consistent with the utility's assessment of the Gracemor area based on historical maintenance activities. Video images documented that root intrusion continues to be a problem in the service area. O&M defects identified by CCTV inspection included roots, grease deposits and defective taps. Examples of O&M defects observed at Gracemor are shown in Figure 5-2.



(a) Root Intrusion, Grade 3 Defect



(b) Grease Deposit, Grade 2 Defect

(c) Defective Tap, Grade 3 Defect

Figure 5-2. Examples of O&M Defects Identified From CCTV Images for the Gracemor Area.
Photos courtesy of Ace Pipe Cleaning, Inc.

In addition to the basic grading of defects, the PACP also uses several indices to characterize the overall condition of a pipe segment. These indices are based on the number of occurrences for each grade of defects. The structural pipe rating index (SPRI) and maintenance pipe rating index (MPRI) discussed in this section are calculated by dividing the overall pipe rating by the number of defects and signify the distribution of defect severity over each pipe segment. These indices use the same 1 to 5 scale as the defect grades discussed previously where a 1 indicates excellent condition and a 5 indicates severe defects and a deteriorated condition. An SPRI or MPRI of 0 indicates that no defects were observed on the pipe segment.

SPRI results (Table 5-1) show that 18 of 33 pipe segments, representing approximately 60% of the inspected pipe length, currently have a deteriorated structural condition (Grades 3-5).

Table 5-1. Gracemor CCTV Findings on Overall Structural Condition.

Defect Grade Assigned for SPRI	Pipe Length (ft)	% of Total Pipe Length Inspected	No. Pipe Segments
0: No Defects	1,438	20.5	8
1: Excellent	328	4.7	1
2: Good	1,069	15.3	6
3: Fair	1,765	25.2	8
4: Poor	1,947	27.8	8
5: Immediate Attention	462	6.6	2
Total	**7,009**	**100**	**33**

SPRI = structural pipe rating index

MPRI data (Table 5-2) show that 89% of the pipelines are in good to excellent condition in terms of O&M issues.

Table 5-2. Gracemor CCTV Findings on Overall Maintenance Condition.

Defect Grade Assigned for MPRI	Pipe Length (ft)	% of Total Pipe Length Inspected	No. Pipe Segments
0: No Defects	679	9.7	4
1: Excellent	1,004	14.3	4
2: Good	4,571	65.2	19
3: Fair	590	8.4	5
4: Poor	165	2.4	1
5: Immediate Attention	0	0	0
Total	**7,009**	**100**	**33**

MPRI = Maintenance Pipe Rating Index

Line Creek Interceptor

The CCTV inspection of the Line Creek Interceptor identified maintenance defects in most pipe segments. No structural defects were detected. The prominent maintenance defects noted were damaged service taps and encrustation (i.e., deposits left by the evaporation of infiltrating groundwater containing dissolved salts (NASSCO, 2001). Examples of maintenance defects observed in the Line Creek Interceptor are illustrated in Figure 5-3. Based on the difficulties encountered with the CCTV crawler and pontoon, some debris is known to exist in the Line Creek Interceptor. However, traditional CCTV inspection cannot effectively document or quantify defects below the water surface such as sediment or other settled debris.

(a) Encrustation Grade 2 Defect (b) Damaged Service Tap, Grade 2 Defect

Figure 5-3. Examples of Maintenance Defects Identified From CCTV Images for the Line Creek Interceptor.

Photos courtesy of Ace Pipe Cleaning, Inc.

Five pipe segments representing more than 37% of the inspected pipe length were assigned a MPRI of 3 or 4, indicating fair or poor maintenance condition. Additional information on MPRI results is summarized in Table 5-3. The SPRI was 0 for all pipe segments.

Table 5-3. CCTV Findings for Overall Maintenance Condition of Line Creek Interceptor.

Defect Grade Assigned for MPRI	Pipe Length (ft)	% of Total Pipe Length Inspected	No. Pipe Segments
0: No Defects	1,069	21.1	3
1: Excellent	0	0	0
2: Good	2,096	41.4	4
3: Fair	1,412	27.9	3
4: Poor	487	9.6	2
5: Immediate Attention	0	0	0
Total	**5,064**	**100**	**12**

MPRI = Maintenance Pipe Rating Index

5.1.2 Production Rate and Cost

Gracemor

The CCTV inspection of the Gracemor area included 7,009-ft of 8-in. to 12-in. sewers (See Figure 4-1 for a map of inspected pipelines, and Tables 5-4 and 5-5 for inspection lengths by pipe diameter and date). The crew did not work full days on August 18^{th} or August 19^{th};

therefore, the total production time was estimated to be 3.5 days, for an average production rate of 2,003-ft per day.

Table 5-4. Gracemor CCTV Inspection Summary.

Pipe Diameter (in.)	Total Inspection Length (ft)
8	4,292
10	2,283
12	434
Total	**7,009**

Table 5-5. Gracemor CCTV Inspection Schedule.

Date	Pipe Segments Inspected	Total Inspection Length (ft)
August 16, 2010	No. 1-9	1,709
August 17, 2010	No.10-18	1,895
August 18, 2010	No. 19-25	1,485
August 19, 2010	No. 26-33	1,920
Total	33	**7,009**
Average		**2,003**[1]

[1] Average based on 3.5 days work.

The total cost for the CCTV baseline evaluation at the Gracemor area was $19,614 or $2.80 per ft. This work included light cleaning and root cutting in addition to equipment deployment, inspection, and report preparation. Sewer cleaning costs included $7,600 for a jet truck and $1,500 for water service.

Line Creek Interceptor

The CCTV baseline evaluation of the Line Creek Interceptor included inspection of 5,064-ft of sewer (See Figure 4-2 for a map of inspected pipelines, and Tables 5-6 and 5-7 for inspection lengths by pipe diameter and date). As described in Chapter 4, the crew experienced difficulties inspecting this pipeline on the first two days due to debris in the pipe invert. The total production rate of 2,026-ft per day is based on 3 days of work, discounting for the first 2 days where no measurable progress was achieved.

Table 5-6. CCTV Inspection of Various Pipe Diameters at Line Creek Interceptor.

Pipe Diameter (in.)	Total Inspection Length (ft)
60	2,779
66	1,796
72	489
Total	**5,064**

Table 5-7. CCTV Inspection Schedule at Line Creek Interceptor.

Date	Pipe Segments Inspected	Total Inspection Length (ft)
August 16, 2010	none	0
August 17, 2010	none	0
August 18, 2010	No. 1-3	1,832
August 19, 2010	No. 4-8	2,276
August 20, 2010	No. 9-12	956
Total	12	**5,064**
Average Daily	4	**1,688**

For the Line Creek Interceptor, the total cost for the CCTV baseline evaluation was $15,192 or $3.00 per ft. This work included equipment deployment, inspection, and report preparation but no pre-cleaning.

5.2 Zoom Camera Inspection

This section presents zoom camera performance results including sight distance, defect identification, production rate and cost. A comparison of zoom camera performance results with other technologies is provided in Chapter 6.

In the Gracemor area, zoom camera inspection of connecting pipelines at 81 manholes (Figure 4-3) was conducted from August 10th through 14th, and on August 26th. Pre-cleaning was not performed prior to the inspection.

The zoom camera inspection of the Line Creek Interceptor was conducted on August 14, 2010 from two manholes (See Figure 4-4 for a map of inspected pipelines). Four additional manholes were opened but not inspected because the depth of the manhole structures was greater than 30-ft, exceeding the practical extension limit of the 24-ft pole on which the camera was mounted. Pre-cleaning was not conducted prior to the inspection.

5.2.1 Sight Distance

Gracemor

Although the 81 manholes provided access to more than 22,000-ft of connecting pipelines, zoom camera images were obtained for only 4,595-ft (approximately 20% of the total length). The maximum sight distance observed in an 8-in. VCP line was between 65-ft and 105-ft, according to the zoom camera. Sight distance was reported as a range within which the camera is in focus. Table 5-8 summarizes sight distance results for the Gracemor area. Most 8-in. pipe segments had a sight distance of less than 50-ft and only a few pipes had a sight distance range up to 105-ft. All occurrences of the 105-ft sight distance in 8-in. pipe were achieved on Wednesday, August 12th, the first day that the replacement camera (same make and model) was used. These results may also be due to the cleanliness and configuration (i.e., straightness, lack of obstructions) of the pipelines inspected that day. The maximum sight distance obtained in 10-in. and 12-in. pipe was 50-ft. The lengths of pipeline between manholes were verified against as-built drawings or field measurements.

Table 5-8. Zoom Camera Sight Distance Results for Gracemor.

Pipe Diameter (in.)	Sight Distance Each Manhole (ft)	Total Sight Distance (ft)	Pipeline Length Between Manholes Accessed (ft)	Total Pipeline Length Between Manholes Accessed (ft)	% of Pipeline Inspected
8	1-105	4,170	13-405	20,350	20.5
10	25-50	230	103-316	1,120	20.5
12	15-50	195	144-328	1,268	15.4
Total	**--**	**4,595**	**--**	**22,738**	**20.2**

Sight distance was limited by spider webs, fine roots, and debris in the pipeline. Also, sight distance was reduced by condensation on the camera lens caused by the temperature differential between the ground and subsurface. Condensation was evident in the sewer lines due to the extremely hot outside temperature and cooler temperature in the pipes. Although the camera operators experimented with both manual and automatic modes for focusing as well as standard and fish-eye camera lenses, they were unable to improve the camera's sight distance.

The sight distance results listed in Table 5-8 were obtained by analysis of zoom camera video images following the field inspection. The data technician determined the range within which the camera was in focus, and the reported sight distances represent the upper value in this range. The project team's field representatives attempted to verify the camera sight distance results by reviewing zoom camera images on a laptop in the field, counting visible pipe joints and estimating sight distance by assuming a standard length for each pipe segment (e.g., 5-ft sections of 8-in. VCP). However, the field analysis and this estimation method based on counting joints have limitations. In the field, depending on the light conditions, it was often more difficult to view zoom camera images on the laptop screen as compared to an office environment. As the camera zoomed farther down the pipe, the joints appeared to be closer together, making it difficult to count the number of visible joints.

Line Creek Interceptor

The two manholes accessed for zoom camera inspection in the Line Creek Interceptor had 2,855-ft of connecting pipelines. However, the actual length of pipeline inspected was 245-ft (9% of the total length). Inspection results (Table 5-9) show that the sight distance ranged from 35-ft to 140-ft in the 72-in. pipe, and was 25-ft in the one 60-in. pipe segment inspected. Similar to the Gracemor demonstration tests, the camera's sight distance was limited by heavy condensation on the camera lens.

Table 5-9. Line Creek Interceptor Zoom Camera Inspection Sight Distance Results.

Pipe Diameter (in.)	Sight Distance Each Manhole (ft)	Total Sight Distance (ft)	Pipeline Length Between Manholes Accessed (ft)	Total Pipeline Length Between Manholes Accessed (ft)	% of Pipeline Inspected
60	25	25	695	695	3.6
72	35-140	220	700-749	2,160	10.2
Total	**--**	**245**	**--**	**2,855**	**8.6**

5.2.2 Summary of Defects

The zoom camera inspection videos were imported into the Granite XP asset inspection software for reviewing images and coding defects using PACP specifications.

In the Gracemor area, no defects were observed in 70 of the 162 pipe segments inspected. For the remaining 92 pipe segments, a total of 121 defects was identified. Eighty-five of these defects (approximately 70% of the total defects) were maintenance type defects including root intrusion (72 defects) and sediment deposition (13 defects). The remaining 36 defects (approximately 30% of total defects) were structural defects including:

- Off-set joints (6 defects);
- Fractures (7 defects);
- Cracks (13 defects);
- Broken pipe (2 defects);
- Protruding joint seals (5 defects); and
- Intruding service taps (3 defects).

Figures 5-4 and 5-5 illustrate the types of maintenance and structural defects, respectively, found in the Gracemor area.

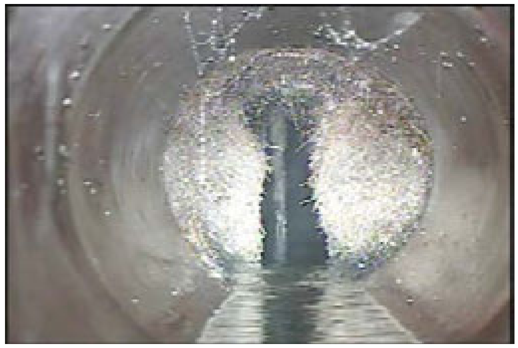
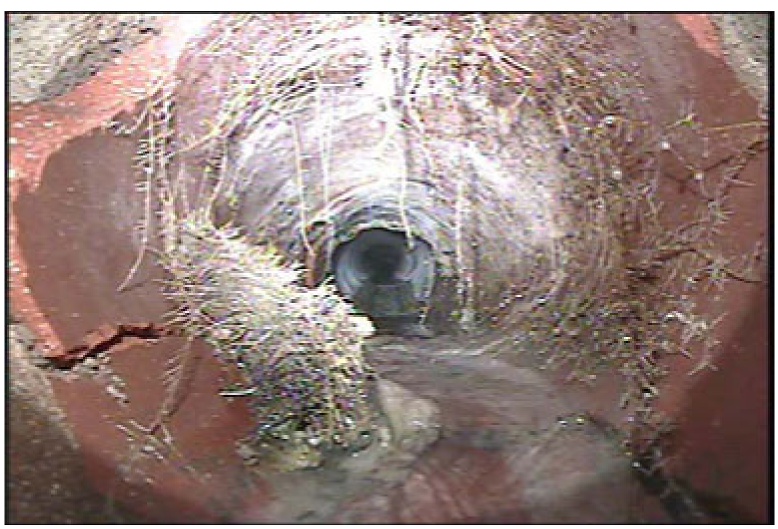


Figure 5-4. Grade 4 Root Intrusion (Maintenance Defect) in MH 100-101 Identified from Zoom Camera Images in the Gracemor Area.
(Photos Courtesy of TREKK Design Group)

(a) Grade 2 Off-set joint in MH 136-137

(b) Grade 2 Circumferential Fracture in MH 125-127



(c) Grade 3 Broken Pipe in MH 127-128

Figure 5-5. Examples of Structural Defects Identified from Zoom Camera Images in the Gracemor Area.
(Photos Courtesy of TREKK Design Group)

In the Line Creek Interceptor area, no defects were observed in 2 of 3 pipe segments inspected. One maintenance type defect was identified in the third pipe segment, a Grade 3 active infiltration defect. No structural defects were observed.

5.2.3 Production Rate

The production rate for zoom camera inspection depended on several factors including the initial daily set-up of the camera and associated equipment, daily calibration of the camera, equipment set-up at each manhole, inspection of the pipe, troubleshooting, and equipment repair. This evaluation of productivity did not include time for data analysis and reporting, which were completed post-inspection in the office. The time required to complete the various steps are summarized in Tables 5-10 and 5-11 for Gracemor and Line Creek Interceptor, respectively.

At Gracemor, the inspection time at each manhole ranged from 12 to 24 min. over the demonstration period. Longer inspection times (18 to 24 min.) on the first two days were attributed to equipment malfunction and troubleshooting. Continuing problems with the high temperatures and condensation in the manhole caused additional time for troubleshooting on days 3 and 4.

Table 5-10. Zoom Camera Production Results at Gracemor.

Date	Number of Manholes Accessed	Total Production Time (hrs)				Production Rate[1] (MH/hr)
		General Site Set-up and Camera Calibration	Equipment Set-up and Inspection at each Manhole	Troubleshooting and Equipment Repair Time	Total Time	
August 10, 2010	8	1.0	4.17	2.33	7.50	1.5
August 11, 2010	4	0.5	1.42	4.58	6.50	2.1
August 12, 2010	21	0.33	7.17	0.50	8.00	2.8
August 13, 2010	20	0.42	6.67	0.91	8.00	2.8
August 14, 2010	12	0.05	3.62	0	3.67	3.3
August 26, 2010	16	0.50	5.67	0	6.17	2.6
Total	**81**	**2.80**	**28.72**	**8.32**	**39.84**	**--**
Average Daily	**14**	**0.47**	**4.79**	**1.39**	**6.64**	**2.6**

[1] Number of manholes (MH) accessed divided by time for equipment set up and inspection. Down-time for troubleshooting and equipment repair not included.

General site set-up time at Line Creek Interceptor included time spent opening up several manholes that could not be inspected due to their depth.

Table 5-11. Zoom Camera Production Results at Line Creek Interceptor.

Number of Manholes Accessed for Inspections	Total Production Time (hrs)				Production Rate[1] (MH/hr)
	General Site Set-up and Camera Calibration	Equipment Set-up and Inspection at each Manhole	Troubleshooting and Equipment Repair time	Total Time	
2	1.25	1.0	0	2.25	0.9

[1] Number of manholes accessed divided by time for equipment set up and inspection. Down-time for troubleshooting and equipment repair not included.

5.2.4 Cost

The total cost of the zoom camera inspection at Gracemor and the Line Creek Interceptor was $25,356 including $2,257 for planning, $7,731 for field work, and $15,368 for data assessment and reporting. The cost of data analysis was approximately 61% of the total inspection cost. This value may be skewed higher because of the research-oriented nature of the demonstration program; the report included evaluation of items not typical of a zoom camera inspection report (i.e., sight distance, production rates). The total cost per manhole access was approximately $305 based on inspection of 83 manholes.

5.2.5 Duplicate Runs

The precision of the zoom camera inspection results was evaluated by conducting duplicate inspections of the 8-in. VCP pipe segment located between SMH 103 and SMH 102 which was 256-ft long. The first inspection collected images up to 10-ft from SMH 103 and observed a Grade 1 circumferential crack at 0-ft and an abandoned survey at 10-ft. The second inspection collected images up to 25-ft from SMH 103 and observed a Grade 1 circumferential crack at 4-ft and an abandoned survey at 25-ft.

5.3 Electro-scanning Inspection

The electro-scanning inspection covered over 8,000-ft of pipeline in the Gracemor area. This section presents performance results including identification of defects and anomalies, production rate and cost, repeatability of results, and a comparison of the FELL-41 model with the Mount Sopris prototype unit.

5.3.1 Summary of Defects

Inspection results are presented as graphs of electrode current (in units of amps) vs. distance along the pipe in units of ft (Figure 5-6). Increases in electrode current along the pipe length are considered to be anomalies and appear as spikes on the graph. These anomalies typically represent areas of potential leakage and may be a result of pipe defects, joint defects, faulty service connections, or defects at manholes. The type and severity of the suspected defect(s) associated with each anomaly are inferred based on the electric current amplitude, the length of the anomaly along the pipe, and the location along the pipe. For example, if pipe joint intervals are known and can be superimposed on the electrode current graph, anomalies that coincide with these joint locations would point to leaky joints. Anomalies that do not match joint locations may represent structural defects (e.g., cracks in the pipe) or leaks at service connections. Anomalies with amplitude of 1 to 4 are typically classified as small defects while anomalies with amplitude of 4 to 7 and greater than 7 are classified as medium or large defects, respectively.

