GasNet^{TM}:

Gas Main Sensor and Communications Network System

Phase III Final Report

Reporting Period Start Date: October 1st, 2004
Reporting Period End Date: April 30th, 2006

Report compiled by
Hagen Schempf, Ph.D.

and submitted on
April 30th, 2006

as a final deliverable under
Contract # DEFC26-02NT41320

for work performed by

AUTOMATIKA

Automatika, Inc.
137 Delta Dr.
Pittsburgh, PA 15238
(412) 968-1022, -1023 Fax
http://www.automatika.com
info@automatika.com

Technical Contact:
Hagen Schempf, Ph.D. (412) 968-1022, X-11

Administrative Contact:
Dr. Noellette Conway (412) 968-1022, X-10

Document Number: REP-GOV-DOE-123105

Notice

This report was prepared with the support of the US Department of Energy, under Award No. DE-FC26-02NT41320. However, any opinions, findings, conclusions, or recommendations expressed herein are those of the author(s) and do not necessarily reflect the views of the Department of Energy.

04-30-06

Dr. Noellette Conway, CEO **Date**
Automatika, Inc.

04-30-06

Dr. Hagen Schempf, Chief Scientist **Date**
Automatika, Inc.

DISCLAIMER

ABSTRACT

Automatika, Inc. was contracted by the Department of Energy (DOE) and with co-funding from the Northeast Gas Association (NGA), to develop an in-pipe natural gas prototype measurement and wireless communications system for assessing and monitoring distribution networks. This projected was completed in April 2006, and culminated in the installation of more than 2 dozen GasNet nodes in both low- and high-pressure cast-iron and steel mains owned by multiple utilities in the northeastern US. Utilities are currently logging data (off-line) and monitoring data in real time from single and multiple networked sensors over cellular networks and collecting data using wireless bluetooth PDA systems.

The system was designed to be modular, using in-pipe sensor-wands capable of measuring, flow, pressure, temperature, water-content and vibration. Internal antennae allowed for the use of the pipe-internals as a waveguide for setting up a sensor network to collect data from multiple nodes simultaneously. Sensor nodes were designed to be installed with low- and no-blow techniques and tools. Using a multi-drop bus technique with a custom protocol, all electronics were designed to be buriable and allow for on-board data-collection (SD-card), wireless relaying and cellular network forwarding. Installation options afforded by the design included direct-burial and external pole-mounted variants. Power was provided by one or more batteries, direct AC-power (Class I Div.2) and solar-array.

The utilities are currently in a data-collection phase and intend to use the collected (and processed) data to make capital improvement decisions, compare it to Stoner model predictions and evaluate the use of such a system for future expansion, technology-improvement and commercialization starting later in 2006.

Table of Contents

I. EXECUTIVE SUMMARY

II. TECHNICAL DISCUSSION

1.0 Introduction 4
2.0 Project Overview 4
3.0 Technology Relevance 5
3.1 Vision and Discussion of Improvement over Existing Technologies 5
3.2 Qualitative Benefits 6
3.3 Quantitative Benefits - Rough Estimates 6
3.4 Application Examples and Demonstration of Engineering Breakthroughs 7
4.0 Background - Technical State of the Art 9
4.1 Overview 9
4.2 GasNet Phase I Results 10
4.3 GasNet Phase II Results 10
5.0 System Design Concept 12
5.1 Overview 12
5.2 Concept Description 12
5.3 Installation Concept 14
6.0 System Design Description 15
6.1 Overview 15
6.2 Sensor-Wand 16
6.3 Electronics Enclosure 18
6.3.1 Overall Housing 18
6.3.2 Electronics Boards (PCBs) 19
6.3.2.1 Sensor-Wand 19
6.3.2.2 Bridge-PCB 19
6.3.2.3 Datalogger-PCB 20
6.3.2.4 Wireless-PCB 20
6.4 Battery Unit 21
6.5 Operational Configurations 22
6.5.1 Valve-Box (Datalogger & Wireless Slave) 22
6.5.2 Pole-Box (Wireless Repeater and Master) 23
6.6 No-blow wand installation 23
6.7 Data Collection Approach 24
6.7.1 Graphical User Interface - GUI 24
6.7.2 Wireless Bluetooth PDA 24
6.8 Software Architecture 26
7.0 Experimental Results 28
7.1 Laboratory Testing & Calibration 28
7.2 Independent Calibration Validation 29
8.0 Field-Trial Validation 30
8.1 ConEd Installation 30
8.2 KeySpan Installation 33
8.3 NiMo Installation 36
9.0 Data Collection and Interpretation 39
9.1 Data Sets 39

9.2 Data Evaluation Summary 43
10.0 Project Summary 44
11.0 Conclusions and Recommendations...46

III. APPENDICES

1.0 Acknowledgements 49
2.0 Patenting 49

List of Figures

Figure II-1 : State-of-the-Art picture gallery covering sensing, sensor-processing and computing, communications, power and live-pipe access 11
Figure II-2 : Overall GASNETTM system concept: Sensing-, RF-Communications, Computing- and Power System with an Installation View 13
Figure II-3 : Overall GASNETTM system concept: Urban Deployment & Operator Console Interface 13
Figure II-4 : GasNet installation concepts - Master, Slave & Logger 14
Figure II-5 : GasNetTM System Overview and as-built ready-to-ship assembly 15
Figure II-6 : Sensor-wand design and associated sensor layout 16
Figure II-7 : Sensor-plug design and associated components....................16
Figure II-8 : Simplistic block-diagram of electronics architecture....................17
Figure II-9 : Populated sensor-wand assembly....................17
Figure II-10 : Fully assembled sensor wand installed in a test-pipe....................18
Figure II-11 : Electronics Enclosure Unit....................18
Figure II-12 : Sensor-Wand PCBs....................19
Figure II-13 : Bridge PCB 19
Figure II-14 : Datalooger PCB....................20
Figure II-15 : Wireless PCB 20
Figure II-16 : Battery power enclosure with discharger....................21
Figure II-17 : Valve-box field installation design 22
Figure II-18 : Pole-mounted master/repeater electronics/power installation....................22
Figure II-19 : No-blow installation tools and setup....................23
Figure II-20 : GUI screen-capture layout showing real-time single-node data 24
Figure II-21 : Wireless bluetooth enabled PDA unit for field data-collection 25
Figure II-22 : Software mode flow chart diagram 27
Figure II-23 : Laboratory testing and calibration pipe network setup 28
Figure II-24 : SwRI Metering Test-Loop Calibration Setup 29
Figure II-25 : Field trial setting with ConEd in New Rochelle, NY....................30
Figure II-26 : Cast Iron installation site with ConEd in New Rochelle, NY 31
Figure II-27 : Installation Image Collage - Low Pressure Cast-Iron - Dataloggers - Consolidated Edison - New Rochelle, NY 32
Figure II-28 : Field trial setting with KeySpan in East Rockaway, NY 33
Figure II-29 : Installation Image Collage - High Pressure Steel - Wireless Spider Network - KeySpan - East Rockaway, NY....................35
Figure II-30 : Field trial setting with NiMo in Glenns Falls, NY 36
Figure II-31 : Installation Image Collage - High Pressure Steel - Wireless Star Network - Niagara Mohawk - Glen Falls, NY....................38
Figure II-32 : Typical gas main flow-speed data-log plot 39
Figure II-33 : Steel Gas Main Pressure - Representative data-log plot 40
Figure II-34 : Cast Iron Gas Main Pressure - Representative data-log plot....................40
Figure II-35 : Gas Main Water Content Data-Plot 41
Figure II-36 : Temperature data-log - Multi-node temperature distribution....................42
Figure III-37 : GasNet Patent #6,778,100 Cover Page 49

List of Tables

I. EXECUTIVE SUMMARY

Gas utilities have little, to no, information about the in situ process variables in their gas distribution networks. This severely hampers gas distribution infrastructure management efforts. Automatika Inc., in partnership with the NorthEast Gas Association (NGA[1]) and its associated utilities, under funding from the Department of Energy (DoE) National Energy Technology Laboratory (NETL) Strategic Center for Natural Gas (SCNG), developed a cast-iron and steel gas main system called ***GASNET***^{TM}, a stand-alone, distribution pipeline sensor network system for real-time monitoring of live distribution gasmains. The objectives of the ***GASNET***^{TM} program are to provide gas distribution utilities with the information they need to 1) access, maintain, monitor, and repair gas distribution systems, 2) track distribution system related activities - particularly third party activities which may pose safety concerns, and 3) model and design new networks.

GASNET^{TM} is a wireless, self-powered stand-alone or network of open-hole no-blow installed and post-restoration accessible field-sensors capable of measuring, storing and communicating wirelessly through the pipe, key process variables such as pressure, flow, vibration, etc. The data is stored in on-board removable memory-media and can also be sent in real time to a utility's central-control station. This process information will allow utilities to monitor the delivery process across their entire network from a single computer-console. The ***GASNET***^{TM} system concept addresses 5 key needs of gas distribution network managers. The system can 1) detect certain types of third party damage, 2) enable detection of leaks, 3) result in cost effective monitors and sensors, 4) result in virtual models for gas system analysis, and 5) provide improved and cost effective data acquisition, system monitoring, and control capabilities.

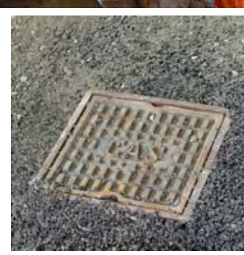
The entire three-phase project effort for the development and field-deployment of a prototype ***GasNet***^{TM} system has been very successful overall. The main technologies, ranging from sensing, communications, software and display to in-field installation, safety design, real-time and off-line data logging were shown to be feasible in both cast-iron and steel mains. The project resulted in the development of three key technical subsystems (sensor-wand, electronics and power system) as well as the embedded software and graphical user interface (GUI) to collect, display and store all the measured data. The wand design was developed as a modular unit to allow for the inclusion of flow- and wireless components for various-diameter pipes. The wand-plug was designed to be used with existing live-pipe installation tools and methods for both low- and high-pressure mains, regardless of their size. The electronics were designed around a modular concept for key modules (sensor, datalogger, bridge, modem, etc.) to sit on a common bus and make customization of the system for various models (datalogger, wireless-node, etc.) straightforward. The power system was designed to be flexible and allow the use of batteries, solar-cell or even AC power hook-up (with converter). All pipe-external electronics were housed with components capable of extended

1. NGA (NorthEast Gas Association) is the association of publicly owned gas utilities in NY State. Through its research and development committee it provides funding and supports a portfolio of innovative R&D projects.

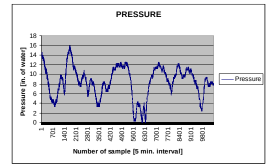
burial and immersion in the elements (water, soil, etc.), while also allowing The design for live low-/no-blow installation in low-/high-pressure distribution mains (cast-iron/steel) of multi-sensory probes (using existing commercial tools and methods), coupled with external data-sampling, -collection, -storage and -communication software and hardware was proven to be a very viable approach for instrumenting critical distribution network sections. The flexibility of he design to include the ability to tailor the system to local datalogging with wired/wireless data-dump, and the ability set up pipe-internal communication networks and cellular real-time data-links for real-time monitoring proved to be technically feasible. Critical areas of safety-design, logistics and system-modularity were addressed successfully in this program, resulting in multi-dozen units currently installed and operational in the field.

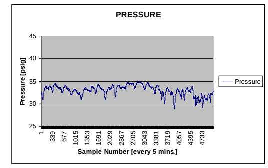
The selected sensors and the distributed microprocessor system were shown in the lab and field to perform as expected, in both low-pressure (sub-atmospheric) and high-pressure (up to 85 psig - limited by pressure-sensor saturation) environments. The wireless communications link was also shown to work in a dynamic network setting, with varying operational modes implemented in software (emergency, monitor, datalogger, alarm, etc.). The modularity of the system allowed it to be configured in a variety of models (datalogger, slave, master, repeater, etc.), with multiple data-interfaces (batch-log, bluetooth-dump, cellular-relay, memory-card exchange) and various external power-options (battery, solar-cell, AC-drop). Each of these options was implemented and is in one combination or another installed in the field. For the real-time cellular-relay, the graphical user interface (GUI), was developed for flexible data-display, -conversion and data-storage in an accessible database for each utility. Said GUI is also used to collect and store data collected in the field (via bluetooth PDA or memory-card exchange) into the same database for later access and processing.

Field installations included low-pressure cast-iron datalogger nodes with PDA-based bluetooth data-collection interfaces, spider-/star-networked master/repeater/slave networks in higher-pressure steel mains with cellular data-relay and remote GUI display of quasi real-time data, as well as stand-alone cellular relay and AC/solar powered nodes for critical node monitoring. A total of six (6) utilities were assigned a set of nodes, with five (5) of them having installed nodes and currently collecting data on their distribution networks. Additional modifications for a proprietary SCADA data-interface to GasNet for a particular utility is currently in the planning phases.



Experimental field-testing showed that low-pressure cast-iron mains could be monitored and data logged, collected and visualized as expected, proving the viability of the GasNet system. Establishing pipe-internal networks in bell-and-spigot cast-iron networks was experimentally determined to not be possible beyond $^{1}/_{4}$-mile inter-node spacings. Nodes installed in high-pressures (welded or flange-bolted) steel mains proved to also be viable, resulting in local and relayed data from pipe-internal wireless multi-node networks. Different patterns of networks were shown to be feasible, with quasi real-time data being viewable at a remote site using cellular networks. The extent of inter-node spacings was controlled by pipe-diameter, pipe-junction losses, and any other non-conductive pipe-inserts; distances of multi-thousand feet were however possible as long as electrical continuity was guaranteed.





The initial data sets collected during the installation period of the nodes, again verified that the gas flow rates exhibit highly dynamic and oscillatory behavior varying widely across the pipe run in terms of amplitude (flow-rate) and flow-direction as a function of time-of-day. Pressure measurements showed that pressures were in the statically-predicted range, with variations due to consumption, ambient temperature and regulator settings. Gas temperature was found to be extremely steady, with higher temperatures of the gas flow than ambient, and correlated to daytime temperature fluctuations, preheated-gas mixing ratios and conductive cooling due to the surrounding soil as a function of distance travelled; these are critical measurements to better understand freeze/thaw impact on cast-iron mains as well as avoiding regulator freeze-up due to water-content freeze up in the main. Water content was found to be extremely low and measured at less than 1% by volume. Mechanical pipe-wall vibration measurements proved to only be possible within the vicinity of an instrumented pipe-section due to the segmented and isolating nature of the cast-iron bell-and-spigot design; measurements did however show that road-traffic could be ignored, while road-surface jack hammering was readily detected, as were impact-loads as small as a hammer-strike on the pipe-wall.

Utility representatives from Consolidated Edison, Keyspan Energy, Niagara Mohawk, NYSEG and Central Hudson all participated in the field-trials, with PSE&G still planning system modifications prior to installation under separate funding. Data-collection by all participating utilities is still ongoing as of this point in time to asses the utility and needs for commercialization for the GasNet system beyond the current prototype units.

Based on these results, one can conclude that a ***GASNET***^{TM} system has valid applications in more than one form within the gas main distribution and transmission markets. Sensing and communications options are vast enough to cover any existing utility preference and are upgreadable as technology evolves. The use of the collectable data by the utilities has yet to be explored in depth, in terms of its use as a monitoring, emergency, or even a capital-expenditure planning tool, but we believe this to be only a matter of time before utilities come up with more ways to integrate this data into their operations.

II. TECHNICAL DISCUSSION

1.0 Introduction

Utilities need information about the in-situ process variables in their distributed network with sufficient resolution to enable them to better manage their infrastructure. When a utility lays out a new network, a computer-model of the network is utilized[1] to predict pressures and flows in the system. This allows the utility to size compressors and/or storage facilities, to provide for the necessary flow and pressures. Once installed however, the only real-time monitoring (and control) that occurs in the field is typically at the actual pumping/storage/regulating facilities. This severely hampers gas distribution infrastructure management efforts. Pressure and flow-variables are used to adjust supply and demand from the field - a basic reactive system approach. Additionally, data from every individual gas-meter is collected over time and used for billing in an offline process. Comparison of metered-and-billed volumes and those measured at the supply centers as having been pumped, can give some indication of the state of the network. The power-meter industry has allowed electrical utilities to make a phone-connection with their meter at each dwelling, thereby reading the consumption regularly with minimal manual effort. However, this is not considered a real-time network-wide measure. Gas utilities are beginning to realize the importance of automated pipeline management systems, but they are far from widely applying these technologies.

2.0 Project Overview

Automatika, Inc. (AI) in partnership with the North East Gas Association (NGA) have teamed and engaged in a system prototype development and demonstration of ***GasNet***[TM], a distributed network of multipurpose sensors wirelessly communicating information on the real-time state of the distribution network to utility operators through the pipe-internal void. Through the use of wireless and micro-miniature sensor technologies, ***GasNet***[TM] is intended to improve the safety and operational capabilities of the distribution network while substantially reducing the cost of operations. ***GasNet***[TM] is intended to address 5 key issues generic to the gas utility industry, namely **1**) provide improved cost effective data acquisition, system monitoring and control, **2**) result in cost effective monitors and sensors, **3**) detect certain types of third party damage, **4**) result in virtual models for gas system analysis, and **5**) enable detection of leaks in the future. This effort was carried out in a multi-phase program. The first phase of which has already been completed and reported upon in a topical report (OSTI ID: 816706; **www.osti.gov/dublincore/gpo/servlets/purl/816706-X0cFFq/native/**), with the Phase II effort having been described in a follow-on topical report (OSTI ID: 836824; **http://www.osti.gov/bridge/purl.cover.jsp?purl=/836824-OHcrzR/native/**). This report serves to provide a summary overview on all phases, especially the Phase III effort.

