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

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Abstract

Utilities in the U.S. operate over 75,000 km (47,000 miles) of old cast-iron pipes for gas distribution. The bell-and-spigot joints 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 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 (which results in enormous expense to utilities).

Technical challenges include: 1) repair sleeves must compensate for diametric variation and eccentricity of 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 repair operations on live mains.

The development effort is divided into eleven tasks. Task 1 – Program Management was previously completed. Two reports, one describing the program management plan and the other consisting of the technology assessment, were submitted to the DOE COR in the first quarter. Task 2 – Establishment of Detailed Design Specifications and Task 3 – Design and Fabricate Ratcheting Stainless-Steel Repair Sleeves are now well underway.

First-quarter activities included conducting detailed analyses to determine the capabilities of coiled-tubing locomotion for entering and repairing gas mains and the first design iteration of the joint-sealing sleeve. The maximum horizontal reach of coiled tubing inside a pipeline before buckling prevents further access was calculated for a wide range of coiled-tubing string designs and pipe environments.

Work conducted in the second quarter consisted of: 1) selecting a preferred pan/zoom/tilt camera; 2) initiating design of the digital control electronics and switching power supply for the

control and operation of the in-pipe robotic modules; 3) continuing design of the repair sleeve and 4) initial testing of the wall-cleaning device.

Most recently, activities in the third quarter included: 1) development of the system's pan/zoom/tilt camera control electronics and operating software, and implementing these in the surface and downhole modules and 2) further testing of the wall-cleaning elements used to clean the inside of the bell and spigot joints. Details of these activities are described in the body of the report along with a summary of events scheduled for the fourth quarter.

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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 bell-and-spigot design, tend to leak. Current repair practices are to either: 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) the 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. Technology 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 delivery system for providing primary locomotion, power and data communications between the in-pipe robot and 4) surface control and display electronics.

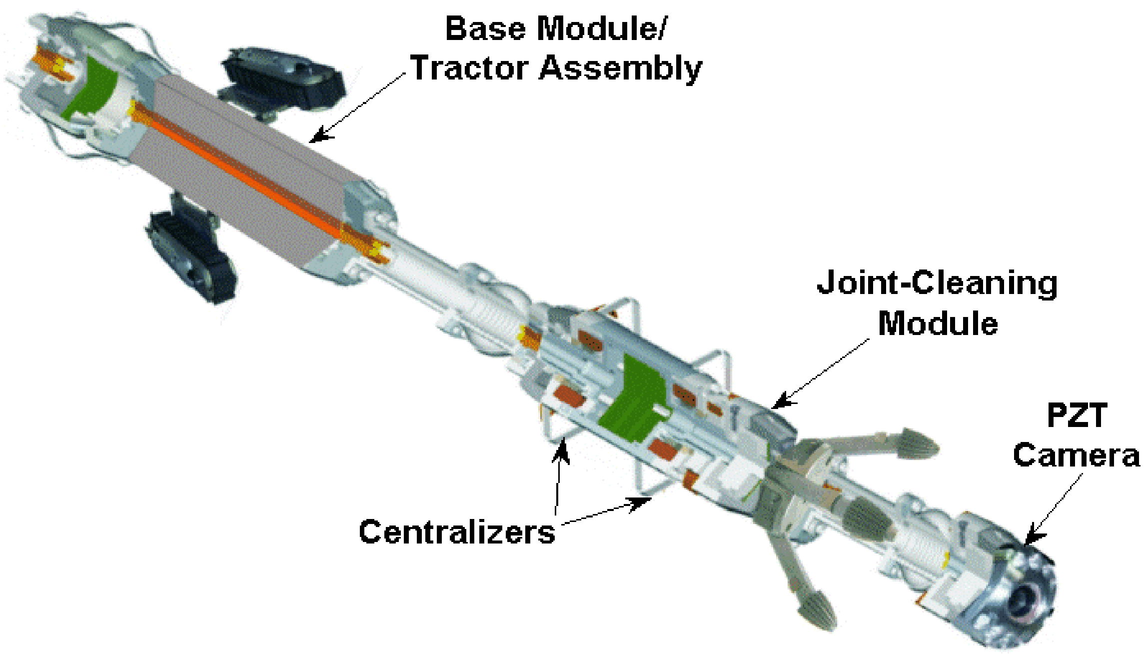


Figure 1. Pipe Wall Preparation Robot Train

Based on the analysis completed to date, it is envisioned that two in-pipe robot trains will be required. The first robot train will have a front-mounted camera that is used to visually locate each bell and spigot joint (**Figures 1 and 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 may also be fitted with a retractable plow to break down and level debris piles. 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.

In operation, the camera/brush/base module train will be pushed by the coiled tubing 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 coiled-tubing 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.

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

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 coiled-tubing 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 coiled-tubing 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.)