The electro-scanning results suggest that all of the pipe segments inspected for this project have defects that are potential sources of infiltration or exfiltration. Summary statistics are provided in Table 5-12**,** and illustrated in Figure 5-6. Key results are as follows:

- ***Overall:*** 677 anomalies were detected, with an average of 17 per pipe segment. About 87% of anomalies were considered to represent small defects as defined above. When the anomalies were normalized as a percentage of pipe length, an average of 3.7% of the pipe length consisted of areas of potential leakage.
- ***Joint Defects***: 43% of all anomalies were interpreted to be caused by faulty pipe joints. The majority of the defects had a magnitude less than 3 which represents a small defect. Of all joints, only 15% were classified as defective. Pipe joints are considered to be in generally good condition and a minor source of infiltration and exfiltration.
- ***Service Connections***: 87% of the service connections detected showed defects. The amplitude of the defect peaks ranged from small to medium. It was concluded that the service connections are in poor condition and considered to be a significant source of infiltration and exfiltration.
- ***Manhole Connections***: 74% of the manhole pipe penetrations showed defects. The amplitude of the defects ranged from small to large. The manhole penetrations were shown to be in poor condition and are likely a major source of infiltration and exfiltration. It was also noted that the first and second pipe joint in the majority of segments showed defects. This may be attributed to settlement at the manholes.

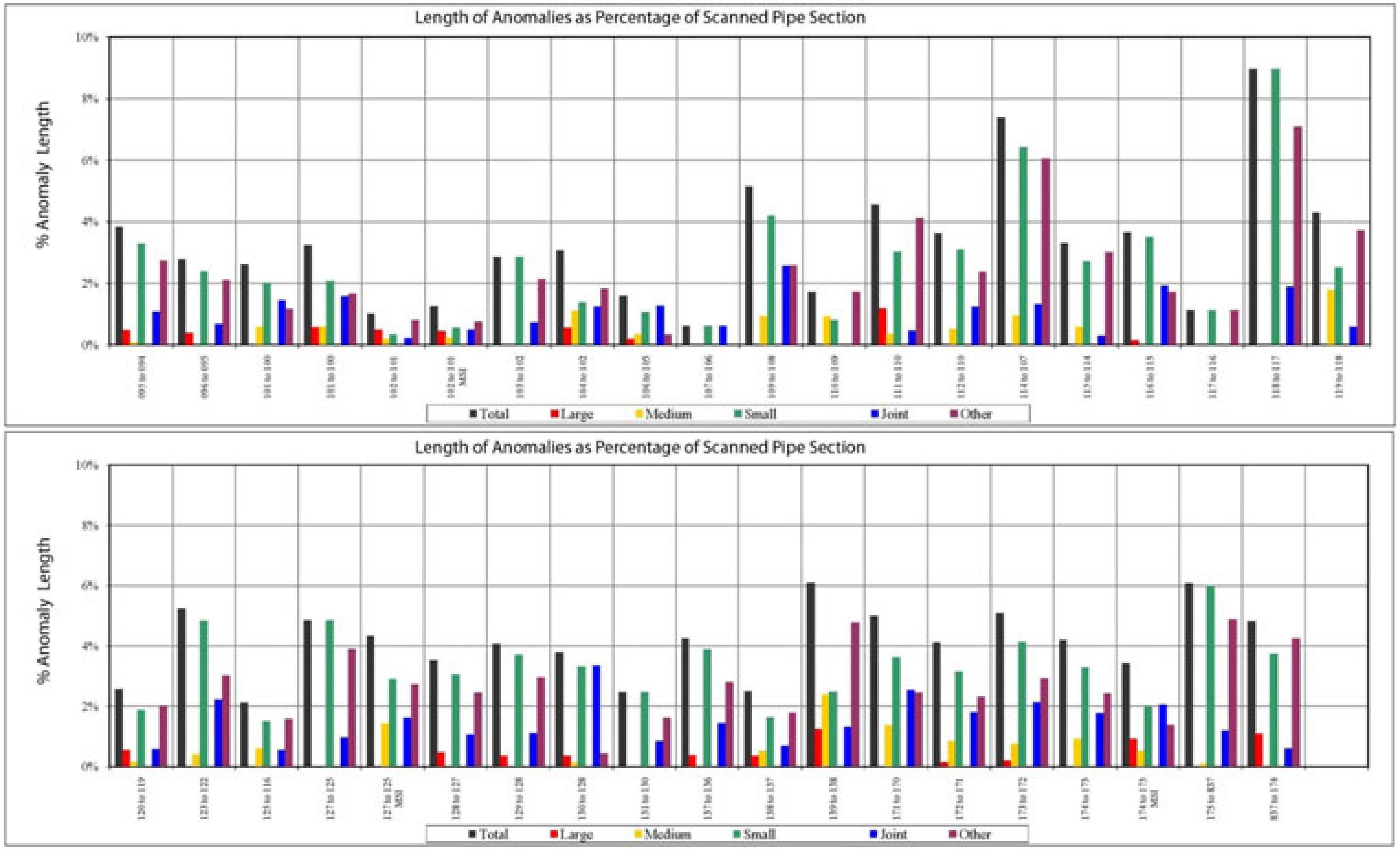
Table 5-12. Summary of Electro-scanning Data.

	Length (ft)	Number of Anomalies						% Anomaly Length of Pipe Tested						Joints		
		Grade			Type			Grade			Type				Defective	
		Large	Medium	Small	Joint	Other	Total	Large	Medium	Small	Joint	Other	Total	Total	Number	%
Total	9,783	36	51	590	294	383	677							1,907	282	14.8
Mean per pipe segment	250.8	0.9	1.3	15.1	7.5	9.8	17.4	0.3%	0.5%	3.0%	1.2%	2.5%	3.7%	48.9	7.2	15.7
SD	63.3	1.0	1.1	6.4	5.0	3.6	6.6	0.4%	0.6%	1.7%	0.8%	1.5%	1.7%	14.3	4.9	12.2
% of total		5.3	7.5	87.2	43.4	56.6										

SD = standard deviation

Electro-Scan Sewer Pipe Defect Identification
Sewer Condition Assessment Field Demonstration
Task Order 59 EPA Condition Assessment of Wastewater Collection Systems
City of Kansas City, Missouri

Appendix B



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Notes: (1) x-axis displays different type of defects (e.g., small, medium, large, total) at each pipe segment (e.g., MH 127-125).
(2) y-axis represents the length of each defect (i.e., anomaly) as a percentage of the scanned pipe length.

Figure 5-6. Length of Anomalies as Percentage of Scanned Pipe Section.

5.3.2 Production Rate

Production rates for each day of electro-scanning were calculated based on the length of pipeline inspected, and the estimated time for equipment set-up and inspection (Table 5-13). Down-time for troubleshooting, equipment repair, lunch breaks, on-site safety and planning meetings, weather delays and confined space entry were not included in the productivity calculations.

Table 5-13. Electro-scanning Production Rate.

Date	Work Duration (hr)	Equipment Set-up Time (hr)	Total Inspection Time (hr)	Down-Time (hr)	Total Pipeline Length Inspected (ft)	Production Rate (ft/hr)[1]
Aug. 23, 2010	9.0	5.0	3.0	1.0	1,765	221
Aug. 24, 2010	9.0	5.0	3.0	1.0	2,189	274
Aug. 25, 2010	9.5	4.0	4.0	1.5	1,981	264
Aug. 26, 2010	7.25	5.0	2.0	0.25	2,361	337
Aug. 27, 2010	4.5	3.5	1	0	511	113[2]
Total	**39.25**	**22.5**	**13.0**	**3.75**	**8,807**	**--**
Average	**7.85**	**4.5**	**2.6**	**0.75**	**1,761**	**242**

[1] Production rate equals total pipeline length divided by time for equipment set up and inspection. Down-time for troubleshooting, equipment repair, confined space entry and weather delays not included.
[2] Slower production rate was attributed to lack of flushing truck for surcharging pipe.

The time required to set up the equipment at a manhole pair, conduct the inspection, and move the equipment to the next manhole pair was as short as 30 to 45 min. under optimal conditions, but often took about an hour. The time could exceed two hours if difficulties were encountered. Setting up the flushing truck and sliding plug to surcharge the pipe generally took 20 to 30 min.; however, at some of the deeper manholes, it took longer to retrieve the hose and bullet as it arrived at the upstream manhole. In one case, human entry into a deep manhole was required to attach the plug to the hose and attach the sonde. On August 27th, the flushing truck was not used to surcharge the pipe as the pipelines had higher flow rates; however, without the flushing truck, it took more time to surcharge the pipe, affecting the overall daily production rate. The overall duration was also affected by equipment problems (e.g., damaged cables and connectors) and a thunderstorm. Equipment breakdown and travel to the next manhole pair generally took about 15 min.

The overall production rate for the 5 days of electro-scanning inspection was 260 ft/hr, but rates exceeded 300 ft/hr under good conditions.

5.3.3 Cost

The total cost of the electro-scanning inspection at Gracemor was $28,881 including $11,047 for planning/mobilization, $11,817 for field work, and $6,017 for data analysis and reporting. The total cost ($28,881) per total length of pipe assessed (9,784-ft) was $2.95 per ft.

5.3.4 Duplicate Runs

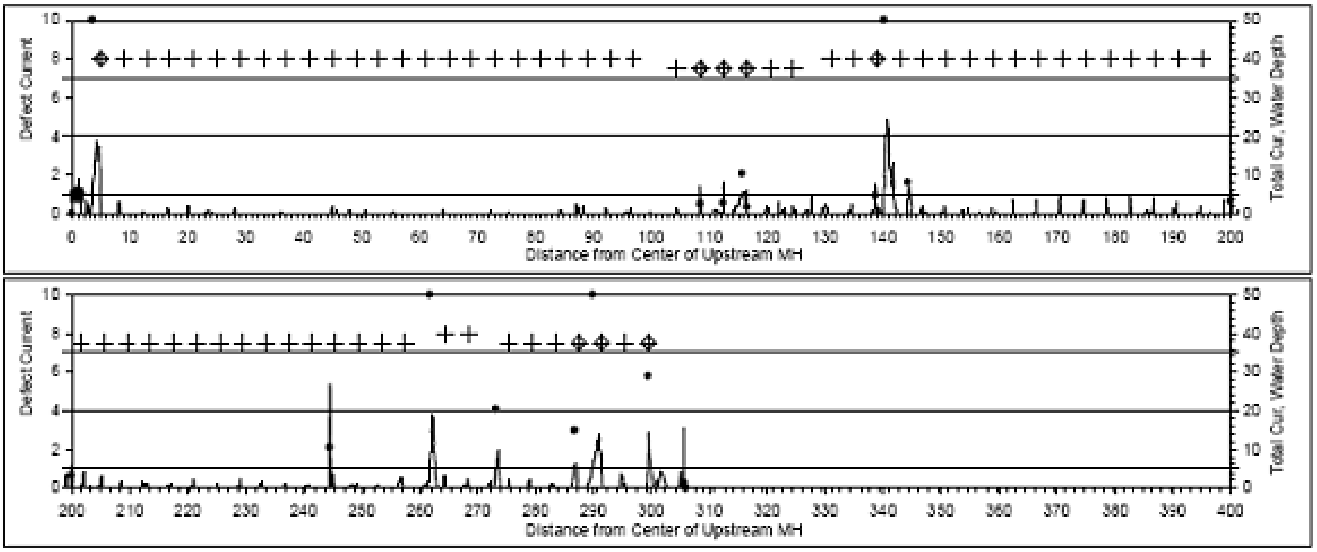
The precision of the electro-scanning results was evaluated by duplicate inspections of the pipe segment from SMH 101 to SMH 100 which was 306-ft long (See comparisons in Table 5-14 and Figure 5-7). The two scans were very similar; scan B revealed only three more defects than scan A. The two scans had several differences including a small defect at 29-ft, which is only seen in the second scan, and a defect at 6-ft, which had a higher electrode current in the second scan (i.e., a higher severity). The observed differences in results may be attributed to changes in the sonde's travel rate which occurred at the start and end of the scan. The high current at the end of the second scan may have been caused by a steel pole used to move the probe into the middle of the downstream manhole. Although the ground stake placement varied between the two scans, it was not expected to affect the results.

Table 5-14. Comparison of Scan A and Scan B Results for Pipe Segment SMH 101 to SMH 100.

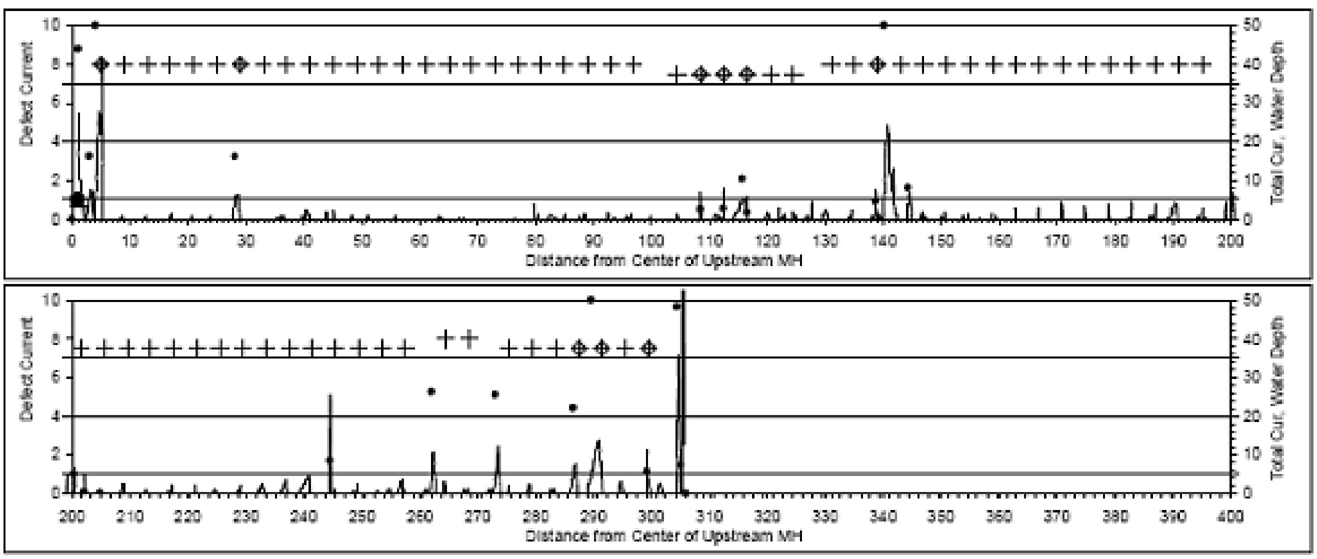
Scan	Anomaly Summary (Number of Defects)						Anomaly Length (% of Pipe Length Tested)						Joints (Number)	
	L	M	S	Joint	Other	Total	L	M	S	Joint	Other	Total	Total	Defects
A	0	2	16	9	9	18	0	0.6	2.0	1.4	1.2	2.6	71	8
B	2	2	17	10	11	21	0.6	0.6	2.1	1.6	1.7	3.3	71	9

L = large; M = medium; S = small

Scan A: Pipe Segment 101 to 100 with Ground Stake 10 ft from manhole 101 on sewer line



Pipe Segment 101 to 100 with Ground Stake 30 ft from manhole 101 perpendicular to sewer line



Notes: (1) x-axis represents the distance (ft) from the center of the upstream manhole (MH)
(2) y-axis represents the defect current (amplitude)

Figure 5-7. Duplicate Electro-Scans for Pipe Segment 101 to 100.

5.3.5 Comparison of Electro-scanning Models

Comparison of results for the FELL-41 and MSI-1620 electro-scanning systems obtained for three pipe segments (SMH 102 to SMH 101; SMH 127 to SMH 125; and SMH 174 to SMH 173) shows that the FELL-41 generally registered more increases in electrode current than the MS-1620 (Tables 5-15, 5-16, and 5-17; Figures 5-8, 5-9 and 5-10). Figures 5-8, 5-9, and 5-10 show more small current spikes, some of which exceeded the threshold and are listed as small defects. Anomalies that are seen on the traces for both instruments tend to be greater on the FELL-41 results. For example, in pipe segment 102-101, small joint defects at 74-ft, 100-ft, and 287-ft detected by the FELL-41 system were not detected above the threshold by the MSI-1620. However, current spikes at the pipe entry for SMH 101 were significantly greater for the FELL-41. For the segment from SMH 127 to SMH 125, FELL-41 detected small joint defects at 6-ft, 175-ft, and 185-ft. These were not detected above the threshold by the MSI-1620. These results suggest that the FELL-41 unit may be more sensitive than the MSI-1620.

Table 5-15. Comparison of FELL-41 and MSI-1620 Results (SMH 102 to SMH 101) (Distance 294-ft).

	Anomaly Summary (Number of Defects)						Anomaly Length of Pipe Length Tested (%)						Joints (Number)	
Scan	**Large**	**Med.**	**Small**	**Joint**	**Other**	**Total**	**Large**	**Med.**	**Small**	**Joint**	**Other**	**Total**	**Total**	**Defects**
FELL	2	1	7	5	5	**10**	0.5	0.2	0.3	0.2	0.8	**1.06**	**63**	5
MSI	1	1	4	2	4	**6**	0.5	02	0.6	0.5	0.8	**1.3**	**63**	2

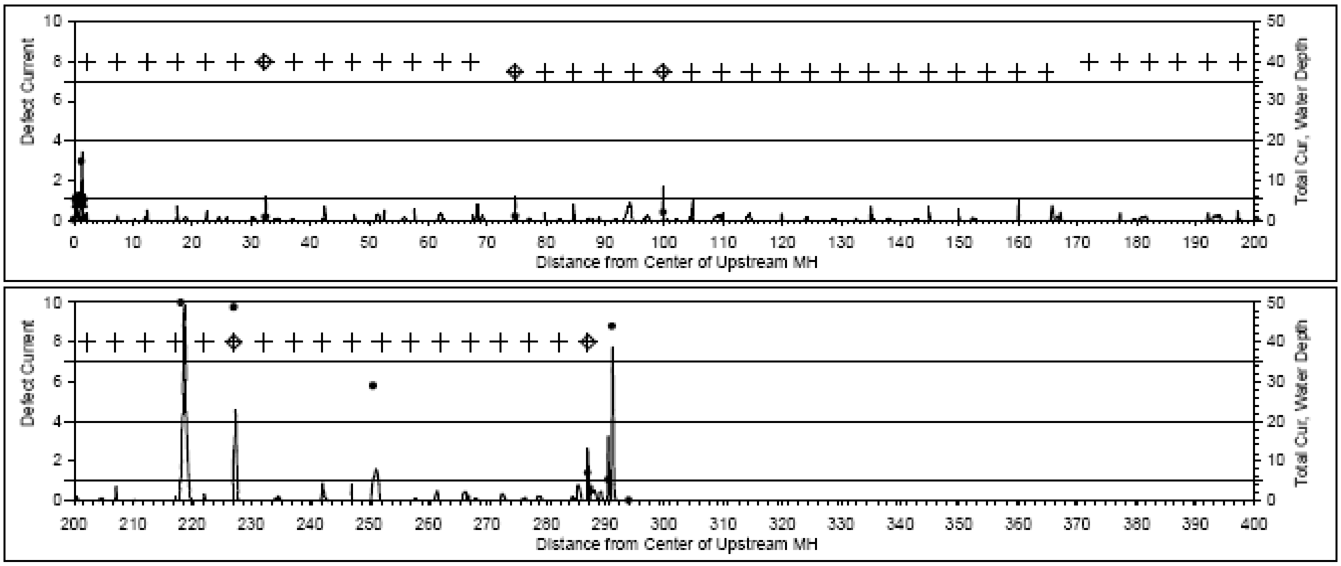
Table 5-16. Comparison of FELL-41 and MSI-1620 Results (SMH 127 to SMH 125) (Distance 222-ft).