1. so-called ***Stoner*** Model

3.0 Technology Relevance

3.1 Vision and Discussion of Improvement over Existing Technologies

Many technology experts have characterized the upcoming decade as the decade of ***Sensors***. The advent of manufacturing processes developed for the massive and inexpensive production of semiconductors can now be used for the manufacturing of digital and analog sensor devices based on piezo- and micro-machinable and photo-etchable semiconductor materials. In conjunction with the recent advances in micro-machines, Very Large Scale Integration (VLSI) video, and other miniature systems, these manufacturing techniques promise to provide us with sensors capable of measuring various physical parameters and the ability to interact with the physical world; i.e. by actively responding to the information collected via the measurement-devices. In addition, developments in wireless communications allow the distant communication of such sensors/ activators with the user in a real-time fashion. This ongoing development opens up to the utility industry the possibility for a truly interactive, real time communication between utility personnel and their distribution pipeline network system.

Based on this technological transformation of the sensor/communication landscape[1], gas distribution companies have been looking into the potential of using these technologies for applications related to improving the efficiency, management, and safety of the gas distribution infrastructure. NYSEARCH has concluded, via extensive strategic sessions, that the use of automation technologies by its member companies is the primary source of anticipated operational-leap improvements in safety and efficiency in utility operations. DoE has reached similar conclusions through its own strategic sessions (as evidenced by their publications associated with this and prior BAAs). The DoE and utility industries realize the need to prepare for the next decade of growth, and are looking for innovative solutions to meet their needs (currently 53% of homes in the US use natural gas - by 2020, experts predict a 50% increase in natural gas consumption [DOE/NETL-2000/1130]).

GasNet™ represents a technology that promises to offer gas utilities the means to implement such technologies so that they can step up to the new operational level required to meet the demands that customers, contractors, regulatory and local governments will place on them over the next decade. The major advantage of this system is its ability to expand and/or be modified to take advantage of the anticipated emergence of a large variety of sensory devices in the immediate and near future. Such sensory devices could allow us to monitor real-time not only the flow, pressure, and temp/ humidity inside the pipe (which we can accomplish today and will be the focus of this early effort) but also pipe conditioning, gas leakage, third-party interference and pipe movement among others.

In this prototype system development effort described here, ***GasNet™*** will address the immediate need that utilities have for complete, accurate, and real-time data to be provided to the operators at low cost and in real time, describing the state of the delivery network all the way from the pumping/ valving station to the point-of-sale (customers' gas-meter). Presently, many procedures for collecting data from critical points of the distribution network (like regulator stations) are through periodic personnel visits to read data-loggers and collect historical operating data, or through off-hour (hence non real-time) wireless individual meter pollings. Centralized gathering, management, and processing of remote and distributed data measurements is the only way to collect real-time on-demand information that will result in substantial improvement is safety and operations. ***GasNet™*** represents the solution for utilities to accomplish this task.

The currently-developed ***GasNet™*** prototype system will provide a new level of operational data type, quality, and granularity previously not available. The technology is expected to impact (i)

1. With concrete results already present in sensors measuring pressure, temperature, acceleration, etc., primarily in large-volume applications such as the automobile industry.

operations for the utility and its contractors; (ii) the use and management of distributed network information; and (iii) real-time and off-line use of information in emergency, monitoring, and design activities for expansion and upgrading the network to safely meet the ever-increasing demand for natural gas. Utilities realize that low-cost, real-time, on-demand, distributed-data access from a network has many uses and is a crucial asset as it will result in large cost savings, safety benefits, reduced customer delivery problems, and more efficient day-to-day management of the distribution network system.

Real-time process-data access from a large network in a central location is expected to help the utility better monitor, control, and supply its network with an on-demand approach. Process-control of the gas-supply through such real-time data-sets would provide information as to size, efficiency, and distribution of supply-nodes to better balance loads, and would allow for better decisions regarding expansion or load-increases in the future. Instantaneous emergency-condition (excess flow/pressure, out-of-spec acoustic-noise and/or vibrations) detection & reaction will be possible, tightening the safety net and reducing third-party damage potential, especially if combined with third-party access and closeness monitoring capabilities that ***GasNet***^{TM} can provide. If expanded, the ***GasNet***^{TM} sensor network, when teamed with co-located local activation of sophisticated sensing and actuation (valves, stoppers, etc.) devices, would provide for real-time centralized-control interactions for emergency and/or scheduled maintenance activities at a far lower cost than currently required. All of the above points are important if we are to safely, effectively and economically aid the utility-industry in meeting the current and future large increase in natural gas demand projected by the industry and its overseers and regulators in the decade(s) to come.

3.2 Qualitative Benefits

National gas supplies 20% of the world's energy needs. In the US, over 1 million miles of distribution pipelines carry natural gas to almost 60 million homes, representing over 50% of the population. In the Energy Information Administration's Annual Energy Outlook for 1999, forecasted gas consumption by the year 2020 is anticipated to increase by as much as 50%. This increase in demand for natural gas will need to be met by a combination of expanded infrastructure and extended use of existing infrastructure. It is economically infeasible to build enough new pipeline to meet demand. The existing, aging infrastructure needs to be managed so as to extend infrastructure life and throughput without increased safety issues or excessive costs.

In our discussions with gas utilities we have consistently heard that operators and managers feel they have almost no information about their system - they are working blind when diagnosing problems. Utilities generally react to problems that have occurred and rely on delayed data from gas dispatchers and customer calls. They rarely have information about why a problem occurred and have little operational data that can be used to predict and prevent problems in delivery.

The outcome of the ***GasNet***^{TM} program implementation industry-wide is expected to provide gas distribution utilities with technical solutions which will provide the information needed to increase infrastructure capacity, infrastructure reliability, and infrastructure safety, and to decrease infrastructure degradation problems. The ***GasNet***^{TM} system will achieve these goals by providing utilities with the information required to 1) inexpensively access, maintain, monitor, and repair gas distribution systems, 2) track distribution system related activities - particularly third party activities which may pose safety risks, and 3) model and design new networks.

3.3 Quantitative Benefits - Rough Estimates

Provision of information to facilitate predictive maintenance and improved pipeline life span.

GasNet^{TM} is expected to provide information on performance and operations which will facilitate proactive maintenance and repair - increasing the useful life of a pipeline. Typically it costs a utility $200 to install a foot of distribution pipeline in an urban setting, and about $50/foot in a rural setting. This is about $1 million/mile and $260,000/mile for urban and rural settings respectively. Assuming that a pipeline lasts 100 years (and the figure is probably less than that), we can arrive at a rough estimate of the cost for a "pipeline year", or the amount it costs to install one year's worth of pipeline for one mile. This cost is an estimate of the costs saved for each additional year added to the life of a mile of pipe. These cost savings amount to $10,000 for a mile of urban pipeline and $2,600 for a mile of rural pipeline. In the case of a small urban utility with about 10,000 miles of pipeline, increasing life span by 1 year could amount to $100 million for their entire network.

Provision of information to facilitate improved capacity for the current system

Expanding the capacity for the existing network removes the amount of additional pipeline that needs to be added to the system to meet increased demand. The information provided by ***GasNet***^{TM} can be used to determine under-performing areas of pipeline, bottlenecks in the system etc. These can then be improved and optimized. If one conservatively estimates that the detailed operational information from ***GasNet***^{TM} increases system throughput/capacity by 5%, it would be equivalent to adding 5% more pipeline. For the 10,000 mile utility example, this would be the equivalent of 500 miles. In an urban environment, this 500 miles would cost $500 million to build. In a rural setting, the 500 miles would cost $130 million (using the $1million/mile estimation described earlier). If 5% were added to the capacity of the 1.1 million miles of distribution pipeline in the US, it would save the country the costs of building 55,000 miles of pipeline. This cost varies from $55 billion to $14.3 billion nationwide depending on location. These figures do not consider increased costs associated with pumping/compressing and storing the additional gas-capacity at the source, but they indicate the potential magnitude of the impact.

Detection of safety breaches and third party interference.

Since 1986 there have been 273 fatalities, 1,213 injuries, and a cumulative property damage cost of $235 million associated with gas line operation in the US (Office of Pipeline Safety database - *http://ops.dot.gov/starts/dist_sum.html*). Annual costs associated with safety breaches and third party interference range between $6 and $50 million, with the average being about $15 million. The DOT Office of Pipeline Safety reports that each year between 50% and 80% of these incidents are the result of damage by third parties or outside forces. If one conservatively assumes that 50% of the incidents are the result of third party operators, and the use of ***GasNet***^{TM} nationwide could avoid 5% of these costs, then annual estimated property cost savings could be: $15 million x 0.5 (accidents resulting from third party) x 0.05 (% accidents avoided) = $375,000. If 20% of the accidents were avoided, this figure would amount to $1.5 million. More importantly, about 20 people die each year, and about 80 people are seriously injured as a result of these accidents. Reducing and avoiding third party accidents would clearly save lives.

Keyhole installation techniques.

Keyhole excavation saves about 65% of the costs associated with accessing pipelines. A typical excavation and repair job costs about $1,000.-, with 800,000 such repairs affected each year in the US alone. For every current excavation that can be achieved with keyhole excavation over $500 could be saved. Developing cost-effective keyhole technologies for this program could save as much as $40,000,000 nationwide, assuming repair systems compatible with keyhole technology are available.

Wireless communication and no-dig pipeline-access capabilities.

GasNet^{TM} could also allow for immediate and easy deployment of wireless and untethered inspection and repair systems (autonomous or teleoperated) in the future. Savings could be large, as they compete with costs of manually locating & full-excavation repairing leaks/faults.

3.4 Application Examples and Demonstration of Engineering Breakthroughs

In order to provide a clear image of the eventual potential of ***GasNet***^{TM}, we have listed below just a few of the possible applications of this technology in different operational applications, some of which have been implemented in this program:

- ***Network Data-Relaying/-Collection: Sensor-Data Communication & Transmission***

Utilities currently have a small net of dedicated pressure-sensing stations that they use to collect (typically pressure-) data during the day, and then physically visit these locations to download the data. The more advanced methods, based on retrofitted sensor-stations, allow them to recall said data over a cellular/paging wireless network connection. Since wireless connection costs can be substantial, utilities typically let each station amass data during the day, store it locally, and then recall the data at night/early morning to save call-charges. ***GasNet***^{TM} could allow all data from all currently-existing sensor-stations to be sent through the pipe to a central data-collection location in **real-time** and **on-demand**. This data-collection location could either be directly at the operations-monitoring offices, or at another remote site, which could uplink the data onto an existing cellular/pager network or an always-on phone line. The benefits here are obviously in the immediate availability of real-time data from the entire network, with drastically reduced data-collection costs (one uplink node irrespective of sensor-nodes, rather than one uplink-node per sensor-node). Hence the ***GasNet^{TM}*** system can serve as a communication-relay system inside of pipes, and add additional pressure/flow/etc. data to the current data-set sought and needed by operators.

- ***Third-Party Access Monitoring: Activity and Closeness Monitoring***

Closeness of third-party activity near gasmains would be possible through the use of integrated vibration- and acoustic (microphone) sensors, which would distinguish excavation and impact-noise and vibration from the background (mostly thermal) signal and report such activity (presence and location) immediately to the control center. In the case of authorized access, 'hooking' into the pipe and imparting an AC EM-field to the conductive pipe, would allow an excavator outfitted with a simple passive coil-sensor to ensure a safe digging distance from the pipe. All in all, ***GasNet^{TM}*** can be capable of providing great safety margin to networks with almost no retrofit to the mains, installation of additional internal or even external sense-wires (such as fiber-optics).

- ***Pumping Station Monitoring: Valve/Manifold Pressure-Drop Monitoring***

Due to the low-cost sensing and computing systems associated with ***GasNet^{TM}***, the system is currently being used downstream from pumping and regulator stations, to monitor flows and pressures across different 'legs' of a localized valving-, regulator- and distribution-system. The system collects large amounts of data in a highly distributed fashion, and is capable of up-linking the same over the already in-place wireless connection (cell/pager). Power is being provided locally, and installation of the system is very straightforward. The data will be used in real time or daily batch-processing modes to monitor and optimize the loads on the network.

- ***Supplier Product Monitoring: Moisture-Content Monitoring***

Urban distribution companies have an interest in monitoring the moisture-content of the natural gas fed to them from the transmission-network company(ies). The ***GasNet^{TM}*** sensor system is capable of determining in real-time the relative humidity content of the supplied gas at the supply-node, and relay this information to the operations center (again, wirelessly or even over a phone-line). This information is vital to ensuring that the distribution company is receiving product that falls within the specification of what they and their customers are paying for. The only way to monitor this variable cost-effectively is through real-time monitoring and low-cost data-access provided by the ***GasNet^{TM}*** system.

- ***Critical Performance Monitoring: Node-Pipe Junction Monitoring***

Sensor pods are outfitted with a pressure-, vibration- and In the future) acoustic- (microphone) sensor to monitor the state of a pipe-segment close-to or near/in an area subject to high/repetitive third-party damage potential (monitoring for excessive vibration, noise from excavator striking the pipe, sudden pressure-drops, etc.). The pods can be spaced so as to cover a substantial footage of pipe-length and be able to provide measurements over a distributed area. Thresholds set on-board (and changeable though the bi-directional wireless link) are monitored and warning/alarm messages sent by whichever sensor and transmitted via leap-frog back to an antenna within the pipe and directly to an operator in-situ or via other extension to a computer at a monitoring station.

- ***Problem-Area Monitoring: Transients-Measurement***

The most generic use for the sensor-pod is their use in areas where short- to mid-term monitoring of dynamic conditions over a fairly sizeable area, is to be accomplished at minimal cost and with minimal infrastructure-modification implications. The main application being implemented by the current ***GasNet^{TM}*** system, utilizes a few dozen of these sensors placed at key locations of the network over a widely-spaced acreage, monitoring node-points in real time and providing data to a single antenna-port for re-transmission or logging/processing. The notion is to determine through (in)direct sensor measurements what the steady- or dynamic-state of the pipe-network is.

- ***Network-Area Monitoring: Modelling-Data Collection for Verification***

An alternate use of the collected sensor data is to provide a low-cost model-verification of the network-design at crucial locations by measuring pressures and flows using the scheme and deployment detailed in the previous bullet, allowing for a computation and verification of Stoner design-models in an off-line batch mode.

4.0 Background - Technical State of the Art

4.1 Overview

In order to better understand the technology subsystem selections for the ***GasNet^{TM}*** system, it is of value to briefly look at the state of technology in the respective subsystem areas that form part of the entire system. This is best accomplished by looking at each major subsystem or area separately, as discussed below; note also that pictorial references are made based on Figure II-2 on page 11.

(i) Sensing - The gas industry has mainly targeted the transmission, processing, and main-node industries and locations/market segments, where accuracy requirements are high, and space and power issues not a major concern (larger pipes, etc.). The industry is only beginning to consider miniaturization of their sensory elements in order to perform measurements on a smaller and more distributed scale. As is obvious, performing such a miniaturization and more compact integration effort is thus a key strategic step for the sensing-industry in this century. There are several main areas that sensors are targeted towards, namely gas-quality and -composition, pressure, and flow. Industry has provided solutions that are primarily targeted at single-point larger-scale production-settings. Miniaturization has had an effect, but has not yet evolved to the point where the industry could make real use of it.

(ii) Integrated Sensor Processing and Computing - Prior-art evidence of computing typically in use with stand-alone sensors or distributed sensors can be found in the industrial automation arena. There, sensors are used to detect events with both binary and analog sensors. Sensor data is typically read directly over a short-run well-shielded cable, or a localized printed circuit board (PCB) molded into the sensor. The PCB takes care of sampling & filtering the signal and packaging it into a certain type of communication stream (serial, parallel, analog, binary, etc.). Hence remote data can be acquired at a central point via direct-sampling or over a distributed communications backbone. Other sensors perform the computation right at the sensor, and pass lower-bandwidth information back to a central decision-making computer over one of several communication backbone types utilizing one of many communication protocols.