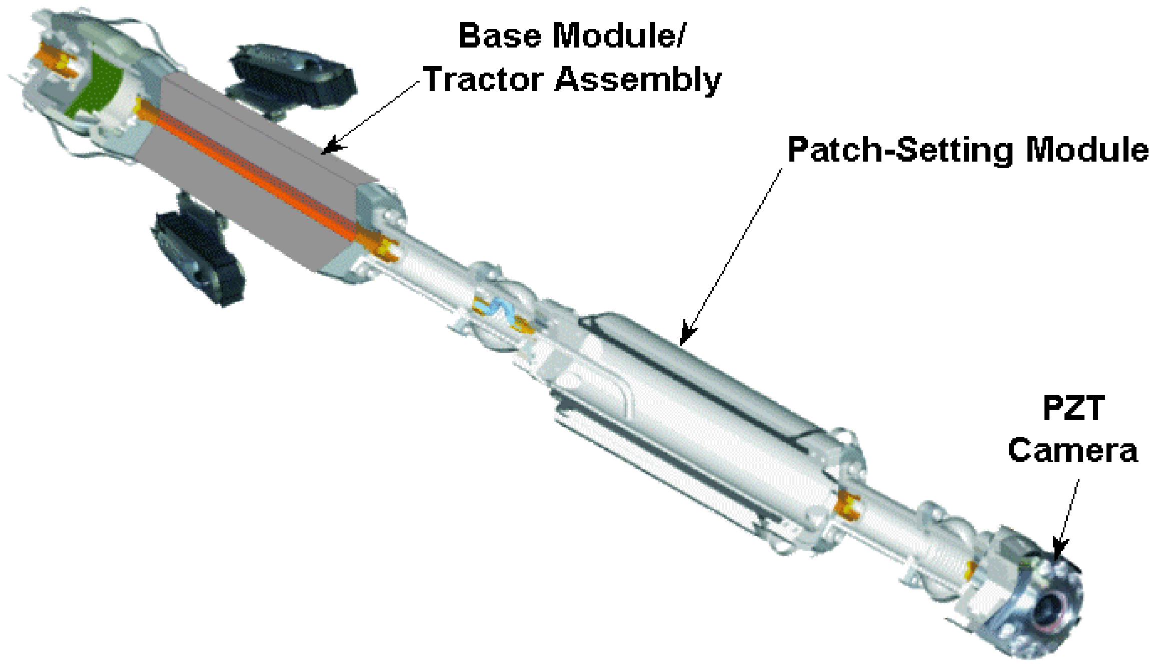


Figure 3. Patch-Setting Robot Train

3. Summary of Work Performed

The project work structure consists of the 11 tasks described below. Work during the first three quarters has focused on Tasks 1 – 5.

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 is to be described and documented in a written report to DOE. The report is to include task descriptions, schedules and planned expenditures as well as major milestones and decision points.

In addition, a Technology Assessment is also to be prepared. The assessment is to establish the state-of-the-art of the technologies to be developed along with those technologies against which it must compete. The report is to describe 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 will 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 coiled-tubing (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 will include a list of performance and size specifications that provide the basis for follow-on detailed design activities.

The mechanical, material and operational differences between small-diameter steel mains and large-diameter cast-iron mains have been defined. The primary challenges posed by the large diameter cast iron mains involve the 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 which is being considered through the use 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 the 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 now being focused on producing detailed designs for the entry fitting, cleaning elements and repair sleeves for this size application.

The coiled-tubing pushing/buckling analysis was completed in the first quarter with results presented in a previous quarterly report.

Task 3 – Design and 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 8) will be 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**). The corrugations, consisting of folds spaced on 1-inch centers, improves the structural stiffness of the device so it does not deform during the setting process.

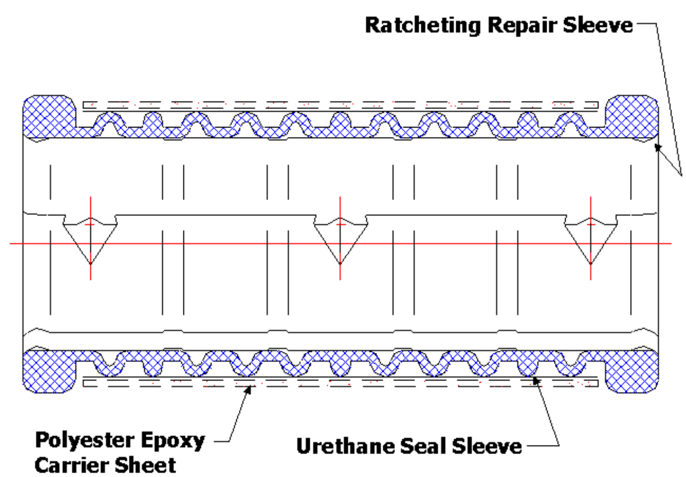


Figure 4. Ratcheting Repair Sleeve

The sleeve also features three rows of ratchets (see **Figure 6**). The three rows allow the sleeve to be mechanically locked for diameter variations up to 0.50 inches.

The most obvious visual trait of the urethane seal sleeve is the fact it has grooves or ribs. This new design allows for compensating for the axial shortening that would otherwise occur if an non-ribbed sleeve was allowed to radially expand significantly. The end elements feature increased thickness and act as 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 are currently being prepared.

Figure 5. Coiled Diameter Comparison for 28 and 24 Gage

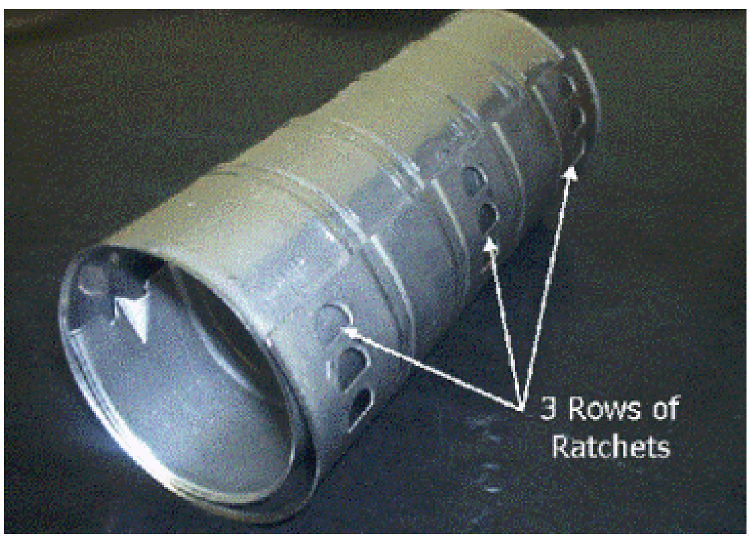


Figure 6. Sleeve Ratcheting Design

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

To assure the stainless sleeve engages along the same set of ratchet locks along its entire length, it is proposed to use a three-chamber expander rather than the single chamber expander normally used in steel pipe applications. The single chamber, only being constrained on both ends, can possibly exhibit some ballooning, which if left unattended may produce a situation of the center set of locks being on a larger radius than the end locks. By dividing the same expander length into three chambers, the degree of ballooning can be greatly minimized. **Figure 7** compares the two expander designs.

