Sealing Large-Diameter Cast-Iron Pipe Joints Under Live Conditions

Quarterly Report
March 25, 2005 – June 24, 2005

By:
Kiran M. Kothari
(Gas Technology Institute)
and
Gerard T. Pittard
(Maurer Technology Inc.)

July 2005

DE-FC22-02NT41316

GAS TECHNOLOGY INSTITUTE
1700 South Mount Prospect Road
Des Plaines, Illinois 60018-1804

MAURER TECHNOLOGY INC.
13135 South Dairy Ashford, Suite 800
Sugar Land, Texas 77478-3686

Disclaimer

Abstract

Utilities in the U.S. operate over 75,000 km (47,000 miles) of old cast-iron pipes for gas distribution. Bell-and-spigot joints that connect pipe sections together tend to leak as these pipes age. Current repair practices are costly and highly disruptive. The objective of this program is to design, test and commercialize a robotic system capable of sealing multiple cast-iron bell and spigot joints from a single pipe entry point. The proposed system will perform repairs with the pipe in service by traveling through the pipe, cleaning each joint surface, and installing a stainless-steel sleeve lined with an epoxy-impregnated felt across the joint. This approach will save considerable time and labor, minimize excavation, avoid traffic disruption, and eliminate any requirement to interrupt service to customers (which would result in enormous expense to utilities).

Technical challenges include: (1) repair sleeves must compensate for diametric variation and eccentricity of old cast-iron pipes; (2) the assembly must travel long distances through pipes containing debris; (3) the pipe wall must be effectively cleaned in the immediate area of the joint to assure good bonding of the sleeve; and (4) an innovative bolt-on entry fitting is required to conduct safe repair operations on live mains.

The development effort is divided into eleven tasks. Task 1 (Program Management) and Task 2 (Establishment of Detailed Design Specifications) were completed previously. Task 3 (Design and Fabricate Ratcheting Stainless-Steel Repair Sleeves) progressed to installing prototype sleeves in test cast-iron pipe segments. The sleeve system design has been improved based on laboratory testing in preparation for field trials.

Efforts in the current quarter continued to be focused on Tasks 4–8. Highly valuable lessons were learned from field tests of the 4-inch gas pipe repair robot in cast-iron pipe at Public Service Electric & Gas. (These field tests were reported previously.) Several design issues were identified which need to be implemented in both the small- and large-diameter repair robots. For Task 4 (Design, Fabricate and Test Patch Setting Robotic Train), previous problems with bladder design and elastomeric material expansion in the large mains were addressed. A new bladder based on a commercially available design was obtained and tested with success. Minor improvements (such as additional rows of ratchets) were highlighted during patch-setting tests and have been added to the design.

For Task 5 (Design and Fabricate Pipe-Wall Cleaning Robot Train with Pan/Zoom/Tilt Camera), previous field tests showed clearly that, in mains with low gas velocities, it will be necessary to improve the system's capacity to remove debris from the immediate vicinity of the bell and spigot joints. Otherwise, material removed by the cleaning flails falls directly to the low side of the pipe and accumulates in a pile. This accumulation can prevent the sleeve from achieving a leak-free repair. Similarly, it is also deemed necessary to design an assembly to capture existing service-tap coupons and allow their removal from the inside of the pipe. These improvements were added to the system.

Task 6 (Design and Build Surface Control and Monitoring System) was begun early in the project with the development of control and computer display functions being operated through LabVIEW. This task was revisited during the quarter with the fabrication and testing of a field-ready surface control module in anticipation of full-scale testing of the drilling assembly in the laboratory and field. Control routines for the coupon catcher are also being added to the system software.

Task 7 (Design and Fabricate Large-Diameter Live-Access System) progressed to completing the detailed design, fabrication and testing of a bolt-on entry fitting for 12-inch diameter cast-iron pipe in the current quarter. The drilling assembly for cutting an access hole through the wall of the gas main was also designed, fabricated and tested, along with a plug assembly to allow removing all tools from the live main and setting a blind flange on the entry fitting prior to burial. In preparation for field tests (Task 9), the system will soon undergo full-scale testing at MTI's shop facilities to completely exercise the equipment and procedures and to train the team to effectively operate the system. This will include assembling a test main from three joints of 12-in. ductile cast-iron pipe, cutting multiple access holes to perfect operational procedures and then setting multiple patches within the test main.

Task 8 (System Integration and Laboratory Validation) continued with the development of the robot module inter-connects and of a master LabVIEW-based system display and control software.

Task 9 (Field Testing and System Refinement) was initiated with several discussions between GTI, MTI, Public Service Electric & Gas, and other utilities for scheduling field tests in the next quarter. These are now expected to be conducted in late August or September 2005.

Table of Contents

List of Tables

List of Figures

1. Introduction

Utilities in the U.S. operate over 75,000 km (47,000 miles) of old cast-iron pipes for gas distribution. Most of this pipe is in highly urbanized areas and its replacement is prohibitively expensive. While the cast-iron pipe itself generally retains acceptable mechanical competency, the joints, which are of bell-and-spigot design, tend to leak. Current repair practices are to: (1) excavate and expose each joint and encapsulate it externally; or (2) take the line out of service and apply repair sleeves or cured-in-place liners. Both methods are costly and highly disruptive.

The objective of this program is to design, test and commercialize a robotic system capable of sealing multiple cast-iron bell and spigot joints from a single pipe entry point. The proposed system will perform repairs while the pipe remains in service by traveling through the pipe, cleaning each joint surface, and attaching a stainless-steel sleeve lined with an epoxy-impregnated felt across the joint. This approach will save considerable time and labor, avoid traffic disruption, and eliminate the requirement to interrupt service, which results in enormous expense to utilities and considerable inconvenience to customers.

This development effort represents an aggressive expansion of existing technologies. Applying this technique inside large-diameter cast-iron pipes poses a number of technical challenges, among them: (1) repair sleeves must compensate for diametric variation and eccentricity of cast-iron pipes; (2) the assembly must travel long distances through pipes having significant levels of debris; (3) the pipe wall must be effectively cleaned in the immediate area of the joint to assure good bonding of the sleeve; (4) an innovative bolt-on entry fitting is required to conduct repair operations on live mains; (5) coiled-tubing equipment must be designed to optimize push distance from a single pipe entry point.

2. Experimental

Experimental Objectives

The objective of this development program is to design, test and commercialize a robotic system capable of sealing multiple cast-iron bell and spigot joints from a single pipe entry point. The proposed system will perform repairs while the pipe remains in service by traveling through the pipe, cleaning each joint surface, and attaching a stainless-steel sleeve lined with an epoxy-impregnated felt across the joint. This approach will save considerable time and labor, avoid traffic disruption, and eliminate any requirement to interrupt service to customers (which would result in enormous expense to utilities).

System Description

The robotic joint-sealing system will be comprised of four main subsystems. These are: (1) two sequentially run, multiple-module robot trains; (2) pipe-access hardware for safely admitting into and removing the robot trains from the live gas-main environment; (3) a coiled-tubing (CT) delivery system for providing primary locomotion, power and data communications between the in-pipe robot and (4) surface control and display electronics.

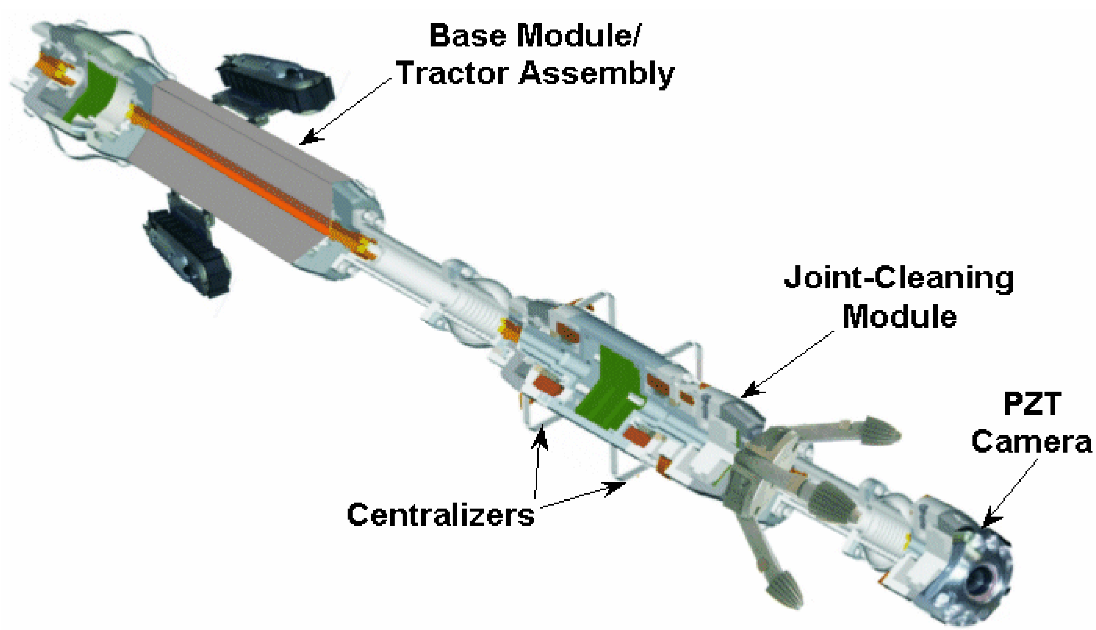


Figure 1. Pipe Wall Preparation Robot Train

Based on the analysis completed to date, two in-pipe robot trains will be required. The first robot train has a front-mounted camera that is used to visually locate each bell and spigot joint (Figure 1 and Figure 2). Directly behind this camera is a counter-rotating brushing module whose function is to remove debris from the pipe wall within the cast-iron bell and spigot joint. This module will now be fitted with a retractable brush to remove debris piles from the immediate vicinity of the joint. The third and final module consists of a combination base/supplemental locomotion module. The base module provides all power and micro-controller control of the camera and brush modules. The supplemental locomotive will be used to provide additional axial movement forces as necessary.

Figure 2. Camera's View of Bell and Spigot Joint Seam

In operation, the camera/brush/base module train will be pushed by the CT to the farthest cast-iron bell and spigot joint to be repaired from a given launch location. The brushing module will then be activated to clean the joint by moving the brushing assembly back and forth across the joint location. Proper cleaning of this joint will be visually confirmed by the operator through the camera and may require one or more passes depending on the amount and tenacity of the debris coating the pipe wall. The CT unit is then used to withdraw the train back to the next joint where the cleaning process is repeated. This sequence is continued until all joints have been prepared for patching and the pipe-wall preparation train has been brought back into the pipe-access fitting and withdrawn from the main.

The brush module is then removed from the train and replaced with the stainless-steel patch-carrier/patch-setting module (Figure 3). The stainless-steel sleeve is slid over the carrier along with its polymer sleeve and polyester felt, which has been saturated with epoxy. The CT unit is then used to deliver the patch-setting train to the most distant bell and spigot joint. This location is confirmed both with the quadrature encoder footage counter and visually with the camera. Once the camera is located exactly at the bell and spigot-joint gap, the fine-resolution odometer on the camera is set to zero. The CT unit is then used in conjunction with the camera's odometer to move the patch setting train forward by a known, fixed distance which assures the patch is properly aligned with the bell and spigot joint. A control command is then issued from the surface unit to the base unit to release nitrogen from a stainless-steel pressure vessel on-board the patch-setting module into its expandable rubber bladder. This causes the bladder to inflate and locks the stainless-steel sleeve into position via its interlocking, ratcheting barbs. The epoxy is allowed to cure and reaches full strength within 12 hours. During the interim, a gas-tight seal is assured by the polymer sleeve which has been energized against the joint by the hoop stress of the stainless-steel sleeve. (Note: The volume and rate at which the nitrogen is bled from the inflation bladder results in no appreciable dilution of the BTU quality of the natural gas.)

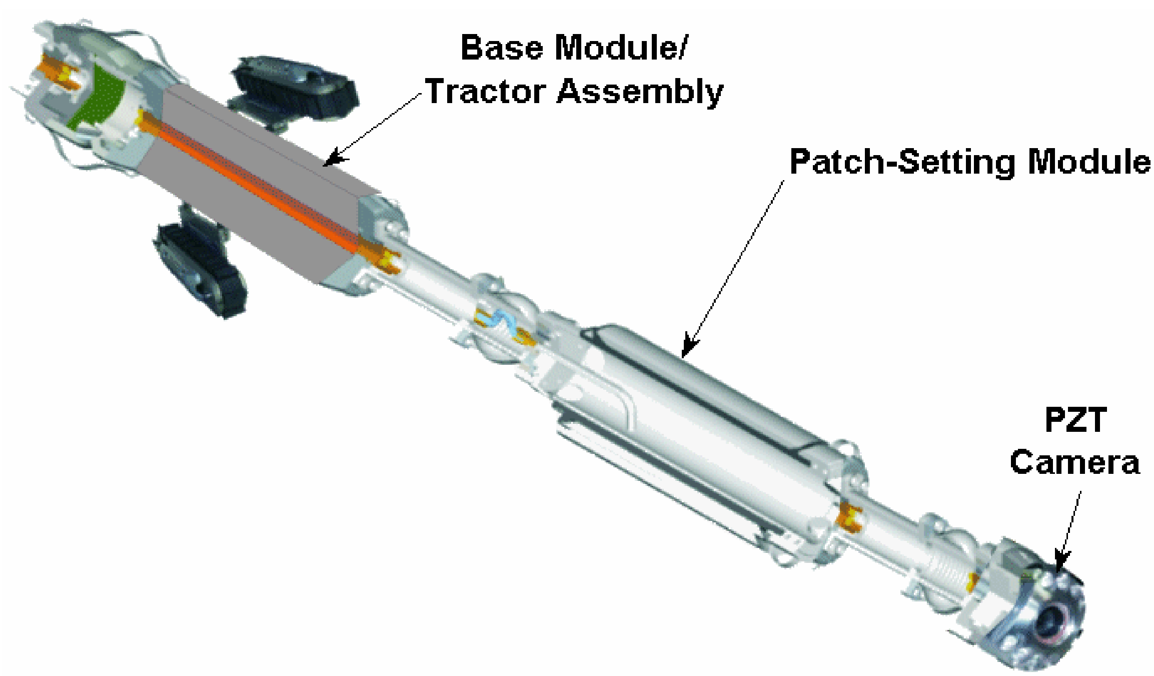


Figure 3. Patch-Setting Robot Train

3. Results and Discussion

The project work structure consists of the 11 tasks described below. Work during the first thirteen quarters has focused on Tasks 1–10. Specific results and progress are described under each task. Work planned for the next quarter is discussed at the end of the chapter.