(iii) Communications - Communications technology has developed at an accelerated rate, especially at the wireless end of the spectrum. Cell phone technology and wireless networks have driven the technology to a level of miniaturization, cost-effectiveness and bandwidth sufficient for our most immediate needs. This technology is on top of the more established satellite-phone based telephone and the paging network systems already in use since the 1970s and 1980s. Since then, wireless LAN technology for ethernet and BlueTooth personal communications standards and hardware have begun dominating the market in customer and light industrial applications. Other solutions range from PC-Card products, to integrated, to embedded solutions for wireless communications, whether serial- or ethernet. Software protocols and easy connectivity have played a large role in making wireless communications more widely usable and maintainable. The notion of using data-over-wire/-air to allow gas companies to collect field-data has been an important factor in reducing companies operating costs, whether this be for meter-reading or other more process-related variables. Within the processing/valving/pumping/compressor station of a gas utility, process variables are typically conveyed over a wire-carrier using either current, serial or other protocol streams. Exchange of data with other location can then occur over an intranet and/or the internet, or even over a telephone line. Field-data, such as meter-readings, can be conveyed either over a phone-line (akin to those used by power companies to read customer meters), a paging network, or even a radio-frequency based communications network. Such systems are known as AMRs (Automated Meter Readers), with a wide selection available.

To counter the commonly misheld opinion that wireless RF-communications inside pipes is not feasible, we offer the experimental results developed as part of another DoE-funded project with NGA under the Gas Infrastructure Reliability Program. Said program has positively proven that wireless communications inside of 6-inch diameter steel pipes via customized wireless hardware and software protocols utilizing the DSS-protocol, even at low power-levels (6mW), is feasible to ranges of 2,000+ feet at data-rates of 11 to 1 Megabit/second. Smaller pipe-diameters will have shorter ranges, while larger pipes will have longer ranges. These pipes need not all be straight, and the experimental data accounted for bends, Ts, Ys, etc.

(iv) Power - The use of stand-alone field-equipment is well-practiced. Meteorological stations and other remote- or long-duration systems work in environments with little human supervision or interference/support. Power, and its availability, is one of their main considerations when it comes to developing such units. This criteria is no different for any process- or field-equipment in use by gas utilities. The need to power sensors and computing is typically solved through hardwiring (if accessible) to the local power-grid (long-term solution), solar-powered battery-bank (low-power long-term solution), generators (short-term use), to power-cells/batteries (shorter-term use unless rechargeable). Gas- and power meters that are remotely interrogated are typically powered by the residence power-net. Sensors that operate on very low power and need not be accessed often can get away with primary (non-rechargeable) cells, while others where access is possible, will use rechargeable cells.

(v) Live Gasmain Access - The newer methods of accessing live gasmains have revolved to this date around the deployment of both camera-internal inspection and repair systems. ARIES (Niagara-Mohawk-funded), MEI (GRI-funded), Consumers Gas (ConEdison co-funded), and NICOR (Gaz de France funded) have all developed access-systems for different specific equipment. Such access-systems require the use of a backhoe for mechanical excavation of a complete (typically) 6-foot by 4-foot hole, which on average can take up to an hour and cost $750.- (incl. restoration). Keyholes, typically no more than 2-foot by 2-foot by up to 6-feet deep or more, can be excavated pneumatically using a poker-bar and a suction-hose from a vacuum-truck. Keyhole excavation is fairly common if topside pipe-access only is required and the location of the pipe is accurately known. Some keyhole excavations utilizing vacuum extraction have been successful in emplacing a circular screw-on clamp onto low-pressure mains - higher-pressure mains have so far been unfeasible. British Gas has supposedly developed a new fully-functional keyhole excavation system, but data is not yet publicly available.

4.2 GasNet Phase I Results

As reported in the Phase I Topical Report (OSTI ID: 816706; **www.osti.gov/dublincore/gpo/servlets/purl/816706-X0cFFq/native/**), the development of GasNet represents a new state of the art and should be considered as a baseline for the final report details and results.

4.3 GasNet Phase II Results

As reported in the Phase II Topical Report (OSTI ID: 836824; **http://www.osti.gov/bridge/purl.cover.jsp?purl=/836824-OHcrzR/native/**), the continuation of the development of GasNet into Phase II should be considered as a baseline for the final report details and results.

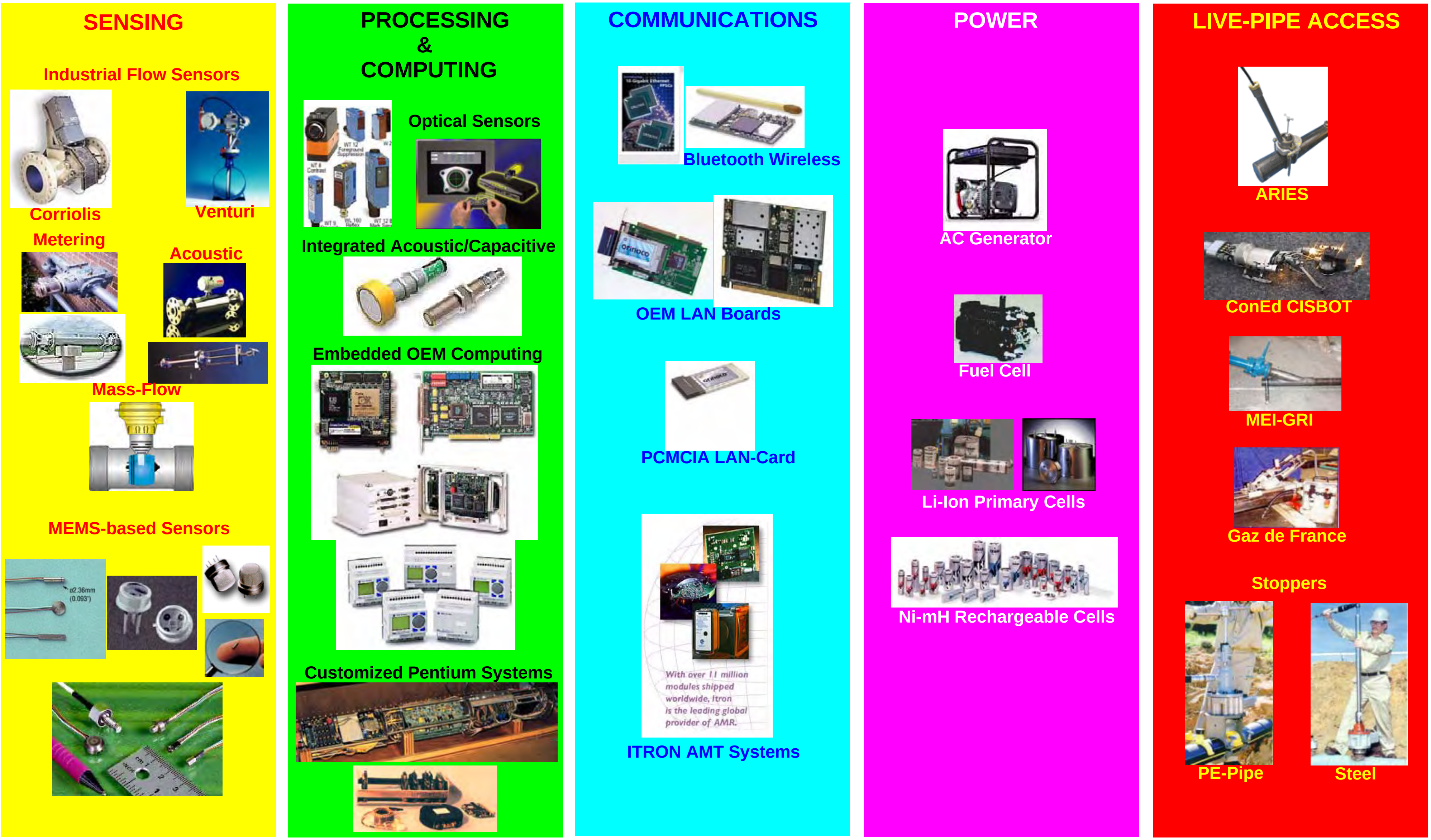


Figure II-1 : State-of-the-Art picture gallery covering sensing, sensor-processing and computing, communications, power and live-pipe access

5.0 System Design Concept

5.1 Overview

GasNet^{TM} is a wireless, self-powered network of open-hole-installed and field-replaceable pipe-sensors capable of measuring, and communicating key process variables wirelessly through the pipes. These variables can cover a wide range of operating parameters, depending on the availability of appropriately sized and accurate sensory devices. For the initial Phase I engineering effort, the system was designed around measuring variables for which appropriate off-the-shelf sensor technologies was available (such as pressure, flow, vibration and moisture-content); this was similar for Phase II, except that we updated the design to allow for interchangeable sensing-elements depending on whether we were deploying into low-pressure cast-iron or higher-pressure steel mains. The process information gathered in the in-pipe network setup, allowed utilities to monitor the state of the delivery process across the monitored network section from a single computer-console. The Phase II ***GasNet***^{TM} sensor-wands (particularly their mounting and pipe-interface) were developed for natural gas distribution infrastructure, for both low-pressure cast-iron networks and high-pressure steel mains.

In the final Phase III, the sensor-wands were designed for long-term installation. The sensing sections were designed in a manner to allow the modular addition of flow-sensing for varied-diameter pipes, and perform a no-blow installation in higher-pressure (up to 124psig) steel mains using specialized equipment and techniques. In addition, electronics were packaged for burial and designed for modular interchangeability and the ability to customize the electronics to individual utilities. Power-options ranging from serial batteries to AC-power and solar-based power supply were added. Software for the GUI was developed around accessing data off removable memory cards and over real-time cellular connections.

5.2 Concept Description

The ***GasNet***^{TM} system concept our development team started with in Phase I, is shown in Figure II-2 and Figure II-3 on page 13, which depict the installed system 'tapped' into a pipe with its installed electronics/batteries and above ground interface port (I.1a); up-close details of the preliminary pressure/flow/moisture/etc. sensory-modules (I.1b); depictions of such installations in a typical urban setting during an excavation and third-party interaction situation (I.2a); and a potential operator feedback screen provided through remote computerized processing at a utilities' central control station (I.2b). The overall system consists of an in-the-field open-hole-installed unit with an in-pipe sensor and processing module, and a buried power and access-port unit at ground level. The sensor module is installed under no-blow conditions into the pipe by way of a standard field-installed fitting. Inside the field-fitting, resides a sealed and removable sensor wand, which contains the main sensory elements. For illustration purposes, we are depicting a radio-wave transmitter at the tip of the wand, a set of flow-passages for a hot-wire anemometer flow-measurement system, a multi-channel acoustic-level sensor, and multi-planar micro electromechanical systems (MEMS) based pressure and methane-composition sensors atop the main body of the sensor. The flexible joint allows the wand to flex out of the way should equipment need to pass the location (repair or inspection from within the pipe for instance)[1]. The sensor power and data-lines are run to a local embedded processing system, which reads, filters, scales and processes the data. Real-time communication of the data-set back to the central control station is accomplished via a local radio frequency (RF) transmitter board-set which transmits the data via

1. Since the sensors and antenna are elevated immersion in water/oil is unlikely and contaminant-deposits are also highly unlikely due to cleanliness of todays' natural gas

the antenna into the pipe-space. The data is picked up by the next transmitter, and re-sent in a relay-node mode until it reaches the control-station receiver. The data is then identified with respect to transmitting origin and decoded and displayed/logged at the local control-station. Since communication is over a a standard interface, all other existing systems owned by the utilities can be interfaced to the new console-system.

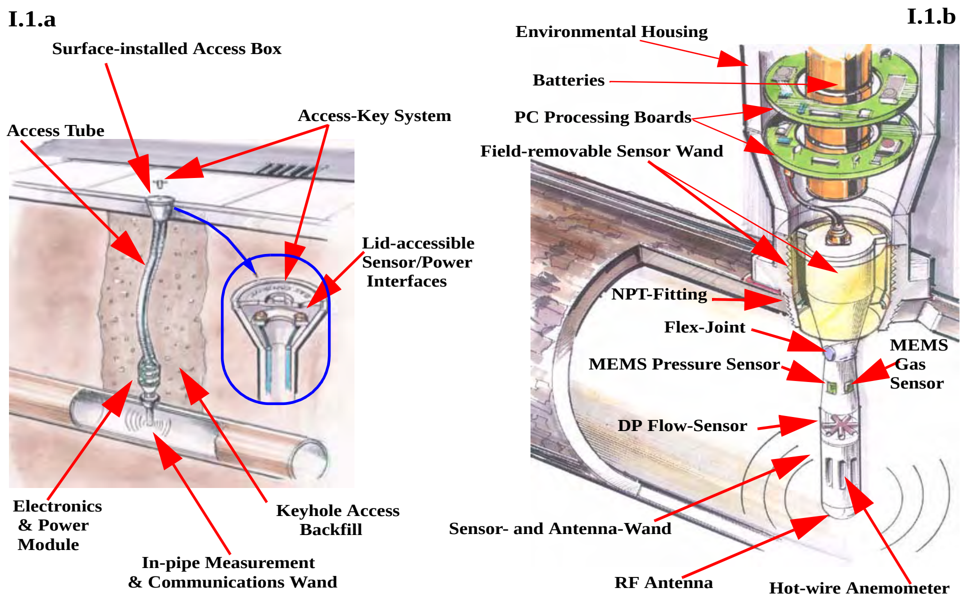


Figure II-2: Overall ***GASNET™*** system concept: Sensing-, RF-Communications, Computing- and Power System with an Installation View

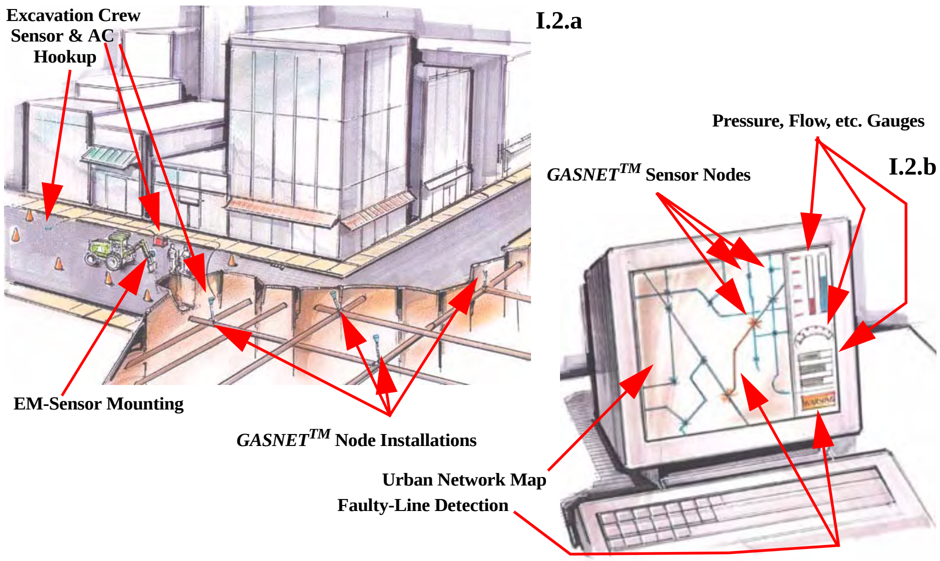


Figure II-3 : Overall ***GASNET™*** system concept: Urban Deployment & Operator Console Interface

The ***GasNet™*** system was also conceived to be able to track and monitor third party activities. One method was intended to use embedded vibration (accelerometer) and (not yet undertaken) acoustic (microphone) sensors to pick up above-background signals to warn the utility in real time of the presence and location of the disturbance (digging backhoe impact or displacement). The supervised approach would involve giving a contractor access to the lid-protected interface. The contractor would then plug in a special connector or flip a hard-wired switch. This in turn would signal to the central control station of ongoing activity in the area. If authorized, the sensors surrounding that area could be monitored as to flow and pressure, to assess the potential for breaching of the line. In addition, the contractor might choose to apply an AC-current between two such sensor locations bordering the planned work site. It would also be feasible to use a single sensor-location, with a return cathode rammed into the ground (to close the current loop) slightly beyond the work area. Once tied into the pipe this way, a simple passive electromagnetic (EM) field detector, on the excavation equipment or manually deployed hand-equipment, would sense the AC-induced magnetic field emanating from the pipe. This signal would then be used to warn the contractor as to presence (binary signal) and closeness (analog field-strength) to the pipe, without any costly *a priori* site-mapping (such as with GPR) or costly real-time sensor-hardware.