	Anomaly Summary (Number of Defects)						Anomaly Length of Pipe Length Tested (%)						Joints (Number)	
Scan	**Large**	**Med.**	**Small**	**Joint**	**Other**	**Total**	**Large**	**Med.**	**Small**	**Joint**	**Other**	**Total**	**Total**	**Defects**
FELL	1	0	22	7	16	**23**	0	0	4.9	1.0	3.9	**4.9**	**51**	7
MSI	0	2	9	4	7	**11**	0	1.4	2.9	1.6	2.7	**4.3**	**51**	4

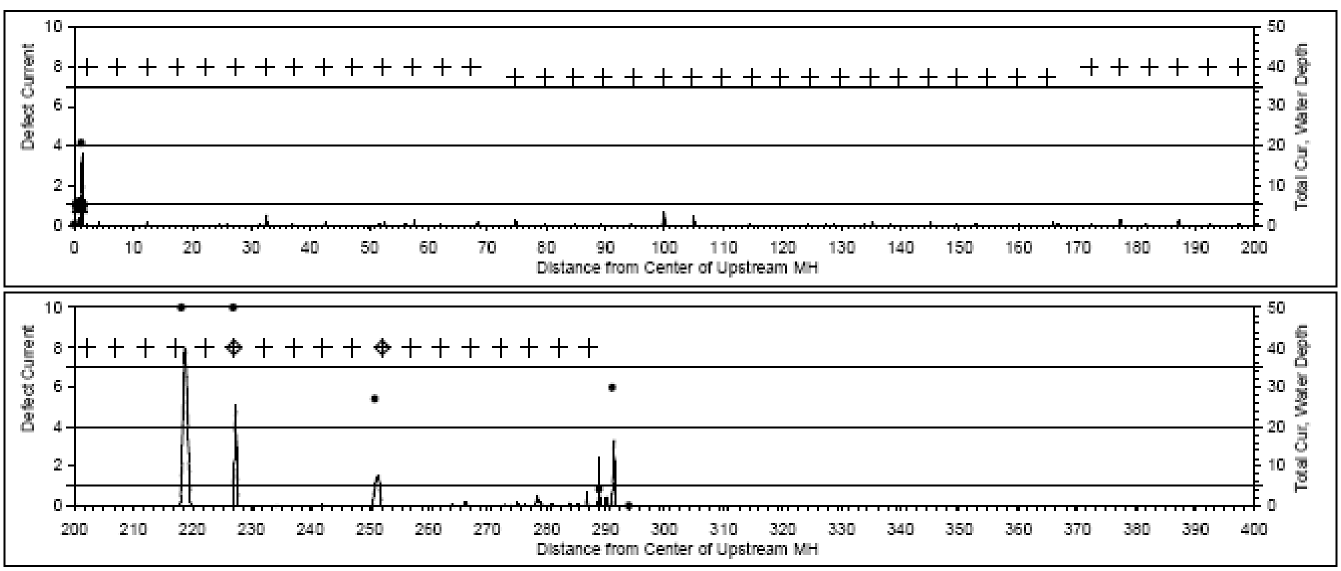
Table 5-17. Comparison of FELL-41 and MSI-1620 Results (SMH 174 to SMH 173) (Distance 278-ft).

	Anomaly Summary (Number of Defects)						Anomaly Length of Pipe Length Tested (%)						Joints (Number)	
Scan	**Large**	**Med.**	**Small**	**Joint**	**Other**	**Total**	**Large**	**Med.**	**Small**	**Joint**	**Other**	**Total**	**Total**	**Defects**
FELL	0	4	14	8	10	**18**	0	0.9	3.3	1.8	2.4	**4.2**	**52**	8
MSI	1	2	13	6	10	**16**	0.9	0.5	2.0	2.0	1.4	**3.4**	**52**	6

FELL-41™ Electro-Scan for Pipe Segment 102 to 101

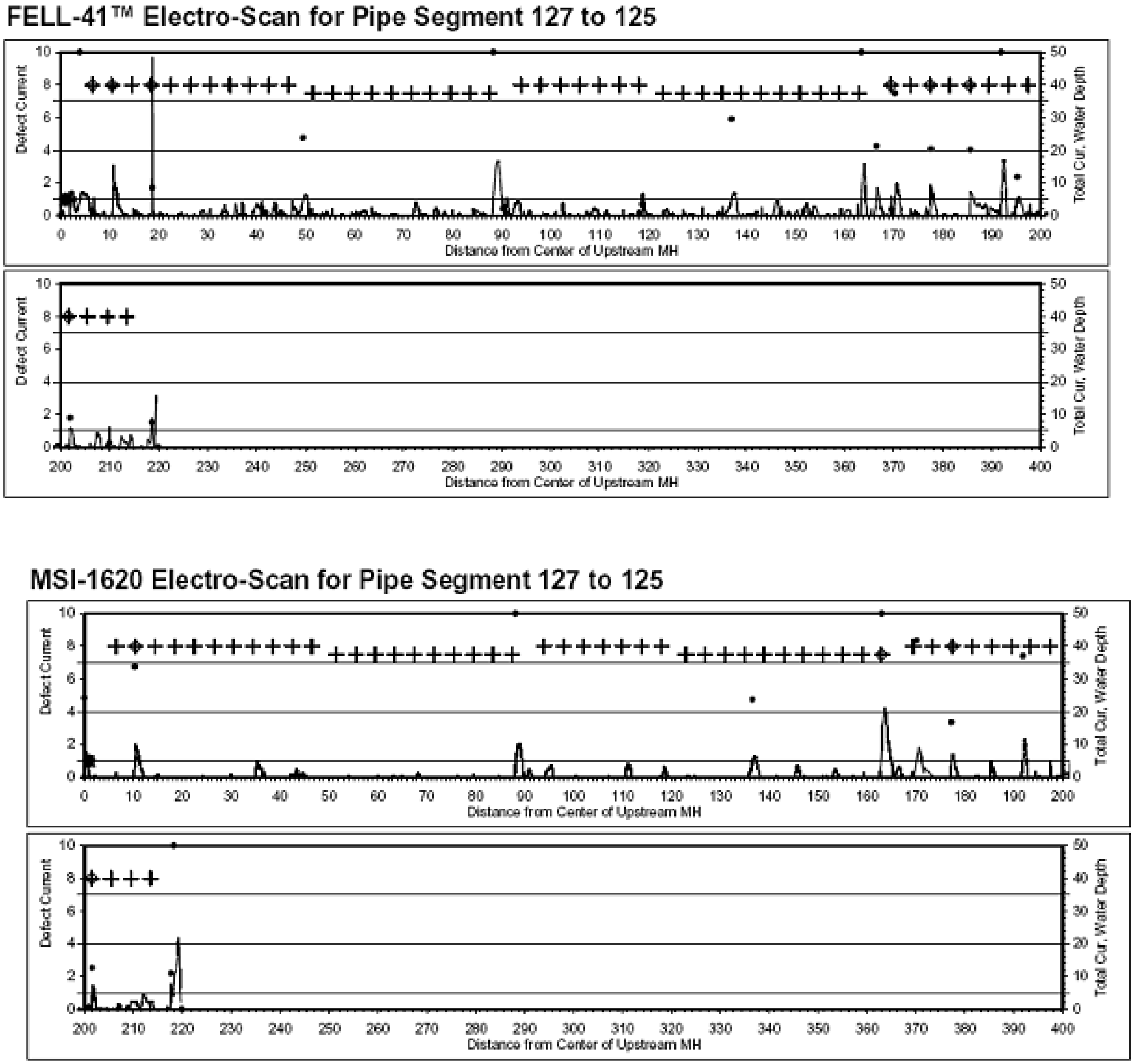


MSI-1620 Electro-Scan for pipe segment 102 to 101



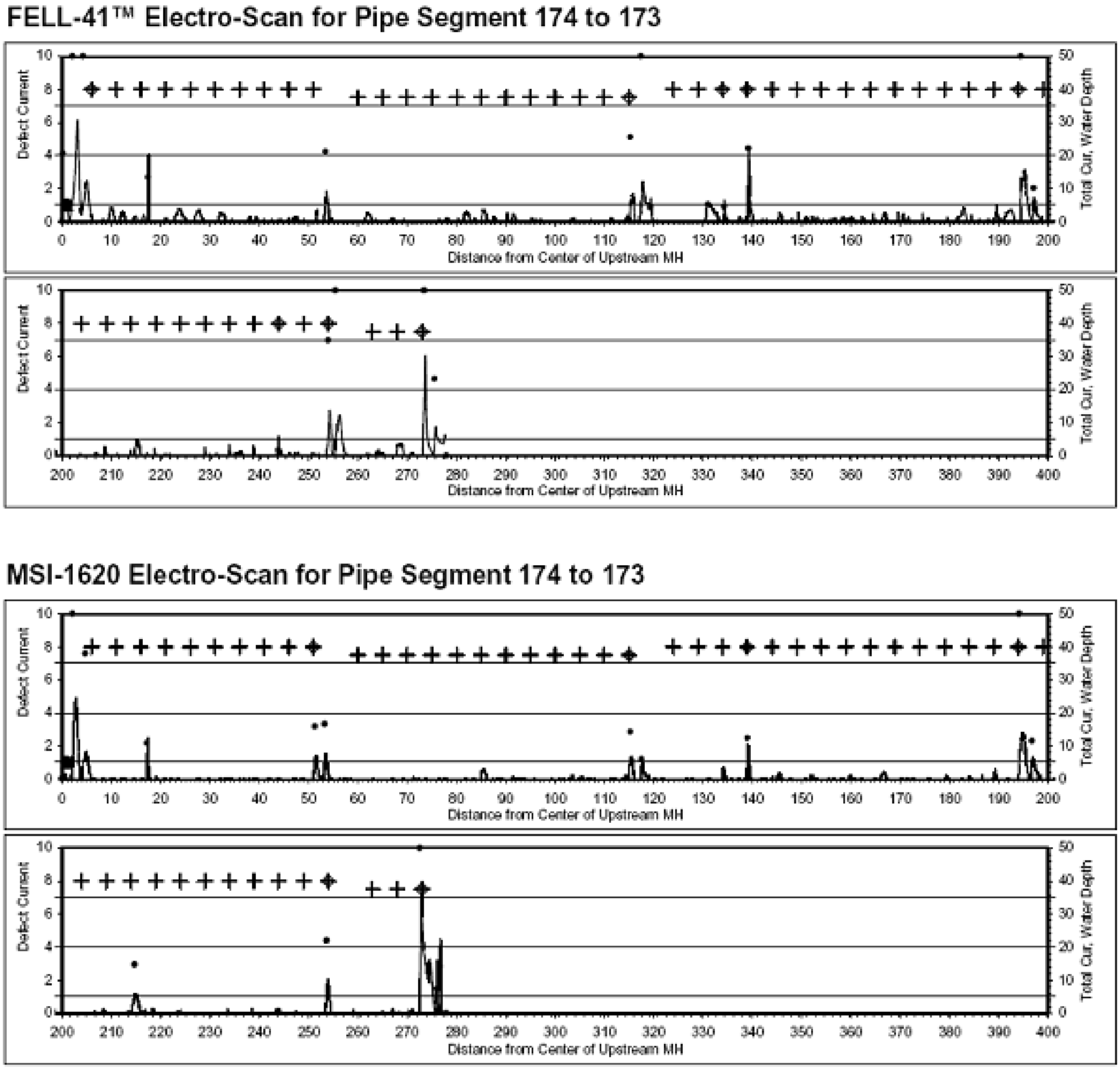
Notes: (1) x-axis represents the distance (ft) from the center of the upstream manhole (MH)
(2) y-axis represents the defect current (amplitude)

Figure 5-8. Comparison of FELL-41 (upper) and MSI-1620 (lower) for Pipe Segment 102-101.



Notes: (1) x-axis represents the distance (ft) from the center of the upstream manhole (MH)
(2) y-axis represents the defect current (amplitude)

Figure 5-9. Comparison of FELL-41 (upper) and MSI-1620 (lower) for Pipe Segment 127-125.



Notes: (1) x-axis represents the distance (ft) from the center of the upstream manhole (MH)
(2) y-axis represents the defect current (amplitude)

Figure 5-10. Comparison of FELL-41 (upper) and MSI-1620 (lower) for Pipe Segment 174-173.

5.4 Multi-sensor Inspection

The multi-sensor inspection of the Line Creek Interceptor was conducted on August 10 and August 11, 2010. A total of 7,188-ft of large diameter (60-in., 66-in., and 72-in.) reinforced concrete sewer was inspected. See Figure 4-11 for a map of pipelines inspected, and Tables 5-18 and 5-19 for information on the total inspection length by pipe diameter and date.

Table 5-18. Line Creek Interceptor Multi-sensor Inspection Summary.

Pipe Diameter (in.)	Total Inspection Length (ft)
60	2,686
66*	1,704
72	2,420
Total	**6,810**

* Does not include 378 ft from replicate scan between SMH 6 and 5.

Table 5-19. Line Creek Interceptor Multi-sensor Inspection Schedule.

Date	Pipe Segments Inspected	Total Inspection Length (ft)
August 10, 2010	SMH3 to SMH6	4,010
August 11, 2010	SMH6 to SMH64	2,800
Total	**18**	**6,810**

5.4.1 Summary of Defects

This section first discusses inspection results for each of the three technologies individually, and then presents and discusses integrated images of the pipe surfaces that combine inspection results.

Digital Scan Results

Digital scanning results were analyzed to determine overall structural and maintenance condition of the Line Creek Interceptor (Tables 5-20 and 5-21, respectively). Results show that 89% of the inspected pipe length was free of structural defects or in excellent structural condition, and 11% was in fair structural condition. In terms of maintenance condition, 93% of the inspected pipe length was in good to excellent condition, and 7% was in fair to poor condition.

Table 5-20. Determination of Overall Structural Condition Based on Digital Scanning.

Defect Grade Assigned for SPRI	% of Total Pipe Length Inspected	No. Pipe Segments
0: No defects	28.9	5
1: Excellent	60.2	11
2: Good	0.0	0
3: Fair	10.8	2
4: Poor	0.0	0
5: Severe	0.0	0
Total	100.0	18

SPRI = structural pipe rating index

Table 5-21. Determination of Overall Maintenance Condition Based on Digital Scanning.

Defect Grade Assigned for MPRI	% of Total Pipe Length Inspected	No. Pipe Segments
0: No defects	29.8	4
1: Excellent	3.9	2
2: Good	59.6	9
3: Fair	6.6	2
4: Poor	0.2	1
5: Severe	0.0	0
Total	100.0	18

MPRI = maintenance pipe rating index

The most common maintenance defect identified during the inspection was sediment accumulation at the pipe invert. The majority of the sediment had accumulated in the first three pipe segments from SMH 3 to SMH18 (i.e., approximately 76% of the entire pipe length). The HD video revealed minimal maintenance defects beyond those identified in the CCTV scan.

Laser Scan Results

The combination of the laser and sonar scanners allowed identification of structural defects, such as material loss or corrosion, along the entire circumference of the pipe interior. The analysis of laser and sonar data was not based on a standard defect coding system but relied on engineering judgment (i.e., knowledge of pipe wall construction) to assess the severity of defects and the need for subsequent maintenance.

The laser data, presented in tabular format in Table 5-22, shows that the maximum corrosion depth of 1.5-in. was found between SMH9 and SMH8. Seven of the eighteen segments had maximum corrosion depths of greater than 1.0-in.

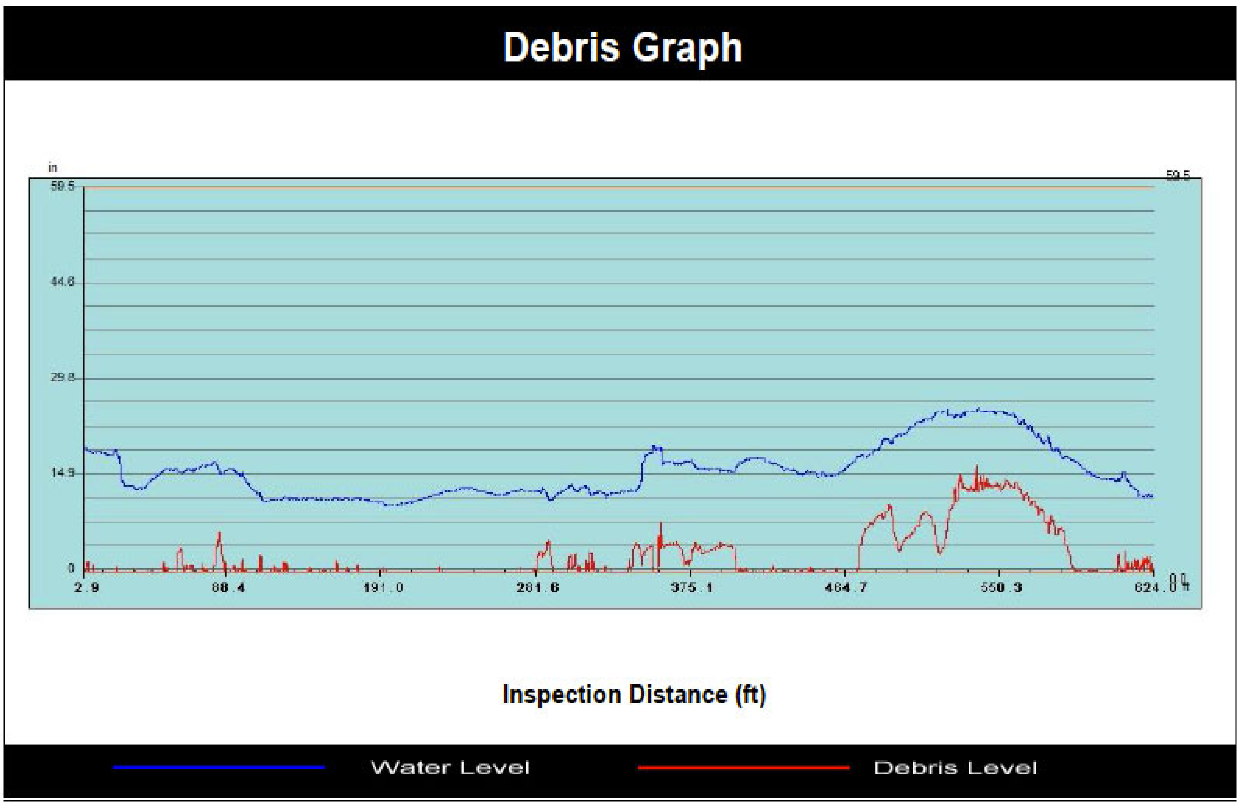
Table 5-22. Summary of Corrosion Data from Laser Scan.

Pipe Section	Maximum Corrosion Depth (in.)	Locations of Corrosion (ft from start of pipe segment)
3-2	1.0	299.9
2-1	1.1	2.5, 100
1-18	1.1	517.1
18-17	0.5	349.9
17-10	1.0	249.7
10-9	1.2 (estimated)	15.2
9-8	1.5	4.1
8-6A	0.6	9.3
6A-GW6A	0.9	0.9 (in MH)
GW6A -7	0.5	4
7-6	None noted	
6-5 First Inspection	0.8	18.7
6-5 2nd Inspection	0.8	18.1
5-28	None noted	
28-808	None noted	
808-3A	1.0	8.4
3A-3	1.4	1.4 (in MH)
3-2	0.7	1.2
2-64	0.9	507.9

Although no reinforcement steel was visible during the inspection, the corrosion losses at certain locations along the pipe alignment may be of a depth to affect the reinforcement. The typical protective concrete covering for reinforcement in concrete pipe varies between 1-in. and 1.5-in. with a required minimum of 1-in. (ASTM, 2010).[1]

Sonar Scan Results

The sonar scan results provide information on the depth and location of debris (e.g., sediment) in the pipe. For example, in the pipe segment between SMH 3 and 2 (Figure 5-11), the deepest accumulation of debris appears to be located at a distance of 550-ft downstream of SMH 3. The debris graph provides information that aids the utility in soliciting accurate bids for pipe cleaning.