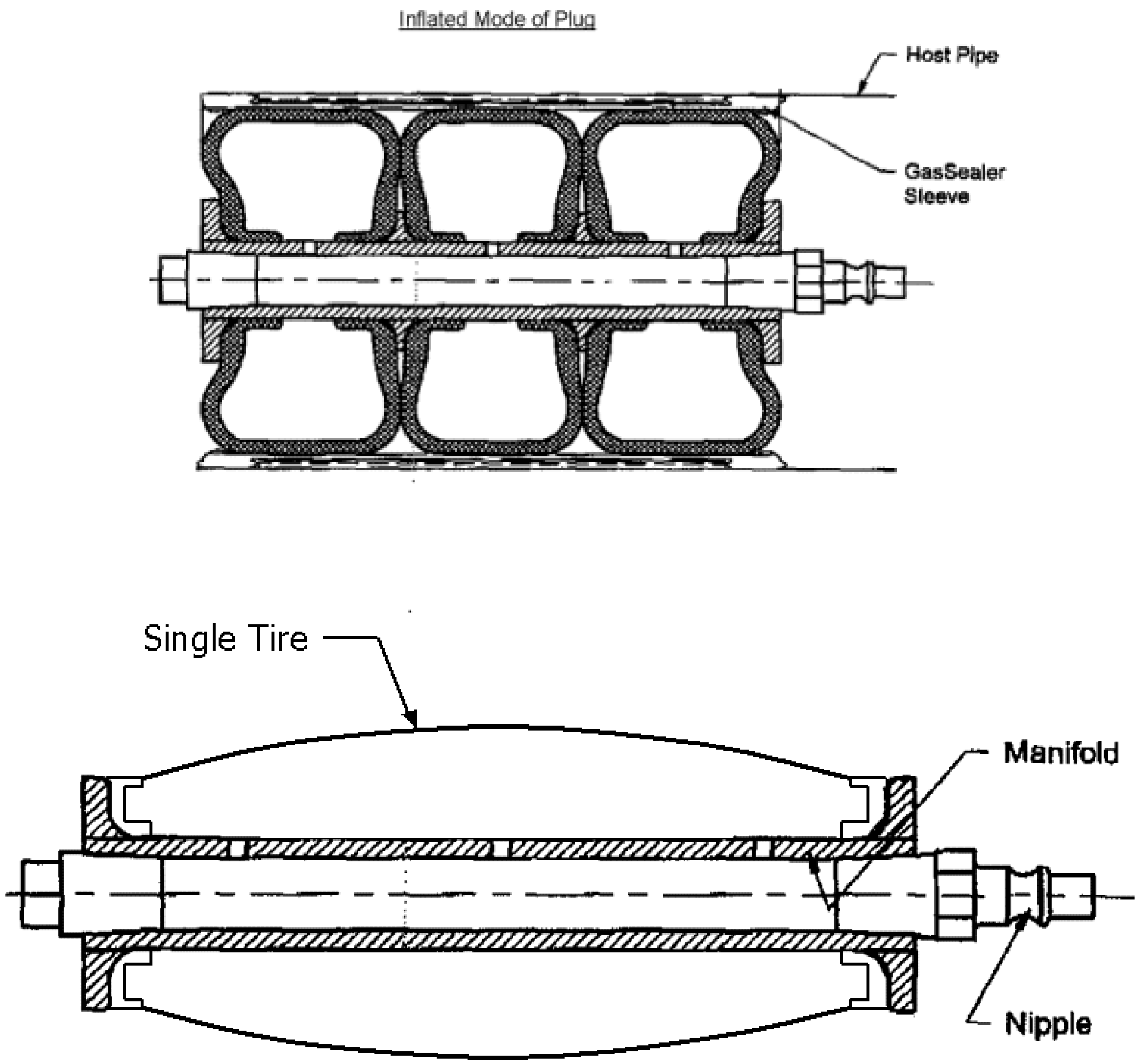


Figure 7. Expander Comparison

In the second quarter, detailed design drawings were prepared for both the repair sleeves and the repair installation (patch setting) modules shown in **Figure 8**. Rolling of the sleeve into two diameter sizes is being evaluated with the goal of finding the smallest collapsed diameter which can be successfully set (expanded) across the bell and spigot joint. The two sizes are a 5-inch diameter rolled stainless steel sleeve and a 6.5-inch diameter sleeve – both measuring 12 inches in overall length.