5.3 Installation Concept

The concept that was developed for installing a self-powered node, whether a datalogger/slave (logs and re-transmits to a master-node) or the master node itself (battery/line-powered and collects all data and is hooked up to an external communication link) are shown in Figure II-4:

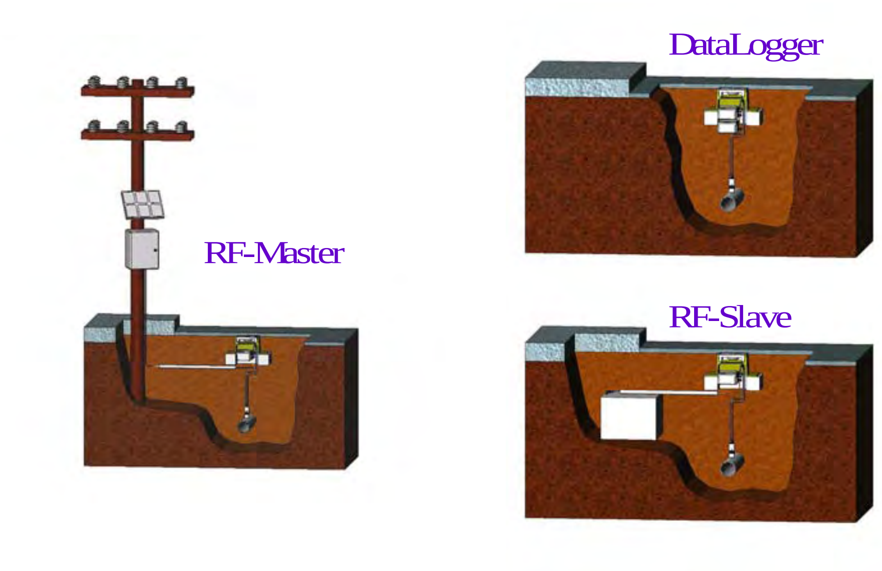


Figure II-4: GasNet installation concepts - Master, Slave & Logger

All methods relied on a no-blow live installation using tapped-thread/weld-on-nipples to hold the plug carrying the sensor-wand. All signals, power and antenna-data were carried through dedicated connectors and carried to/from an electronics box buried with a battery (of variable size, depending on the power-requirements) underground, yet accessible from the street/sidewalk through a valve-box. A datalogger was intended to store data locally only (on removable memory-media), allowing users to exchange memory cards (through the valve-box access) or download the data using a PDA and wireless bluetooth. The RF-Slave and -Master setups intended to measure all data locally (and also store it on removable memory media locally) and transmit their data (slaves) to a repeater (if needed) who would then transmits its own data and any other data it received, onwards to a master-node. The master node would add its own data to all other data, store it on its own removable media card and also re-transmit it over phone or cellular lines to a central office for near real-time monitoring.

6.0 System Design Description

The ***GasNet™*** system, consisting of the pipe-internal sensor-wand, electronics-housing and power-supply, as well as the remote graphical user interface subsystems are described in more detail in this section. This section is laid out to address the overall system layout, and then delve into each subsystem in more detail.

6.1 Overview

The entire system design, as visualized through CAD renderings, was made up of the pipe-internal sensor wand, the remote external electronics enclosure housing the main control systems, the off-board power supply unit, and the remote user interface. A depiction of this system architecture is shown in Figure II-5, as well as a ready-to-ship system assembly:

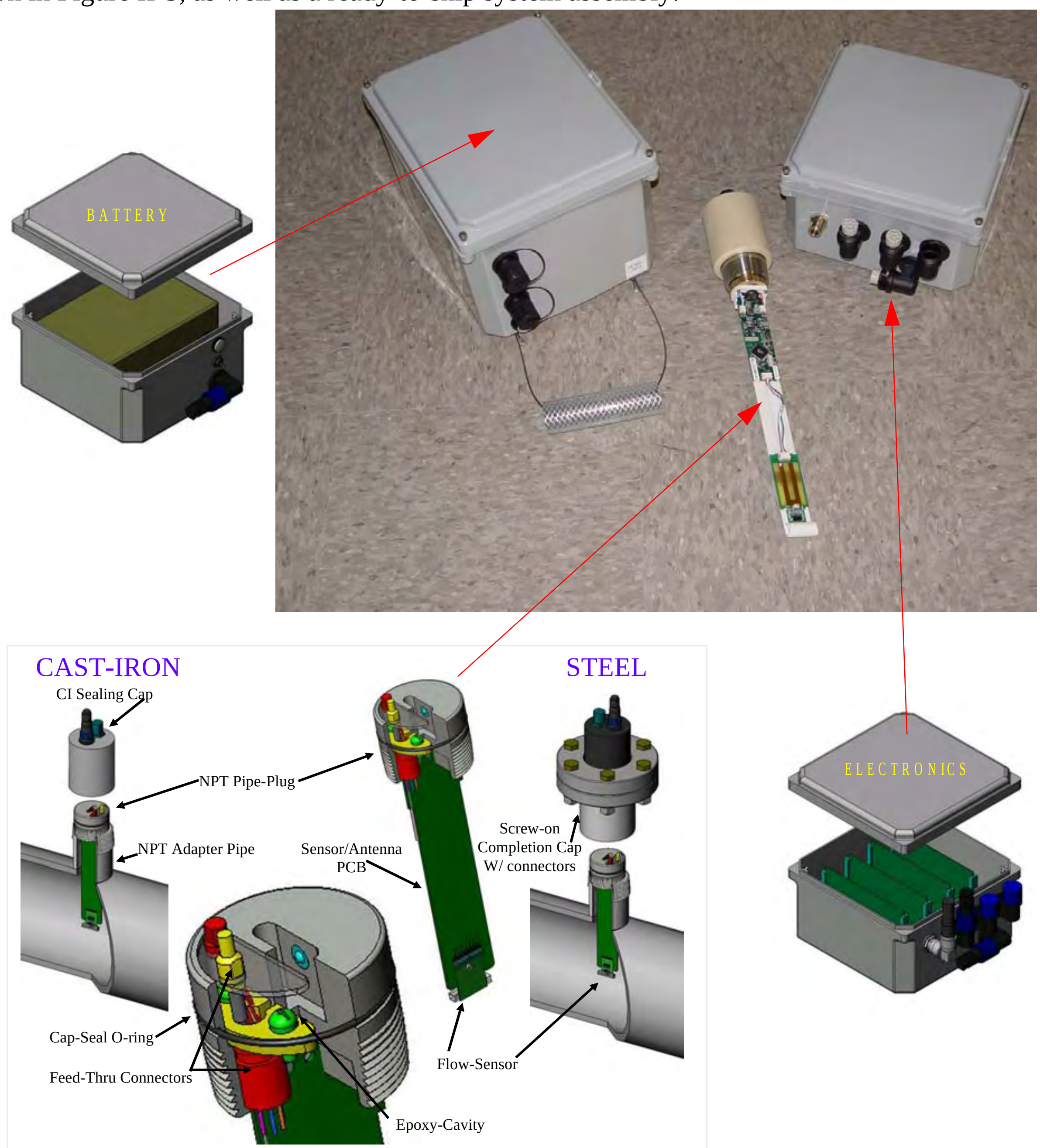


Figure II-5: ***GasNet™*** System Overview and as-built ready-to-ship assembly

6.2 Sensor-Wand

The sensor-wand itself consisted of a two-stage PCB, coupled through a variable-length epoxy holder to both support the two PCBs as well as place the flow sensor at/near the center of the pipe for more accurate flow measurements. The different elements and main sensor elements were laid out on the sensor-wand in the proper locations. A diagrammatic overview of the wand and its associated sensors, can be see in Figure II-6.

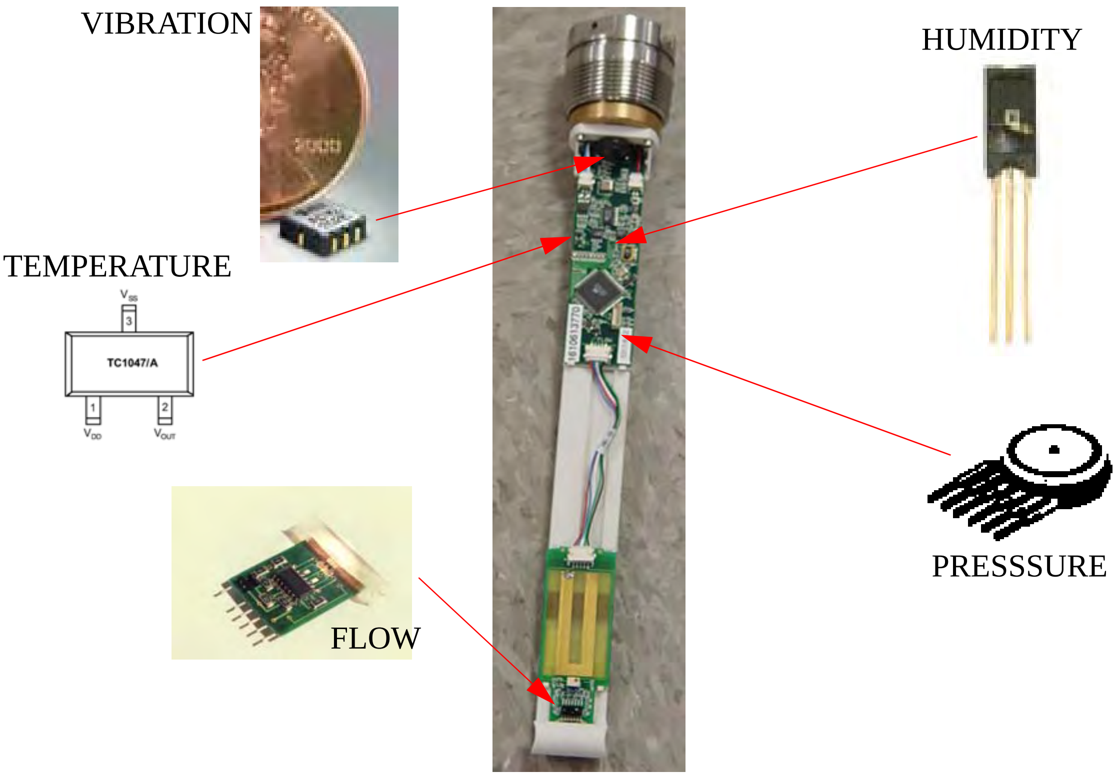


Figure II-6: Sensor-wand design and associated sensor layout

The top PCB was mounted to an NPT-threaded plug containing an internally o-ring sealed insert, that allowed the entire assembly to be aligned with the flow-direction once the NPT-plug was no-blow inserted and sealed. An image of the plug and its separate parts is shown in Figure II-7:

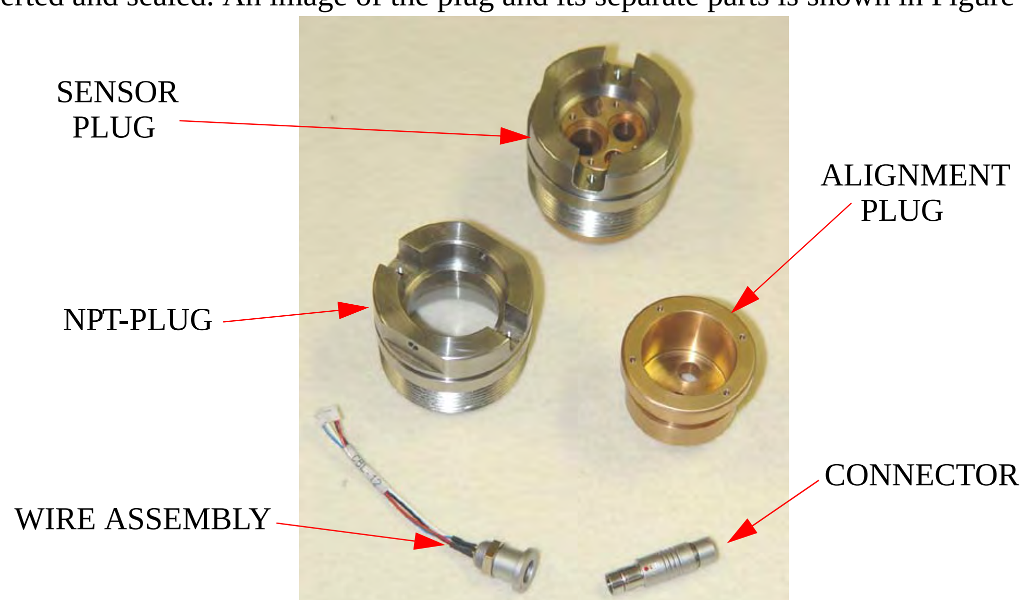


Figure II-7: Sensor-plug design and associated components

The electronics were based on a simple architecture, relying on a dedicated microprocessor to poll all the sensors on the wand, while interfacing to the wireless RF-electronics over a multi-drop (proprietary) bus with a pre-established communications protocol. The diagrammatic depiction of the simple architecture is shown in Figure II-8:

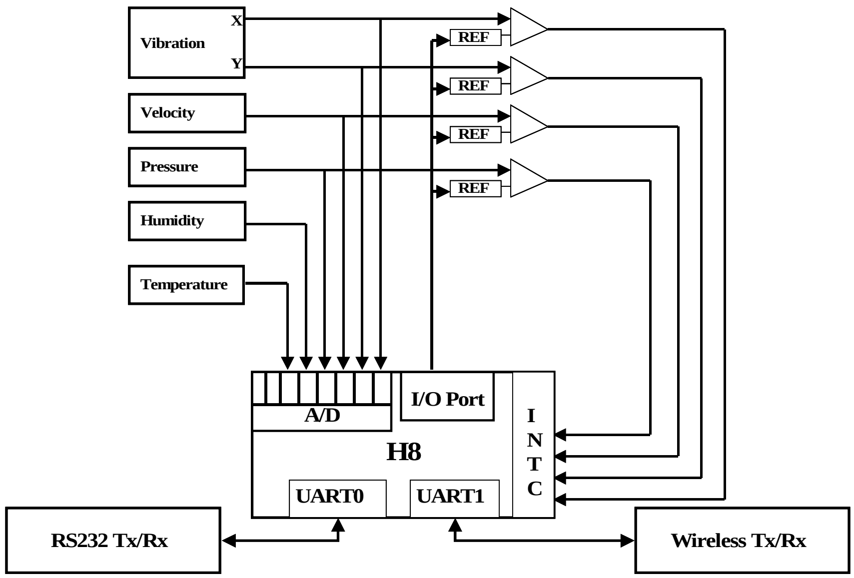


Figure II-8: Simplistic block-diagram of electronics architecture

The wand-PCB and associated parts, when fully populated and assembled is shown in Figure II-9:

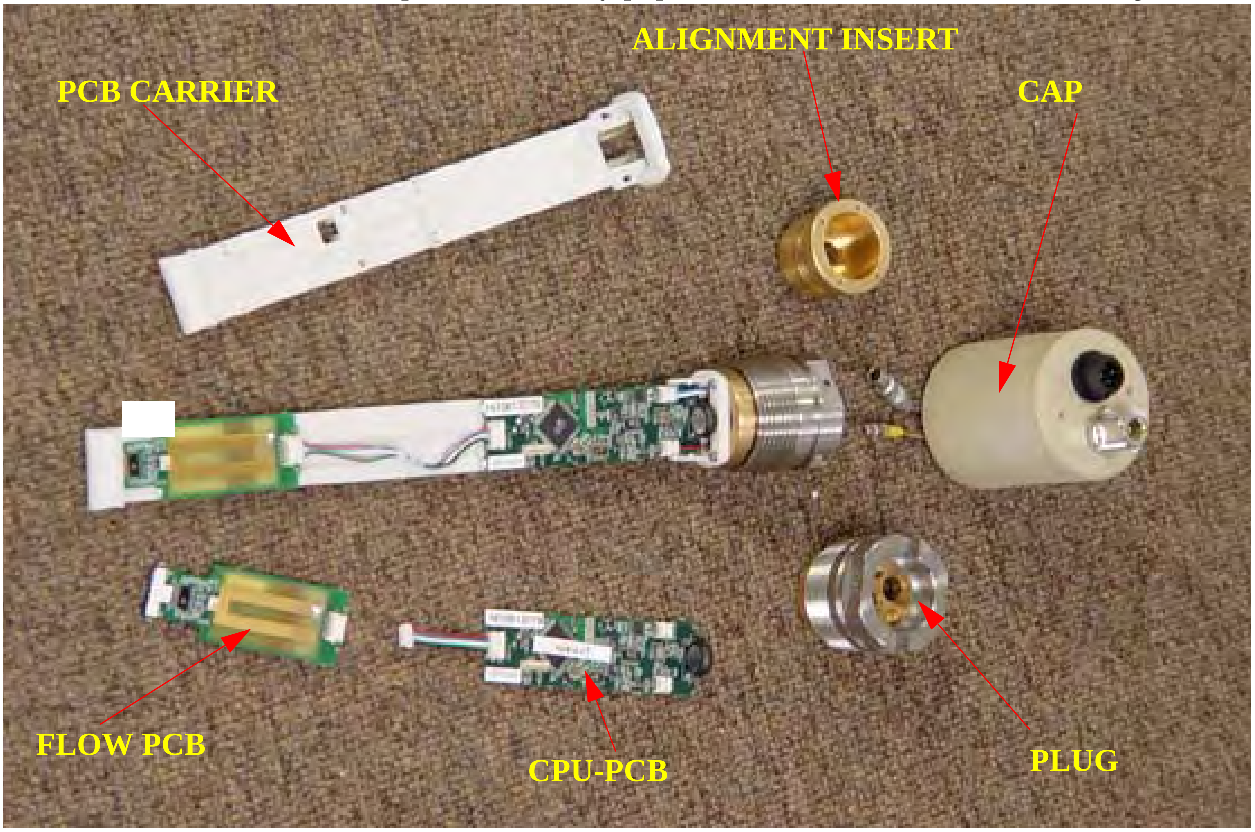


Figure II-9: Populated sensor-wand assembly

A finished (populated and potted) sensor wand (prototype) and also installed in a (laboratory-setup) pipe is shown in Figure II-10:

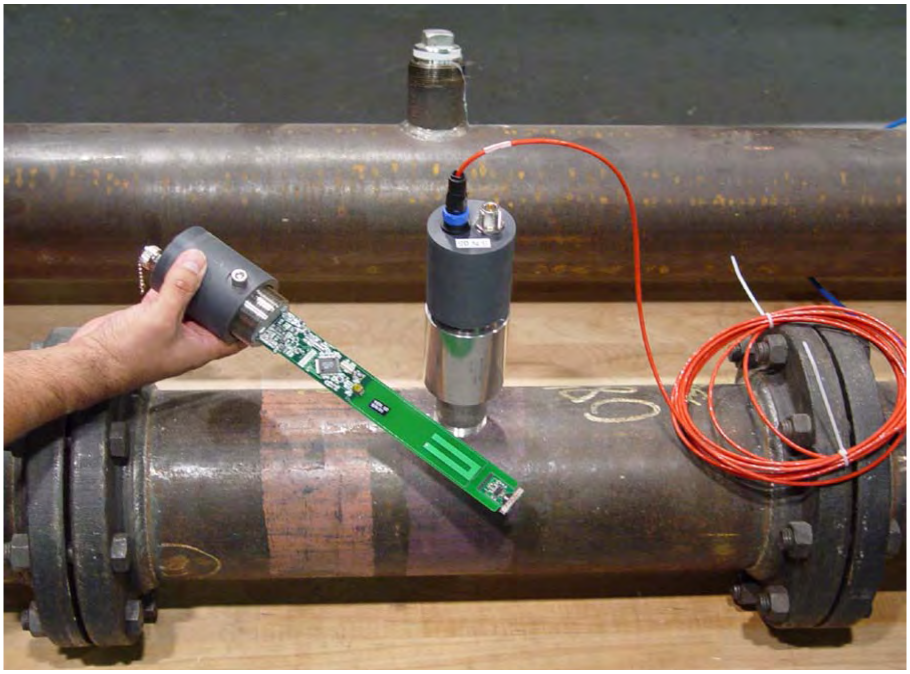


Figure II-10: Fully assembled sensor wand installed in a test-pipe

6.3 Electronics Enclosure

6.3.1 Overall Housing

The electronics enclosure that was developed to connect to the NPT-plug to provide power, RF-signals and data-communications between the main processing computer and the remote sensor-wand with its own sensor hardware inside the main. A picture of the enclosure housing, including some of the associated electronics boards for control/communication/data-logging and external interfacing, is shown in Figure II-11:

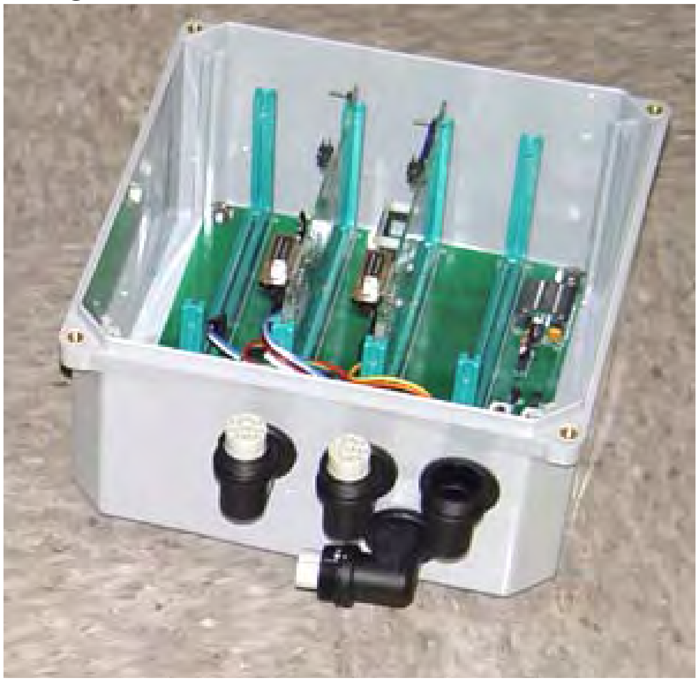


Figure II-11: Electronics Enclosure Unit

6.3.2 Electronics Boards (PCBs)

6.3.2.1 Sensor-Wand

The sensor-wand PCB consisted of a rectangular shaped PCB with several sensors and the 8-bit microprocessor. The unit was mounted to the internal alignment plug of the sens0r-plug and attached to the carrier-board. An image of the CPU- and Flow-PCBs are shown in Figure II-12:

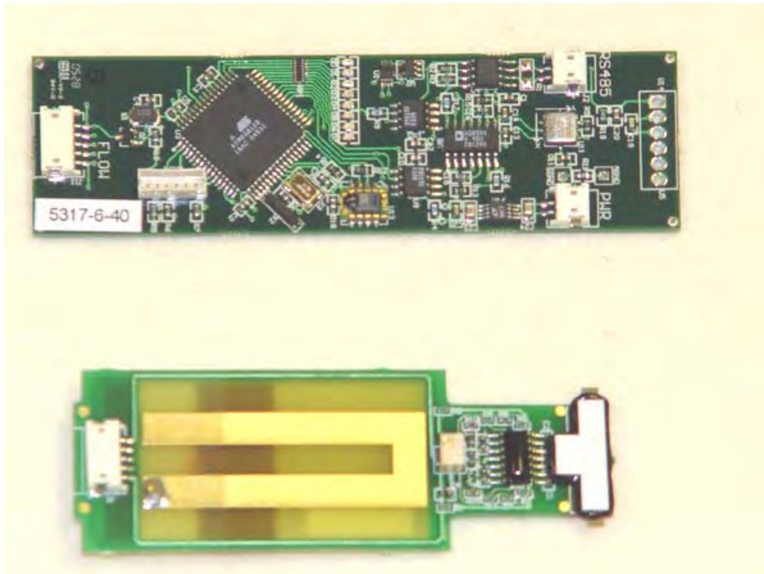


Figure II-12: Sensor-Wand PCBs

6.3.2.2 Bridge-PCB

The so-called bridge-PCB carried the main 8-bit processor that was used to coordinate all communications and data-flow control. It also provided for the interface to the outside world in terms of being able to send data to an external comm-port so as to allow other real-time data transfer (such as would be required for real-time cellular monitoring). An image of the bridge PCB is shown in Figure II-13:

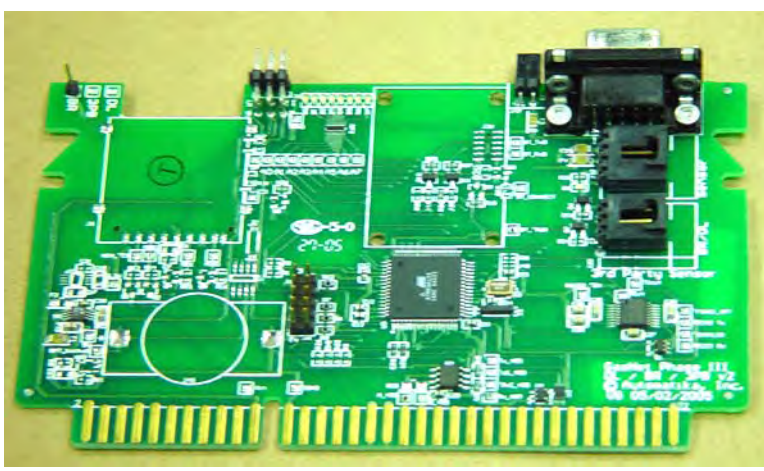


Figure II-13: Bridge PCB

For the sake of parts-count and cost-reduction, the bridge-PCB was laid out identically to the datalogger-PCB (see unpopulated outlines) and simply re-used with different sections populated.

6.3.2.3 Datalogger-PCB

As mentioned previously, the datalogger-PCB is identical in layout to the bridge-PCB, yet with different sections of the board populated. This board served to house the processor and the SD memory-card used to store all sensor-data from said module. The SD-card was removable so as to allow long-term datalogging onto multiple memory cards. The card also supported a bluetooth module that allowed external access (without removal and exchange of the SD-card) to the data on the memory card for drive-by data-collection (such as when the system was housed in a valve-box). As with all boards, this unit also had a coin-cell battery backup to retain critical parameters in case of battery failure. An image of the datalogger PCB is shown in Figure II-14:

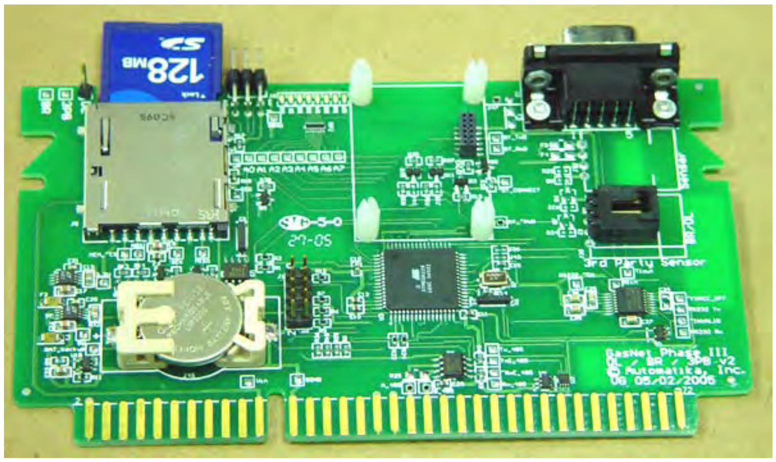


Figure II-14: Datalooger PCB

6.3.2.4 Wireless-PCB

The wireless interface for communications inside the pipe, was enabled through the use of a wireless communications PCB. Said PCB also utilized an 8-bit microprocessor to take data from the sensor-wand placed on the multi-drop bus and pass it to an integrated wireless RF-stage electronics module. The data would be encoded and sent using a customized protocol through the antenna cable back to the sensor-wand and radiated out the antenna-section on the sensor-PCBs. The same path would be used by the same RF-module to listen inside the pipe (in the case of a repeater or master) for data sent by other nodes (only slaves and repeaters) for the purpose of re-transmission through the pipe or out over the bridge-PCB to an external data-link - all relayed data also gets saved to the repeater/master datalogger SD-card. An image of the wireless PCB is shown in Figure II-15:

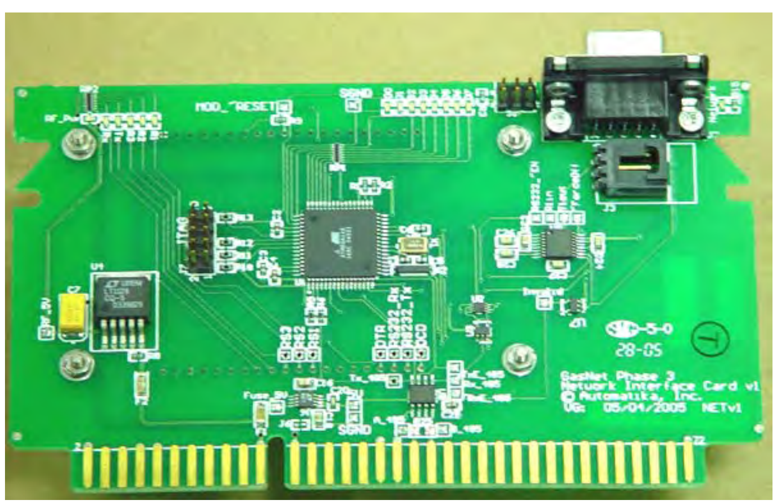


Figure II-15: Wireless PCB

6.4 Battery Unit

The power subsystem consisted of an enclosure with an OEM sealed lead-acid battery. The unit had a simple power-on indicator and a sealed on/off switch. The unit was connectorized using a screw-on sealed connector pigtail with a 30-foot long power-cord to allow it to be remoted from the pipe and placed inside a valve-box for access. The battery unit was designed for it to be daisy-chained so that two batteries could be placed in parallel to increase endurance of the buried sensor-wand (whether datalogger or wireless slave). An image of the battery unit is shown in Figure II-16:

Figure II-16: Battery power enclosure with discharger

The battery monitoring circuit was housed inside the enclosure and provided for an updated charge-state to the main CPU. Charging was also monitored and status lights used to indicate the state of charge internal to the unit (mounted to the PCB). A resistive discharge plug was also developed to ensure that each battery was fully discharged prior to a new ground-up charge cycle.

6.5 Operational Configurations

Depending on the type of monitoring desired by utilities, gasNet was developed to allow the sensing to be performed in multiple fashions, which in turn had an impact on the field installation. For those utilities making simple (long or short term) localized measurements, a datalogger setup was utilized. For the utilities wanting a network of sensor-data collected over a distributed area, both wireless slave-nodes buried in underground valve-boxes and repeaters (if needed) and master-nodes were installed in pole-mounted boxes due to their need for continuous power, making buried batteries infeasible. Both of these installation types are elaborated on below.

6.5.1 Valve-Box (Datalogger & Wireless Slave)

For single-point data-collection, whether in a datalogger or wireless slave mode, the electronics and battery units (1 or 2) were buried in the same excavation hole as was made for the installation of the sensor-wand. A valve-box (can vary from utility to utility) with a removable lid is used to complete the backfill/restoration. This method allowed access to the power unit for battery-exchange as well as possible memory-card exchange. A CAD rendering of the battery and electronics enclosure(s) is shown in a cut-away view in Figure II-17:

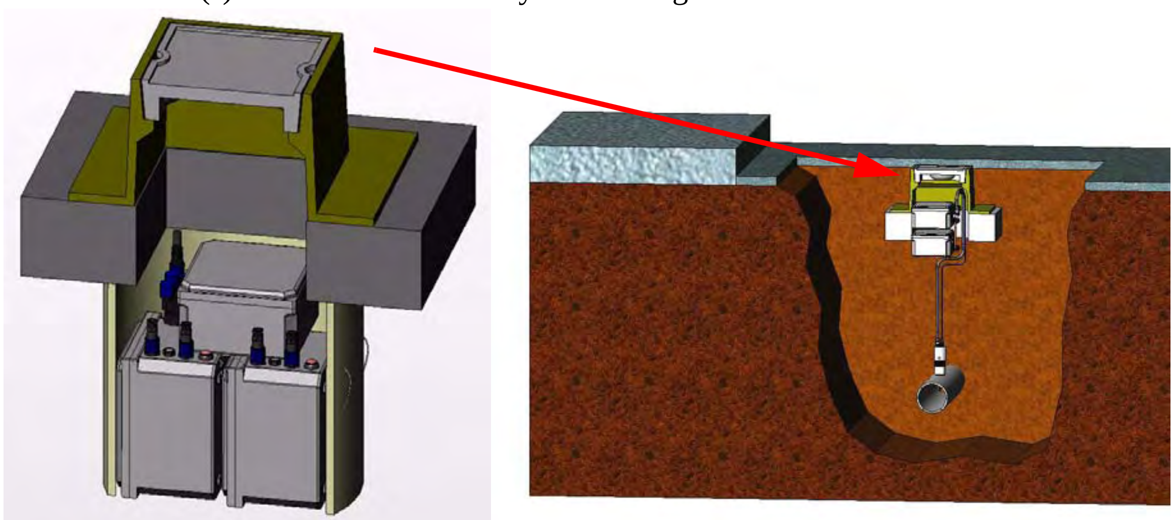


Figure II-17: Valve-box field installation design

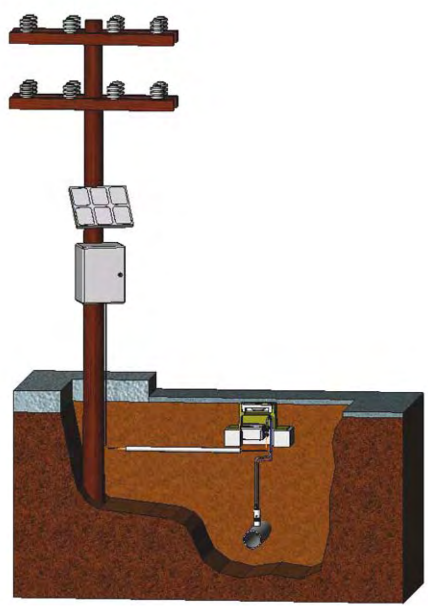


Figure II-18: Pole-mounted master/repeater electronics/power installation

6.5.2 Pole-Box (Wireless Repeater and Master)

In the case of high-power (always-on) repeater and master-nodes, utilities would mount the electronics enclosure inside of another environmental enclosure, which would also house a power-converter unit - in the case of a master-node, it would in addition house a phone or cell modem to allow for real-time data relaying. In most cases, power was provided by an AC-drop, which was converted into the required DC-level using a Class I Division II, Group D compliant AC/DC power-converter. An alternate method would utilize a separate solar-panel and backup battery assembly (on the same pole), to provide the required DC- power to the electronics enclosure. A rendering of the CAD-design of this installation option in shown in Figure II-18 on page 22.

6.6 No-blow wand installation

The no-blow installation of the NPT-threaded plug was designed to utilize the Mueller line of tools, which includes a valve, tool and various adapter tools. A specialized tool was designed to mount and hold the plug inside the tool under pressure and then once removed would expose a set of slots to align the flow-sensor wand inside the pipe. The collection of tools and their combination, are shown in Figure II-19.