Note: The match to reference is the point that best indicates the shape and size of the original conditions of the pipe.

Figure 5-11. Debris Graph of Line Creek Interceptor from SMH 3 to 2.

[1] According to ASTM C-76 paragraph 8.1.2, a pipe having two lines of circular reinforcement shall have a minimum protective covering of concrete over the circumferential reinforcement of 1.0-in. Based on Class III RCP with an inner and outer reinforcing cage, the pipe with diameters of 60-in., 66-in., and 72-in. would have a wall thickness of 6-in., 6.5-in, and 7-in. respectively. It should be noted that the pipe was placed in service in the 1960s and cover to reinforcing steel may be greater.

Table 5-23 summarizes debris volume and depth for each pipe segment based on the sonar scan data. The first three pipe segments from SMH 3 to SMH18 contained the majority of the debris (approximately 76% of the total). Less debris was detected downstream of SMH 17. Unfortunately, the sonar unit ceased operating following a float rollover event at SMH 5 that occurred on the morning of the second day of inspection. The shutdown of the sonar unit was not discovered until the next day, leaving 2,798-ft of pipe (or approximately 39 % of the total inspection length) without a sonar profile.

Table 5-23. Multi-sensor Inspection – Sonar.

Pipe Section	Length (ft)	Debris Volume (cubic ft)	Average Debris Depth (in.)	Maximum Debris Depth (in.)
3-2	466	691	7	13.2
2-1	688	345	3	9.7
1-18	624	263	2	13.3
18-17	658	31	<0.1	6.9
17-10	250	3	<0.1	4.8
10-9	358	4	<0.1	1
9-8	418	2	<0.1	<0.1
8-6A	10	2	2	<0.1
6A-GW6A	206	92	3	10.1
GW6A-7	266	139	3	7.3
7-6	66	4	<0.1	6.4
6-5	380	133	2	8.9

Note: No sonar data collected downstream of SMH 5.

Integrated Data Analysis

The multi-sensor unit used for this demonstration was a combination of several inspection technologies mounted on a floating assembly. The assembly included a high-resolution digital camera (see detailed description in Section 3.4), a laser scanner (see Section 3.5), and a sonar head (see Section 3.6).

The inspection data from the three technologies were integrated to produce images of the pipe interior surfaces above and below the water line that can be used to review the entire pipe for defects. These data were presented in several ways including:

1. A Flat Graph™ showing the material loss (or corrosion) on a yellow/red color scale and material gain (or debris) on a blue color scale along the longitudinal distance of the pipe;

2. A three-dimensional (3-D) view of the laser and sonar data;

3. A cross-sectional graphic of the pipe circumference;

4. A debris graph showing the accumulation of debris and water level along the pipe; and,

5. A 4-in-1 video combining the cross-sectional view of the pipe, with the actual HD video, and the longitudinal view along the pipe using the Flat Graph™.

Figure 5-12 provides an example of the Flat Graph™ for the pipe segment between SMH 1 and 18. The graph shows that debris, as denoted in dark blue, had accumulated to a thickness of 3-in. at the invert location (i.e., six o'clock) between 470-ft and 580-ft downstream of SMH 1. Figure 5-12 also shows that corrosion loss of approximately 1-in., denoted in yellow, occurred at the same location.

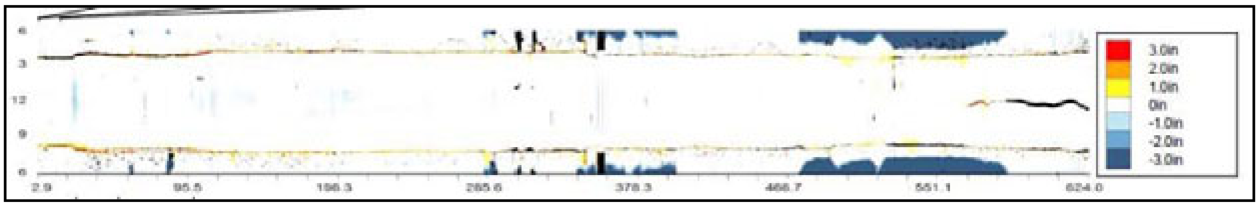
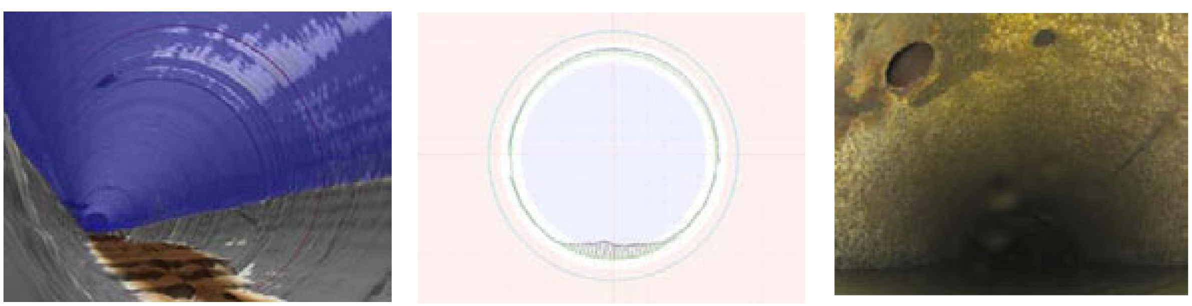


Figure 5-12. Flat Graph™ for Pipe Segment from SMH 1- 18.

A more detailed view of the pipe cross-section is provided by three distinct images (Figure 5-13) at the same location along the pipe (approximately 516-ft to 518-ft downstream of SMH 1). Together, the images show location and cross-sectional area of debris and corrosion loss, and a service connection at the pipe crown.



(a) 3D image at 518.1-ft (b) cross-sectional graphic at 517-ft (c) HD image of the pipe crown at 516.5-ft.

Figure 5-13. Single Location Multi-sensor Images Showing Debris, Corrosion Loss, and Connecting Pipe.

In a similar manner, other notable defects (e.g., protruding lateral) can be reviewed using the cross-section graphic and HD image as shown in Figure 5-14.

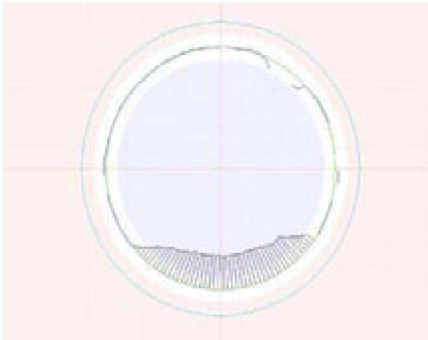
 

Figure 5-14. Cross-Sectional and HD Images of 2.5-in. Protruding Lateral at 528.4-ft.

5.4.2 Production Rate

The time required for equipment set-up, inspection and down-time for the multi-sensor technology are summarized in Table 5-24. The equipment setup included the initial mounting and assembly of the sensors, batteries, and PODs on the float unit. The down-time included troubleshooting and equipment repair.

Table 5-24. Multi-sensor Production Rates.

Date	Work Duration (hr)	Total Equipment Set-up Time (hr)	Total Inspection Time (hr)	Down-Time (hr)	Total Pipeline Length Inspected (ft)	Production Rate (ft/hr)[1]
August 10, 2010	12	2.25	3.5	6.25	4,010	697
August 11, 2010	12	2.5	2.75	6.75	2,800	533
Total	**24**	**4.75**	**6.25**	**13.00**	**6,810**	**--**
Average	**12**	**2.38**	**3.13**	**6.50**	**3,405**	**618**

[1] Total inspection length in ft divided by time for equipment set-up and inspection. Down-time for troubleshooting and equipment repair not included.

The average production rate for the multi-sensor technology for the two day inspection was approximately 615-ft per hour based on total time for equipment set-up and inspection excluding down-time.

5.4.3 Cost

The total cost of the multi-sensor inspection at the Line Creek Interceptor was $30,268, including $4,000 for mobilization, $13,650 for field work, and $12,618 for data assessment and reporting. The cost of data analysis was approximately 42% of the total inspection cost. The processing of the digital scan was labor intensive, and processing the laser and sonar data required specialized software. The total inspection cost per ft was $4.21 based on the inspection of 7,188-ft of pipe (including the 378-ft of replicate inspection between SMH 6 and 5).

5.4.4 Duplicate Runs

The precision of the multi-sensor results was evaluated by inspecting the pipe segment from SMH 6 and 5 twice; results are compared in Table 5-25 and Figure 5-15. Because the sonar unit was not operating properly during the second run, evaluation of the sonar data was not possible.

Table 5-25. Comparison of Replicate Multi-sensor Inspections - SMH 6 to 5.

First Inspection		Second Inspection	
Distance (ft)	**Observation**	**Distance (ft)**	**Observation**
0	0.5-in. corrosion	0	0.5-in. corrosion
18.7	0.8-in. corrosion	18.1	0.8-in. corrosion
41.3	match to reference size of 65.5-in. diameter	40.7	match to reference size of 65.5-in. diameter
50	3.7-in. debris	50	general observation
101.4	laterals	100	general observation
238.5	8.9-in. debris	150	general observation
249.8	5.5-in. debris	249.9	general observation
299.9	1.4-in. debris	299.9	general observation
378.2	end of inspection	377.2	end of inspection

Notes: General observation is a video image of the same location with no defect detected.

The results from the two inspections were very similar. The only difference, other than lack of debris data (from the sonar), was that the first inspection identified the lateral connections and the second did not. This variation may simply be a judgment that the laterals were not significant to this project and not documented in the second inspection.

First Inspection:

Second Inspection:

Figure 5.15. Comparison of Inspections for SMH 6 to 5.
First Inspection (top), Image at 0-ft; Cross-Sections at 0-ft and 18-ft.
Second Inspection (bottom), Image at 0-ft; Cross-Sections at 0-ft and 18-ft.

6. Comparison of Technologies

The purpose of this chapter is to compare the inspection technologies in terms of technical performance, cost, complexity and ease of operation (the reader is referred to Chapter 5 for a summary of inspection results). Technical performance is measured in terms of versatility, detection of defects, precision, and production rate. Because the technologies vary substantially in operation, metrics for each category are, to some degree, technology-specific. For example, sight distance down the length of a pipe is an important metric for zoom camera but does not apply to sonar.

6.1 Technical Performance – Versatility

Versatility was assessed by analyzing technical performance for each technology under a range of pipe sizes and materials, environmental conditions and sewer line conditions.

6.1.1 Performance for Different Pipe Sizes and Material of Construction

Table 6-1 summarizes the actual pipe characteristics assessed in the field and compares them to the required conditions for each technology. Most technologies were tested for one pipe material, and each was tested for two or three different pipe diameters.

Table 6-1. Required vs. Actual Pipe Characteristics Assessed.

	Required Pipe Characteristics for Technology		Actual Pipe Characteristics Assessed in Field Demonstration	
Technology	**Pipe Material**	**Pipe Diameter**	**Pipe Material**	**Pipe Diameter**
Zoom Camera	Any	>6-in.	VCP, PVC, RCP	8-in., 10-in., 12-in. 60-in., 72-in.
Electro-scanning	Non-ferrous	3-in. to 60-in.	VCP	8-in., 10-in.
Digital Scanning	Any	6-in. to 120-in.	RCP	60-in., 66-in., 72-in.
Laser	Any	>4-in.	RCP	60-in., 66-in., 72-in.
Sonar	Any	≥12-in.	RCP	60-in., 66-in., 72-in.

VCP = vitrified clay pipe; PVC= polyvinyl chloride; RCP = reinforced concrete pipe.

The zoom camera inspections at Gracemor were primarily conducted in 8-in. VCP, but a few inspections were conducted in PVC pipe. Of the VCP pipe tested, 91% of pipe was 8-in. diameter, 5% was 10-in., and 4% was 12-in. diameter. Although the manufacturer reports that the sight distance varies by pipe diameter, field results showed no difference. The maximum sight distance was 50-ft for most pipes, regardless of pipe diameter. The zoom camera inspection of Line Creek Interceptor was limited to four pipe segments, including one 60-in. RCP and three 72-in. RCP segments. Sight distance ranged from 35-ft to 140-ft in the 72-in. pipe and was 25-ft in the one 60-in. pipe segment inspected.

The electro-scanning inspection was completed in 8-in. and 10-in. diameter VCP in the Gracemor area. Electro-scanning performance did not appear to vary by pipe diameter.

6.1.2 Performance Under Different Environmental Conditions

In addition to pipe diameter and material of construction, the versatility of an inspection technology may be affected by environmental conditions (e.g., site access, depth to sewer, traffic, weather). Traffic was not a factor during the field demonstrations. Extremely hot temperatures and high humidity during the first week of testing, however, may have contributed to the zoom camera equipment problems (e.g., possible overheating of an electrical connection at the control head, condensation on the camera lens, equipment failure). The condensation inside the pipe was probably a result of the significant disparity between surface temperature and the temperature at the bottom of the manhole. The zoom camera inspection at Line Creek Interceptor was limited by the depth of some manhole structures which exceeded the length of the zoom camera pole available on-site (24-ft)[2].

The common denominator for most of the commercially available condition assessment technologies was the need for access through manholes. However, access requirements varied amongst the technologies. For example, zoom cameras were used in areas where access was tight by pole-mounting or tripod-mounting the camera instead of the standard truck mounting set up. On the other hand, a zoom camera had to be deployed at every manhole to inspect as much of the line as possible, which might be problematic in areas where manhole access is limited. The crew operating the multi-sensor unit had difficulty inserting and removing the float assembly in the Line Creek Interceptor's narrow manholes (24-in. diameter) and manholes that had sudden changes in geometry (i.e., increase in slope, increase in flow velocity).

At the Line Creek Interceptor, some manholes were difficult to locate as they were surrounded by dense vegetation; also, set-up time at each manhole structure was longer as compared to the Gracemor area because access to the manholes was more difficult. The Gracemor pipelines were easily identifiable, with the majority of access points (i.e., manholes) in the public right-of-way; only one manhole was inaccessible.

6.1.3 Performance Under Different Sewer Line Conditions

Sewer cleaning was completed in the Gracemor area to remove debris that prevented advancement of the CCTV crawler. Because cleaning was not required for the zoom camera or

[2] It is noted that longer poles up to 30-ft are commercially available.

multi-sensor technologies, it was scheduled just prior to CCTV inspection during Week 2. Cleaning of the Line Creek Interceptor was not required for the multi-sensor technology or CCTV because its diameter is large enough to allow the equipment to be transported through the sewer. The results of the multi-sensor inspection during the week prior to the CCTV inspection showed that the line contained debris but it was deemed passable with the CCTV camera.

The field demonstration results illustrated a limitation of zoom camera inspection in pipes that were not cleaned; sight distance was sometimes limited by objects in the pipe (e.g., spider webs, debris, roots). The camera's autofocus feature zoomed in on the object rather than the pipe wall, and was unable to see beyond it; the camera's manual focus was inconsistent in its ability to sharpen the focus any further.

Similar to the zoom camera, electro-scanning (e.g., FELL-41) did not require pipe cleaning before inspection. It did, however, require the pipe to be filled. A sliding plug facilitated this by allowing small portions of the pipe to be filled at a time. Because the pipelines at Gracemor had low flow depths (i.e., approximately 1-in. or less) during the field demonstration, supplemental water was used for the first four days; on the fifth day, adequate flows were present to achieve surcharged conditions with the sliding plug. During the electro-scanning inspection, continuous pressure monitoring was required to maintain the pressure head below the anticipated building invert elevations. At one location, water entered a basement through a floor drain due to the line being surcharged above the basement elevation.

Sonar cannot operate in a dry pipe; if the pipe is not full, it can only image the portion of the pipe that is under water. A minimum depth of flow is required to submerge the sonar head. The actual depth of flow in the Line Creek Interceptor was 12-in. to 15-in. during the field demonstration which allowed simultaneous laser scanning above the water level and sonar inspection under water.

6.2 Technical Performance – Detection of Defects

The detection of defects by the innovative technologies was explored by comparing to defects identified by CCTV.

6.2.1 Comparison of Zoom Camera to CCTV

Table 6-2 compares CCTV and zoom camera inspection results in the Gracemor area. Nineteen pipe segments were inspected using both technologies; additional pipe segments that were only accessed from one manhole for zoom camera inspection (i.e., inspected from one direction only) were excluded from this comparison. Overall, the zoom camera identified 31 defects as compared to 168 defects identified by CCTV for the same pipe segments. The poor results are attributed to the zoom camera's limited sight distance that resulted in partial inspection of each pipe length. Sight distance was limited by spider webs, roots, and grout in the pipeline, and was reduced by condensation on the camera lens caused by the temperature differential between the ground and subsurface.

Table 6-2. Number of Pipe Defects Identified by Zoom Camera compared to CCTV.

Gracemor Pipe Run	# Defects Identified by CCTV	# Defects Identified by Zoom Camera
098-166	2	MH 98: 0 MH 166: 0
094-097	9	MH 97: 0 MH 94: 1
97-98	11	MH 97: 0 MH 98: 0
95-94	9	MH 95: 2 MH 94: 0
102-103	0	MH 102: 0 MH 103: 1
102-101	5	MH 102: 0 MH 101: 1
128-127	6	MH 128: 1 MH 127: 2
125-127	9	MH 125: 3 MH 127: 2
125-116	10	MH 125: 2 MH 116: 2
120-119	13	MH 120: 1 MH 119: 2
119-118	8	MH 119: 0 MH 118: 2
117-118	12	MH 117: 1 MH 118: 2
117-116	5	MH 117: 0 MH 116: 0
116-115	26	MH 116: 0 MH 115: 1
114-115	5	MH 114: 0 MH 115: 1
106-105	6	MH 106: 0 MH 105: 0
104-102	11	MH 104: 1 MH 102: 1
96-95	17	MH 96: 2 MH 95: 0
221-222	4	MH222: 0 MH221: 0
Total	**168**	**31**

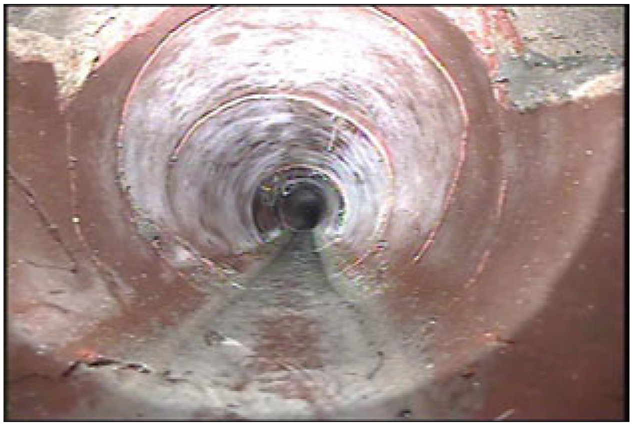
MH = manhole accessed for zoom camera inspection

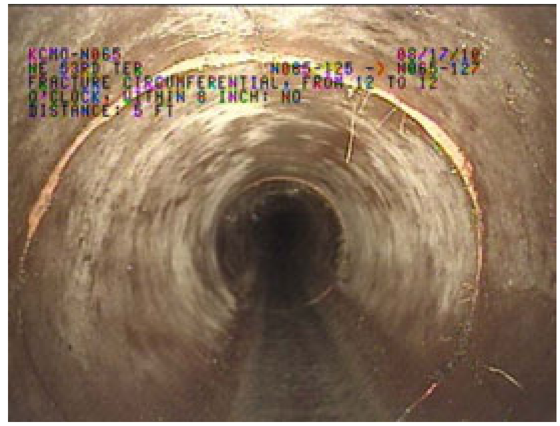
Image quality and type of defect identified by zoom camera and CCTV were more closely evaluated and compared for two pipe segments: 125-127 and 127-128, both in the Gracemor area.