Task 1 – Program Management

A Research Management Plan, consisting of a summary of the program's technical objectives and the technical approach for accomplishing these objectives was described and documented in a written report to DOE. The report was to include task descriptions, schedules and planned expenditures as well as major milestones and decision points.

In addition, a Technology Assessment was also prepared. The assessment was to establish the state-of-the-art of the technologies to be developed along with those technologies against which it must compete. The report describes each technology identifying both positive and negative aspects of using these technologies.

This task was completed in the first quarter.

Task 2 – Establishment of Detailed Design Specifications

The design of a system to inspect, prepare and patch cast-iron gas main joints under live conditions represents a substantial advancement over systems designed for small steel distribution lines. Key differences between small-diameter steel pipes and large-diameter cast-iron pipes should be identified and used to set benchmark design targets for hardware sizes and component functionality. The following subtasks support this benchmarking effort:

2.1 *Identify Mechanical, Material and Operational Differences between Small-Diameter Steel Mains and Large-Diameter Cast-Iron Mains.* The entry system for steel lines can be attached by welding (not an option with cast iron). This carries numerous concerns that must be addressed for the entry/access system, including means to fasten the entry fitting to the main, implementing a continuous seal with long-term reliability, and designing an entry system that can tolerate settling of the joints over time and provide sufficient reinforcement of stiffness of the main both during and after the repair.

2.2 *Prototype Size Selection.* Large-diameter cast-iron gas mains in the U.S. range in size from 20 to 91 cm (8 to 36 in.) nominal diameter. Since there will obviously be size-specific requirements to be addressed, a size must be selected for the prototype system. This will be done through discussions with the GTI Distribution Task Group (DTG) Advisors. It is expected that the selected size will be either 20 cm (8 in.) or 30 cm (12 in.) since 30 cm and smaller sizes combined represent 95.5% of cast-iron mains in the US.

2.3 *Perform Pushing/Buckling Tradeoff Analyses.* Based on candidate CT products, efforts will be aimed to define "sensitive" design targets points for hardware that will be inserted into the cast-iron main. These will include drag forces, weights of the components, bending requirements on the CT, and stiffness concerns for flexible joints between the required hardware modules on the robot train.

Deliverables for this task include a list of performance and size specifications that provide the basis for follow-on detailed design activities.

Mechanical, material and operational differences between small-diameter steel mains and large-diameter cast-iron mains have been defined. Primary challenges posed by large diameter cast-iron mains involve larger variation in inside pipe dimensions (being addressed by use of a ratcheting sleeve design that can effectively lock into placed over a range of pipe sizes); presence of more debris (being addressed through the use of much more aggressive wall cleaning equipment and the possible use of a plow to move debris away from the bell and spigot joint area); and the fact that the entry fitting for cast iron must be a bolt-on design and entry hole size should be minimized to prevent cracking of the brittle cast iron.

Discussions held with several utilities during the second quarter, including KeySpan Energy, Consolidated Edison and Public Service Electric & Gas, showed that utilities prefer the first prototype be sized for operations inside nominal 12-inch diameter cast-iron pipes. As a result, design efforts are focused on producing detailed designs for the entry fitting, cleaning elements and repair sleeves for this size application. A prototype wall-cleaning device and a bolt-on entry fitting for 12-inch cast-iron mains have been designed.

The CT pushing/buckling analysis was completed in the first quarter. It is expected that this analysis will be briefly revisited after the final weights and drag loads on each robotic element are finished.

Task 3 – Design/Fabricate Ratcheting Stainless-Steel Repair Sleeves

Existing repair sleeves are designed for application under “dead” main conditions (i.e., the mains are not in service and there is no internal pressure present). These sleeves cannot tolerate internal pressure. With current designs, a pressure gradient would displace the sealing epoxy prior to curing, thereby creating leak paths. In addition, repair sleeves for large cast-iron mains must be tolerant of misalignments in the bell and spigot joints. Such misalignment can prevent thorough sealing when using existing designs of repair sleeves.

The sleeve must conform tightly to the interior shape of the joint. A repair sleeve with ratcheting features will make this possible. Designs will be tested on cast-iron pipe samples (as available). Test sample joints will be specially fabricated with intentional misalignments to further test as necessary. To address these critical requirements, work efforts will be directed to:

3.1 *Determine Geometrical Spacing of Interlocking Barbs.* This spacing design must allow sufficient adjustment for misalignment of bell and spigot segments of the joints. Samples will be obtained to perform testing with misalignment conditions observed in the field.

3.2 *Perform Sensitivity Analyses.* Sealing design parameters must be evaluated with respect to sleeve geometry and the amount of compression (“squeeze”) on the patch during application. Patches must be able to lock into place while tolerating misalignment as well as lock in such a fashion to provide ample sealing over all required surfaces. Other aspects to be examined include the design thickness of the felt and the impact of this thickness on sealing effectiveness.

There will be two iterations of the interlocking sleeve design. The first design will be thoroughly tested and evaluated. After any augmentations are made to the first design, a second set will be fabricated and evaluated. The deliverables for this task will be the final design of the ratcheting repair sleeves, complete with mechanical drawings and specifications for fabrication and assembly. A sufficient number (about eight) were built following the second design iteration.

During the first quarter, the first design iteration for one type of the repair sleeves under consideration was prepared. This design is based on modifying existing sealing products from a commercial sleeve manufacturer (Link-Pipe Inc.) so that their sleeves can operate in pressurized gas mains, provide a redundant seal, and minimize their overall diameter before they are expansion-set across the bell and spigot joint. The current commercial sleeve design from the manufacturer does not work in pressurized mains and has only one seal method. In addition, the project approach is to minimize sleeve diameter for simplifying launching of the sleeve into the main and allowing it to ride off the bottom of the main (invert) to minimize its contamination with debris.

Figure 4 illustrates the critical design features. A 28-gage, corrugated stainless-steel sleeve (316 SS) is used as the innermost member. Its function is to provide a mechanical means for energizing the urethane seal sleeve against the cast-iron wall to form the first leak seal and to allow the epoxy-saturated polyester carrier to cure to form a second (redundant) leak seal. The sleeve gage (28) is a reduction from the 24 gage normally used. Its use will enable the sleeve to be coiled in a smaller diameter without yielding. Preliminary analysis indicates that the design can be rolled into a diameter of about 55% of the pipe ID versus 75 % of the pipe ID for the 24-gage thickness sleeves (Figure 5). Corrugations, consisting of folds spaced on 1-inch centers, improve the structural stiffness of the device so it does not deform during setting.

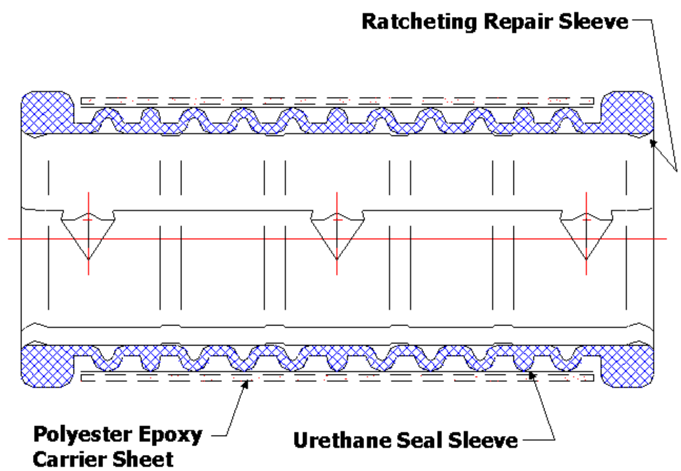


Figure 4. Ratcheting Repair Sleeve

The most obvious visual trait of the urethane seal sleeve is its grooves (ribs). This new design compensates for the axial shortening that would otherwise occur if a non-ribbed sleeve were allowed to radially expand significantly. The end elements feature increased thickness and act as an O-ring once the seal is expanded. Their thickness, coupled with low durometer, should provide an effective pressure seal across a range of cast-iron surface conditions as well as easily compensate for variation in pipe ID. AutoCAD machine drawings of the molds to produce these sleeves in both 8- and 12-inch sizes were prepared.

The final element of the design is a polyester jacket which will carry the epoxy resin. At present, a thixotropic epoxy is being considered that provides about 1 hour of working time before curing begins to create the final seal.

Figure 5. Coiled Diameter Comparison for 28 and 24 Gage

Work has progressed to the fabrication and testing of the second-generation 12-inch repair sleeves featuring ratchets and polyurethane seal sleeves. Components of the most recent sleeve design are shown in Figure 6. The sleeve measures 13 inches long x 7.75 inches diameter in its collapsed (unset) state. Figure 7 shows a sleeve with epoxy applied ready for insertion into the gas main via the inflation module.

Figure 6. Repair Sleeve Components

Figure 7. Repair Sleeve with Epoxy Applied

Several tests were previously conducted to set new 12-inch sleeves in the laboratory inside sample cast-iron joints (Figure 8). The first step was to use the cleaning module to clean debris and scale from the inside of the joint in preparation for running the sleeve (Figure 9).

Figure 8. 12-Inch Cast Iron Pipe Sample

Figure 9. Cast-Iron Pipe ID after Cleaning

The sleeve was successfully set at a maximum inflation pressure of 30 psig (Figure 10). A few challenges yet remain for running and setting the patch (see below). However, pending further testing, this patch design is expected to represent the final design.

Figure 10. Successfully Installed Repair Sleeve

While setting new patches, it became apparent that the existing material used in the inflation bladder (Figure 11) was not adequate. The bladder was observed to fail after a limited number of inflation cycles along the line where the end of the inner sleeve contacts the gum rubber. Options for modifying the bladder include using another compound having a higher tensile strength, or further increasing the thickness of the gum rubber. Figure 12 shows a failed gum-rubber sleeve. Alternatives for modifying the gum-rubber sleeve were investigated.

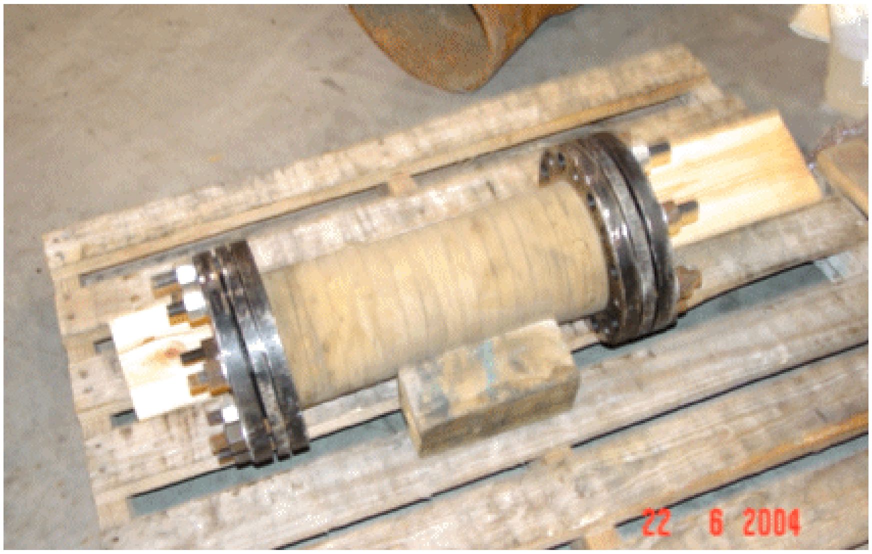


Figure 11. Inflation Bladder

Figure 12. Ruptured Inflation Bladder

During the twelfth quarter, the team acquired and tested a commercial inflation bladder from the company that manufactures the patch assemblies (Figure 13). Initial OD of this system is 6.5 inches and total length is 16 inches without any centralization added. The bladder is constructed from a heavy fiber-reinforced elastomer bonded to an aluminum tube. The bladder requires gas at 40 psi to fully inflate.

A patch setting test was conducted using this off-the-shelf inflator. This included the following:

Figure 13. New Inflation Bladder

1. The ends of sample cast-iron joint were capped (Figure 14) and the internal pressure raised to 2 psi to check for leaks around the bell and spigot joint. Two small leaks were observed using soap spray in the jute area of the joint. These were marked.