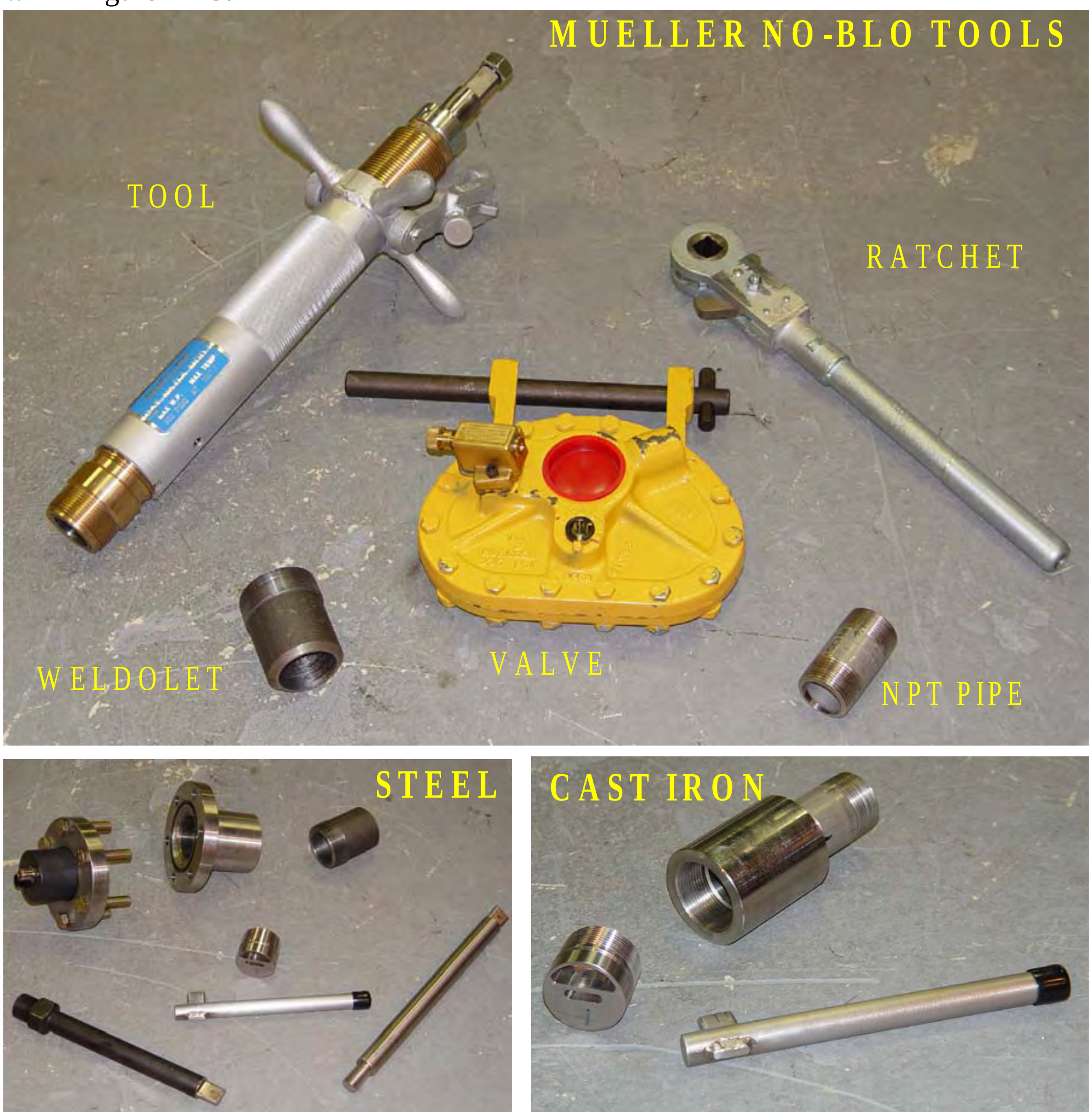


Figure II-19: No-blow installation tools and setup

6.7 Data Collection Approach

6.7.1 Graphical User Interface - GUI

The GUI (Graphical User Interface) was developed based on the premise of displaying multiple unit's data in a large graphical form-factor, while having the data for others readily available and being able to switch which node was being displayed at will. The implementation was carried out using ***LabView***^{R}, and in Visual Basic.Net. The software was expanded to allow for both wired and wireless (cellular) data to be collected in real-time and saved into a database. Data collected using wireless bluetooth over PDA, or removed SD-cards from the field, could be docked to the PC and would be read into the GUI and also saved to the database. Any post-processing desired by a user would be possible through the use of an export function, allowing data from the database to be exported in an EXCEL-compliant tabular ASCII format, for off-line visualization and processing/ filtering.

A screen-capture of the final GUI layout is shown in Figure II-20:

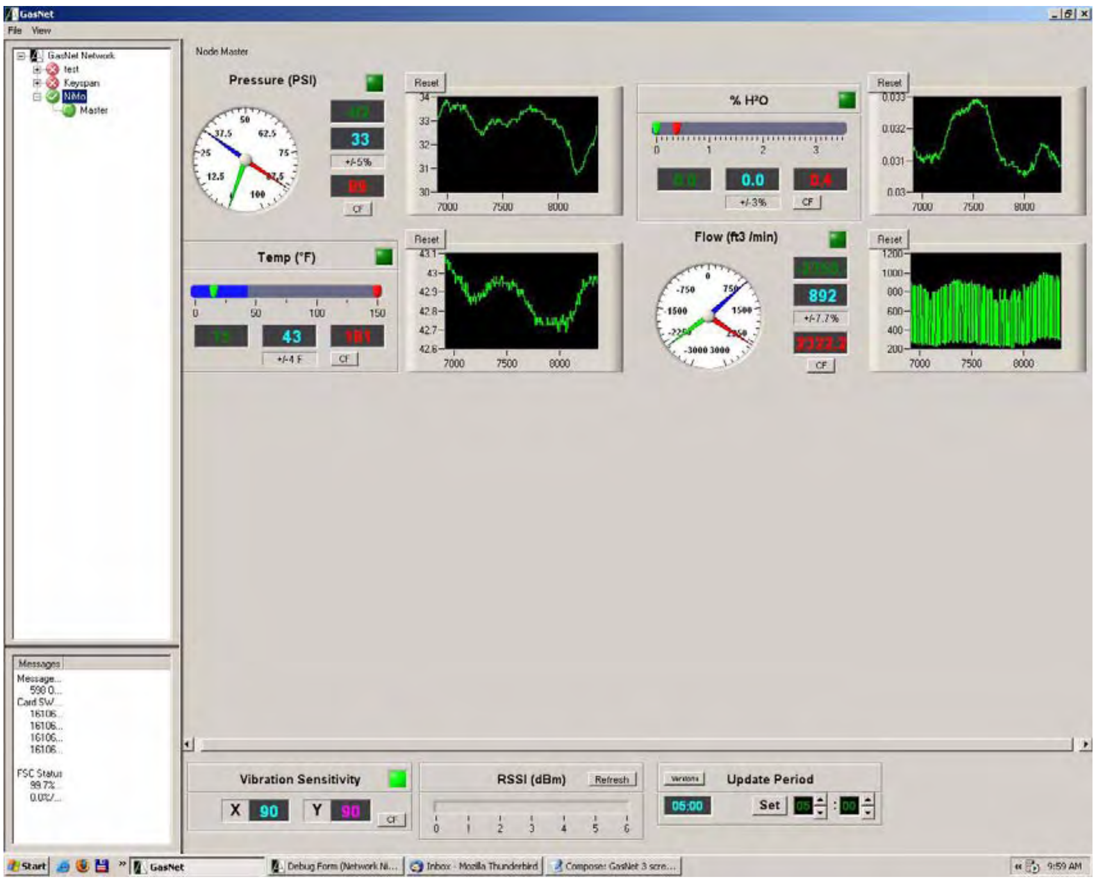


Figure II-20: GUI screen-capture layout showing real-time single-node data

6.7.2 Wireless Bluetooth PDA

For installations with vastly-separated nodes or point-nodes, utilities were able to use a bluetooth enabled PDA running a custom application, to collect data from different datalogging-nodes in the field by simply walking up to the valve-box in the ground, establishing contact with the bluetooth node in the valve-box, selecting a desired data-set range (in time) and performing the download. The data would then be saved on an SD-mounted PC-card, which would be brought back to the office, where it would be docked to the PC and the data uploaded to the GUI and saved to the database.

An image depicting the PDA platform next to a valve-box (in the lab) is shown in Figure II-21:

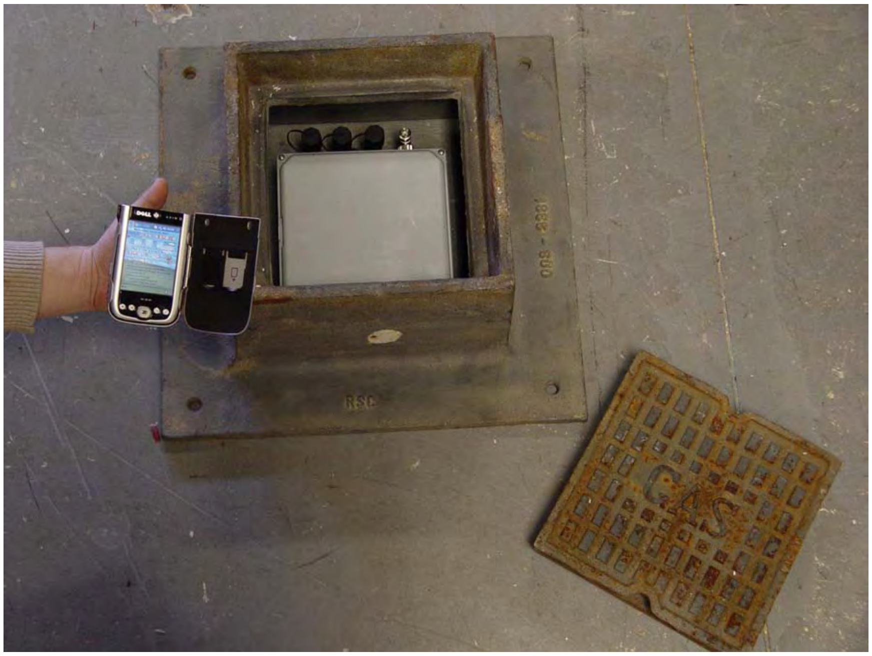


Figure II-21: Wireless bluetooth enabled PDA unit for field data-collection

6.8 Software Architecture

The software resides on an 8-bit micro controller which runs custom firmware to interface to pressure, velocity, relative humidity, temperature, 2-D accelerometer, two serial communication devices and digital potentiometers. The digital potentiometers are set up to provide voltage thresholds for providing ‘alarms’. One serial port (local) is connected to an RS-232 transceiver, while the second port (wireless) is connected to a wireless transceiver unit running its own proprietary software.

On-board configuration switches define each unit’s ID number and master-slave designation. In the final implementation, the system was designed for only one master in the network and all node ID numbers had to be unique. Firmware programmed into the micro controllers differed slightly depending on the master/slave designation of the node. Master nodes were set up to copy messages from the local data-bus to wireless and vice versa, as well as to the datalogger card (PCB) while also serving as a relay node. In this manner, the master relays all messages between a user interface and the rest of the nodes in the system.

The micro controller firmware implements three different work modes: one special work mode state, and two configuration modes. Different work modes are defined to allow different levels of power conservation and interactivity of the system. The flow chart in Figure II-22 on page 27 captures the operation of the firmware in different modes in a single image (configuration modes allow user to configure and run diagnostics on the node).

A more detailed description of the modes. can best be detailed as follows:

- **Work Modes**

  Interactive mode keeps the system continuously running without ever going into a hardware power saving sleep state. This mode is useful for continuous monitoring and reporting of the gas main conditions.

  Monitor mode is useful for periodic checking of the gas main conditions. In this mode, after reporting the data, the node goes into a sleep state for a user-defined period of time.

  Standby mode uses user-defined upper and lower bounds for each sensor. In this mode, the node will behave just like it does in the Monitor mode except the data is only reported if any of the sensors’ readings falls out-of-bounds.

  The node enters an Emergency/Alarm state while in any of the work modes, if one of the hardware alarms is triggered. The emergency state wakes-up and prevents the node from going into sleep mode until the user deals with the alarm conditions. When the alarm disappears, the node returns to the previous work mode.

- **Configuration Modes**

  Transparent mode allows the user to configure wireless modem settings using a local serial port. Once the user exits this mode the system returns to the previous work mode.

  Self-test mode performs a diagnostic on internal sensors and prints results to a local serial port. Once the diagnostic is finished, the system returns to the previous work mode.

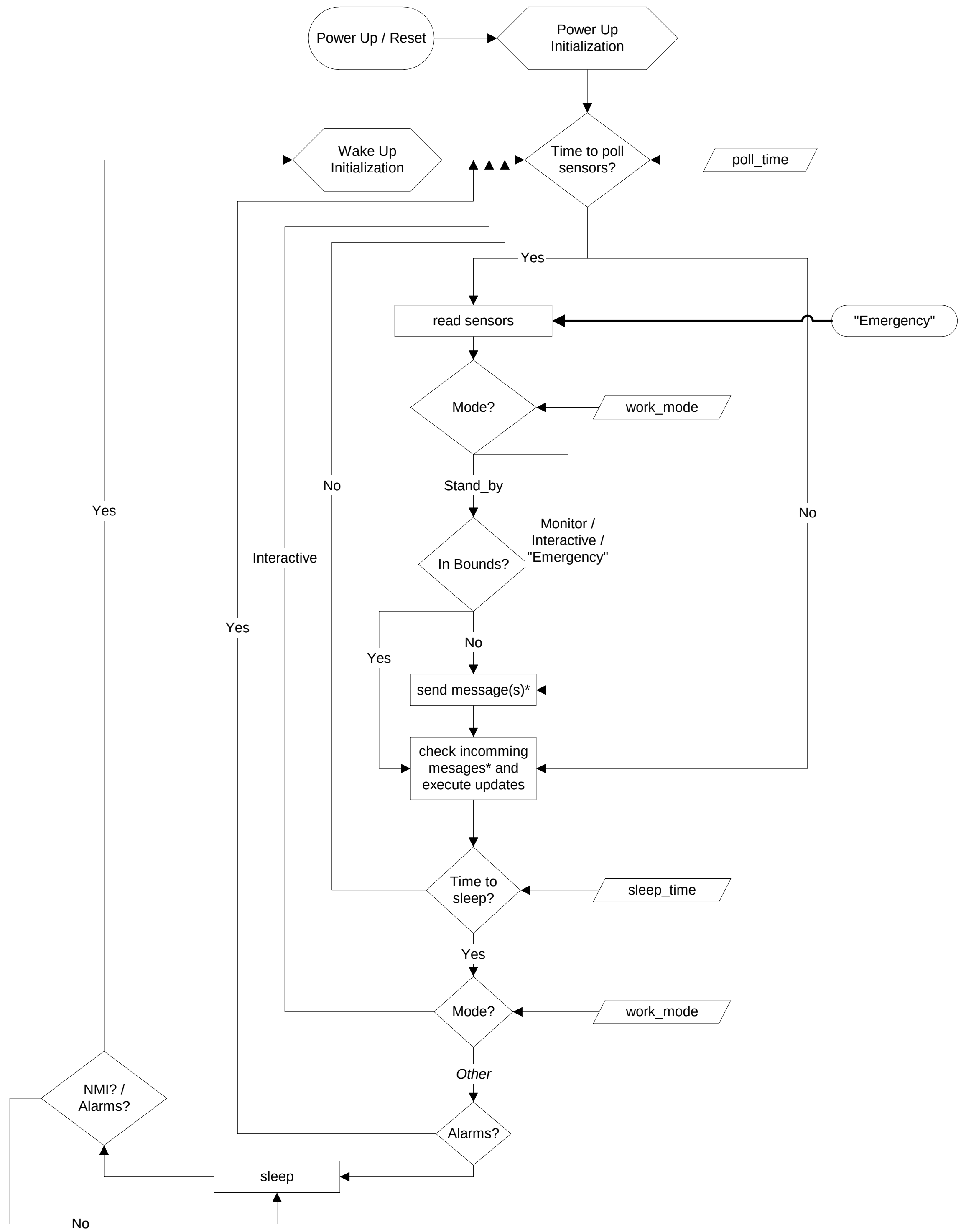


Figure II-22: Software mode flow chart diagram

7.0 Experimental Results

This section details the experimental activities in Phase III of the program. The activities relate to the laboratory and field-trials, and specifically to calibration and field-data gathering.