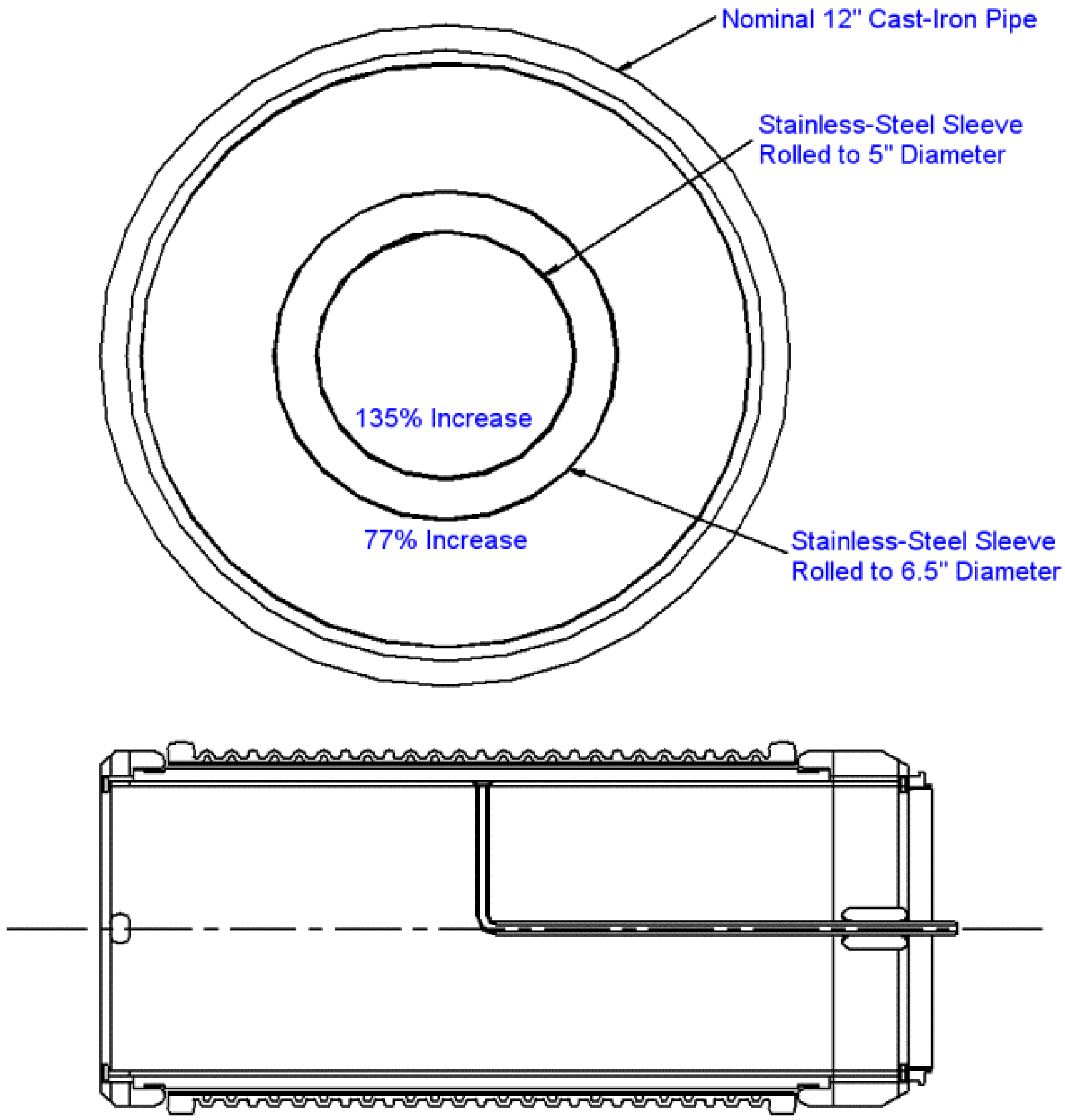


Figure 8. Patch Setting Module

These drawings were used in the third quarter to build prototype inner sleeves (**Figure 9**) of both sizes. Expander tests to determine the force required to open the sleeves to 12-in. diameter will be conducted in the next quarter.

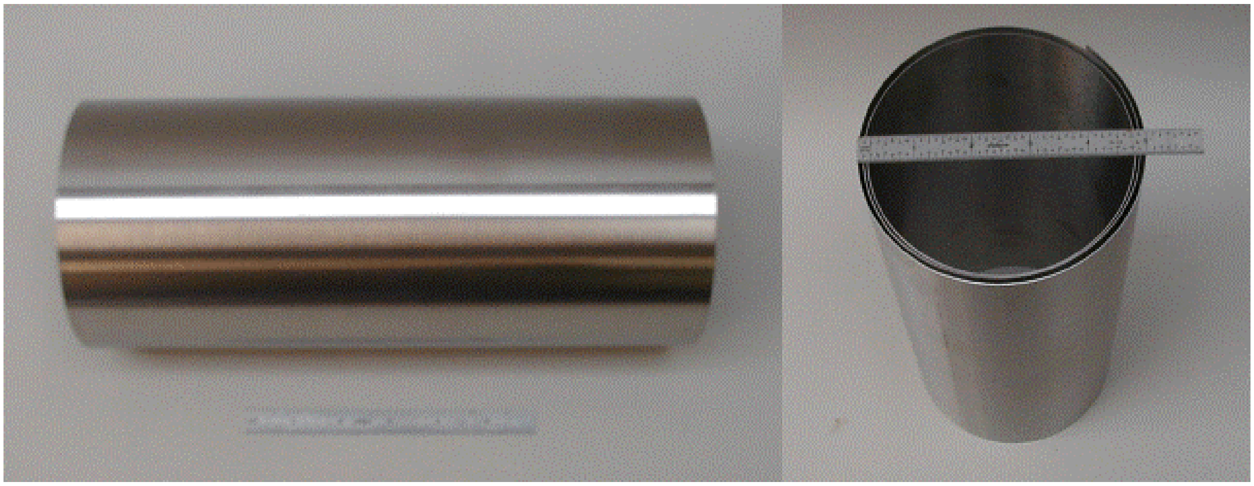


Figure 9. Stainless Steel Inner Sleeve

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 coiled tubing. Its physical form must not impede the flow of gas through the main (thereby maintaining gas delivery to customers). Lastly, it must be able to set the patch 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 the inside of 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.

The overall design of the patch-setting robotic train awaits the test results of the preliminary sleeves described in Task 3. These tests will occur in the next quarter and become the basis of this activity.