Figure 14. Cast-Iron Joint Tested for Leaks

2. Caps were removed from the test joint and the pipe ID was cleaned across the joint area prior to patching.
3. A new patch and patch setting bladder assembly were prepared. The patch was placed at the center of the length of the bladder, and was held in place by slightly inflating the bladder to grip the patch.
4. The patch/bladder assembly was inserted into the joint via a special fixture that allowed the patch to hang in the center of the joint (Figure 15).

Figure 15. Bladder/Patch Assembly Hung in Joint

5. The bladder was inflated to 40 psi (maximum recommended pressure). The bladder required over 10 minutes to completely inflate.

6. Distinct clicking noises were heard during inflation as the ratchets engaged deeper. After inflation was complete, the inflator was left in place for an additional five minutes.

7. Pressure was released on the inflator bladder. The inflation bladder was removed from the cast-iron joint. The caps were again placed on the joint and the inside volume was pressurized to 2 psi. Locations of previous leaks were inspected and tested with soap spray. No leaks were detected.

After the tests were completed, a careful inspection of the set patch indicated that the two outermost rows of ratchets did not engage as deeply as the two inner rows (Figure 16). It appeared that the inflation bladder needs to be about two inches longer on each end to fully engage the patch sleeve ratchets as currently configured.

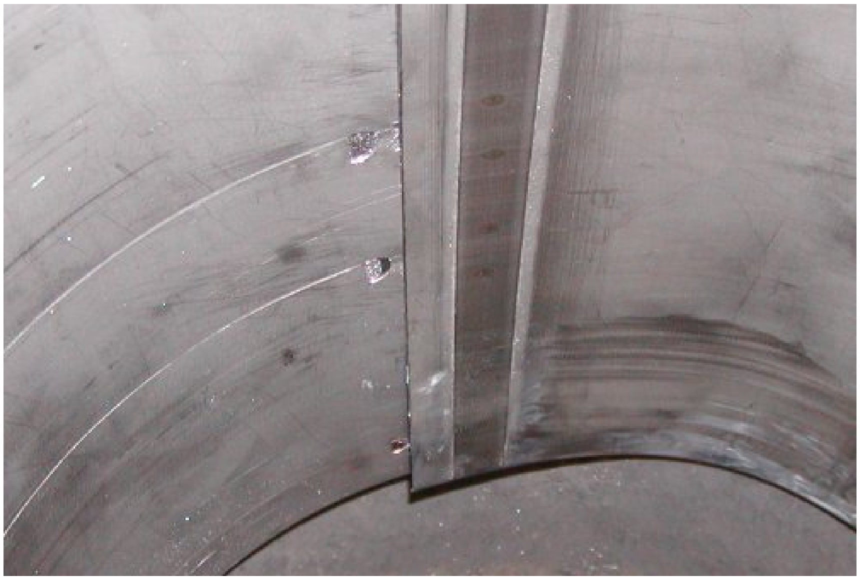


Figure 16. Ratchet Engagement After Patch Setting

Even though the patch set successfully and all leaks were sealed, it was desired to modify the patch or bladder design to allow deeper ratcheting toward the outer edges of the patch. Since use of a standard bladder design is preferred, changes to bladder design were avoided. Another solution was conceived and pursued. The patch manufacturer was asked to stamp two additional rows of ratchets into the sleeve midway between the existing rows. Several prototype sleeves with this modification (that is, a total of six rows of ratchets) were ordered and have been received. These sleeves will be tested during the full-scale system tests to be conducted in MTI's shop facilities during the next quarter (see Task 10).

Task 4 – Design, Fabricate and Test Patch-Setting Robotic Train

To set patches under live main conditions, the patching hardware must meet several key criteria. It must be able to be inserted and removed from the gas mains without damage. It must be able to be translated using CT. Its physical form must not impede gas flow through the main (thereby maintaining gas delivery to customers). Lastly, it must be able to set patches with high reliability. To support the design, the following subtasks will be undertaken:

4.1 *Analyze Weight and Drag.* Hardware must be designed to perform required patch-setting functions while minimizing weight and drag, as these are key drivers in determining the push range and therefore the number of joints which can be repaired from each entry point.

4.2 *Analyze Reactive Force Limits.* The patch-setting equipment will be designed to effectively and reliably set patches while not exerting excessive reactive forces on the cast-iron pipe.

4.3 *Test Patch Integrity.* Testing will be conducted to verify that patches seat properly and to verify that sufficient epoxy comes into intimate contact with the cast-iron joint segments.

4.4 *Safety Testing.* Testing will be conducted throughout the design and testing phases to ensure that the hardware poses no safety risks to the operating gas main. All hardware elements that are operated in the main must not allow a leak path of gas to the surface. All elements will be purged and pressurized with N_2. The differential pressure between the main and inside the hardware elements will be monitored to ensure that a positive differential is maintained. This same approach will be followed in the next task.

The deliverables for this task will be the Patch Setting Robotic Train along with its corresponding electrical/electronics schematics, mechanical drawings, and descriptive report documenting assembly, maintenance and operation.

Various patch-setting inflation modules have been designed, built and used to install the different generations of ratcheting repair sleeves. The latest sleeves are set by inflating the patch setting bladder to 30 psig which is held for a period of 5 minutes before deflation is allowed. This provides sufficient time for the urethane sleeve to be compressed against the pipe wall and the ratchets to fully engage and lock

Setting tests have been successful, so efforts were directed to design of the control electronics to operate the solenoid-controlled valve attached to a pressurized canister of nitrogen. Figure 17, Figure 18 and Figure 19 illustrate key aspects of the equipment. Unlike other robotic elements, bypass of natural gas to prevent interruption of customer service occurs through the central pipe and not in the annular space between the OD of the robotic element and the ID of the cast-iron main.

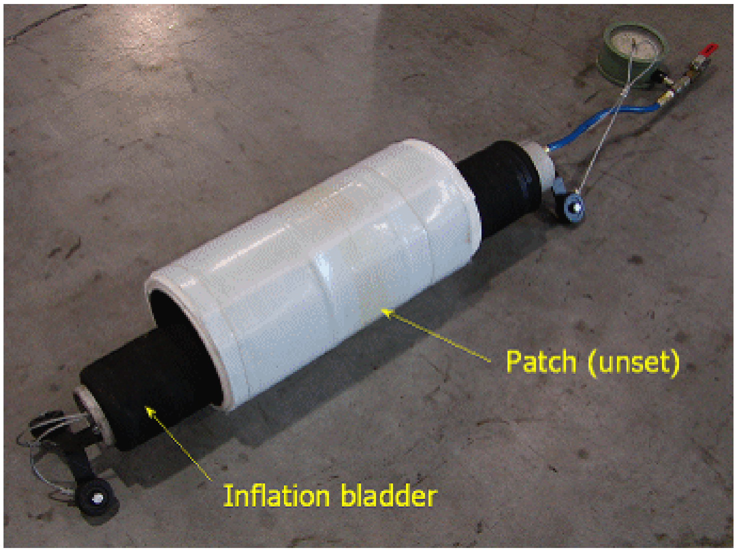


Figure 17. Patch-Setting Module

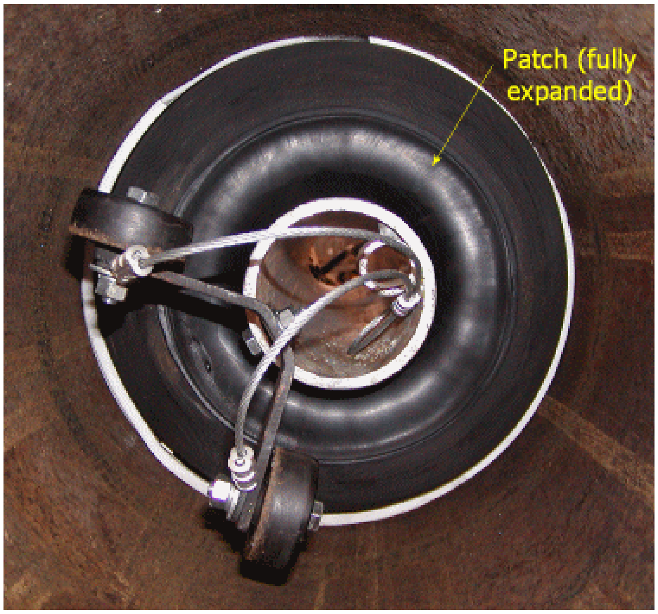


Figure 18. Patch-Setting Test

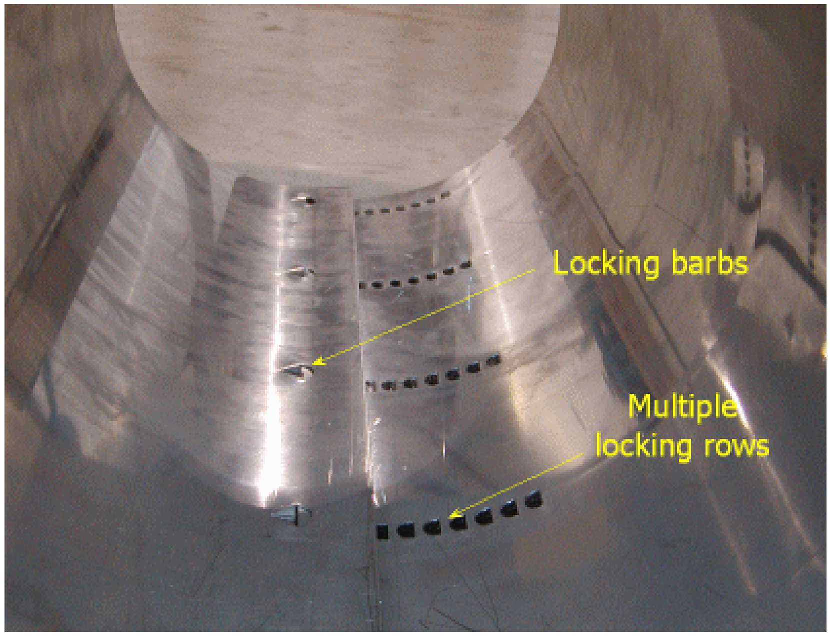


Figure 19. Locking Ratchets on Patch

The patch-setting control system consists of a solenoid valve which allows the air pressure to be admitted into the inflation bladder under computer control, a pressure chamber for storing the nitrogen charge and pressure relief valves which allow adjustment of the charge pressure to compensate for differences in the gas main operating pressure. Figure 20 summarizes the pneumatic inflation circuit.

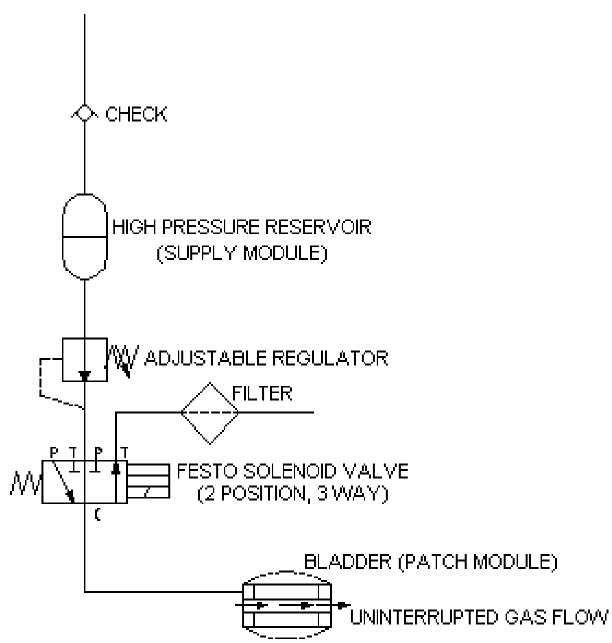


Figure 20. Pneumatic Inflation Circuit

In the current quarter, solenoid controls were implemented into the surface control system software (see Task 6).

Task 5 – Design and Fabricate Pipe Wall Cleaning Robot Train with PZT Camera

Cast-iron gas mains operate at much lower pressure than their steel counterparts; consequently, their interior conditions are often quite different. Lower pressures in cast-iron mains can allow moisture and debris to seep in through leak points if sufficient hydrostatic head (from the local water table) is present outside of the main. In addition, the interior of cast iron is generally not as smooth as steel, due to corrosion and surface roughness from the original manufacturing process. Other complications arise due to deposits of tar residue in the bottom of the main. The source of this residue dates back to when mains carried "manufactured" gas. The molecularly heavier tars and other impurities settled out into the bottom of the mains and then combined with particulate matter to form a hard crust. This crust is porous and must therefore be removed prior to applying a patch repair sleeve. In addition, the pipe ID must be clean and smooth to ensure that the epoxy adheres properly to the cast iron. To address these challenges, the following subtasks are being completed in Task 5:

Figure 21. PZT Camera

5.1 *Analyze Deposits and Scales*. The expected deposits in typical cast-iron mains will be investigated and the most effective way(s) to remove them defined.

5.2 *Design Equipment to Identify Deposit Types via Camera.* Design/select camera and lighting systems to provide sufficient performance to make positive identification and then select the appropriate means to prepare the surface.

5.3 *Design and Test Cleaning/Brushing Equipment.* Equipment will be designed to remove scales and deposits found inside cast-iron pipe. Laboratory and field tests will be conducted on line pipe to ensure that appropriate cleaning is performed by the system.

The deliverables for this task will be the Prototype Pipe Wall Cleaning Robot Train with Pan/Zoom/Tilt (PZT) Camera along with its corresponding electrical/electronics schematics, mechanical drawings, and descriptive report documenting assembly, maintenance and operation.