7.1 Laboratory Testing & Calibration

The laboratory setup was used to test the functionality of the system as well as calibrate most of its sensor systems. The setup consisted of a simple 6-inch steel pipe-loop with bolted flanges. Internal honeycomb sections were inserted in order to straighten the flow of an internal fan used to generate flow-speeds of air at various pressures. Flow and pressure were measured by independent sensors (digital pressure-gauge and hot-wire anemometer). The sensor-wands were all tested in this loop and calibration curves generated for each and stored on the display computer to allow for the acquisition and representation of accurate field-data. Accurate extrapolation[1] was possible though the use of comparative densities and other physical variables published in the literature. An image of the test-setup and an in-process calibration situation are shown in Figure II-23:

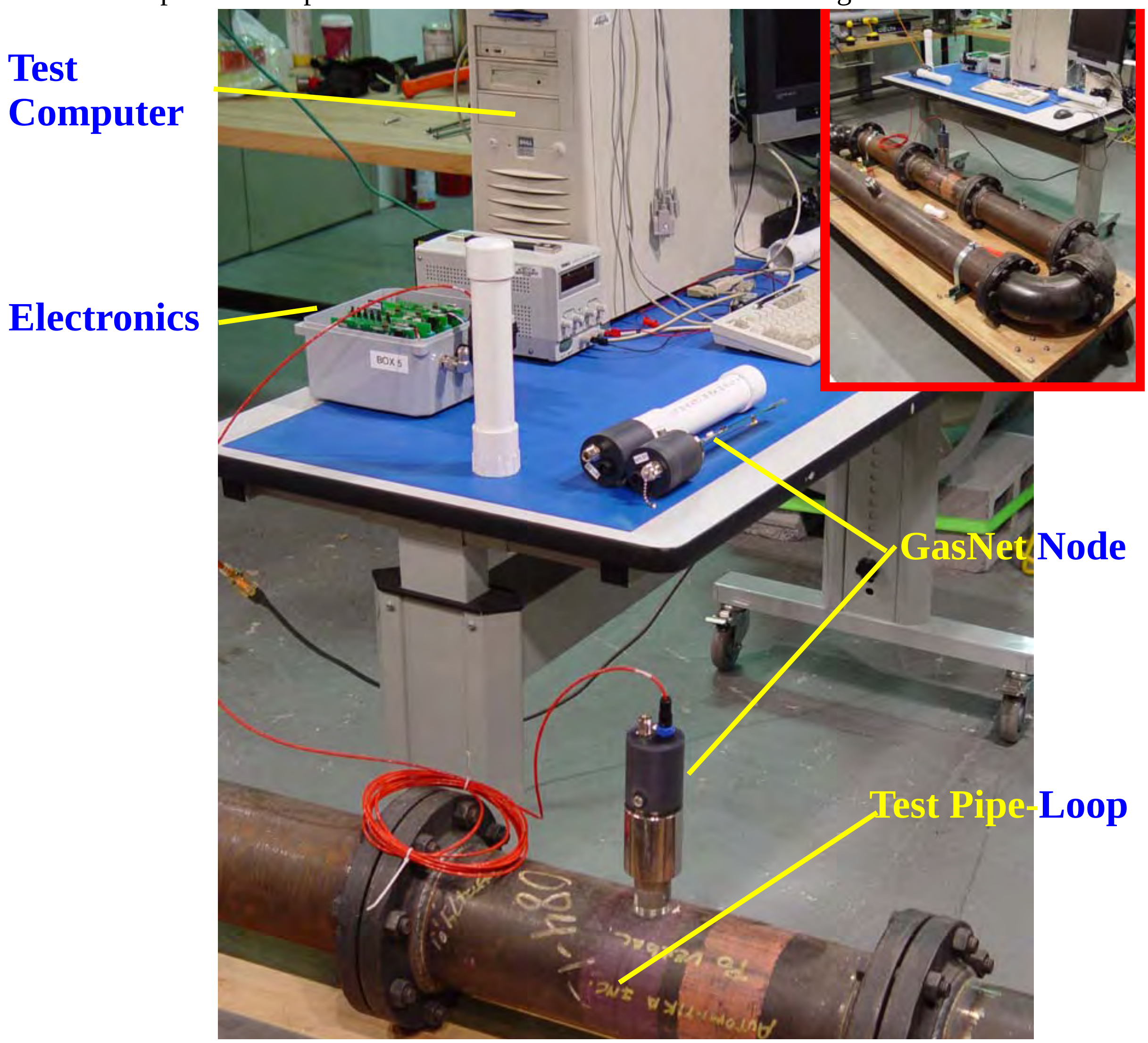


Figure II-23: Laboratory testing and calibration pipe network setup

1. necessitated by the fact that compressed air was used for calibration, rather than compressed natural gas

7.2 Independent Calibration Validation

The engineering team also collected data using several GasNet sensor nodes at the SouthWest Research Institute (SwRI) Flow Meter Test Facility. The setup involved the use of a metered flow at different pressures and flow-rates in order to calibrate the higher-pressure sensor and the flow-rate sensor performance under varying conditions.

Figure II-24: SwRI Metering Test-Loop Calibration Setup

Said data was then used to develop a calibration and conversion formula (partial look-up table and non-linear interpolation algorithm) in order to generate the best-estimate flow-speed value given a known pressure and analog reading. The purpose for this validation was to remove any inaccuracies baed on the pressurized air testing performed in the laboratory pipe network setup. Said calibration information was then incorporated into the GUI to allow for raw data processing and display in usable units.

8.0 Field-Trial Validation

AI carried out three separate long-term installations for several dozen GasNet units in both low- and high-pressure natural gas distribution mains. The goal was to provide installation and training support for multiple utilities, and let them perform their own long-term monitoring and data-collection and -analysis well beyond the end of this program, in order to assess the GasNet system utility and the performance of their networks.

The utilities that received field-installation-support included Consolidated Edison (ConEd), KeySpan and Niagara Mohawk (NiMo - now a part of National Grid). This section will briefly discuss each of the field-trial installations, and wherever available, present very preliminary data collected during installation[1].

8.1 ConEd Installation

Field trials were jointly carried out with Consolidated Edison, Inc. in New Rochelle, NY, a suburb of New York City near the border with Connecticut. The selected mains were 8- and 12-inch diameter and were all cast-iron (CI) with bell-and-spigot inner-sleeve joints. An image of the setting location is shown in Figure II-25.

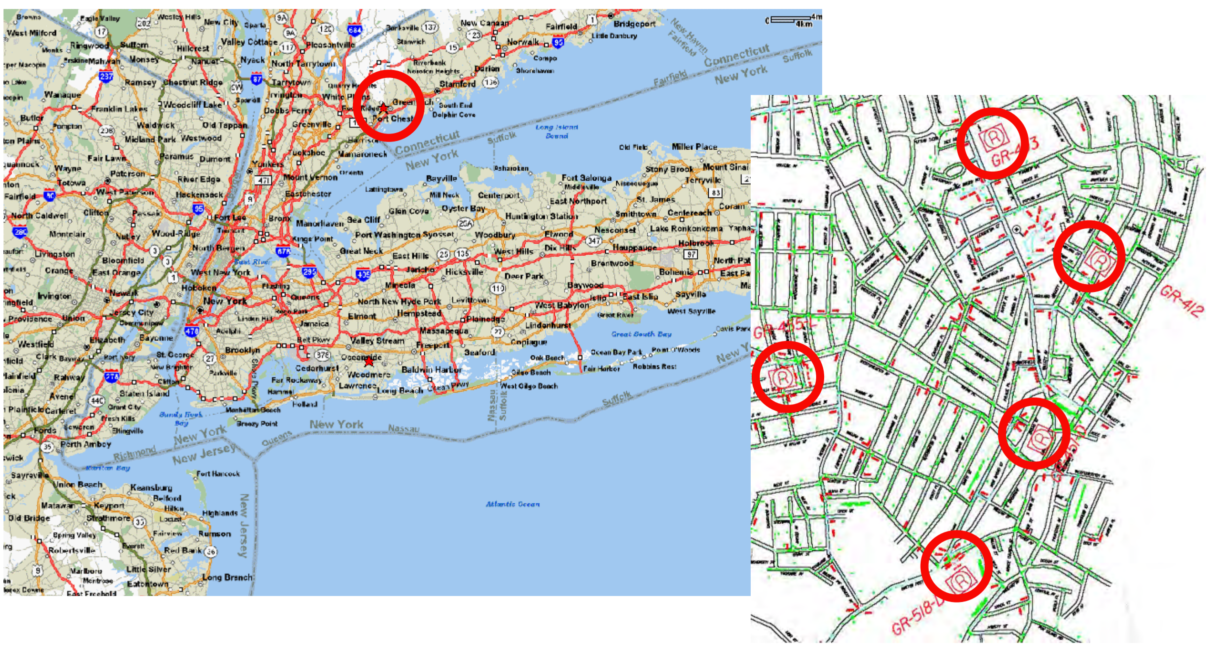


Figure II-25: Field trial setting with ConEd in New Rochelle, NY

The setting involved a total of 5 sensors-units deployed in select locations as dataloggers. The setup for the sensor units was fairly straightforward. Through the assistance of ConEd, all the required excavations were made in the lowest-cost locations wherever possible. The installation and safety process was carried out by trained and certified utility personnel, with the contractor providing to the installer(s) only the training necessary to avoid damage to the units during installation and check-out.

1. most/all data-collection and -analysis is ongoing and performed outside of the scope of this contract by the utilities themselves; said data is also deemed proprietary by the utilities.

The excavation of the necessary 4x4 foot and about 3 to 4 foot deep holes was carried out prior to the contractor team showing up. Once on site, the installation was fairly quick and simple. All sensor-pods were installed within an 8-hour period, and ready for data-collection and experimentation. An image of one of the 5 installation sites is depicted in Figure II-26:

Figure II-26: Cast Iron installation site with ConEd in New Rochelle, NY

ConEd personnel was then also instructed in the use of the PDA for data-collection, as well as physical memory-card removal/exchange. Additional training involved the use of the GUI on a separate computer at the home office, where the PDA and memory-card(s) were docked and data downloaded and 'calibrated' through the GUI and stored in a database. After that point, ConEd was in a position to process and graph any future data collected by the system over the winter and spring months.

A sequential image collage (left-to-right, top-to-bottom) of the installation and completion of the excavation (backfill and restoration) for one of the GasNet datalogger systems, is depicted in Figure II-27 on page 32. Note the use of the two enclosures and their setting within a structural PVC pipe with the top-mounted valve-box prior to complete backfill (after tar-sealing of the node-assembly on the pipe) and tar cold-patching.

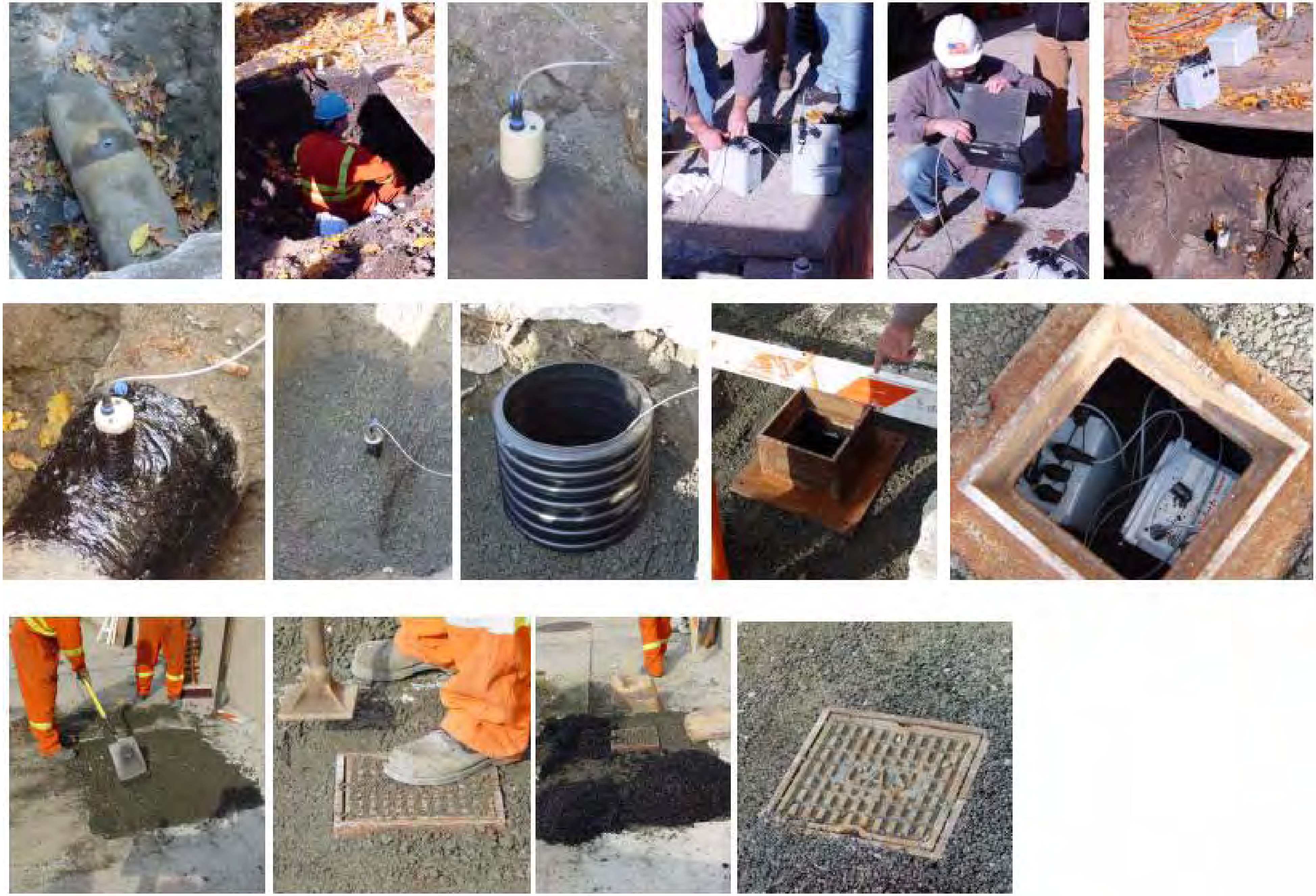


Figure II-27: Installation Image Collage - Low Pressure Cast-Iron - Dataloggers - Consolidated Edison - New Rochelle, NY

8.2 KeySpan Installation

Field trials were also jointly carried out with KeySpan Energy, Inc. in East Rockaway, NY, a suburb of New York City on Long Island. The selected mains were 16-inch diameter and were all high-pressure (99 psig) steel pipes with welded joints. An image of the setting location is shown in Figure II-28.

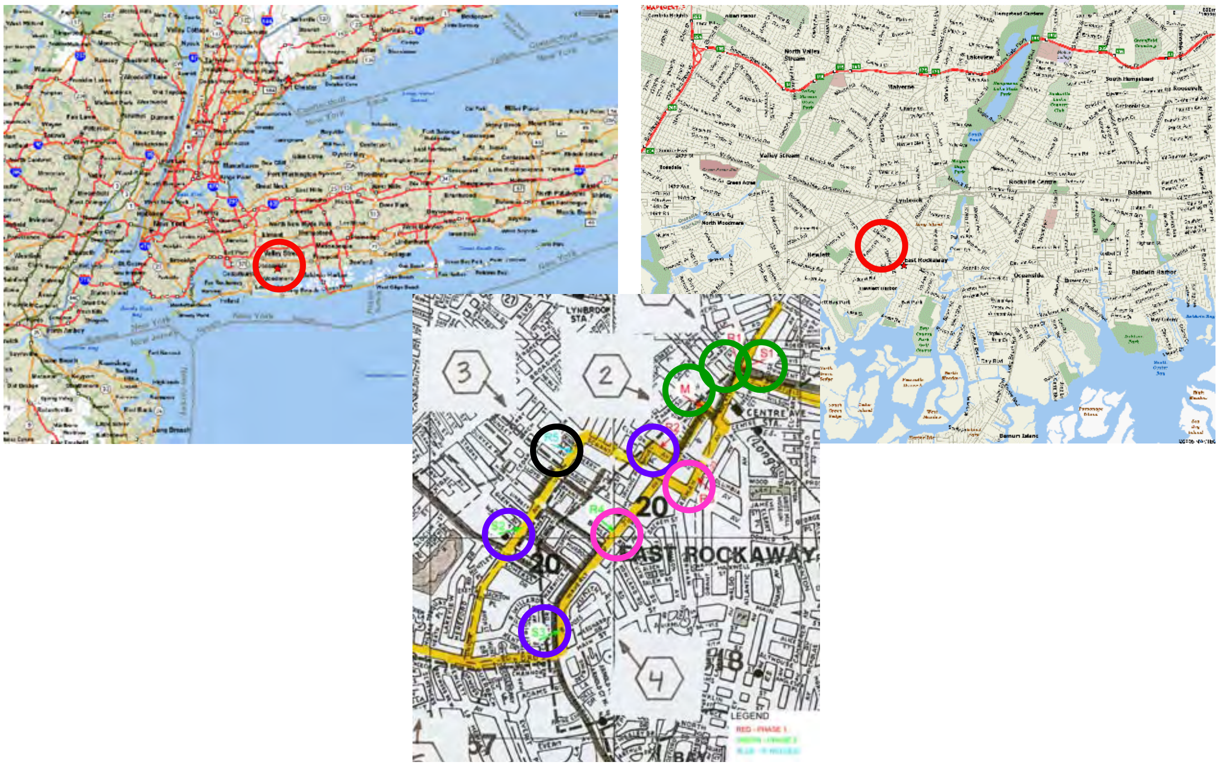


Figure II-28: Field trial setting with KeySpan in East Rockaway, NY

The setting involved a total of 9 sensors-units deployed in select locations in a networked configuration, in the shape of a spider (master with legs radiating with multiple repeaters and slaves). The installation occurred in a 5+4-unit fashion, with 5 units installed before the winter, and the remaining 4 (repeaters and slaves) to be installed in the spring of 2006 under separate utility-sponsored funding.