In pipe segment 125-127, nine defects were identified by CCTV and five were identified by zoom camera including three from MH 125 and two from MH 127 (Table 6-3). The Grade 2 circumferential fracture identified by the zoom camera inspection from manhole 125 (located at 2 ft from manhole 125) appeared to be the same defect as the one identified by CCTV (Figure 6-1); although the defect location appeared to be offset by 3-ft between zoom camera and CCTV, it is noted that distance was difficult to estimate with zoom camera and was often provided as a range. The four other defects identified by zoom camera (at 55, 117 and 219 ft from manhole 125) appeared to be different defects than those identified by CCTV.

Table 6-3. Comparison of Zoom Camera and CCTV Identification of Defect Type and Grade at Gracemor Pipe Segment 125-127.

CCTV Inspection		Zoom Camera Inspection	
Distance from Manhole 125 (ft)	**Defect Type and Grade Identified**	**Distance from Manhole 125 (ft)**	**Defect Type and Grade Identified**
1	Multiple Fracture, Structural Grade 4		
		2	Circumferential Fracture, Structural Grade 2
5	Circumferential Fracture, Structural Grade 2		
5.8	Roots Fine Joint, Maintenance Grade 1		
9.6	Circumferential Crack, Structural Grade 1		
30.3	Defective Tap Break-in, Maintenance Grade 3		
		55	Defective Tap Break-in, Maintenance Grade 3
		55	Roots Ball Connection, Maintenance Grade 4
		117	Roots Ball Joint, Maintenance Grade 4
129.9	Defective Tap Break-in, Maintenance Grade 3		
129.9	Roots Ball Connection, Maintenance Grade 4		
179.5	Defective Factory Made Tap, Maintenance Grade 2		
179.5	Roots Ball Connection, Maintenance Grade 4		
		219	Roots Fine Joint, Maintenance Grade 1





a. Zoom Camera Image

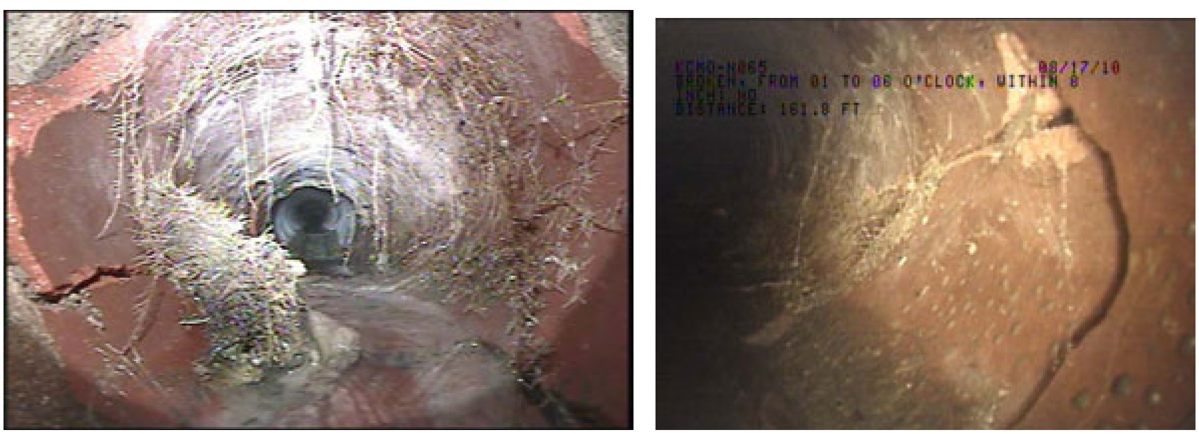
b. CCTV Image

Figure 6-1. Comparison of Zoom Camera and CCTV Images of Grade 2 Circumferential Fracture in Gracemor Pipe Segment 125-127.

In pipe segment 127-128, six defects were identified by CCTV, but only three defects were identified by zoom camera including one defect from the MH 128 access point, and two defects from MH 127 (Table 6-4). The two maintenance defects identified by zoom camera may be the same defect identified by CCTV, although the location along the pipe differs by 1 to 3 ft. The structural defect identified by zoom camera at 1-ft from manhole 127 appears to be different than structural defects identified by CCTV. It could not be determined if the images of broken pipe captured by zoom camera and CCTV (Figure 6-2) were different defects.

Table 6-4. Comparison of Zoom Camera and CCTV Identification of Defect Type and Grade at Gracemor Pipe Segment 127-128.

CCTV Inspection		Zoom Camera Inspection	
Distance from Manhole 127 (ft)	**Defect Type and Grade Identified**	**Distance from Manhole 127 (ft)**	**Defect Type and Grade Identified**
		1	Broken Pipe, Structural Grade 3
		1	Roots Fine Joint, Maintenance Grade 1
3.6	Roots Fine Barrel, Maintenance Grade 2		
5.3	Broken Pipe, Structural Grade 5		
6.7	Pipe Sag, Maintenance Grade 2		
55.2	Defective Tap Break-in, Maintenance Grade 3		
158.6	Defective Factory Made Tap, Maintenance Grade 2		
		161	Roots Ball Barrel, Maintenance Grade 5
162	Roots Ball Joint, Maintenance Grade 4		



a. Zoom Camera Image b. CCTV Image

Figure 6-2. Comparison of Zoom Camera and CCTV Images of Broken Pipe in Gracemor Pipe Segment 127-128.

For the Line Creek Interceptor, only one pipe segment (between SMH 2 and 3) was inspected with both CCTV and zoom camera. However, the zoom camera inspection was limited to one of two manhole access points (SMH 2) due to the depth of the sewer (>30-ft) at SMH 3, and no defects were observed. The CCTV inspection of this pipe segment revealed two defective taps, both maintenance Grade 2 defects.

Overall, the zoom camera provided value in seeing blockages, pipe fractures, and root intrusion; it was not as effective in identifying defective taps unless they protruded into the main pipe. The comparison of CCTV and zoom camera results showed a large difference in the number of defects detected; this difference is primarily due to the zoom camera's sight distance limitations. The comparison is also hindered by difficulties in accurately estimating sight distance.

6.2.2 Comparison of Electro-scanning to CCTV

The goals of the electro-scanning demonstration were to determine whether this method can distinguish among defect types and to illustrate how the information collected by electro-scanning compares to the information obtained by CCTV. Electro-scanning measures the electric current that flows through the pipe wall. It therefore identifies pipe defects through which water can flow into or out of the pipe. CCTV inspections observe structural defects (e.g., cracks, fractures, defective joints, and faulty taps) and the ingress of roots at joints that are inferred to show potential leaks. CCTV also identifies other pipe defects such as pipe sag, grease and sediment deposits that do not indicate potential pipe leaks and, therefore, cannot be detected by electro-scanning.

Figures 6-3 through 6-8 provide a qualitative comparison of the correspondence between observed defects and pipe features obtained by CCTV and electro-scanning for six of the 17 segments for which data were acquired using both technologies. These pipe segments were chosen to provide representative examples, with varying quantities of observed defects. These comparisons are made with the understanding that the location of pipe defects and features along the pipe segment determined by CCTV and electro-scanning may not exactly correspond. It should be noted that defects such as pipe sags and grease deposits were observed by CCTV but not by electro-scanning. Non-defective taps identified by CCTV were included to illustrate cases where electro-scanning identified taps with leak potential.

The defects identified by CCTV are summarized using the PACP method (NASSCO, 2001) (e.g., structural (S), maintenance (M)) and numeric grade of 1 through 5 where 1 represents a minor defect and 5 represents the most severe defect (see Chapter 5 for additional information on PACP coding). The severity of pipe defects identified by electro-scanning are determined to be small (S), medium (M) or large (L) depending on the electrical current value and shape of the anomaly.

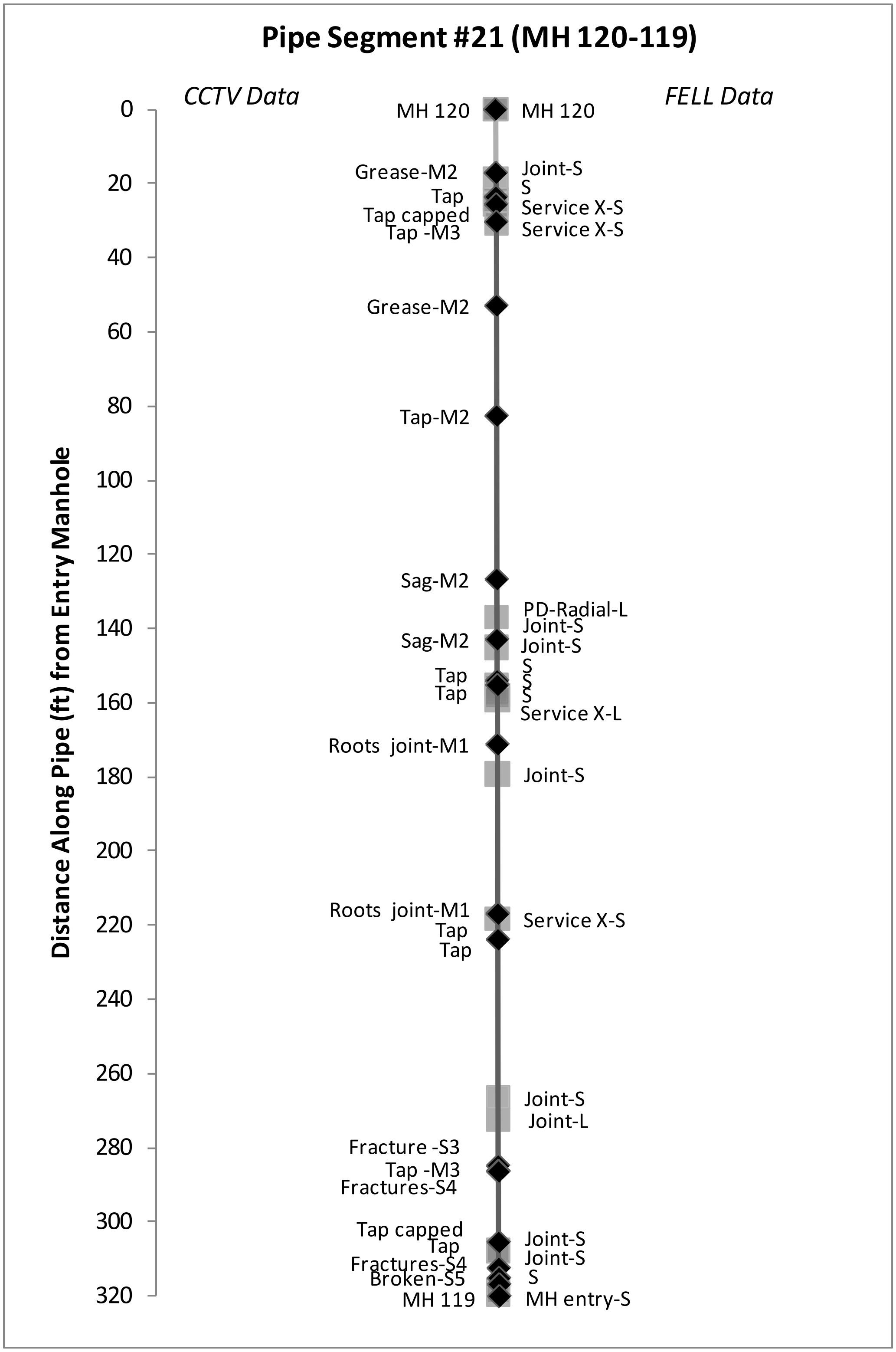


Figure 6-3. Comparison of Electro-scanning and CCTV for Pipe Segment 120-119.

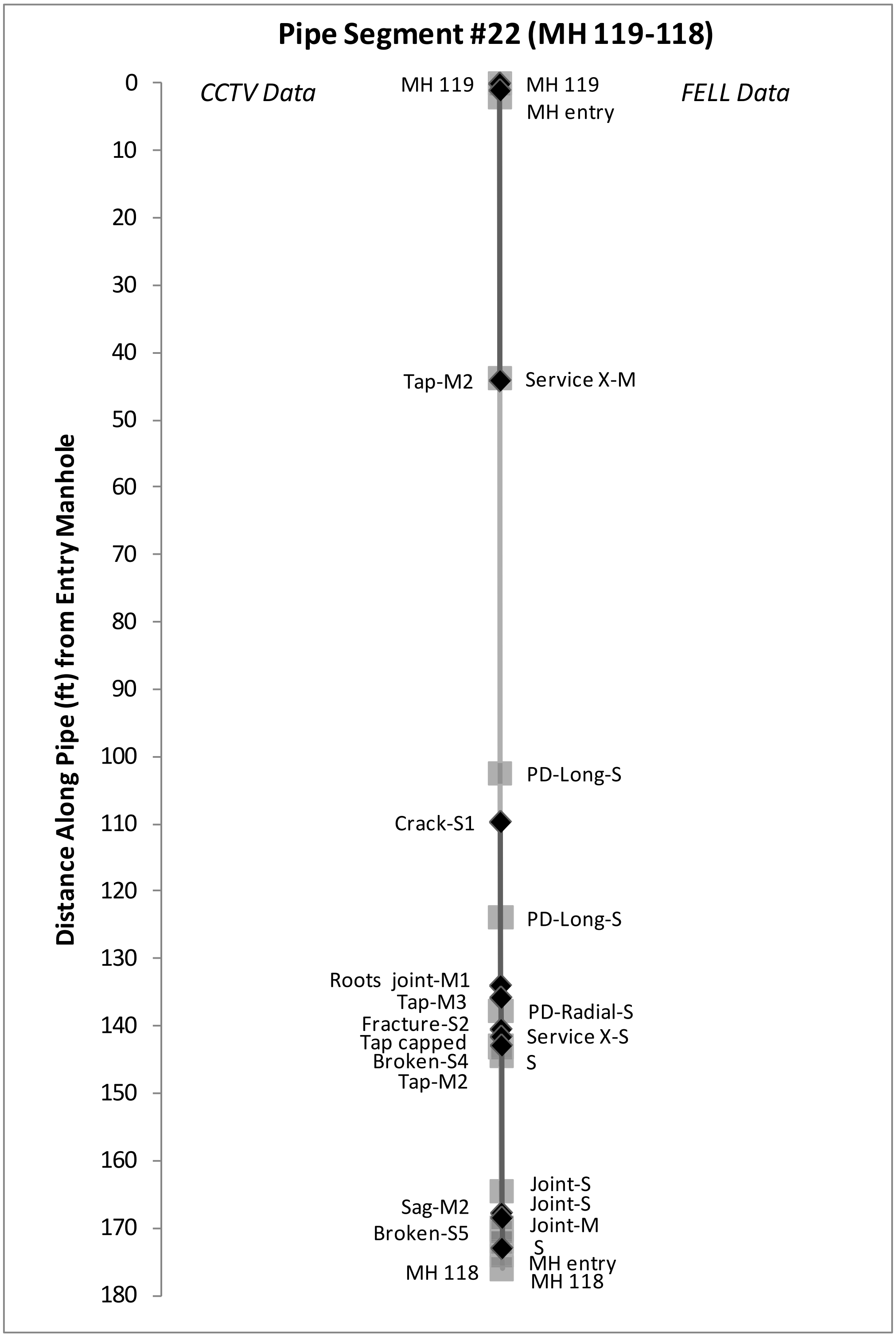


Figure 6-4. Comparison of Electro-scanning and CCTV for Pipe Segment 119-118.

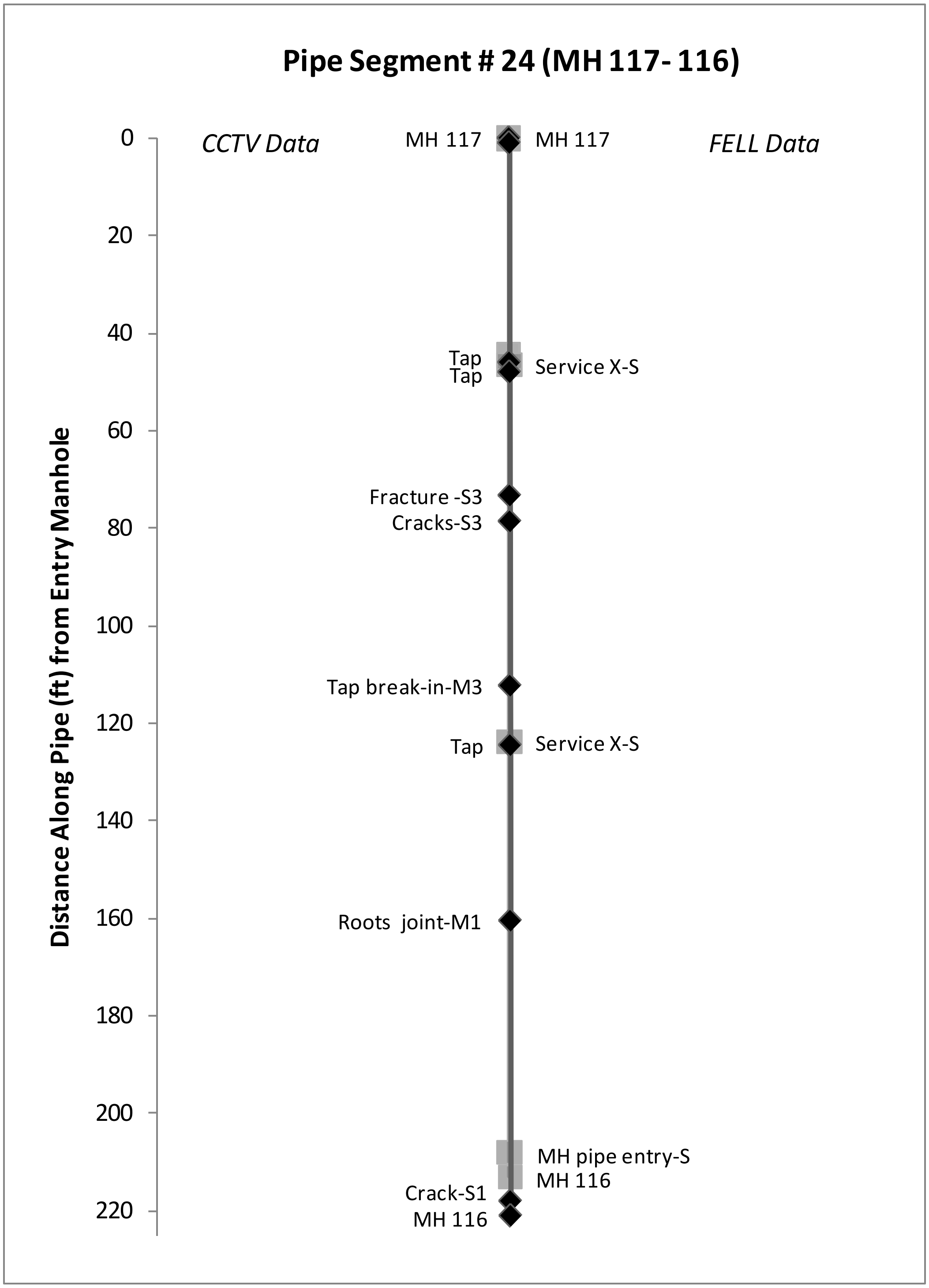


Figure 6-5. Comparison of Electro-scanning and CCTV for Pipe Segment 117-116.