The analysis of different PZT cameras was completed in the second quarter and a preferred design selected. The camera (Figure 21) measures 4 inches OD x 10.5 inches overall length. It features 270° of tilt, 340° of pan and a 72:1 zoom ratio. Its eight high-intensity argon lights were found to provide excellent illumination in tests conducted inside sealed 12- and 24-inch pipes. Specifications are summarized in Figure 22. In normal operations where the camera tether is 100 feet or less, a 16-conductor bundle is used as defined in Table 1.

Table 1. Conventional Camera Wiring

ITEM	FUNCTION
75 ohm coax	Video (+) core, Video (-) shield
18 awg, red	Camera Power (+)
18 awg, black	Camera Power (ground)
18 awg, yellow	Pan (+)
18 awg, orange	Pan (-)
18 awg, white	Tilt (+)
18 awg, blue	Tilt (-)
18 awg, pink and green	Camera Lights (+)
18 awg, purple and clear	Camera Lights (-)
22 awg, grey	Camera Function/Focus (+)
22 awg, black	Camera Function/ground
22 awg, tan	AF indicator/Focus (-)
22 awg, purple	2.5”/4.0” Indicator
18 awg, brown	Camera Fade

SPECIFICATIONS

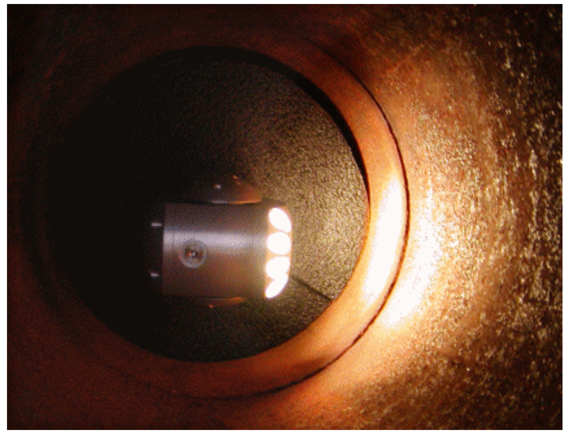
Pick-up Element: ¼" CCD

Lens: 72:1 Zoom (18X Optical, 4X Digital)

Resolution: > 460 TV Lines

Illumination: 3 lux

Horizontal FOV: 48° wide, 2.7° tele (in air)



Standard Camera Controller

Lights: 8 x 6 W argon lights,
variable intensity

Pan Range: 340° mechanical,
(360° visible)

Tilt Range: >270°

Power Requirements: 110/220 VAC

Pan/Tilt Control: proportional

Camera's View of Joint Seam

Figure 22. Camera Specifications

Use of a 16-conductor bundle becomes inefficient inside 1000 ft of small-diameter CT. A preferred approach is to power and operate the camera using seven wires. Two of these will be large-diameter twisted pair to supply high-voltage DC, four smaller wires to transmit digital control signals, and one to transmit video images. This change requires development of a microcontroller-operated switching power supply inside the robot base module and a data-acquisition system at the surface to convert the analog proportional joystick controls for pan, zoom, tilt, light intensity, etc. to digital signals.

During a previous quarter, the robotic system's pan/zoom/tilt camera control electronics and operating software were developed and implemented in both the surface and downhole modules. Camera surface hardware consists of a 95-Volt DC power supply capable of sourcing up to 2.1 Amps for operating camera illumination, lenses and physical orientation within the pressurized gas main, a personal computer having an RS-485 bidirectional communications port, a 15-inch color monitor for displaying camera images and a rack-mounted video cassette recorder. Downhole hardware consists of the camera head and the camera control electronics. The latter is housed inside the robotics base module that is common for all robotic trains.

DC power is supplied to the downhole camera control electronics over an 18-gage twisted pair of conductors. Use of a single high-voltage power source at the surface was chosen over individually supplying all of the regulated voltages needed to operate the camera for two important reasons: (1) it is a highly efficient means of transferring electrical power down the long cables residing inside the steel CT and (2) it minimizes the total number of conductors required for the umbilical. The current design employs a total of seven wires to operate the camera. These include two wires for electrical power, four wires for the RS-485 digital communications link and one micro-coax for the video signal. This compares with a total of 15 wires that would be needed to operate the camera using a conventional analog circuit design.

Table 2 summarizes key attributes of the surface DC power supply and two of the downhole DC/DC voltage conversions.

Table 2. Surface Power Supply Specifications

Manufacturer – Vicor		
95 V	2.1 A	200 W
12 V	4.2 A	50 W
7.5 V	6.7 A	50 W

Camera controls are displayed and operated using a software applications program written inside the LabVIEW environment. The program allows the user to control the following functions through a point and click format:

- Camera Power (On/Off)
- Camera Illumination (Lights On/Off, Lights Dim/Bright)
- Camera Pan (0-340°)
- Camera Tilt (0-270°)
- Camera Zoom (18X optical; 4X digital)
- Camera focus

The LabVIEW platform features excellent visual appeal through its virtual instrument displays, can be easily reconfigured and expanded to add new control capability as each new robot module is brought on line, and has excellent digital and analog support libraries. The user-selected commands are digitized and then communicated to the downhole camera control electronics via the RS-485 communications link. The RS-485 design and protocols were selected on the basis of their ease of implementation, low cost, and its demonstrated ability to support reliable communications over conductors up to 4000 ft in length, well in excess of the 1000-ft span required for this effort. A 20-MHz PIC micro-controller receives the RS-485 messages and actuates the commands accordingly.

Figure 23 shows the physical printed circuit board produced from this schematic. The board is a four-layer board made of FR4 material, measures 3 inches wide x 10 inches long, and is housed inside the robotics base module. Worthy of note are the large heat sinks for the DC-to-DC power converters used to take the single DC voltage supplied from the surface and generate +24V, +12V and +5 VDC regulated power for the various camera functions.

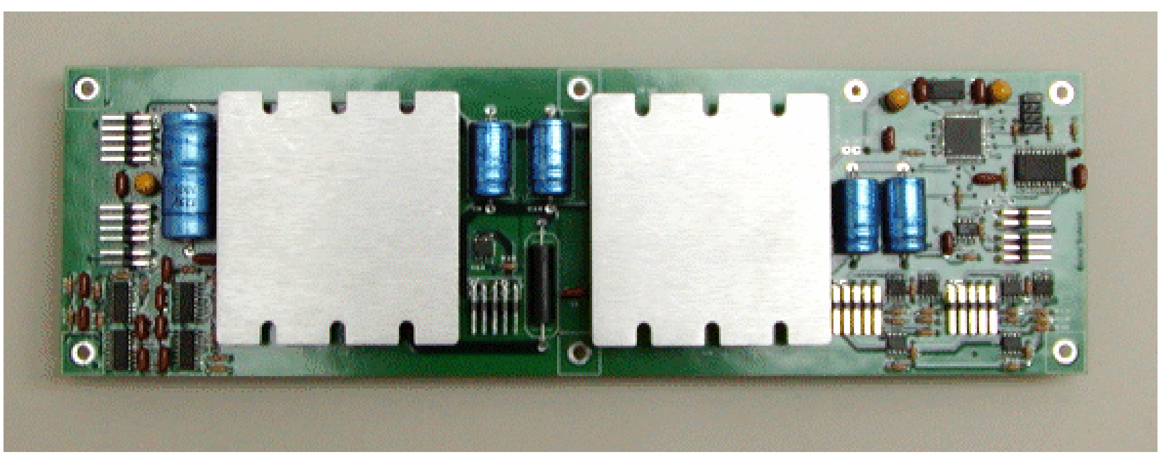


Figure 23. Downhole Camera Control Circuit Board

The PIC controller (PIC16F877) is a 20-MHz CMOS FLASH-based 8-bit micro-controller. It features 256 bytes of EEPROM data memory, self-programming, an ICD, eight channels of 10-bit Analog-to-Digital (A/D) converter, two additional timers, and two capture/compare/PWM functions. The synchronous serial port can be configured as either three-wire Serial Peripheral Interface (SPI™) or the two-wire Inter-Integrated Circuit (I^2C™) bus and a Universal Asynchronous Receiver Transmitter (USART). This controller is designed for more advanced A/D applications in automotive, industrial, appliances and consumer applications.

In the fifth quarter, the camera control software and display were finalized. Figure 24 and Figure 25 show the packaged electronics and camera display/control functions as presented on a laptop computer.

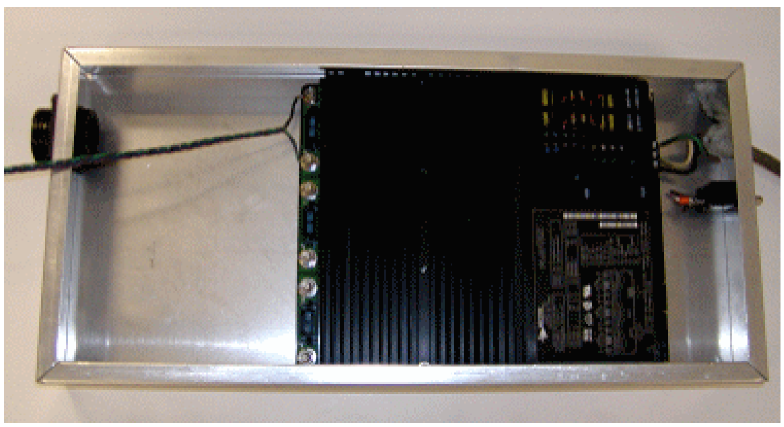


Figure 24. PZT Camera Power Supply

Figure 25. Camera Display and Control Software

A four-arm assembly for cleaning the pipe wall prior to installing the repair sleeve, initially built during the second quarter, was further developed during the third and fourth quarters. It was suitable for removing a wide range of debris including very hard deposits. It had a collapsed diameter of 6.4 inches and could open up to 13 inches under centripetal action.

During the fifth quarter, the arm assembly was redesigned to be packaged as a complete robotic element. This included both design and fabrication of the drive motor, motor controller electronics, cleaning head housing and collapsible arm (Figure 26). The completed robot assembly was tested to clean across several 12-inch cast-iron bell and spigot joints (Figure 27). The preliminary tests were very promising. The most efficient cleaning occurs at rotary speeds of 300 rpm with forward and backward movement across the joint at speeds of 4 inches per minute, for approximately 5 minutes per joint.

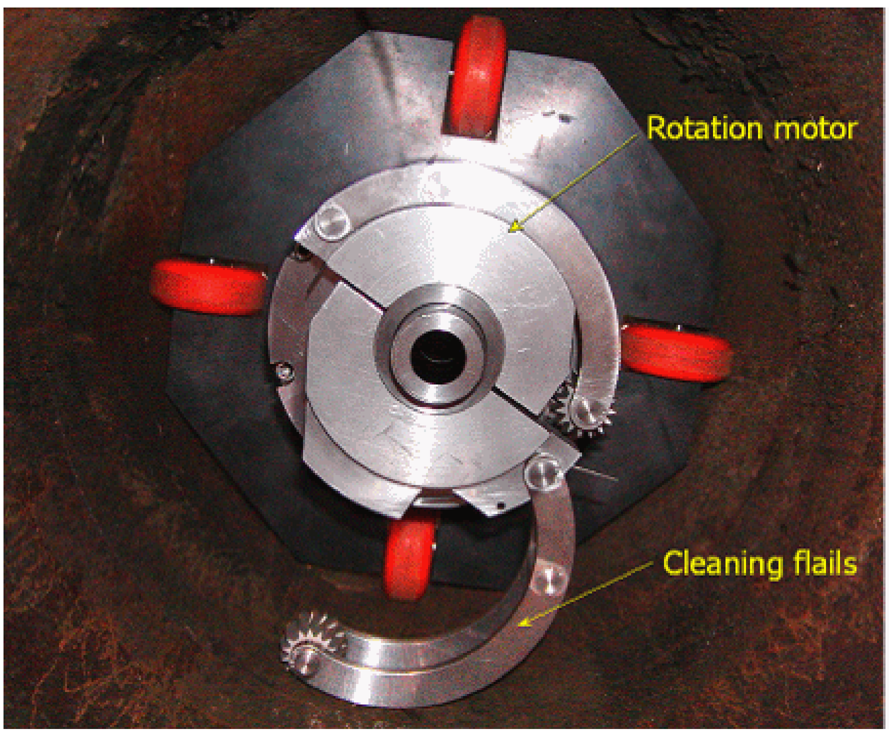


Figure 26. Pipe Wall Cleaning Element

Figure 27. Pipe Wall Cleaning Test

During the tenth quarter, the small-diameter pipe repair robot was field tested for inspecting and repairing 4-inch cast iron bell and spigot joints. Because much of the small system's design and performance closely tracks that used in the large diameter system described herein, these field tests provide valuable experience and insight for design improvements for the large-diameter cast iron pipe repair system.

Based on the field tests of the smaller system, several important recommendations were developed. (These are summarized under "Lessons Learned/Recommendations for Large-Diameter System" under Task 9 below.) The following recommendations regarding debris collection and removal were suggested for the large-diameter system under development.

1. Cleaning flails were very effective. (No change is recommended for large system.)
2. Brush module should be added to move debris away from area surrounding the joint.
3. A magnetic coupon catcher might be added to remove existing coupons created by service tee connections. In the large system, this catcher might mount to the camera and employ the tilt function to capture the coupon.