Task 5 – Design & Fabricate Pipe Wall Cleaning Robot Train with Pan/Tilt/Zoom Camera

Cast-iron gas mains operate at much lower pressure than their steel counterparts; consequently, their interior conditions are often quite different. Lower pressure 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 additives settled out into the bottom of the mains and combining with particulate matter, formed 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 will be completed in Task 5:

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 will be 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 the scales and deposits found on the inside of cast-iron pipe. 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/Tilt/Zoom Camera along with its corresponding electrical/electronics schematics, mechanical drawings, and descriptive report documenting assembly, maintenance and operation.

The analysis of different pan/zoom/tilt (PZT) cameras was completed in the second quarter and a preferred design selected. The camera measures 4 inches OD x 10.5 inches overall length as shown in **Figure 10**. It features 270° of tilt, 340° of pan and a 72:1 zoom ratio. It's eight, high intensity argon lights were found to provide excellent illumination in tests conducted inside sealed 12- and 24-inch pipes. Specifications are summarized

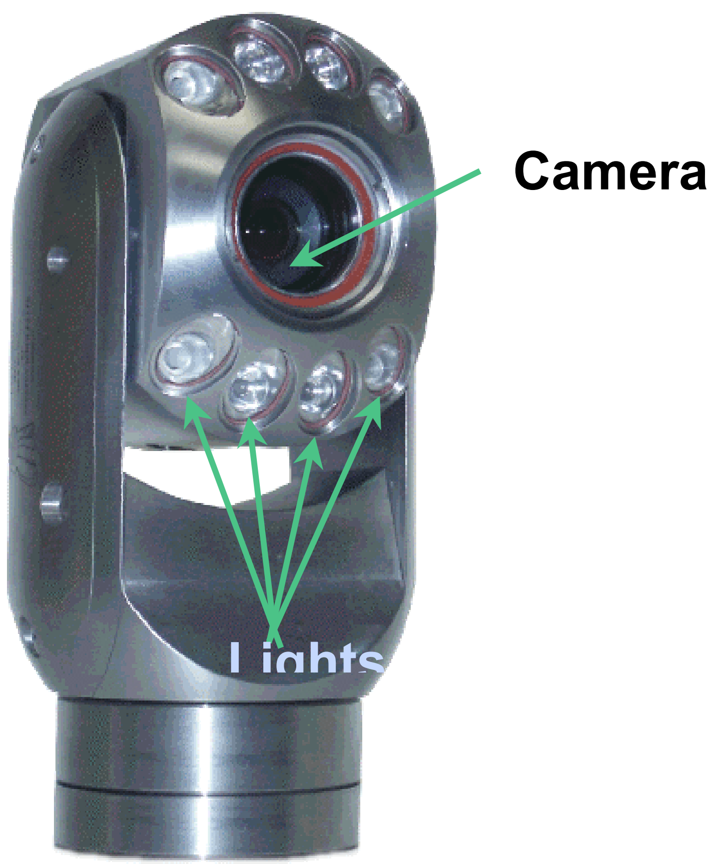


Figure 10. PZT Camera

in **Figure 11**. 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” Indictaor
18 awg, brown	Camera Fade

Pan/Tilt/Zoom (PTZ) Camera

SPECIFICATIONS

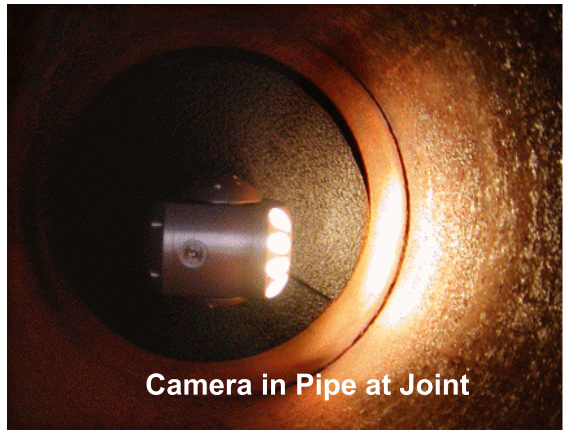
Pick-up Element: ¼” CCD

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

Resolution: > 460 TV Lines

Illumination: 3 lux

Horizontal FOV: 48° wide, 2.7° tele



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 11. Camera Specifications

Use of a 16-conductor bundle becomes inefficient inside 1000 ft of small-diameter coiled tubing. 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.

The primary activity during the third quarter was the development of the robotic system's pan/zoom/tilt camera control electronics and operating software and implementing them in both the surface and downhole modules.

The camera surface hardware consists of a 95-Volt DC power supply capable of sourcing up to 2.1 Amps of current for operating camera illumination, lenses and physical orientation within the pressurized gas main, a personal computer having a RS-485 bi-directional 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 coiled tubing 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 such as shown in **Figure 12**.