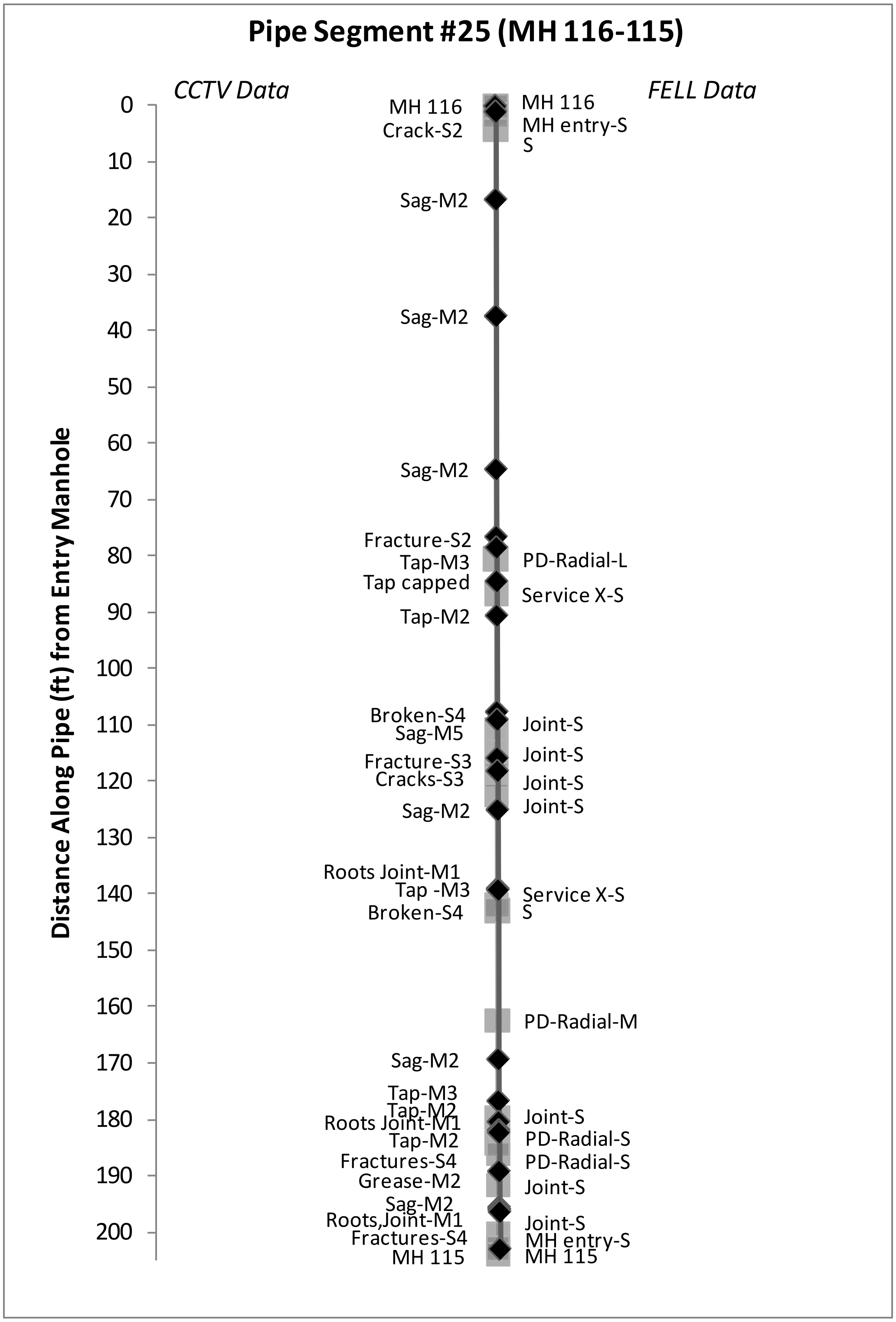


Figure 6-6. Comparison of Electro-scanning and CCTV for Pipe Segment 116-115.

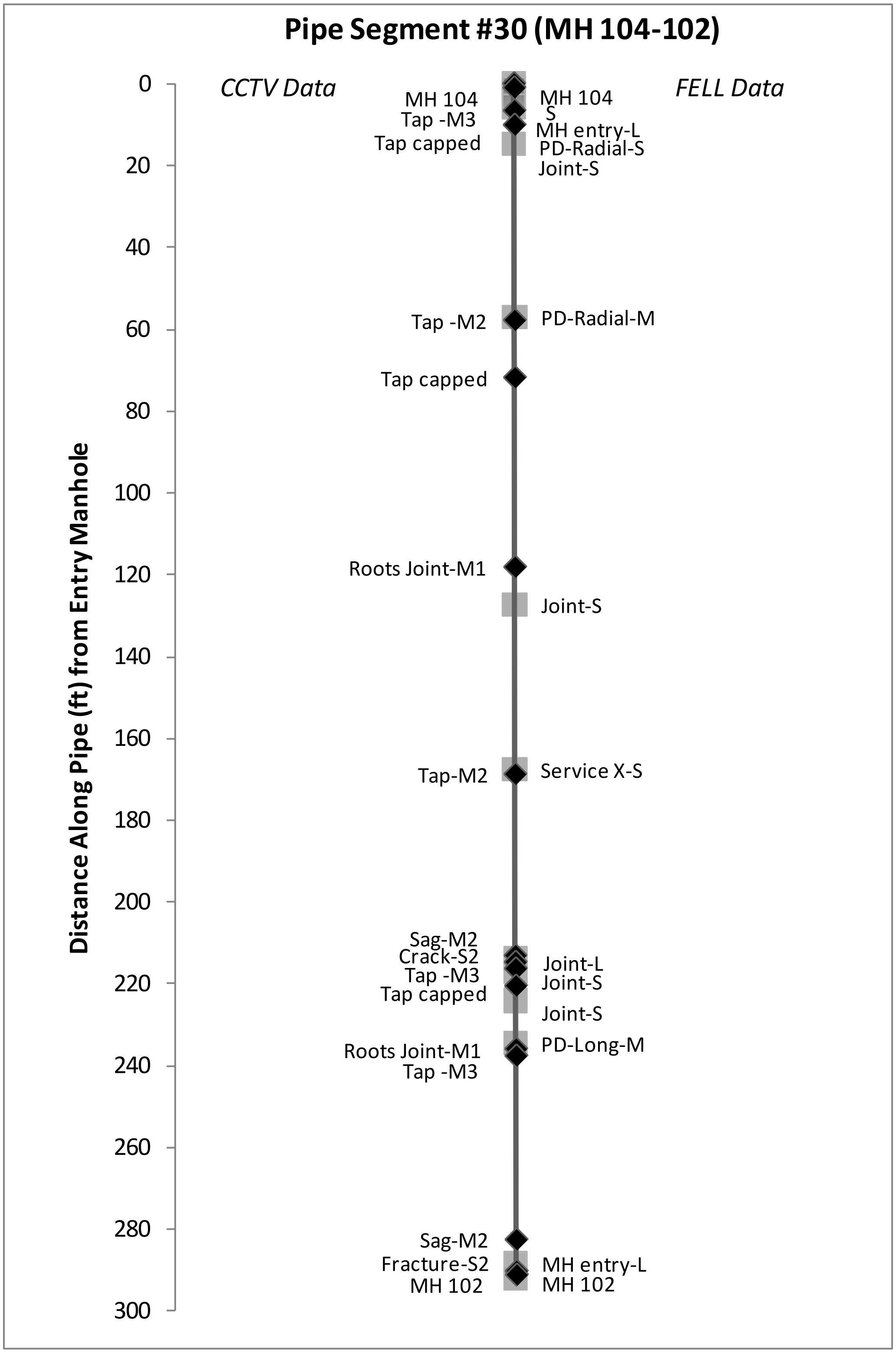


Figure 6-7. Comparison of Electro-scanning and CCTV for Pipe Segment 104-102.

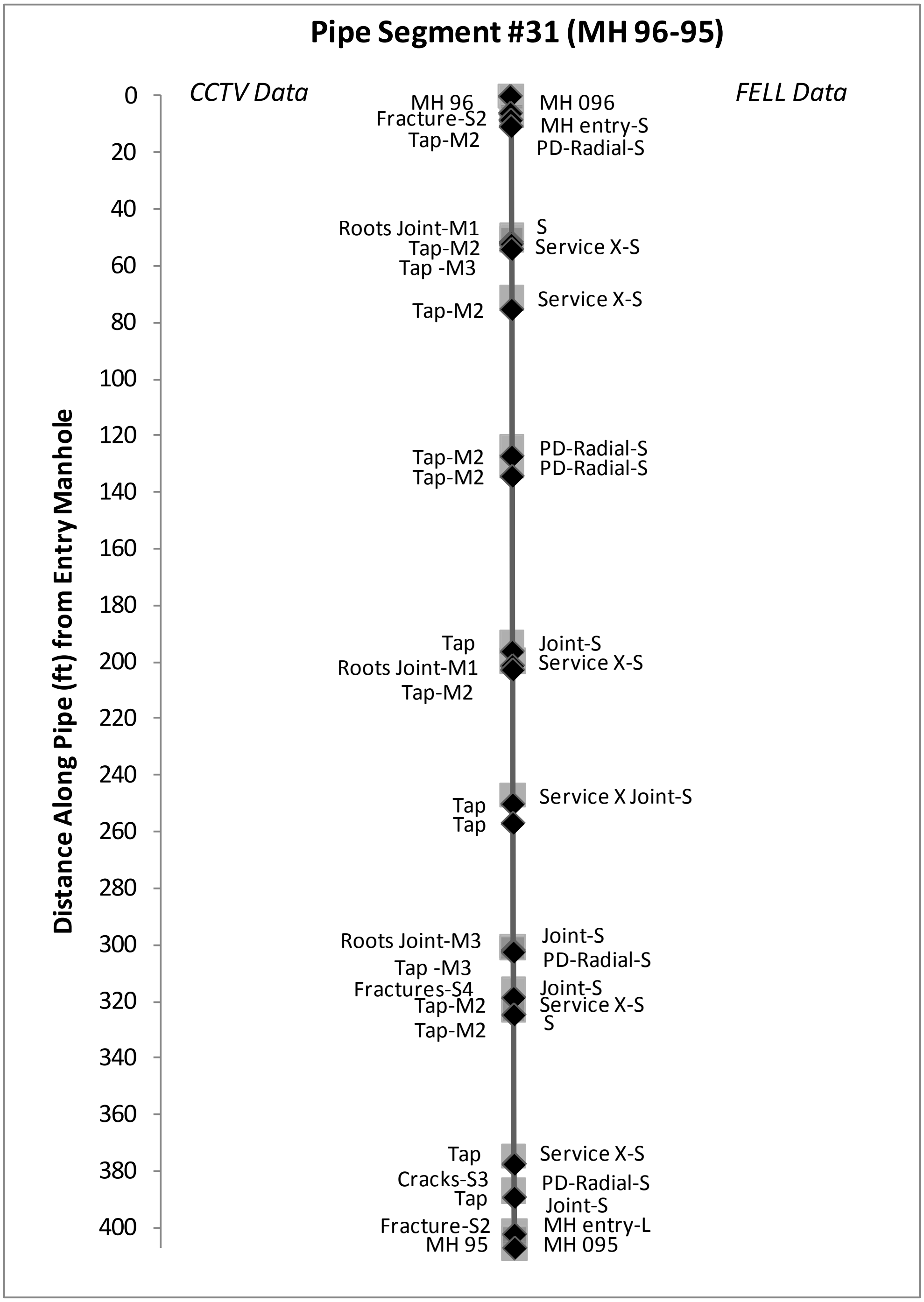


Figure 6-8. Comparison of Electro-scanning and CCTV for Pipe Segment 96-95.

A visual review of Figures 6-3 through 6-8 shows that pipe segments with a larger number of CCTV defects, especially defects associated with leakage (e.g., cracks, fractures, defective joints, faulty taps and root intrusion), generally have a larger number of electro-scanning anomalies (e.g., pipe segment #21 in Figure 6-3). Clusters of CCTV defects also often coincide with clusters of electro-scanning anomalies.

Defective taps observed by CCTV frequently correspond to electro-scanning anomalies identified as leaky service connections. In some instances (e.g., pipe segments #31, #21, #24), taps that were not considered defective from CCTV observations are in fact associated with electro-scanning anomalies, indicating leakage potential that is not apparent from visual observation. In addition, several electro-scanning anomalies interpreted as pipe defects (i.e., cracks) did not have corresponding CCTV crack defects (e.g., segment #21, around 137-ft; segment #25, around 162-ft, and segment #22, around 124-ft). In these cases, electro-scanning has provided information on leakage potential that was not observed by CCTV.

A one-to-one correspondence between CCTV and electro-scanning defects is qualitative due to potential differences in defect location along the pipe length for the two data sets. However, some CCTV defects coded as fractures or breaks of moderate to high severity (PACP Grade 3-5) did not have corresponding medium to large electro-scanning pipe defect anomalies. Examples include segment #24 (at 75-ft), segment #25 (at 105-ft to120-ft and 135-ft), and segment #21 (at 285-ft). These CCTV defects were sometimes near small electro-scanning anomalies labeled as joint or service connection defects. CCTV defects such as cracks and breaks can be readily identified visually, while electro-scanning relies upon the spacing and locations of joints and service connections to aid in interpreting defect type.

The number, type and severity of defects observed by CCTV and electro-scanning were compared for 17 pipe segments in Table 6-5. Unlike the figures above, this table includes only CCTV defects that are potential sources of leakage (joints, taps, manholes, pipe cracks and breaks). Therefore, Table 6-5 provides a direct comparison of CCTV and electro-scanning in detecting sources of potential infiltration/exfiltration. Defect classification is similar to the figures presented previously. Because electro-scanning results explicitly identify anomalies near the ends of pipe segments as manhole entry defects, CCTV defects less than 5-ft from the starting and ending manholes are also classified as manhole defects for the purpose of this comparison in Table 6-5. The “miscellaneous” group shown for electro-scanning includes pipe defects due to a defective tap or a defective manhole pipe entry that had more than one electro-scan peak.

Table 6-5. Number, Type, and Severity of Pipe Defects Identified by CCTV and Electro-Scanning that May Indicate Leakage.

Pipe Segment	CCTV					Electro-scanning					
	Joints	Taps	Pipe Defect	MH Entry	Total Defects	Joints	Miscella-neous	Taps	Pipe Defect	MH Entry	Total Defects
SMH 95-94 (No. 12)	M1-5 M3-1 M4-1		S4-1		**8**	S-22	S-1	S-1	S-2 M-1 L-1	L-1 S-1	**30**
SMH 96-95 (No. 31)	M1-2 M3-1	M2-8 M3-2	S3-1 S4-1	S2-2	**17**	S-5	S-2	S-6	S-5	S-1 L-1	**20**
SMH 102-101 (No. 15)	M2-1	M2-1	S4-1	S4-1	**4**	S-4 M-1	S-1		S-1 L-1	S-1 L-1	**10**
103-102 (No. 11)					**0**	S-5		S-5	S-1	S-2	**13**
SMH 104-102 (No. 30)	M1-1	M2-2 M3-3	S2-1	S2-1	**8**	S-4 L-1	S-1	S-1	S-1 M-2	L-2	**12**
SMH 106-105 (No. 29)	M1-2		S2-2 S5-1	S3-1	**6**	S-8 L-1			S-1	M-1	**11**
SMH 107-106 (No. 28 cleaned)			S4-1		**1**	S-3			S-5 L-2	S-1	**11**
114-107 (No. 22 cleaned)	M1-1	M2-3		S4-1	**5**	S-14	S-3	S-2	S-5	M-1 S-1	**26**
115-114 (No. 23 cleaned)		M2-1 M3-1	S2-1		**3**	S-14	S-4	M-1 S-3	S-3	S-2	**27**
SMH 116-115 (No. 25 cleaned)	M1-3	M2-3 M3-3	S2-1 S3-2 S4-4	S2-1	**17**	S-7	S-2	S-2	S-2 M-1 L-1	S-2	**17**
SMH 117-116 (No. 24 cleaned)	M1-1	M3-1	S3-2	S1-1	**5**	S-1		S-2		S-1	**4**
118-117 (No. 19)	M1-3	M2-3	S2-1 S3-1 S4-1	S2-1 S4-1	**11**	S-1 M-1	S-2	S-4	S-2	M-1 S-1	**12**

Table continues on next page.

SMH = sanitary manhole; No. = number; MH = manhole.
For CCTV results, S = structural; M = maintenance. Each code is assigned a severity grade from 1 to 5 based on PACP grading system. Numbers after dashes represent number of defects of that type and severity
For electro-scanning results, S = small; M = medium; L = large. Numbers after dashes represent number of defects of that type. MH entry indicates a defect at the entry of the pipe into the manhole.

Table 6.5 (Continued)

Pipe Segment	CCTV					Electro-scanning					
	Joints	**Taps**	**Pipe Defect**	**MH Entry**	**Total Defects**	**Joints**	**Miscella-neous**	**Taps**	**Pipe Defect**	**MH Entry**	**Total Defects**
SMH 119-118 (No. 22 cleaned)	M1-1	M2-2 M3-1	S1-1 S2-1 S4-1 S5-1		**8**	S-2 M-1	S-2	S-1 M-1	S-3	S-1 M-1	**12**
SMH 120-119 (No. 21 cleaned)	M1-2	M2-1 M3-2	S3-1 S4-2 S5-1		**9**	L-1 S-7	S-5 M-1	L-1 S-3	L-1	S-1	**20**
SMH 125-116 (No. 20 cleaned)		M2-2 M3-1	S4-1 S5-1		**5**	S-17	S-2	S-2 M-1	S-2 L-1	S-1 M-1	**27**
127-125 (No. 15)	M1-1 M4-1	M2-1 M3-2	S1-1 S2-1 S4-1		**8**	L-1 S-6	S-6	S-4	S-4	S-2	**23**
128-127 (No. 13)	M4-1	M2-1 M3-1	S5-1	M2-1	**5**	S-4	S-1	S-2	S-4	L-1 S-1	**13**
Total	**28**	**45**	**36**	**11**	**120**	**131**	**33**	**42**	**52**	**30**	**288**

SMH = sanitary manhole; No. = number; MH = manhole.
For CCTV results, S = structural; M = maintenance. Each code is assigned a severity grade from 1 to 5 based on PACP grading system. Numbers after dashes represent number of defects of that type and severity
For electro-scanning results, S = small; M = medium; L = large. Numbers after dashes represent number of defects of that type. MH entry indicates a defect at the entry of the pipe into the manhole.

Findings summarized in Table 6-5 show that CCTV and electro-scanning both identified tap and pipe defects related to potential leakage. Electro-scanning frequently registered more total leakage-related defects than CCTV, due primarily to the detection of more defective joints. Joint defects are identified by CCTV by the presence of roots; if a pipe is not in the vicinity of trees or has been cleaned prior to inspection, the ability of CCTV to identify joint defects may be diminished. At this field site, there were abundant trees close to the pipes. Segments that were cleaned prior to inspection are noted in Table 6-5.

6.2.3 Comparison of Multi-sensor Technology to CCTV

The results from the CCTV and multi-sensor inspections performed on 12 segments of pipeline along the Line Creek Interceptor provided a basis for the comparison of defect detection. The CCTV inspection did not identify any structural defects. As a result, the technology comparison was limited to operational defects identified by CCTV and digital scanning (included in the multi-sensor unit). The multi-sensor unit was evaluated by comparing number and type of defects identified, image quality, and overall pipe rating and analysis to CCTV results.