During the eleventh quarter, four designs were developed for improving debris removal. Magnetic assemblies were considered to be practical for removing coupons and other large debris. Dirt is another significant challenge in low-pressure mains that have been invaded by ground water. Options were considered for sweeping debris from the joint area. It is currently planned to attach a sweeper arm to the camera that can push debris forward past the joint. The basic design, to be implemented in the next quarter, is described below.

Sweeper Arm Mounted to Camera

Both ferromagnetic and non-magnetic debris will need to be collected and/or removed from the joint area. It will likely be sufficient to sweep (or plow) the debris forward so that the area surrounding the pipe joint is clean prior to running a patch. The most straightforward approach is to attach a sweeper arm to the camera assembly (Figure 28). This provides the capability to position the brush anywhere on the circumference of the pipe.

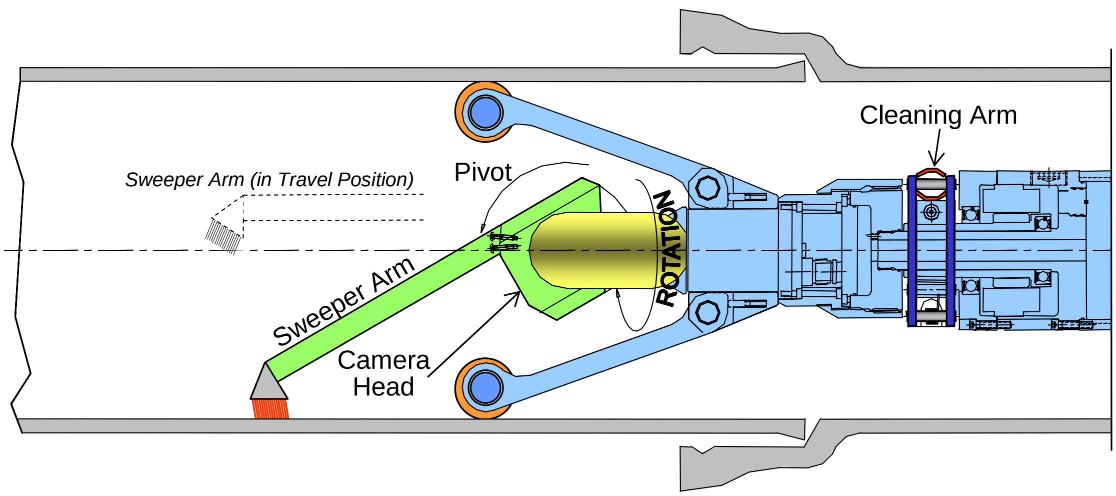


Figure 28. Camera-Mounted Sweeper Arm

Sweeper brushes would be designed specially for each pipe ID to fit the radial curvature of the pipe wall. Width of the brush (how many degrees of pipe wall covered by each stroke) will need to be determined based on weight capacity of the camera. Several passes will be required to sweep the area adjacent to a joint, with camera head rotation providing brush positioning as needed.

An advantage of a camera-mounted debris arm is that the cleaning operation is directly in the camera's view. This allows the operator to effectively monitor and control the cleanup of debris, and to know for certain whether coupons and other large obstacles have been moved or captured.

The disadvantage of this approach is that the camera head would need to be modified. Additional information is needed to ascertain there is sufficient space between the lights on the camera head to add mounting holes for the debris arm. Another potential disadvantage is that the debris arm will be directly in front of the camera at all times and block part of the field of view. However, since the camera can be rotated on its axis to view the entire ID of the main, this loss of field can be compensated for.

Brush Motor Heat Tests

During the current quarter, the brush motors were tested for any problems with heat build-up during extended (continuous) operation downhole. The system was run in a simulated cleaning operation inside a section of cast-iron main. Temperatures of both motors were monitored during a 30-minute test. Results (Figure 29) showed that heat build-up reached a maximum value after about 20 minutes and will not be high enough to damage any downhole components during extended system operation.

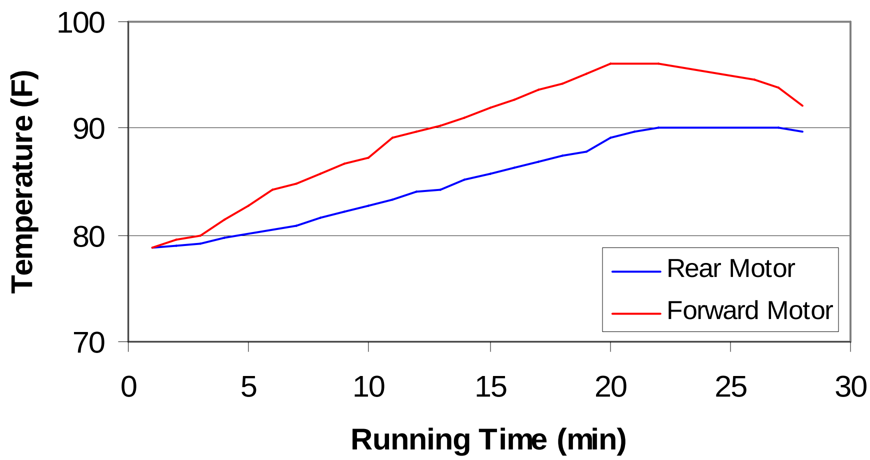


Figure 29. Brush Motor Heat Tests

Task 6 – Design and Build Surface Control and Monitoring System

Surface control and monitoring electronics are being designed to operate inside the LabVIEW platform operated on a high-end laptop computer. To this point, we have completed the control software and visual display for the PZT camera and control software for operating the pipe wall cleaning head. Work has continued onward with development of the control software for setting the patch inside the pipe. Final packaging will be consistent with construction field-ready practices. Deliverables for this task will be the Prototype Surface Control and Monitoring System in addition to all corresponding electrical/electronic schematics, specifications, and parts lists.

During the current quarter, the final control module was fabricated and installed in field-ready packaging and is almost complete. The assembly (Figure 30 and Figure 31) was designed with two power supplies. These are configured in parallel and will provide more than sufficient current to power the camera and other downhole motor assemblies. The module was tested with the CT surface equipment in the laboratory (including running power and signals through 1000 ft of CT on the spool) to confirm correct function and that power supplies will not overheat in normal system operation. System requirements for electrical current and operating temperatures were well within the safe range for these components.

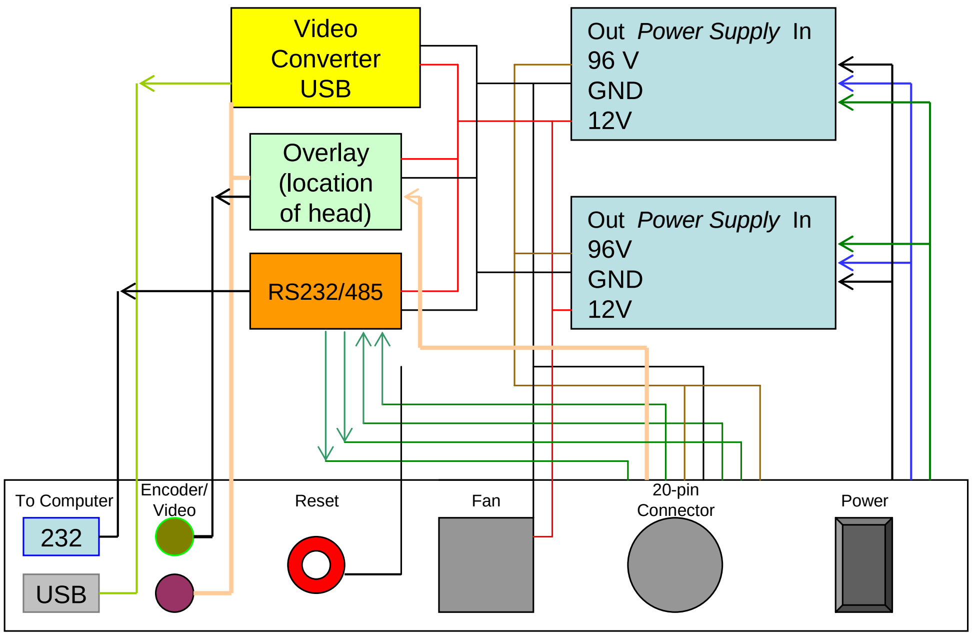


Figure 30. Schematic of Surface Control Module

Figure 31. Control Module Components

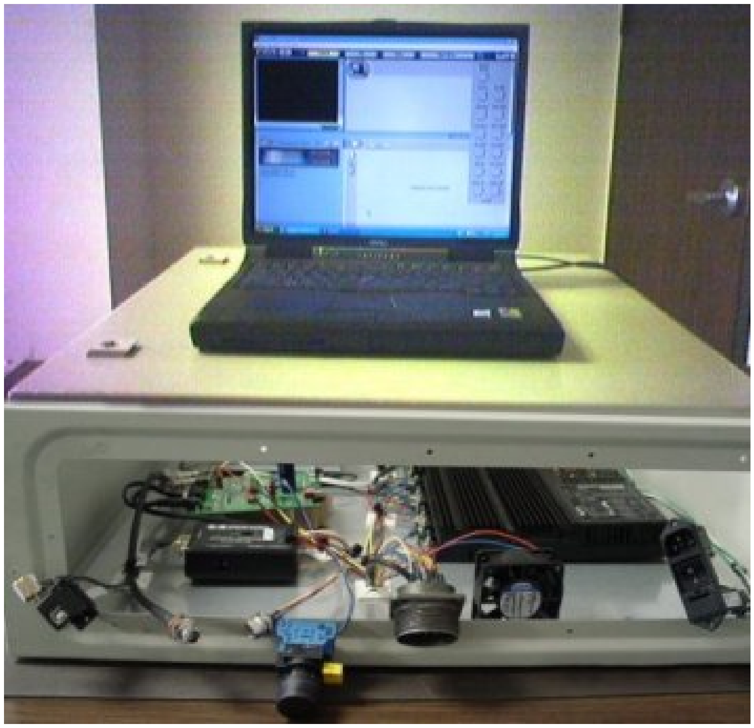


Figure 32. Control Module and Computer

The front panel of the control module is now being completed. Control software is based on LabVIEW and was programmed and tested for controlling (1) the camera, (2) brushing operation and (3) patch inflation system. The control module is ready for final assembly in preparation for full-scale testing in the shop.

Task 7 – Design and Fabricate Large-Diameter Live Access System

Since the entry fitting system for cast-iron pipe cannot be welded directly onto the cast-iron pipe body (as is possible with steel pipelines), some other means of attachment must be used. One choice is to weld the longitudinal seams of the split entry fitting to itself and then to provide an end seal against axial movement and a circumferential face seal by end bolting two end pieces. The entry fitting will enable a port to be cut into the main for inserting all joint-patching equipment. The entry fitting must provide sealing for conducting repair operations, as well as maintain a safe seal over the life of the pipeline since the entry fitting will not be removed from the main. Subtasks include:

7.1 *Perform Stress Analysis*. A certain portion of the main's cross section will need to be removed for access. The entry-fitting system must possess mechanical properties that ensure that basic mechanical integrity of the main/joint is not compromised. The design must take into account bending/flexure loading, settling, reactive forces, and other environmental factors.

7.2 *Design Seal that will be Maintained Under Loaded Conditions*. The fitting and seal design must be robust to accommodate any flexural loading conditions. Seals must remain “energized” at all times during entry and inspection when the main is exposed.

7.3 *Perform Sealing Analysis*. The appropriate material must be selected to meet temperature, environmental, and lifetime requirements. An effective seal must be maintained in the event of settling and varying ground conditions.

MTI and GTI previously met with a leading fitting manufacturer. Numerous designs were subjected to an in-depth review with both the manufacturer and with several utilities who operate significant lengths of large diameter cast-iron pipes. These efforts have produced a recommended design satisfying the standards in-place at each of the utilities interviewed.

In the previous quarters the access fitting was produced in a 4-inch prototype size to validate the design prior to embarking on the fabrication and testing of a 12-inch version (which is considerably more expensive). Sealing tests at pressures up 100 psig were successfully conducted along with preliminary drilling tests. Figure 33 illustrates its key components.

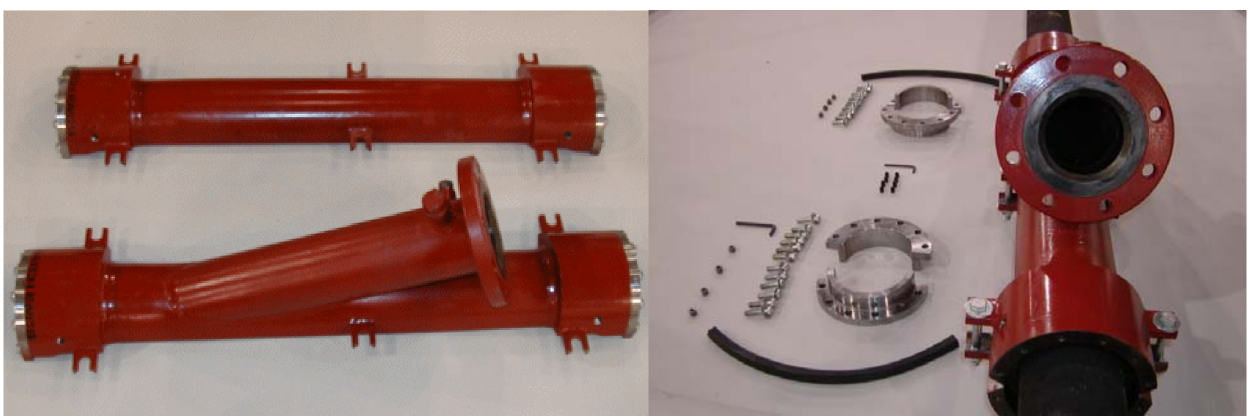


Figure 33. Cast-Iron Entry Fitting (4-inch Prototype)

In the twelfth quarter, a detailed design for a 12-inch bolt-on fitting was completed and the design was manufactured. Two special assemblies were also designed for procedures required before and after inspecting the pipe and running patches. The assembly to drill the access hole through the side of the main was designed and fabricated, as well as that for setting a bridge plug within the fitting to allow removal of equipment and the gate valve prior to setting a blind flange to permanently reseal the main. These assemblies are described below.