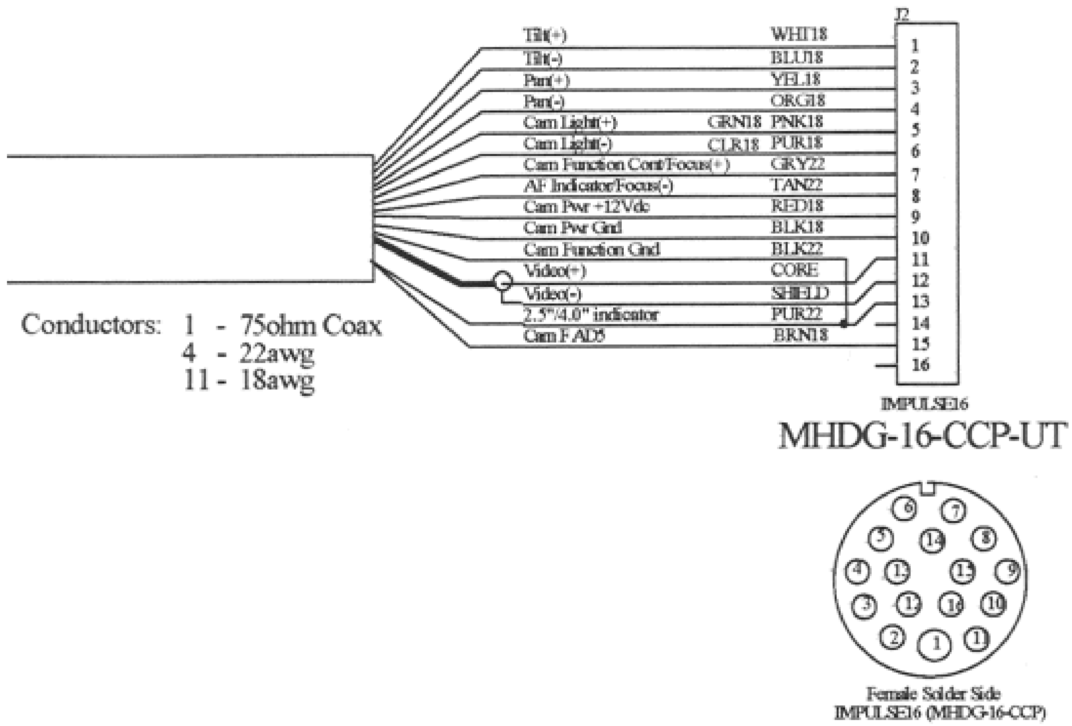


Figure 12. Conventional Camera Control Cable Design

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. The electrical schematic for the downhole camera control electronics is shown in **Figure 13**.

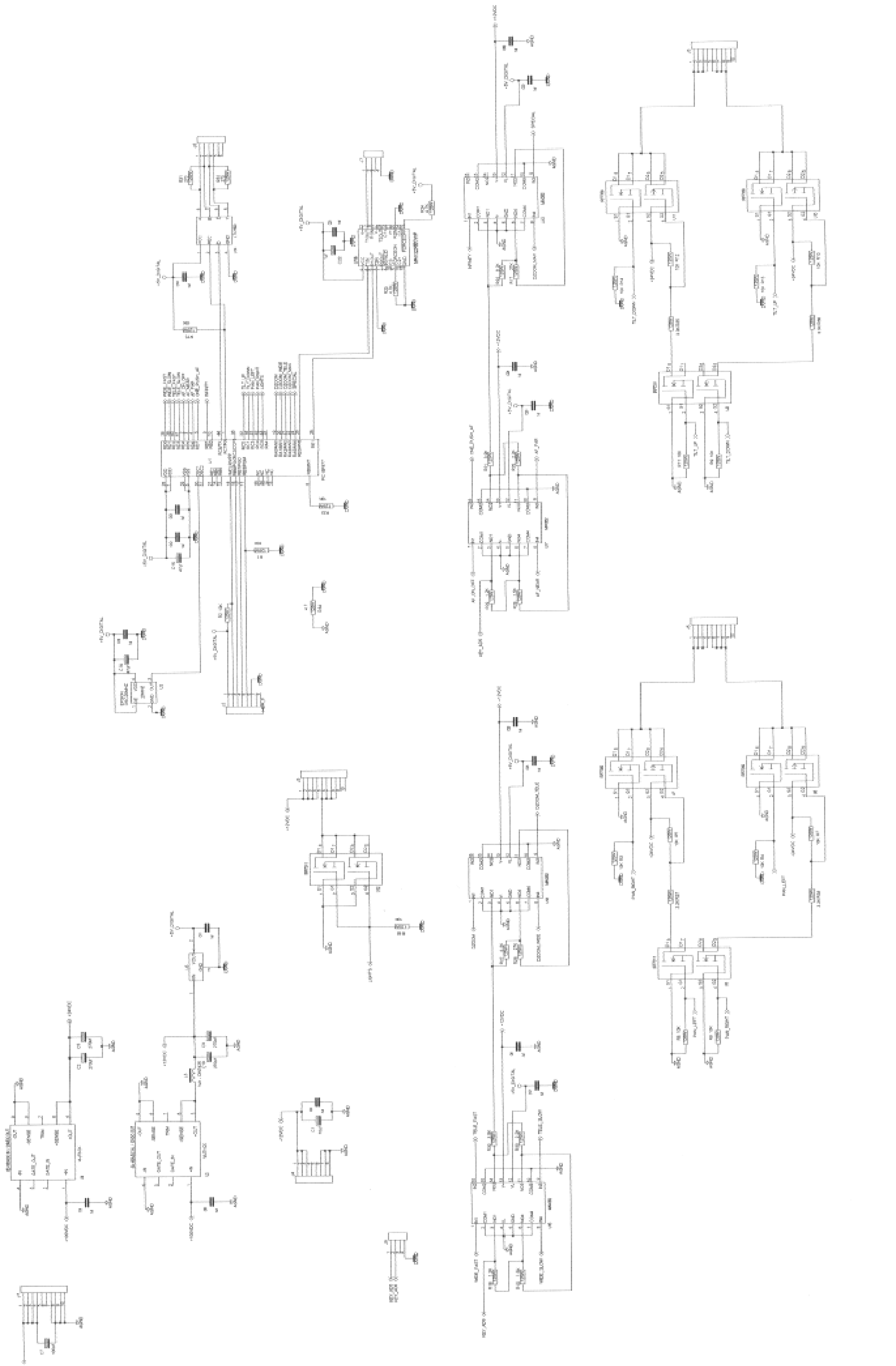


Figure 13. Downhole Camera Control Circuit Schematic

Figure 14 is a photograph of 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.