Number and Type of Defects

Table 6-6 compares the number of defects identified by the conventional CCTV with those identified by the digital scanner. CCTV identified 20 operational defects while the digital scan identified 25 operational defects. To further evaluate results, Figures 6-9 through 6-11 provide a side-by-side comparison of CCTV and multi-sensor defect observations. Discussion follows the figures. The figures use several abbreviations for PACP defect codes:

- DAE = encrustation deposits;
- TBC = capped sewer connections;
- SRI = surface corrosion;
- OBZ = obstacle; and
- DAGS = grease deposit.

Table 6-6. Number and Type of Defects Identified by CCTV and Digital Scan.

Pipe Segment (SMH-SMH)	Digital Scan		CCTV	
	Structural Defects (#)	Operational Defects (#)	Structural Defects (#)	Operational Defects (#)
3-2	2	0	0	2
2-1	15	3	0	4
1-18	2	0	0	2
18-17	2	3	0	3
17-10	4	1	0	0
10-9	2	1	0	0
9-8	2	1	0	1
8-7	4	5	0	3
7-6	2	3	0	1
6-5	2	1	0	0
5-28	2	3	0	1
28-808	2	4	0	3
Total	**41**	**25**	**0**	**20**

SMH = sanitary manhole

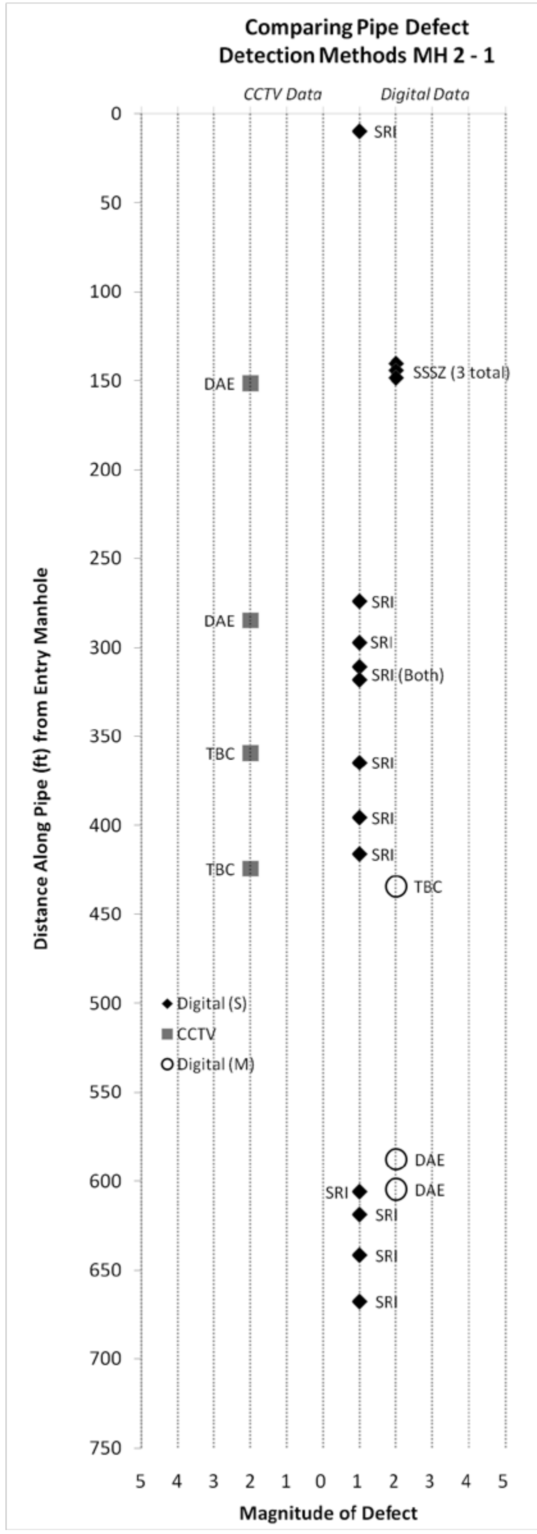


Figure 6-9. Comparison of Digital and CCTV Defect Observations for Pipe Segment MH 2-1.

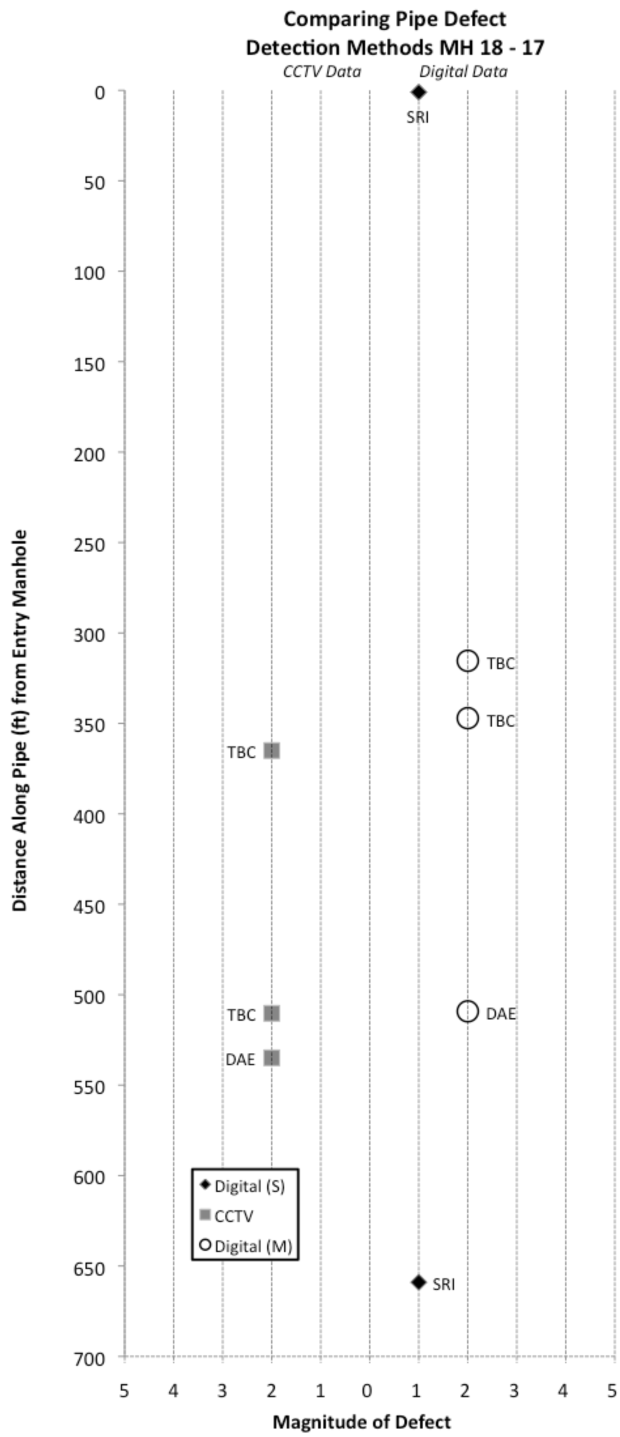


Figure 6-10. Comparison of Digital and CCTV Defect Observations for Pipe Segment SMH 18-17.

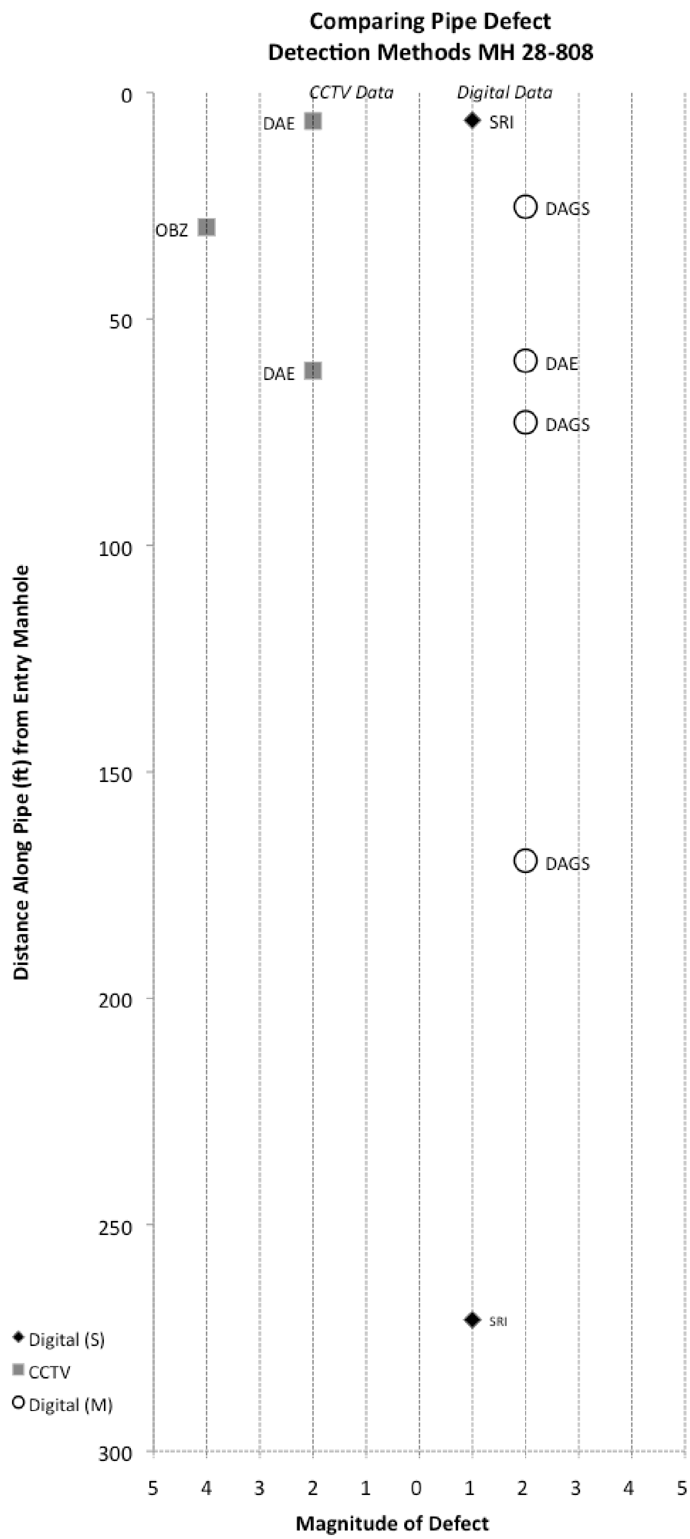


Figure 6-11. Comparison of Digital and CCTV Defect Observations for Pipe Segment SMH 28-808.

The grading of defects identified by the digital scan was compared to CCTV. As shown in Figure 6-9 between SMH 2 and SMH 1, the results of the CCTV inspection appeared to differ from the digital scan. In this pipe segment, both the CCTV and digital scan data indicated a similar number of encrustation deposits (coded as DAE) of the same rating at “2”. However, the two deposits noted in the CCTV inspection were located in the first 300-ft of sewer, while the three deposits noted in the digital scan were located in the last portion of the pipe between 450-ft and 600-ft.

In contrast, as shown in Figure 6-10 for the sewer between MH 18 and 17, the encrustation deposits (coded as DAE) and the capped sewer connection defects (coded as TBC) of the same grade were located in similar locations. For example, a single encrustation deposit was noted in the CCTV data at 535-ft and the deposit noted in the digital scan was located at 509-ft. In addition, a capped sewer connection defect was identified by the CCTV at 365 ft while the digital scan noted capped sewer connection defects at 315-ft and 347-ft.

As shown in Figure 6-11, the operational defects identified by CCTV and the digital scan were similar in location and grade in the first 100-ft of the sewer between MH 28 and 808. For example, the location of the obstacle identified in the CCTV inspection, coded as OBZ, appeared to coincide with the grease deposit, coded as DAGS, noted in the digital scan. Similarly, the encrustation deposit, coded as DAE, noted during the CCTV inspection at 61-ft appeared to coincide with the encrustation deposit, coded as DAE, identified by the digital scan at 59-ft. However, deposits were identified in the CCTV inspection that were not noted in the digital scan (e.g., DAE at 5-ft) and deposits noted in the digital scan that were not identified in the CCTV inspection (e.g., DAGS at 75-ft and at 175-ft).

The digital scan compared well to the baseline CCTV inspection using the metrics of the number of defects identified, their coded location and value.

Image Quality

The image quality of the digital scan video appeared to be superior to the video from the conventional CCTV based on a visual comparison. The still images from the digital scan appeared to be superior to those from the CCTV inspection (Figure 6-12 and Figure 6-13). These figures do not convey the full capabilities of the digital scanning. Its virtual panning and tilting features could be used to produce images of the pipe wall similar to the CCTV image in Figure 6-13.

Figure 6-12. Encrustation Deposit Between SMH 18 and 17
Digital Scan (Multi-sensor) (left), CCTV(right).

532ft Point of Interest - Lateral connection

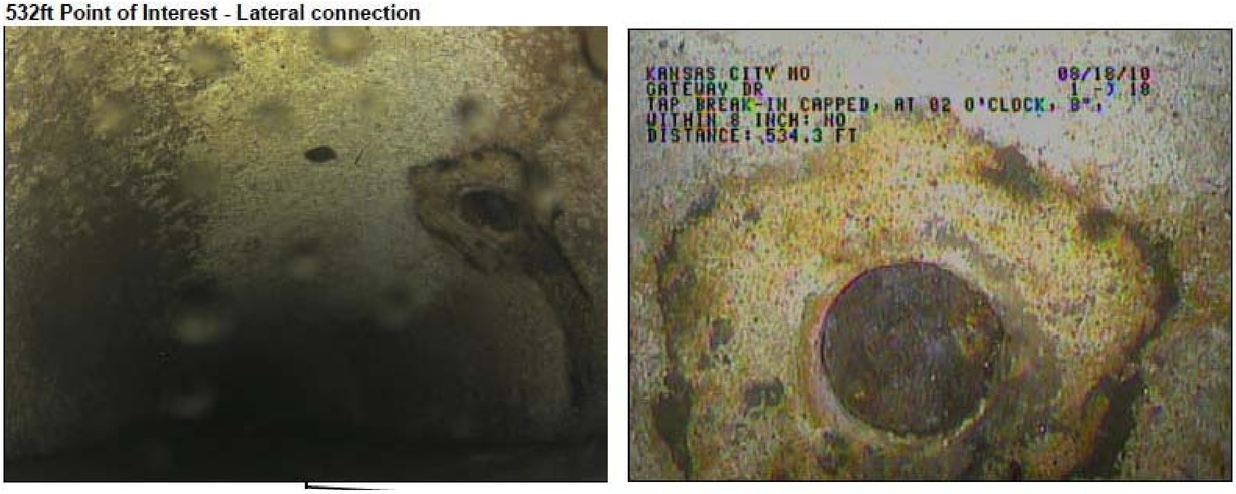


Photo: 19, Tape/Media No.: 081810DJ, 00:12:24
534.3FT, Tap Break-In Capped, at 02 o´clock, 8", within 8 inch: NO

Figure 6-13. MH 1-18, Multi-sensor Data (left) and CCTV Data (right) of Capped Lateral.

Overall Pipe Rating and Analysis

Structural indices (e.g., SPRI) calculated from digital scanning results showed that 16 of 18 pipe segments (i.e., approximately 89% of the inspected pipe lengths) were in excellent structural condition. These results compared well to CCTV inspection results that identified no structural defects. Overall, digital scanning identified 41 areas of surface deterioration (i.e., coded as SRI on the PACP coding diagrams). The laser and sonar results further quantified these areas of corrosion as inches of pipe material lost.

One advantage of the multi-sensor technology was its ability to identify additional defects based on integration of each of the three different data sets. The condition assessment based on these integrated data was different than the assessment based on the CCTV data alone. For example, the digital scan in Figure 6-14 showed widespread surface roughening and the laser measurements showed material loss due to corrosion. Together, these results indicated that the interceptor needs immediate attention in areas where pipe loss was most severe. CCTV data provided a less thorough assessment (Figure 6-15).

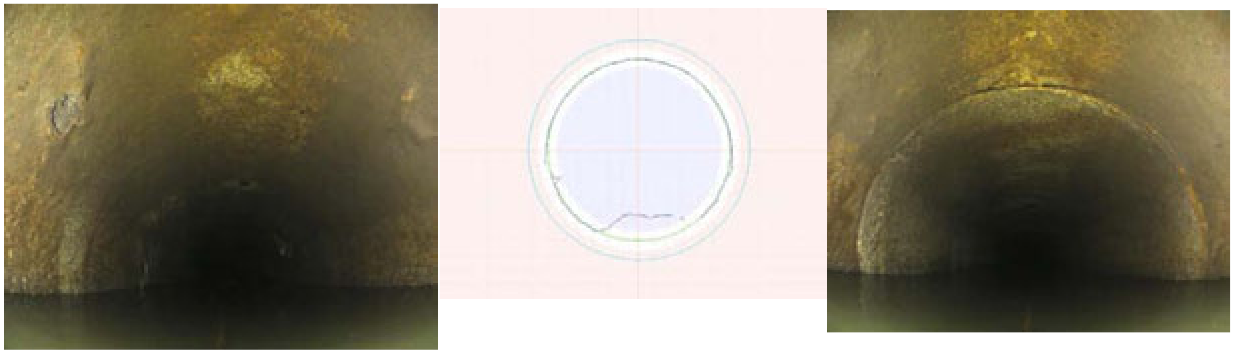


Figure 6-14. Images from Multi-sensor Inspection 148-ft to 150-ft Downstream of MH 2 (left) Evidence of Delamination, (middle) Cross-Sectional View of Debris Accumulation; and (right) Corrosion at Pipe Crown.

Figure 6-15. CCTV Data 150-ft Downstream of MH 2 Showing Encrustation Deposit.

As described in Section 5.4.1, the laser data revealed and quantified corrosion above the water line that the conventional CCTV did not. Seven of the eighteen segments had maximum corrosion depths of greater than 1.0-in. The laser scan did not, however, find deformation defects (ovality and deflection). It is assumed that no deformation was identified in this demonstration because the pipeline was constructed of reinforced concrete.

For areas below the water surface, the sonar data provided additional information on changes in the wall material (i.e., gain or loss) resulting from corrosion, siltation, or deformation (ovality and deflection). Evaluation of pipe below the water surface was not possible by CCTV or the other technologies evaluated.

6.3 Technical Performance – Precision

Precision was assessed by evaluating duplicate inspections of selected pipe segments. Results were presented in Chapter 5 for each technology and are compared in Table 6-7. Zoom camera results showed that duplicate runs identified the same defect and construction feature, but estimates of their location were different by 4-ft to 15-ft. The duplicate runs for the multi-sensor unit both located one corrosion defect and determined the severity for two corrosion defects. Because the multi-sensor's sonar unit was not operating properly during the second run, comparison of sonar results was not possible.

Table 6-7. Comparison of Precision Results.

Technology	Pipe Segment	Similarity of Two Inspections	Differences Between Two Inspections
Zoom Camera	SMH 103-102	Identification of a Grade 1 circumferential crack. Identification of an abandoned survey.	Defect location (0-ft vs. 4-ft from SMH 103); Location of abandoned survey (10-ft vs. 25-ft); and Sight distance (10-ft vs. 25-ft).
Electro-scanning	SMH 101-100	Identification of 71 pipe joints. Location of 18 defects. Severity of 17 defects.	Number of defects identified (18 vs. 21); Severity of 1 defect (small vs. large); and The length of defects as % of pipe length (2.6% vs. 3.3%).
Multi-sensor	SMH 6-5	Location and severity of one corrosion defect; Severity of a second corrosion defect.	Location of one corrosion defect different by 0.6 ft; and First run identified location of a lateral connection.