Large-Diameter Bolt-On Fitting

The bolt-on fitting (Figure 34) is designed for 12-inch cast-iron pipe with a wall thickness of 0.5 inches. Actual OD of the pipe is 13.20 inches. The fitting consists of an upper and lower half and two split end flanges. The end seals used on the fitting are skive cut to allow them to be placed around the main. The seam seals are strip material cut to length and trapped in place with a machined shoulder along the length of the seam.

The end rings of both upper and lower halves are equipped with lifting eye ports and lock screw ports to allow centralization onto the main and to provide resistance to axial and rotational movement relative to the main.

A core catcher is welded to the main at about the center of the excavation length. A tool is used which pilots over the core catcher and within the riser pipe of the upper half of the fitting to align the fitting with the core catcher. Strip seals are glued into the seam gland slot of the lower half of the fitting and trimmed flush with the end ring pilot bore shoulder. Cap screws secure the mating halves on each end. Other cap screws are mounted in tabs along the seam length. Lock screws are used at each end on the fitting to centralize the fitting over the main before final torque is applied along the seam to seat the seal. Skive-cut end seals are placed around the main and into a counter-bore provided on each end of the fitting. Split end rings are placed over the main and cap screws are used to secure them to the fitting. Final torque is applied to seat the seal.

Unlike the smaller bolt-on fitting, no welding is required due to low gas pressure (<2 psi).

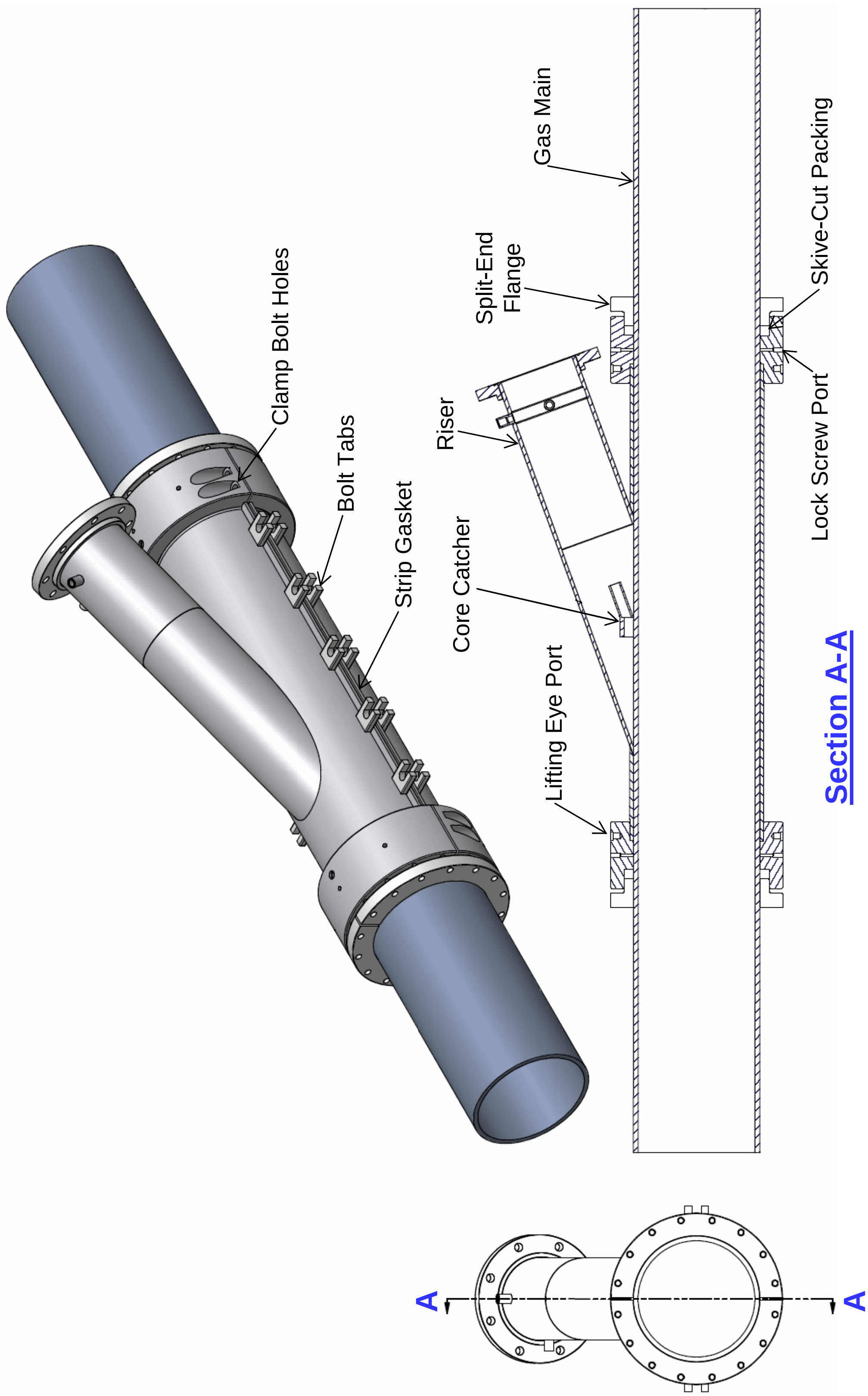


Figure 34. Bolt-On Fitting for Live Access into 12-in. Cast-Iron Mains

Large-Diameter Drilling Assembly

After the bolt-on fitting is attached to the main and pressure tested, a control valve is attached to the flange provided on the end of the riser. The valve is used to control gas flow as the drilling assembly is removed after the entry hole is cut and as robot components are launched and retrieved from the main. A cutter shroud is attached to the top of the control valve. The shroud is used to house the cutter after the entry hole is cut and provides a gas seal until the control valve is closed. This shroud remains attached after the drilling assembly is removed and is used for launching and retrieving operations.

The drilling assembly (Figure 35) consists of a cutter attached to a drive shaft which is attached to a drive motor. The motor is mounted to an adaptor which is threaded into the jack screw translation shaft. A jack screw sleeve is mounted between the motor adaptor and the translation shaft. As the jack screw sleeve is threaded into the shroud end cap, thrust force is applied to the translation sleeve which forces the cutter toward the gas main. Rotational reaction forces are carried through a hexagon drive provided on the extension portion of the jack screw stationary shaft and the end of the bore of the translation shaft. The stationary shaft is locked to the cutter shroud with a sealed lock pin which is removed when the cutter is retracted back into the shroud after the entry hole is cut.

A cutter centralizer guides the cutter through the riser inside bore as it moves toward the main. A wire spear mounted on the end of the drive shaft engages the core catcher as the cutter is advanced. Once it is engaged and the entry hole is cut, the spear retains the coupon within the cutter as the drilling assembly is retracted into the cutter shroud.

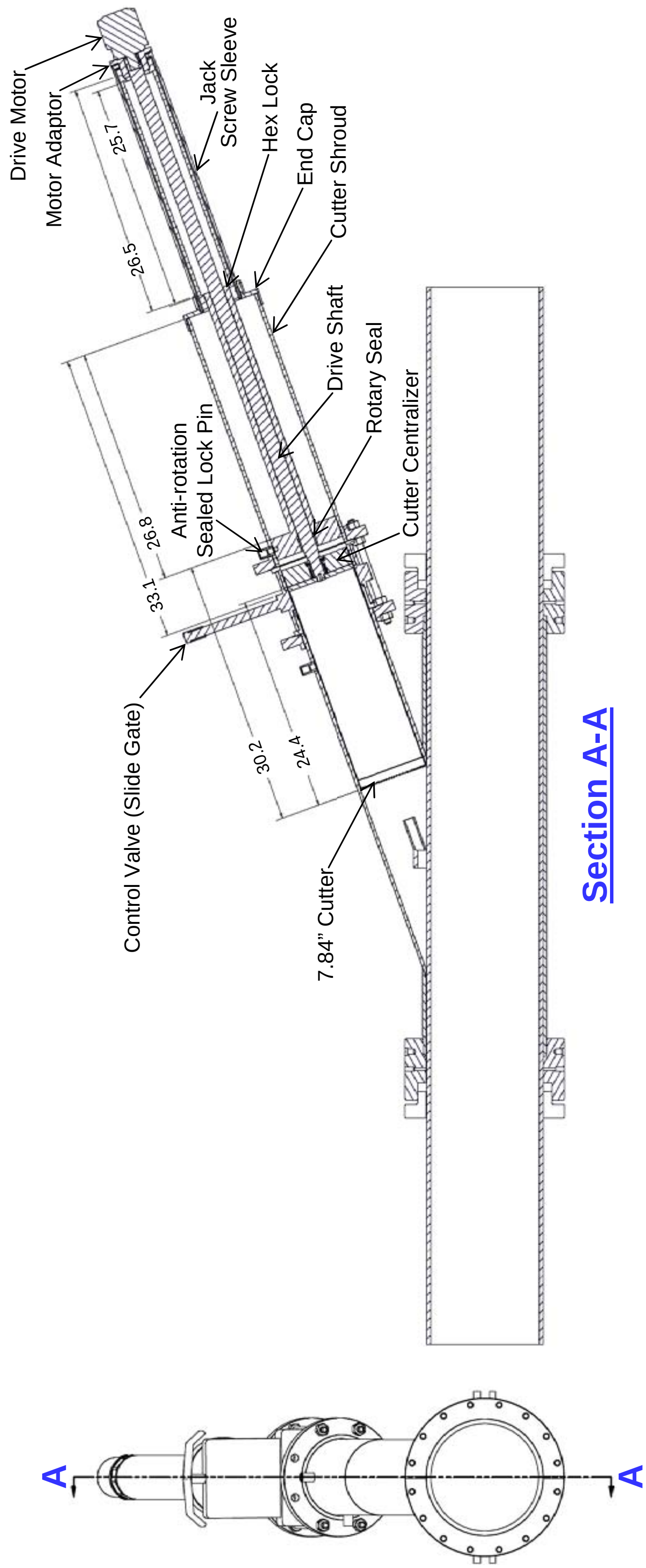


Figure 35. Drilling Assembly for Cutting Access Hole in 12-in. Cast-Iron Mains

The project team sought to minimize the weight of each component. Several items are to be manufactured from aluminum. In addition, a lightweight thermoplastic gate valve was acquired for use with the assembly (Figure 36). This option reduces the valve weight and overall drilling assembly length dramatically. Conventional ball valves for this size are about 18 inches flange to flange and weigh about 400 lb. They are not manufactured commercially using lightweight materials. The lightweight gate valve obtained is about 8 inches flange to flange and weighs only 22 lb.

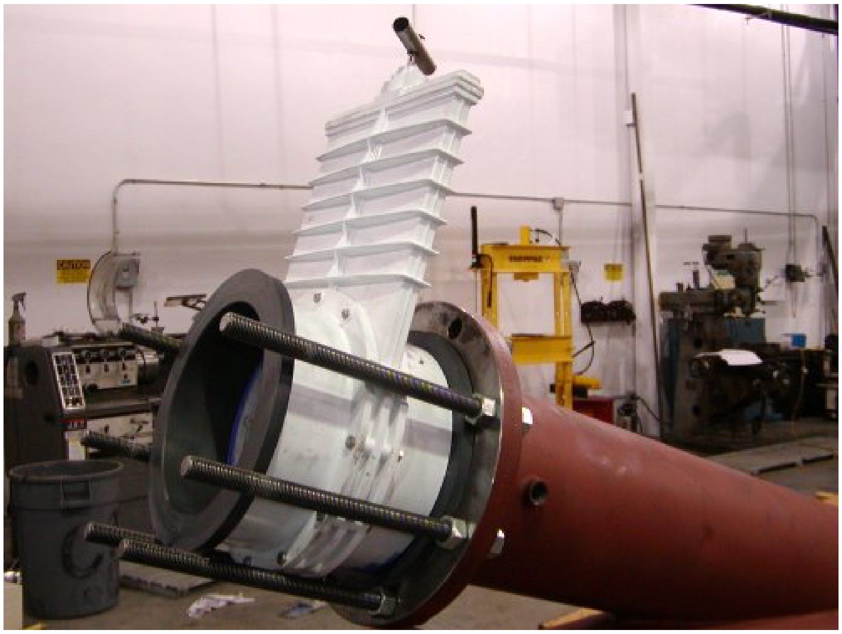


Figure 36. PVC Control Valve

A rotary shaft seal is provided to reduce the seal area and thus the forces produced by the gas main internal pressure. Tooling (large wrench) is provided to allow the operator to manipulate the jack screw sleeve by hand as to maintain operator feed back during drilling operations.