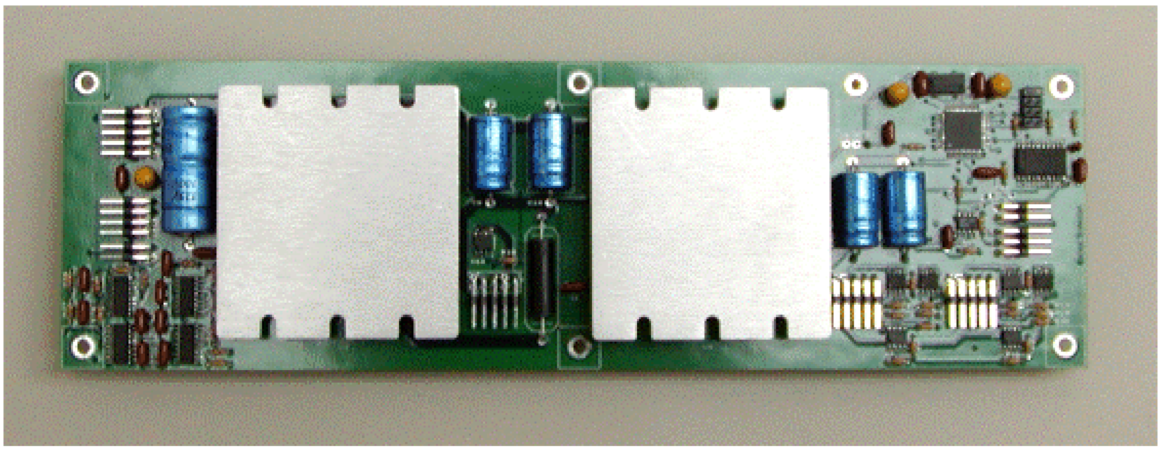


Figure 14. Downhole Camera Control Circuit Board

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.

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 current quarter. It is suitable for removing a wide range of debris including very hard deposits. It has a collapsed diameter of 6.4 inches and can open up as large as 13 inches under centripetal action. The arm assembly is currently undergoing a series of cleaning tests to assess its ability to remove deposits. Measurements of the motor speeds and torques are being recorded during these tests so the electric drive motor for the robot train can be properly sized. (HP = torque (ft-lbs) x speed (rpm) / 5252). The testing activities will be completed early in the fourth quarter and followed by the selection, procurement and integration of the device into the robot train. **Figures 15 and 16** show the cleaning head being evaluated for its performance.

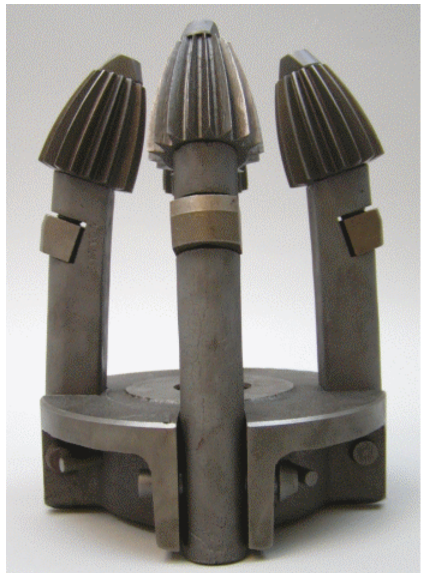


Figure 15. Cleaning Head Collapsed – 6.4-in. OD

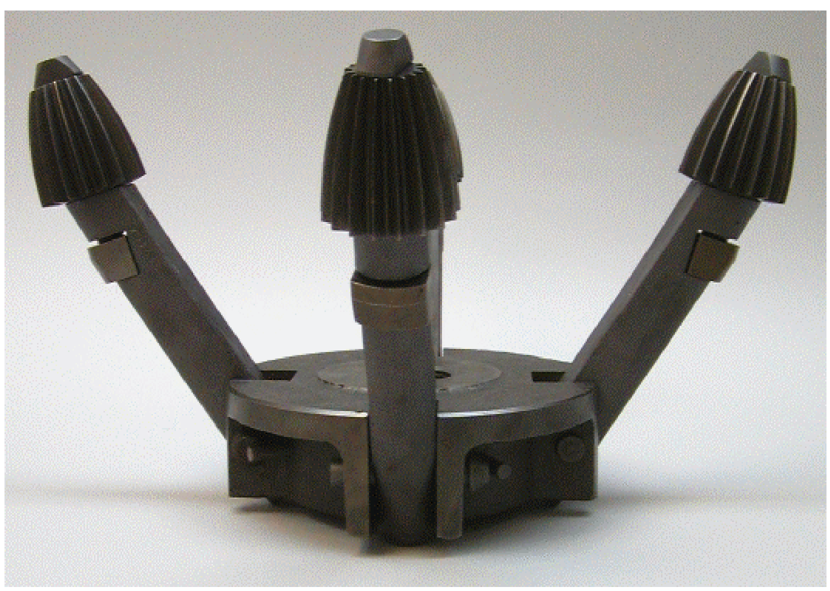


Figure 16. Cleaning Head Fully Opened – 13-in. OD

Performance of the cleaning head is being evaluated by mounting the cleaning head to a computer-controlled rotary drive and linear feed assembly (**Figure 17**). The hydraulic-powered rotary drive allows precise control of the rotation speed and torque provided to the cleaning head.

Similarly, the hydraulic feed cylinder allows precise control of the forward and reverse speeds at which the cleaning head is moved across the bell and spigot joint.

Figure 17. Fixture for Testing Joint-Cleaning Assembly

Taken as a whole, the test apparatus enables us to determine the physical size, planetary gear set and electrical power requirements for the electrical motor that will operate the cleaning elements when packaged into a robotics module. As importantly, the apparatus will establish the preferred rotation speed and movement rate necessary to assure proper cleaning of the cast-iron joints under typical operating conditions. (Sufficient cleanliness of the joint will still be visually confirmed via the camera during field operations.)