6.4 Technical Performance – Production Rate

The time to complete field work for each technology, including equipment set-up, inspection and down-time, was provided in Chapter 5. Table 6-8 compares results amongst the technologies. Because the zoom camera inspection resulted in limited sight distance, production was assessed in terms of manholes accessed rather than the length of pipeline inspected. Therefore, it was not possible to compare production rates for zoom camera and the other technologies, or zoom camera vendor claims to actual rates observed in the field demonstration program. The zoom camera inspection of larger diameter pipelines was slower than for smaller diameter pipelines due to the depth of the pipelines. Table 6-8 shows that production rates for CCTV and electro-scanning were similar, while the multi-sensor inspection was two to three times faster.

Table 6-8. Comparison of Production Rates.

Technology	Pipe Diameter (in.)	Average Daily Production[1] (ft of pipe inspected or MH accessed)	Average Daily Time for Equipment Set-up and Inspection[2] (hr)	Average Daily Down-time[3] (hr)	Average Daily Production Rate[4]
CCTV	8-in. to 12-in.	2,003-ft	8	0	250 ft/hr
CCTV	60-in. to 72-in.	1,688-ft	4.8	3.2	352 ft/hr
Zoom Camera	8-in. to 12-in.	14 MH	5.3	1.4	2.6 MH/hr
Zoom Camera	60-in. to 72-in.	2 MH	2.3	0	0.9 MH/hr
Electro-scanning	8-in. to 10-in.	1,761-ft	7.1	0.75	242 ft/hr
Multi-sensor	60-in. to 72-in.	3,405-ft	5.5	6.5	619 ft/hr

[1] Total inspection length or manholes accessed divided by number of days of inspection; MH = manholes.

[2] Total hours for equipment set-up and pipe inspection divided by number of days of inspection.

[3] Down-time includes time to complete troubleshooting and equipment repair and delays due to weather. Reported as average daily value for whole inspection period.

[4] Average daily production divided by average daily hours for equipment set-up and inspection.

6.5 Complexity and Ease of Operation

Complexity is a measure of the level of training and certification required to implement an inspection program and perform data analysis. This metric considers the costs and time required for training and certification programs. The complexity metric also factors in the standardization of a technology. For example, technologies for which there is an ASTM or NASSCO standard (e.g., PACP) have equipment and software platforms that may be transferable to utilities. Ease of operation is a measure of the number and difficulty of steps involved in setting up field equipment and performing inspections.

The complexity and ease of operation were determined for each technology based on input from technology vendors, project team experience, and project stakeholder input. Results are summarized in Table 6-9.

Table 6-9. Complexity and Ease of Operation for Each Inspection Technology.

Contributing Factor	CCTV	Zoom Camera	Electro-scanning	Multi-sensor (Laser, Sonar and Digital Scanning
Training Requirements	Medium	Medium	Low	Medium
National Certification	PACP	PACP	None required	PACP for Digital Scanning
Equipment Operation	Low	Low	Medium	Medium
Pipe preparation	Cleaning may be required	None required	None required	None required
Data Analysis	Low to Medium	Low to Medium	Low	High
Overall Complexity Rating	Low to Medium	Low to Medium	Low to Medium	Medium to High

PACP = Pipeline Assessment Certification Program

Four days of training are typically required to operate camera-based technologies. Additional training is also required for coding the defects identified on camera images, and is provided by organizations that have developed defect coding systems. For example, NASSCO offers a two day training program on the PACP (http://www.nassco.org/training-edu/te-pacp.html).

For electro-scanning, approximately one day of training is required to operate the equipment. For FELL-41, training is provided by experienced equipment vendors because the manufacturer no longer supports the product. This technology is not currently part of any national certification program; however ASTM Standard F2550-06 (ASTM, 2006) describes the standard practice. Electro-scanning equipment operation is relatively straightforward, although use of a hydraulic truck to assist with surcharging the pipe adds extra complexity to the operation. In addition, retrieval of the jet nozzle from the upstream manhole to attach the sliding plug can be difficult. Use of a hydraulic truck, however, increases the inspection rate. Electro-scanning output is simply a graph of changes in current with distance and does not require elaborate processing or interpretation from the field operator.

Multi-sensor instruments such as the Cleanflow system, which incorporate high-definition imaging, sonar, and laser, can entail complex data analysis. Cleanflow produces detailed reports including 3-D color-coded images. Data processing and report generation, however, can take weeks. Data analysis requires a specific skill set. A system that uses standardized software, on the other hand, is more easily adopted by utilities with minimal training. The digital scan, which is based on NASSCO PACP defect coding, can be performed by any certified NASSCO analyst. The equipment does require operator training and equipment operation is straightforward. The manufacturer would likely provide employee training as part of the equipment purchase. Trained CCTV inspection staff could transition into operating the equipment following the training program. In comparison to the zoom camera technology, the training requirements for the multi-sensor technology would be significantly greater.

6.6 Cost

Table 6-10 compares actual costs for field demonstration of the different inspection technologies; assumptions are provided as footnotes to the table. The total cost includes costs for planning/mobilization, field work, and data analysis/reporting. Costs of field work are further detailed by equipment set-up and calibration, pipe cleaning, water service, inspection work, equipment troubleshooting, and repair. Cost data are reported as 2010 dollars and include labor costs, inspection equipment provided by a service contractor, and miscellaneous field supplies. Traffic control was not required and no service disruptions occurred, so no costs were included for these potential cost elements.

Table 6-10. Cost Comparison of Inspection Technologies.

Cost Element	CCTV	Zoom Camera	Electro-scanning	Multi-sensor (Laser, Sonar and Digital Scanning
Total Cost				
Planning/Mobilization	--	$2,257	$11,047	$4,000
Field Work	$34,806	$7,731	$11,817	$13,650
Data Analysis and Reporting	--	$15,368	$6,017	$12,618
Total	**$34,806**	**$25,356**	**$28,881**	**$30,268**
Cost per Ft				
Total	**$2.80** [1] **$3.00** [2]	**$0.99** [3]	**$2.95** [4]	**$4.21** [5]
Daily Cost				
Total	$5,608[6] $6,078[7]	$1,222-6,415[8]	$5,776[9]	$15,134[10]
Cost as % Total Inspection Costs				
Planning	--	8.9	38.3	13.2
Field Work	100	30.5	40.9	45.1
Data Analysis and Reporting	--	60.6	20.8	41.7
Total	100	100	100	100

[1] $2.80/ft for Gracemor area based on total cost of $19,614 and inspection of 7,009-ft of pipe; includes light cleaning and root cutting; and includes data analysis and reporting. Costs include $10,514 (inspection), $7,600 (jet truck) and $1,500 (water service).

[2] $3.00/ft for Line Creek Interceptor based on total cost of $15,192 and inspection of 5,064-ft of pipe; includes no pre-cleaning; and includes data analysis and reporting.

[3] Based on total cost of $25,356 and inspection of 25,593-ft of connecting pipe accessed via 83 manholes (22,738-ft at Gracemor and 2,855-ft at Line Creek Interceptor).

[4] Based on total cost of $28,881 and inspection of 9,784-ft of pipe.

[5] Based on total cost of $30,268 and inspection of 7,188-ft of pipe (including the 378 ft of replicate inspection between SMH 6 and 5).

[6] For Gracemor area, based on average production rate of 2,003 ft/day and $2.80/ft.

[7] For Line Creek, based on average production rate of 2,026 ft/day and $3.00/ft.

[8] Daily cost based on cost per manhole accessed ($305.49). Number of manholes accessed each day varied from 4 to 21 due to equipment problems, weather, depth to sewer and other factors.

[9] Daily cost based on a total cost of $28,881 and five days of work.

[10] Daily cost based on a total cost of $30,268 and two days of work. Although both days were 12 hr long, equipment problems caused 6 to7 hr of unproductive time each day.

Mobilization costs varied widely as field crews originated from different cities. Both CCTV and zoom cameras were based locally in Kansas City. The electro-scanning crew travelled from Dallas, Texas and the multi-sensor crew mobilized from their home office in Louisville, KY.

Although the total cost per ft of pipeline inspected was lowest for zoom camera, this metric is misleading because the zoom camera had limited sight distance and did not provide inspection results for all connecting pipelines between manholes.

Data analysis was expensive for the multi-sensor and zoom camera at 42% and 61% of the total inspection costs, respectively as compared to 21% for electro-scanning. The processing of the digital scan is labor intensive, and processing the laser and sonar data requires specialized software.

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Appendix A: Field Demonstration Planning

Introduction

This appendix details the steps involved in planning the field demonstration phase of this project, including identification of host utility, development of the work plan and quality assurance project plan, selection of pipe segments, and coordination with the host utility. This information is intended to augment the material in Chapter 2 of this report and to benefit utilities and other entities who wish to conduct their own field demonstration programs.

Planning Steps

Planning activities took place over a 17 month period (March 2009 to July 2010) in parallel with other project research work. The initial step was selection of technologies based on findings from the Project's Technology Forum in September 2008. These technologies are discussed in Section 3. Other planning activities are discussed in this appendix and are presented generally in chronological order.

Identifying a Host Utility

One of the first steps was to identify a wastewater utility that would allow the field demonstration program to be conducted within their collection system. Utility support was essential for the success of the program. The wastewater utility must have the necessary range of pipe sizes, materials, and conditions for the selected technologies and must have access to historical data such as system maps, maintenance records, and inspection reports to select the best pipelines. A utility with an existing condition assessment program may be optimal. The following criteria were considered in the evaluation:

- Cooperation of wastewater utility;
- Availability of historical data and system information;
- Hydraulic conditions;
- Pipe characteristics; and
- Site access.

A primary criterion is the willingness of a utility to be an active participant in the research program. The ideal utility will grant full access to the collection system, provide logistical support, and would not restrict the use of data collected during the program. The utility benefits from the research by acquiring firsthand experience with alternative condition assessment technologies and receiving new data about the condition of their collection system.

The KCMO Water Services Department was selected as the host utility for this project; more information about the utility is given in Section 2.

Developing the Field Demonstration Work Plan

A draft work plan was developed to document specific procedures and protocols that would be used in the field demonstrations. The work plan contained the following elements:

- Descriptions of condition assessment technologies selected for field demonstration.
- Standard operating procedures for each inspection technology including personnel qualifications, general set-up and calibration procedures, the inspection procedure, data verification, data assessment and reporting procedures, and records management.
- Site selection criteria.
- Overview of the quality assurance project plan (QAPP).
- Health and safety plan requirements.
- Performance metrics by which each technology will be evaluated.

The draft work plan was reviewed by the project stakeholder group and USEPA. In particular, stakeholder comments on pipe size and inclusion of sonar were very helpful in shaping the field demonstration program such that the findings would be representative and useful to many utilities. The final work plan addressed all review comments. It was provided to the host utility, technology vendors and other interested parties.

Selecting the Demonstration Sites

To select specific pipelines for the demonstrations, the project team collaborated with the host utility. The project team met with utility staff in several face-to-face meetings to introduce the project and research objectives, to discuss data needs and review maps, and to discuss the logistics of the field activities. Pipes were identified using several evaluation criteria: pipe material and diameter, maintenance and operational history, the pipe's current physical and hydraulic condition, accessibility, and worker safety. System information and maps were reviewed to find pipe segments with known defects or a high probability of defects. Streets with minimal traffic were selected preferentially over busier areas that would require special permits and a traffic control officer.

The hydraulic conditions required to support inspection were considered. Many of the technologies proposed for field testing only function within dry areas; other technologies require full pipe conditions. Factors influencing hydraulic conditions include the time of day, season, wet weather, and tidal elevations in coastal areas. Therefore, inspection should be scheduled at a time that provides the appropriate hydraulic conditions.

Different site conditions are appropriate for the various technologies as illustrated by the minimum requirements listed in Table 2-1. Pipe material was not a key factor for these technologies except for electro-scanning (FELL-41), which is only applicable to non-ferrous pipelines. However, both size and hydraulic conditions needed to be taken into account. Areas that met the accessibility criteria were identified by reviewing system maps and relying on the system operator's knowledge of manhole locations and traffic volume on each street. Descriptions of the two areas (Gracemor and Line Creek) are given in Chapter 2.

Developing the Quality Assurance Project Plan

Prior to performing the field demonstration, the project team was required to prepare a Category III Quality Assurance Project Plan (QAPP) per EPA guidelines and to seek USEPA review and approval. The QAPP addresses the collection of primary data during the field demonstrations. It outlines goals for various data quality criteria (e.g., accuracy, precision, bias, completeness, representativeness, comparability and sensitiveness) to ensure that the field data are reliable and useful to the target audience. The QAPP also outlines research questions and objectives, data collection and analytical procedures, and standard operating procedures for each technology to be demonstrated.

Selecting Technology Vendors

Technology vendors were selected through a competitive bid process. Requests for Proposals/Request for Qualifications (RFPs/RFQs) were advertised for the following technologies: multi-sensor (simultaneous laser, sonar and digital scanning); zoom camera; and focused electrode leak location (i.e., electro-scanning).

Proposals were reviewed based on vendors' technical qualifications, proposed equipment, related company experience, related staff experience, and understanding of the project. Vendor equipment was compared to technical specifications outlined in the RFPs. Cost proposals were evaluated by comparing total costs for planning, equipment mobilization, inspection, and data analysis and reporting. Several assumptions were made to evaluate cost proposals: (1) a daily production rate (i.e., inspection rate) of 1,750-ft; and (2) a total production rate of 8,750-ft for the 5-day field demonstration period.

The vendors selected were:

1. Burgess & Niple (Dallas, TX) with subcontractor Leak Busters Inc. (Rescue, CA) - electro-scanning.
2. TREKK Design Group, LLC (Kansas City, MO) – zoom camera.
3. Hydromax USA (Louisville, KY) – multi-sensor unit (laser, sonar, digital scanning).
4. ACE Pipe (Kansas City, MO) – sewer cleaning, baseline CCTV evaluation.

Assigning Roles and Responsibilities

The following parties were involved in developing and implementing the field demonstration program: USEPA, the project team, technology vendors/contractors, and the host utility. Each party had specific roles and responsibilities for carrying out the program. These roles were defined during the planning phases of the project and are described below:

USEPA: This project was funded by the USEPA Office of Research and Development. USEPA managed the contract and had direct responsibility for the review and approval of all work products developed under this contract. All work products were published in accordance with USEPA format guidelines.

Project Team: The Cadmus Group (Cadmus) was the prime contractor for this task assignment under contract with the USEPA. The following sub-consultants were under contract as team members: The Louis Berger Group, Inc., (Berger), ADS Environmental Services (ADS), and RedZone Robotics (RedZone). The project team was responsible for project planning; coordination with the host utility and technology vendors; communication with utility managers and USEPA; implementation and oversight of the field demonstration program, data assessment, and reporting.

Technology Vendors/Contractors: Multiple vendors were required to provide appropriate equipment, material, and labor to facilitate the program. The roles and responsibilities of vendors were to:

- Provide labor, equipment, and materials necessary to conduct the field demonstrations.
- Modify, as appropriate, SOPs to specifically address the functionality of the equipment and software used to conduct field demonstrations.
- Develop and comply with Health and Safety Plan (HASP).
- Mobilize equipment to demonstration site per project schedule.
- Prepare pipe segments (i.e., clean and flush) in accordance with field protocols to facilitate baseline assessment and inspections.
- Establish site security and traffic control.
- Implement field inspection protocol and procedures in accordance with project-specific documents and referenced standards.
- Implement quality management standards.
- Prepare summary report of field data and observations.

Host Utility: The host utility, KCMO Water Services Department, provided logistical support and access to the wastewater collection system. The utility provided water from hydrants and allowed grit disposal at their sewage treatment facility. The specific responsibilities of the host utility included:

- Assigning a point person to maintain contact with the project team and to coordinate other utility support staff as needed.
- Providing requested historical system data during the planning phase of the project.
- Assisting the project team with logistics prior to field testing such as contacting local service providers for traffic control, sewer cleaning.
- Providing access to testing sites.
- Assigning utility representatives to observe field testing and provide logistical support during field work.

Scheduling the Field Demonstration

The schedule for the field demonstration was determined based on flow conditions and availability of vendor staff. The project team met with vendor representatives to set the final schedule. The program was initially scheduled for May 2010, and nighttime operations were considered to achieve the optimal flow conditions. When the schedule was revised to an August start date, it was determined that daytime flow conditions would be adequate. The final schedule was as follows:

- Week 1 (August 9, 2010) - Multi-sensor inspection (Line Creek Interceptor) and zoom camera inspection (Gracemor and Line Creek Interceptor).
- Week 2 (August 16, 2010) - CCTV baseline evaluation (Line Creek Interceptor and Gracemor) and cleaning (Gracemor only).
- Week 3 (August 23, 2010) – Electro-scan inspection (Gracemor).

Executing a Cooperative Agreement with the Host Utility

At the host utility's request, a cooperative agreement was developed to outline how certain issues related to the field activity would be handled, including: access to the utility's property; data sharing; indemnification/liability; repair of property damage; insurance; and local permits for street closure and traffic control. Prior to executing the agreement, Louis Berger Group, the task leader for the field demonstration work, received review comments and approval from USEPA and The Cadmus Group. The agreement was reviewed by legal counsel for both parties and signed by utility and project team representatives.

Developing Health & Safety Plans

The project team prepared a HASP that covered the project team representatives and other visitors to the demonstration sites. All project personnel that were not performing actual inspection work were considered to be visitors. Each technology vendor prepared a HASP to protect their field personnel conducting the field demonstration work and submitted it to the project team as part of contract requirements. The HASPs were completed prior to any equipment mobilization, site preparation, or inspection work. The HASPs were developed in accordance with applicable Occupational Safety and Health Administration (OSHA), USEPA, and other federal, state, and local regulations.

Two weeks prior to the field demonstration, an on-site survey was completed by representatives from the project team, KCMO Water Services Department, TREKK Design Group LLC and ACE Pipe Cleaning, Inc. to identify any potential health or safety issues on the two work sites and to locate manholes and walk the pipeline to further plan field activities. All potential health and safety issues identified by the on-site inspection on the two work sites were sufficiently addressed in the HASP documents provided by each technology vendor, and no site-specific revisions were deemed necessary.

Lessons Learned

Several key findings from the field demonstration planning process focus on the importance of effective project management practices. These lessons learned include:

1. It is important to clearly define the objectives of the field demonstration program and the data that need to be collected to meet these objectives. The quality assurance plan is a

good place to document these research objectives, data needs, and other data quality objectives.

2. A formal cooperative agreement between the host utility and the project team is an effective vehicle for communicating and coming to terms with important issues such as data sharing and liability. Although the project team did not initially recognize the need for such an agreement, its value became apparent as the agreement was developed and implemented. The agreement's clause on data sharing provides a definite benefit to the utility and allows immediate access to raw data that would otherwise have to be reviewed and approved by USEPA prior to sharing with the utility. The project team advises others to identify the need for a formal agreement early in the planning phase to allow adequate time to meet the requirements of both parties.

3. Face-to-face meetings were the most effective way of sharing project information with the host utility. Three meetings were held during the planning phase: 1) an initial meeting to introduce the project team and project objectives to utility staff; 2) a meeting with the utility engineer to discuss data needs for planning the field demonstration program; and 3) a meeting with the utility engineer to discuss detailed logistics for field activities, visit the study areas and formulate site set-up procedures.

4. The project stakeholder group served a valuable role in providing review comments on the draft field demonstration work plan. In particular, their feedback was used to revise the pipe sizes inspected in the demonstration program to better represent a typical U.S. collection system, a change that will likely increase the value of project findings.