To support use of the 12-inch entry fitting, a saw cutting system was designed to cut an angled hole into the pressurized cast iron gas main. Since the angle of entry is near 20°, the body of the saw must be very deep to receive the elliptical coupon as it is cut. A hole saw for cutting an 8-inch hole was designed and is currently being manufactured (Figure 37). In the left side of the figure, a saw blade is shown on top of a saw body prior to attachment. The hole saw will be powered by a hydraulic motor which is powered by a 50 horsepower, diesel-driven hydraulic power supply. This same power supply also operates the CT unit.

Figure 37. Hole Saw for Cutting Access Hole in Gas Main

Plug-Setting Assembly Description

After patch-setting operations are complete, an expandable plug will be set into the fitting to control gas flow as the control valve is removed from the bolt-on fitting. A special assembly was designed for this procedure (Figure 38). A blind flange is placed on the riser flange to complete the abandonment process. Because the expandable plug remains in place after the fitting is sealed, the blind flange can later be removed to re-enter the main as necessary without any flow of gas.

The expandable plug consists of an end plate, a body, a clamp screw and an assembly screw. An elastomer element is placed between the end plate and body for sealing to the riser inside diameter when compressed. The element is relaxed while lowering into the riser. The plug assembly is attached to a setting shaft which is placed inside the jack screw stationary shaft. Once in place a sealed lock pin is threaded through a side port provided on the riser. The lock pin serves as an anti-rotation stop for the expandable plug body. A hex key is placed through the setting shaft and engages the clamp screw. Rotating the clamp screw with the hex key causes the end plate and the plug body to move together and compress the elastomer element. The element expands until it contacts the wall. The setting shaft and setting key are removed from the plug by retracting through the control valve and cutter shroud. After the shroud and control valve are removed, a second lock pin may be installed through a second port provided on the riser of the bolt-on fitting and a blind flange mounted to the riser flange.

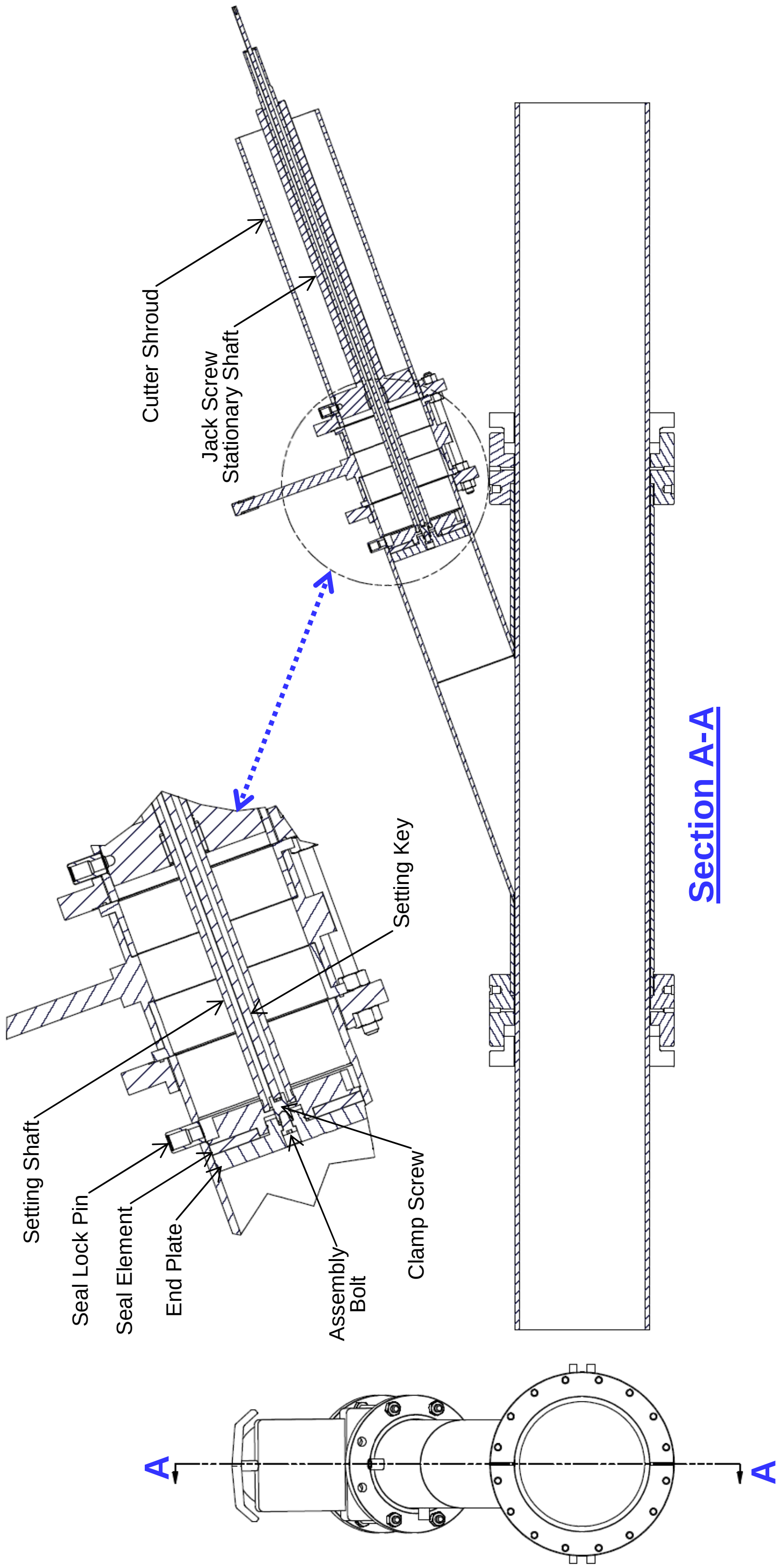


Figure 38. Plug-Setting Assembly for Resealing 12-in. Cast-Iron Mains

Shop Tests of Live Access System

During the current quarter, the bolt-on fitting was assembled on a joint of cast-iron main and mock-up tests conducted with the drilling assembly and plug-setting assembly. Initial fitting tests showed that various adjustments to the internal dimensions were needed to increase tolerances to allow smooth passage of components through the fitting. The fitting was then returned to the machine shop, modified as required and was reassembled in MTI's shop.

Initial assembly of the fitting includes correct positioning of the coupon catcher onto the main (Figure 39). After correct angular alignment of the coupon catcher is achieved, it is welded onto the main and the upper half of the fitting is lowered into position (Figure 40).

Figure 39. Initial Assembly of Large-Diameter Bolt-On Fitting

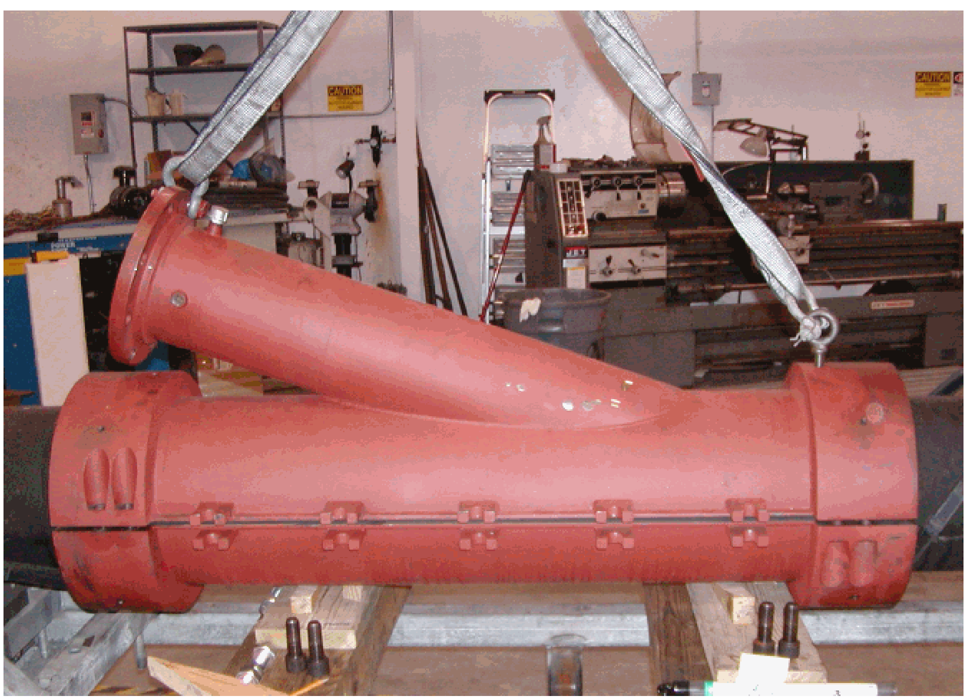


Figure 40. Bolt-On Fitting Lowered into Position

The fitting is shown after being completely made up to the pipe in Figure 41. The assembly was pressure tested successfully to 5 psi**.**

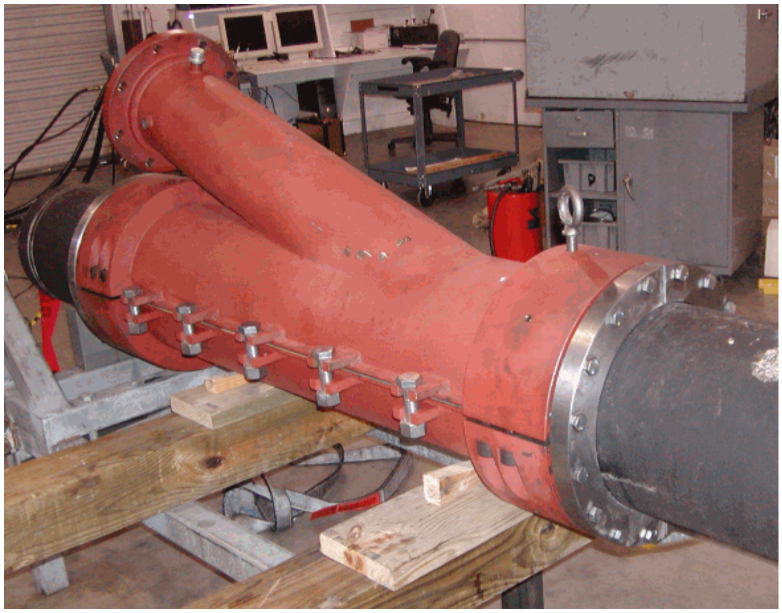


Figure 41. Large-Diameter Bolt-On Fitting Installed

The drilling assembly (Figure 42 and Figure 43) has also been fabricated and tested in the shop for fit and function. (Design and operation of the drilling assembly is described under "Large-Diameter Drilling Assembly" on page 34.)

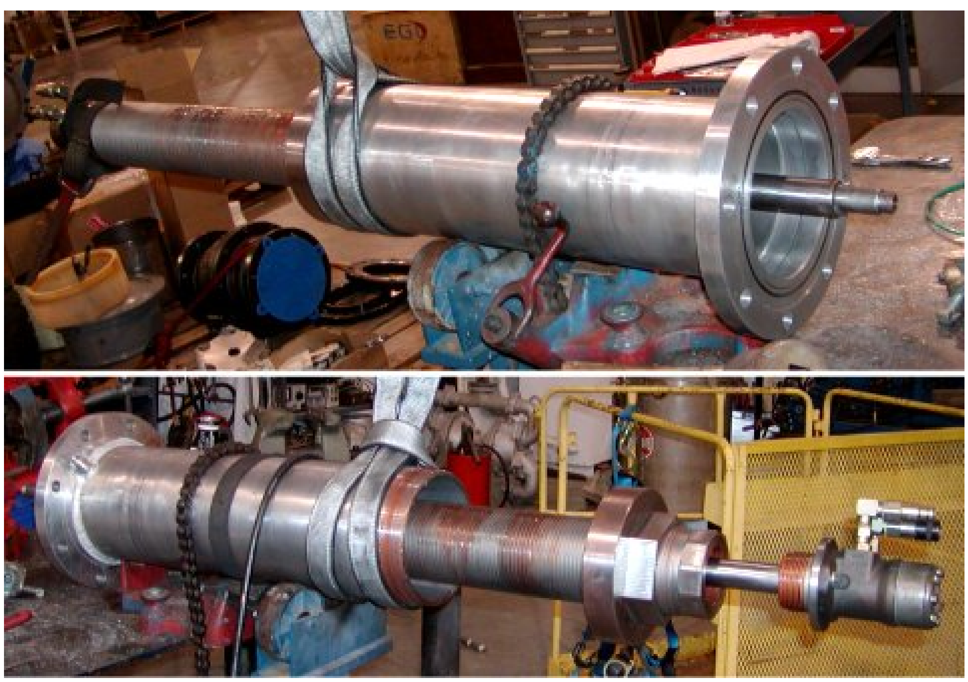


Figure 42. Drilling Assembly for Large-Diameter Pipe

Figure 43. Drilling Assembly with Hole Saw

Mock-up tests in MTI's shop show that the large-diameter bolt-on fitting and the subassemblies are now ready for full-scale patch setting tests in the shop. These will be conducted early in the next quarter.

Task 8 – System Integration and Laboratory Validation

While the previous tasks were aimed at addressing specific areas of the proposed work, some aspects of performance will be difficult to assess until components are integrated. To support the evaluation of system performance, a detailed **Test Plan** will be written. Many aspects of the design cannot be accurately evaluated until an integrated test is performed. Some of these items are listed below along with potential means of mitigating difficulties encountered. The test plan will be written as the design progresses to ensure that all sensitive points will be examined as part of an integrated test program.