A limited number of cleaning tests have been conducted to date using 12-inch diameter cast-iron joints removed from actual gas-distribution piping networks (**Figure 18**). These data are currently being quantitatively analyzed with results to be reported next quarter. Qualitative observations show that this particular style of cleaning element is capable of efficiently removing debris adhering to the cast iron wall.

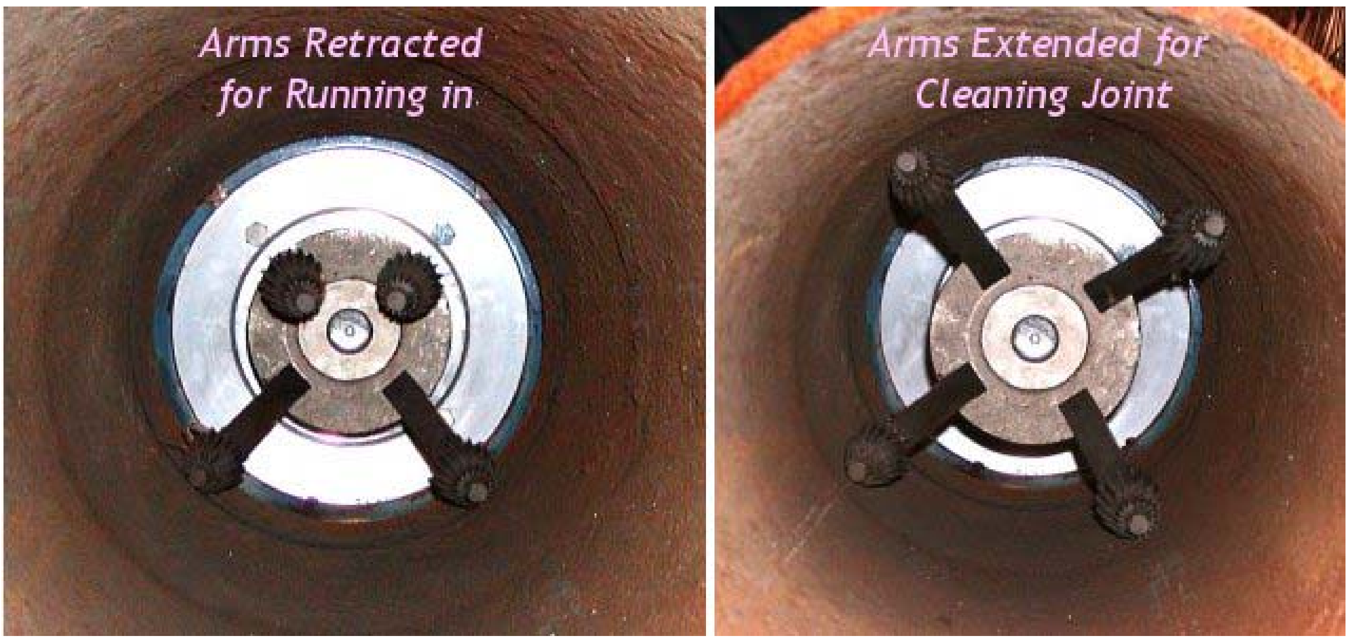


Figure 18. Joint-Cleaning Assembly in Testing Fixture

Task 6 – Design and Build Surface Control and Monitoring System

Once all in-pipe hardware designs are complete, the surface control and monitoring system will be designed. Not until this point will it be known which parameters must be monitored and for which component(s) control must be provided. This unit will provide all communication, control, video, and monitoring interfaces with the equipment in the gas main. Packaging will be consistent with construction field-ready practices.

The 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.

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

Since the entry fitting system for cast-iron pipe cannot be welded into place (as is the case with steel pipelines), some other means must be used. The only viable choice is a mechanical clamp of some type. The entry fitting will enable a port to be cut into the main for inserting all necessary 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.

No activity occurred in this task in the current 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 the 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, NUI/Elizabethtown Gas, 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.

No activity occurred in this task during the current quarter.

Task 10 – Benefits Analysis

After the field tests are completed, detailed discussions will be held 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.

No activity occurred in this task during the current quarter.

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.

4. Work Planned for Next Period

Planned activities for the next three months will encompass elements of Tasks 3 – 6. The specific work items will include:

1. Complete joint-cleaning tests on the 12-inch cast-iron bell and spigot joints
2. Use the cleaning data to select and procure the geared electric drive motor
3. Design, build and test surface and downhole electronics for operating the joint-cleaning module
4. Implement camera and cleaning controls into the LabView user-interface/robotics-control environment
5. Design and build the repair-sleeve setting module
6. Conduct repair-sleeve setting tests using prototype sleeve design

5. Conclusions

Activities in the third quarter included: 1) development of the system's pan/zoom/tilt camera control electronics and operating software, and implementing these in the surface and downhole modules and 2) further testing of the wall-cleaning elements used to clean the inside of the bell and spigot joints. Work in the current quarter included testing of the cleaning-head elements used to remove debris from the inside pipe wall across the bell and spigot joint to ensure proper adhesion of the epoxy to the pipe wall. Tests are being conducted by mounting the cleaning head to a computer-controlled rotary drive and linear feed assembly.

A limited number of cleaning tests have been conducted to date using 12-inch diameter cast-iron joints removed from actual gas-distribution piping networks. These data are currently being quantitatively analyzed with results to be reported next quarter. Qualitative observations show that this particular style of cleaning element is capable of efficiently removing debris adhering to the cast iron wall.

Work to be accomplished in the next quarter was summarized (see Chapter 4).