8.1 The team will accumulate valuable experience with the equipment to assure proficiency in the field, to verify that all elements work in concert, etc.

8.2 Actual push and pull loads will be measured, because these affect ultimate push range of the integrated hardware assemblies and therefore the number of cast-iron pipe joints which can be repaired from a single entry point

8.3 Measurement of actual end loads and reduction of these loads (if necessary) to achieve targeted performance

8.4 Evaluation of "whip" (flexible) joint design for fatigue resistance and stiffness under actual entry, translation and removal processes

The deliverable for this task will be the Integrated Test Plan. No activity occurred in this task during the current quarter.

Task 9 – Field Testing and System Refinement

The first-generation system will be evaluated in a series of three field tests. These tests will highlight improvements to "harden" the system for commercial viability. Iterative design augmentations will be implemented and verified. Prior working relationships exist between the project team and the following major U.S. gas utilities: KeySpan Energy (Brooklyn Union Gas and Boston Gas), Consolidated Edison of New York, Public Service Electric & Gas of New Jersey, and Baltimore Gas & Electric. These utilities operate the vast majority of large-diameter cast-iron gas mains in the U.S. and are logical candidates for participating in field tests.

During the current quarter, discussions have been ongoing between GTI, MTI, Public Service Electric & Gas, and other utilities for scheduling field tests in the next quarter. These are now expected to be conducted in late August or September 2005. In preparation for field tests, the system will soon undergo full-scale testing at MTI's shop facilities to completely exercise the equipment and procedures and to train the team to efficiently operate the system.

During the tenth quarter, the small-diameter pipe repair robot was field tested at Public Service Electric & Gas. The field test consisted of the inspection and repair of 4-inch cast-iron bell and spigot joints. Because much of this system's design and performance closely tracks that used in the large-diameter system, these test results have a direct bearing on system design parameters. As such, a summary of this field test is included below along with a list of design recommendations to be implemented in the large-diameter cast-iron pipe repair system.

Summary of Field Tests of Small Robotic System

On August 24-26, 2004, MTI/GTI conducted field tests of the small robotic joint-repair system in a gas main provided by Public Service Electric & Gas (Figure 44). The location was in a residential neighborhood on Woodland Avenue in the town of Oradell, New Jersey.

Figure 44. Field Test Site

Over three days of field testing, a range of operations were performed representing a typical joint-patching operation of bell and spigot joints on cast-iron pipe. After the main was uncovered and prepared for the tests, the coupon retention fitting was welded to the pipe. Next, the 20° angled entry fitting was secured to the pipe (Figure 45) and then seam-welded to the main.

Figure 45. Attaching Entry Fitting to Pipe Prior to Welding

A hole saw assembly was then prepared for cutting through the wall of the main. The access hole was successfully cut through the pipe and the hardware for admitting the repair robots into the live gas main installed in a total time of 36 minutes.

The coupon was successfully retrieved. Next, a magnetic cleaning assembly (Figure 46) was run into the pipe for three passes to remove the vast majority of metal filings created by the sawing process.

Figure 46. Magnet Assembly for Removing Filings

The first train assembly consists of (1) a CCD camera to inspect the main, (2) a brush module for cleaning the bell and spigot joints selected for repair, and (3) a base module which supplies electrical power, communication and control signals between the surface hardware and the in-pipe robot elements. After the assembly was passed through the entry fitting (Figure 47), the first run down the pipe was to inspect the environment and log the location of potential target joints and other features.

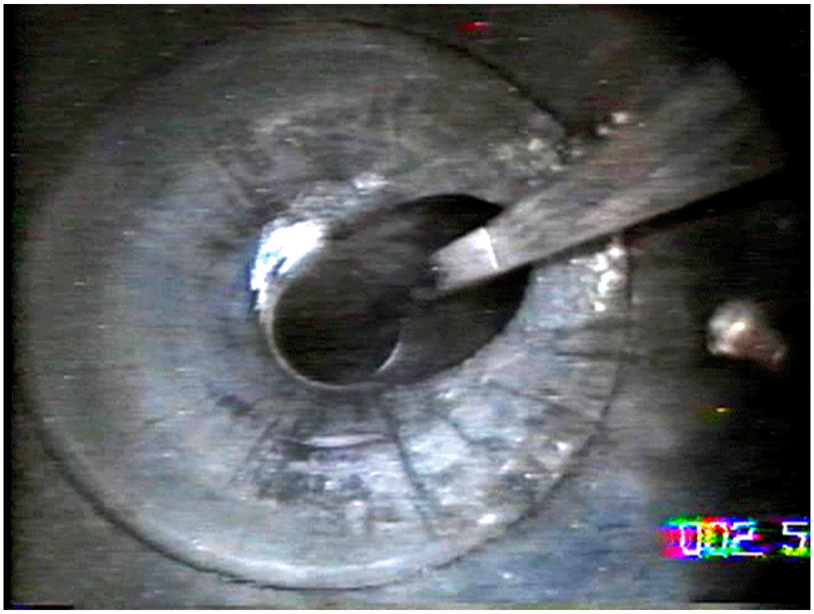


Figure 47. Moving through Entry Fitting

Several locations at pipe joints were brushed (cleaned) to remove debris from the pipe. Due to extremely low pressure and low gas velocity in the pipe, debris was not swept away from the joint but tended to fall and accumulate across the joint.

Next, a total of six sleeve patches were run into the pipe. These included two successful patches, two partially set patches, and two failed patches that were retrieved from the main. A summary of patching operations is presented below.

- Two sleeves (at 128.8 ft and 93.7 ft) were run and set 100% successfully (Figure 48).

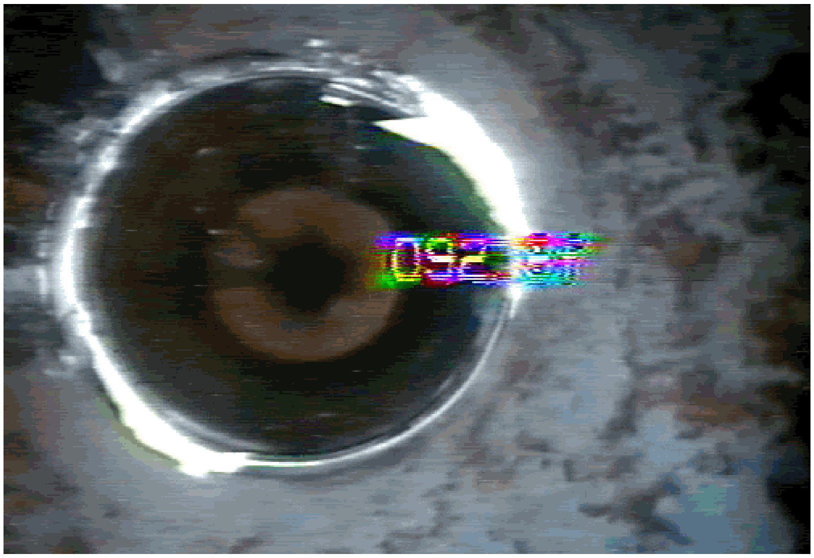


Figure 48. Successfully Set Patch at 93.7 ft

- One sleeve (at 58.6 ft) failed in the first attempt to set it, was carried with the assembly back to the entry point, and was then rerun and set successfully (although the ratchets did not engage completely (Figure 49)).

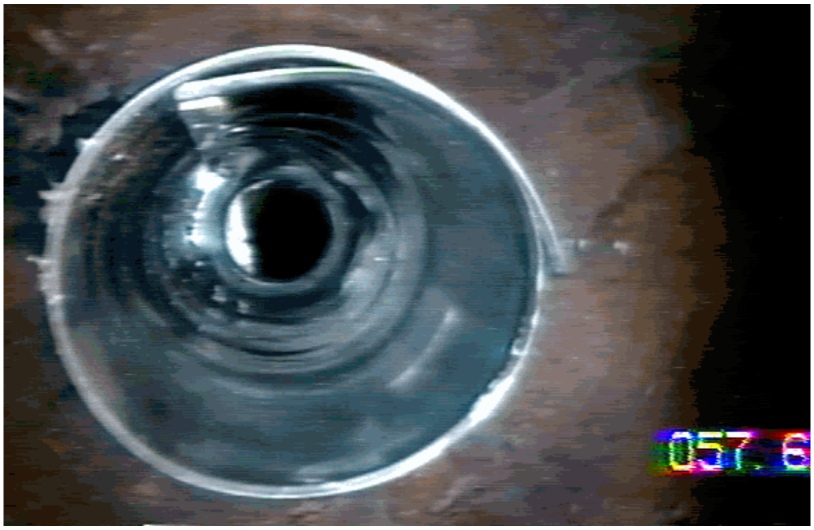


Figure 49. Partially Engaged Patch at 58.6 ft

- One sleeve (at 6.1 ft) was partially set (ratchets did not engage properly).
- Two sleeves were run (to 42.0 ft and 24.1 ft) but were not able to engage the ratchets.

Potential causes for the failure of two patches to set are (1) pipe ID may have been smaller than the first row of ratchets at these two bell and spigot locations, (2) the debris levels may have been too high or 3) the bell and spigots were angularly misaligned. No problems were observed with the repair sleeve setting train either in the field or after its return to Houston. Consequently, the team believes that the patch-setting failures were due to geometric issues.

After all in-pipe operations were complete, the equipment was removed from the pipe and disassembled. A seal plug was then inserted into the 20° riser section of the entry fitting. Once the seal plug is set, the gate valve was then removed from the main. A blind flange was then attached to the 20° riser to create a second (redundant) gas seal and allow future re-entry into the pipe is so desired. The sealed entry fitting ready for burial is shown in Figure 50.


Figure 50. Entry Fitting Ready for Burial

Lessons Learned/Recommendations for Large-Diameter System

Based on the field tests of the smaller robotic system in 4-in. cast-iron mains, several valuable lessons were learned. The following recommendations are suggested for the large-diameter system under development:

Entry Fitting

1. Develop a bolt-on version of the fitting
2. Coupon catcher design is finalized and successful.
3. Cuttings-removal magnet was very effective for small system and should be finalized similarly for large-diameter system.
4. Guide shoe design was very effective for small system, and should be finalized similarly for large-diameter system.

Wall Cleaning

5. Cleaning flails were very effective. No change is recommended for large system.
6. Brush module should be added to move (plow) debris away from area surrounding joint.
7. A magnetic coupon catcher should be added to remove existing coupons created by service tee connections. In the large system, this catcher might mount to the camera and employ the tilt function to capture the coupon.

Patch Setting

8. Carry sufficient moles of gas with the patch assembly to support at least two patch-setting procedures per run.

Task 10 – Benefits Analysis

Initial work on data collection for conducting benefits analysis was begun. (Note that the majority of work in this task will be conducted after the completion of field tests and detailed discussions with the utilities hosting the tests.) These discussions will address the end-to-end process of implementing the proposed large-diameter cast-iron main repair system in a real-world field environment. Only in this way can the true benefit of the new system be assessed. All aspects of the job will be analyzed, particularly costs of labor (number of personnel and time), traffic management, impact on future maintenance operations for the repaired main, impact to customers, and acceptability of the repair technique. The deliverable of this task will be a report detailing these benefits with a focus on cost and overall benefit to infrastructure reliability using the proposed system.

Task 11 – Final Report

The project final report will document all aspects of design and operation of the system. Final results of the project will be presented to the NETL COR in a meeting in Pittsburgh.

No activity occurred in this task during the current quarter.

Work Planned for Next Period

Planned activities for the next quarter will encompass elements of Tasks 5–11. Specific work items will include:

1. Continue testing of the pipe wall cleaning module in conjunction with the PZT camera under increasingly more difficult and realistic conditions. These tests will be conducted in the laboratory with larger in-pipe travel distances, introduction of more debris, and full exercise of the control electronics and software.

2. Continue testing of the patch-setting module and its use in setting the latest generation of 12-inch repair sleeves. Test results will be used to optimize design of the patch assembly and the patch-setting robot train.

3. Continue testing of 12-inch version of the cast-iron bolt-on entry fitting.
4. Test of the hole saw used to cut and angled access hole into pressurized cast-iron pipes.
5. Conduct full-up tests of the system in the shop in late July to early August. This will include cutting two or more access holes through the bolt-on fitting and setting several patches across joints in the test main.
6. Continue implementation of software controls and system displays into the LabVIEW user-interface/robotics-control environment.
7. Collect additional information and data to conduct benefit analysis.
8. Conduct field test demonstration of large-diameter system tentatively scheduled for August or September 2005.
9. Begin preparing draft of Final Report documenting all project activities during this phase of the development.

4. Conclusions

Activities in this quarter focused on Tasks 4–8. Important accomplishments are described in Section 3. In Task 6, a field-ready surface control module was fabricated and tested in anticipation of full-scale testing of the drilling assembly in the laboratory and field. Control routines for the coupon catcher are also being added to the system software. Task 7 (Design and Fabricate Large Diameter Live Access System) progressed to testing the prototype of the final design of a bolt-on entry fitting for 12-inch diameter cast-iron pipe in the current quarter. The design incorporates lessons learned with 4-in. prototype entry fittings that were tested in the field. The drilling assembly for cutting an access hole through the wall of the gas main was also fabricated, along with a plug assembly to allow removing all tools from the live main and setting a blind flange on the entry fitting prior to burial.

Full field testing of the large-diameter patching system is to be conducted during the next quarter.

5. References

(No references are cited in this Quarterly Report.)