The setup for the sensor and communication system was a 2-day undertaking. Through the assistance of KeySpan, all the required excavations were made in the lowest-cost locations wherever possible, including existing valve-/regulator vaults as well as nearest to pole-locations (for external AC-power for master and repeaters). The installation and safety process was carried out by trained and certified utility personnel, with the contractor providing to the installer(s) only the training necessary to avoid damage to the units during installation and hookup.

The excavation of the necessary 4x4 foot and about 3 to 4 foot deep holes was carried out prior to the contractor team showing up. Once on site, the installation was carried out using the methods and tools developed by Mueller and AI. All 5 sensor-pods were installed within two 8-hour periods, and ready for data-collection and experimentation. Network connectivity and data-collection (and -reasonableness) was tested through a laptop connection operating the GUI.

ConEd personnel was then instructed in the use of the GUI on a separate computer at the home office, with the intention to allow them to collect in real time all the data from the 5 nodes (1 master, 1 slave, 3 repeaters) via single cellular modem connection at the master node. After that point, KeySpan was in a position to process and graph any future data collected by the system over the winter and spring months, using the provided cellular modem connection.

A sequential image collage (left-to-right, top-to-bottom) of the installation and hookup (pole-mounted power/data/cell enclosure and under-the-street wiring and hookup) for one of the GasNet (repeater) sensor systems, is depicted in Figure II-29 on page 35. Note the use of the Mueller line of valve and installation tools (post nipple weld-on) as well as the remote wiring and check-out steps for the repeater node. The installation of the master would be identical, while the installation of the slave node is similar to that of a datalogger (detailed earlier).

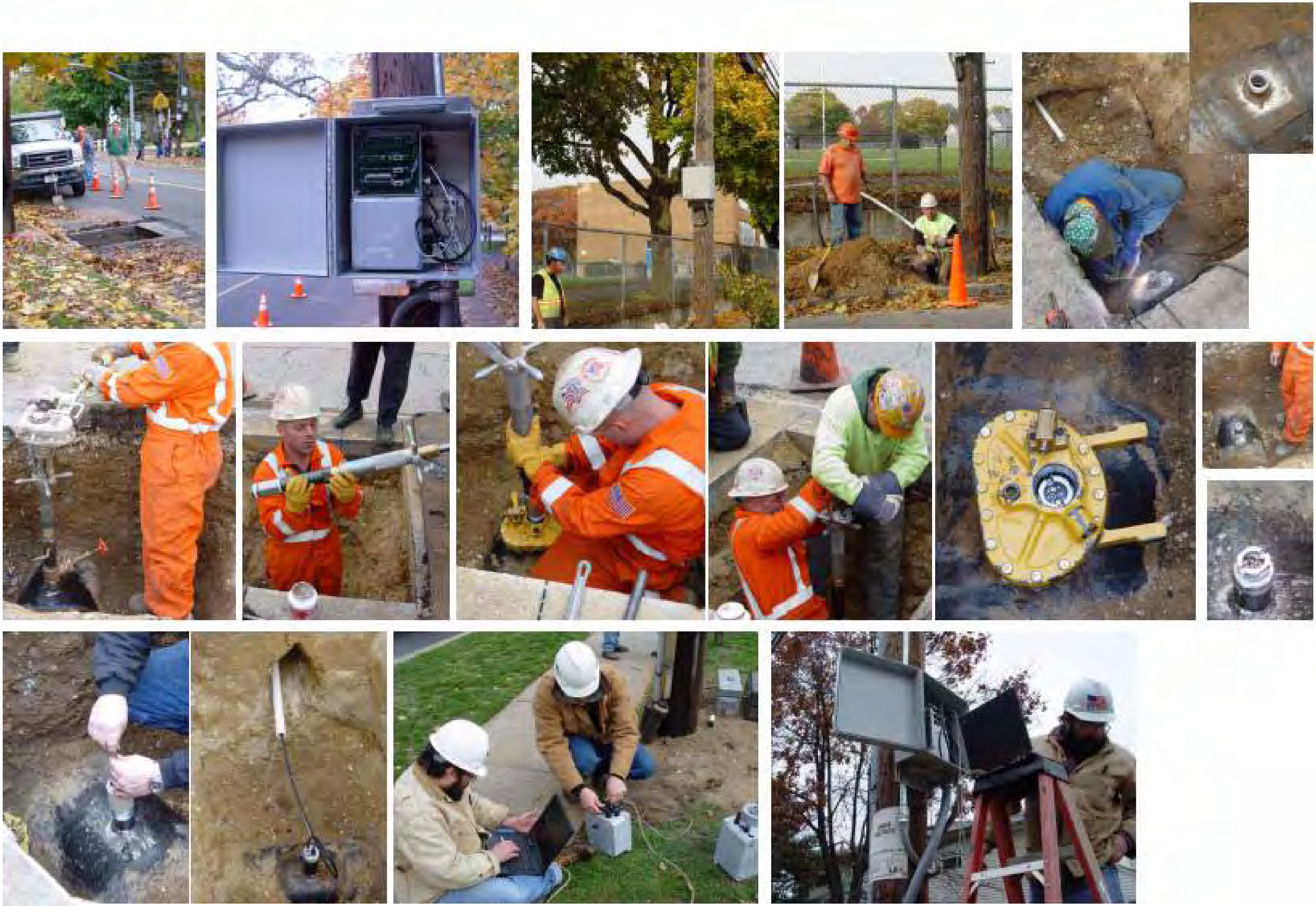


Figure II-29: Installation Image Collage - High Pressure Steel - Wireless Spider Network - KeySpan - East Rockaway, NY

8.3 NiMo Installation

Field trials were also jointly carried out with Niagara Mohawk, Inc. (A National Grid Company) in Glenns Falls, NY, in upstate New York. The selected mains were 8- and 12-inch diameter and were all elevated-pressure (25 psig) steel pipes with welded joints. An image of the setting location is shown in Figure II-30.

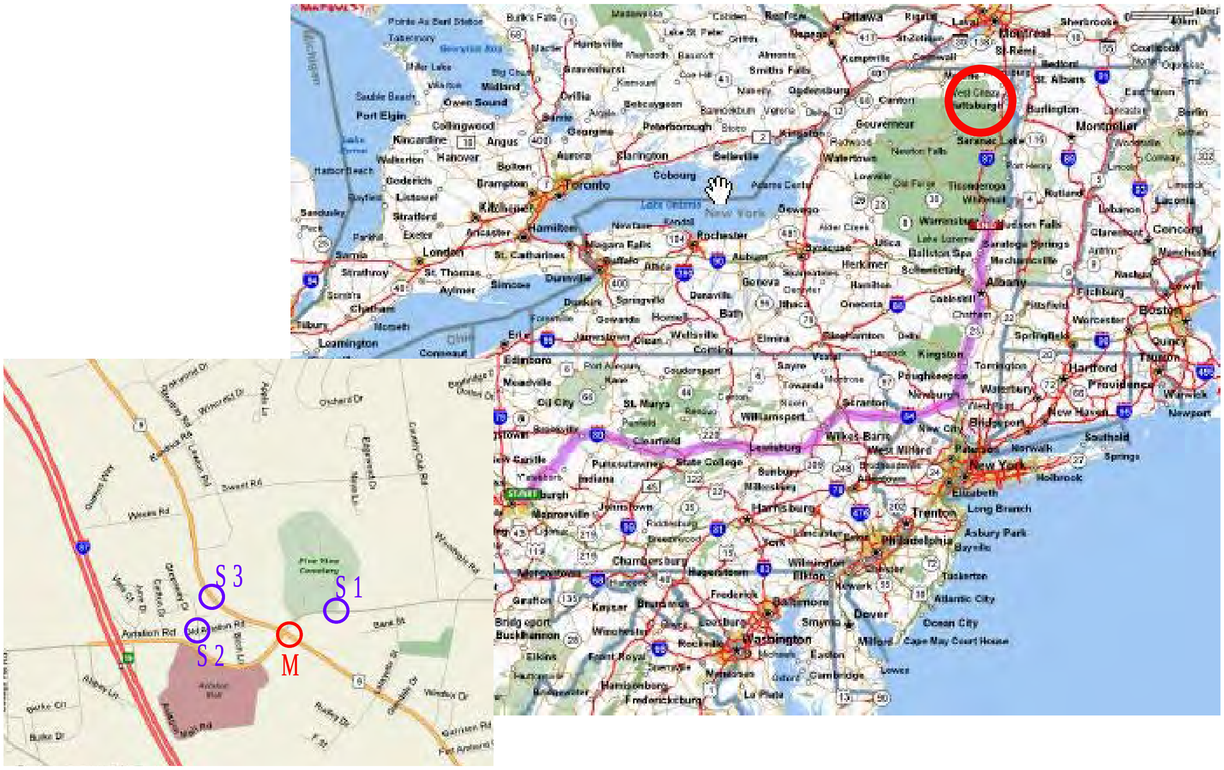


Figure II-30: Field trial setting with NiMo in Glenns Falls, NY

The setting involved a total of 4 sensors-units deployed in select locations in a networked configuration, in the shape of a star (single master with individual legs radiating with slaves at their ends). The installation was schedule with all 4 units installed before the winter in a single deployment.

The setup for the sensor and communication system was a 2-day undertaking. Through the assistance of NiMo, all the required excavations were made in the lowest-cost locations wherever possible, including off-street locations as well as nearest to pole-locations (for external AC-power for the master). The installation and safety process was carried out by trained and certified utility personnel, with the contractor providing to the installer(s) only the training necessary to avoid damage to the units during installation and hookup.

The excavation of the necessary 4x4 foot and about 3 to 4 foot deep holes was carried out prior to the contractor team showing up. Once on site, the installation was carried out using the methods and tools developed by Mueller and AI. All 4 sensor-pods were installed and checked out within two 8-hour periods, and ready for data-collection and experimentation. Network connectivity and data-collection (and -reasonableness) was tested through a laptop connection operating the GUI attached to the master node.

NiMo personnel was then instructed in the use of the GUI on a separate computer at the home office, with the intention to allow them to collect in real time all the data from the 4 nodes (1 master, 3 slaves) via single cellular modem connection at the master node. After that point, NiMo was in a position to process and graph any future data collected by the system over the winter and spring months, using the provided cellular modem connection.

A sequential image collage (left-to-right, top-to-bottom) of the installation and hookup (pole-mounted power/data/cell enclosure and under-the-street wiring and hookup) for one of the GasNet (repeater) sensor systems, is depicted in Figure II-31 on page 38. Note again the use of the Mueller line of valve and installation tools (post nipple weld-on) as well as the remote wiring and check-out steps for the master node, as well as the sealing and valve-box completion of the installation for (one of the) slave nodes.

Figure II-31: Installation Image Collage - High Pressure Steel - Wireless Star Network - Niagara Mohawk - Glen Falls, NY

9.0 Data Collection and Interpretation

The data collection process is intended to be performed over a prolonged (multi-seasonal) period, and was scheduled to be under he control of each individual utility. Each utility treats their own data as proprietary and said data is not available for public release.

In order to provide proof positive as to the operation of the GasNet system, AI was able to collect some short runs of data (multi-hour to multi-day) from each installation during the setup and pre-calibration phase of the individual node(s). Representative datasets for each main variable are presented in this section, without reference to utility or location, and are to be treated as raw and unfiltered.

9.1 Data Sets

• **Gas Flow Speeds & Flow Rate**

As is expected, the most interesting variable for the utilities revolves around the flow rate of the gas in the mains. The sensor utilized measured only flow-speed, and was converted to flow-rate based on an iterative procedure to determine flow-type (laminar or turbulent) and then flow-rate based on the knowledge of sensor-location, pressure, density, etc. as well as the calibration-curves obtained in laboratory testing. Flow-speed was thus collected, interpreted and flow-rate deduced from the same. A typical flow-speed plot is shown in Figure II-32:

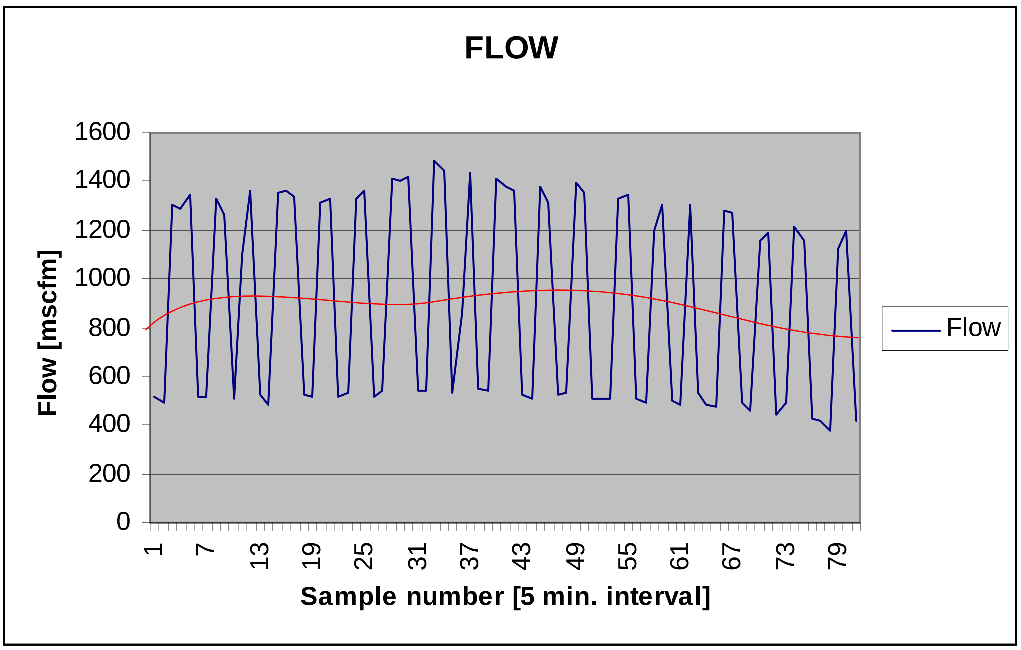


Figure II-32: Typical gas main flow-speed data-log plot

Notice how the raw flow-speed oscillates about a lower-frequency (post-processed) ‘average’. The oscillation component can be contributed to mainly warm-up issues of the sensor and the potential oscillatory behavior of the flow under elevated pressure and flow conditions. This phenomenon will need to be studied further to better be able to extract a more representative true-flow data set form the existing system. Note though that the flow does indeed vary at this location by up to 25%, which over the sampling period, is a behavior that will help utilities better understand their supply and demand models in the future.

- **Gas Main Pressure**

  The high-pressure readings possible with the new sensor system allowed the monitoring of lines at elevated pressures, implying they are typically made of bolted/welded steel. Notice from Figure II-33, that the pressure is variable within +/- 8%, with a seeming strong 24- and a weaker 12-hour pattern, which is information that utilities can use to better control their upstream regulators to try to maintain a more constant supply-pressure.

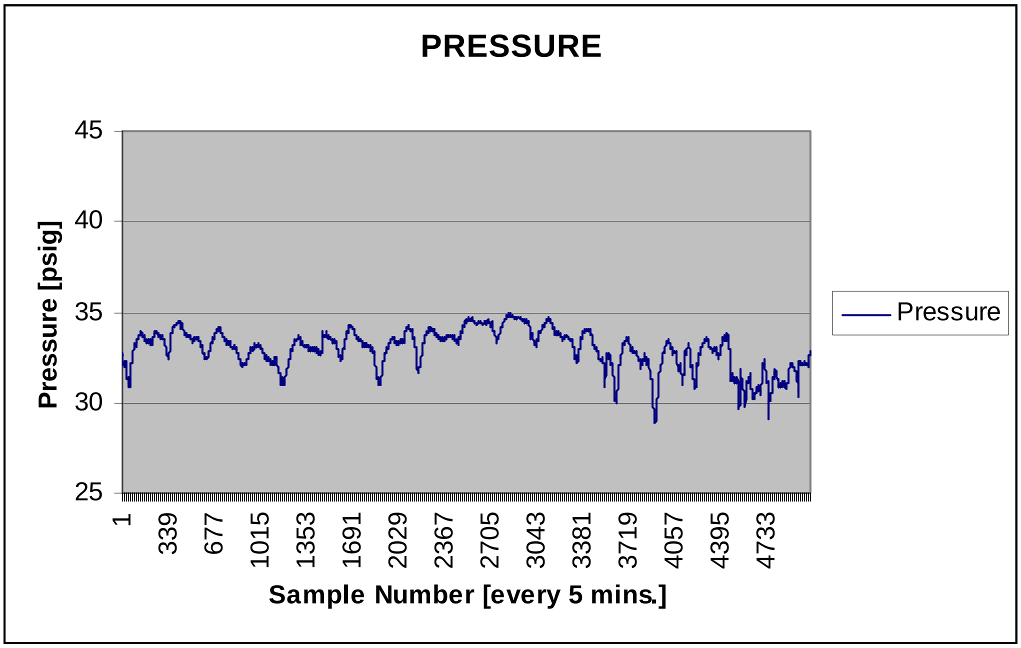


Figure II-33: Steel Gas Main Pressure - Representative data-log plot

A similar plot was generated for an installation with low-pressure gas in cast-iron mains - see Figure II-34.

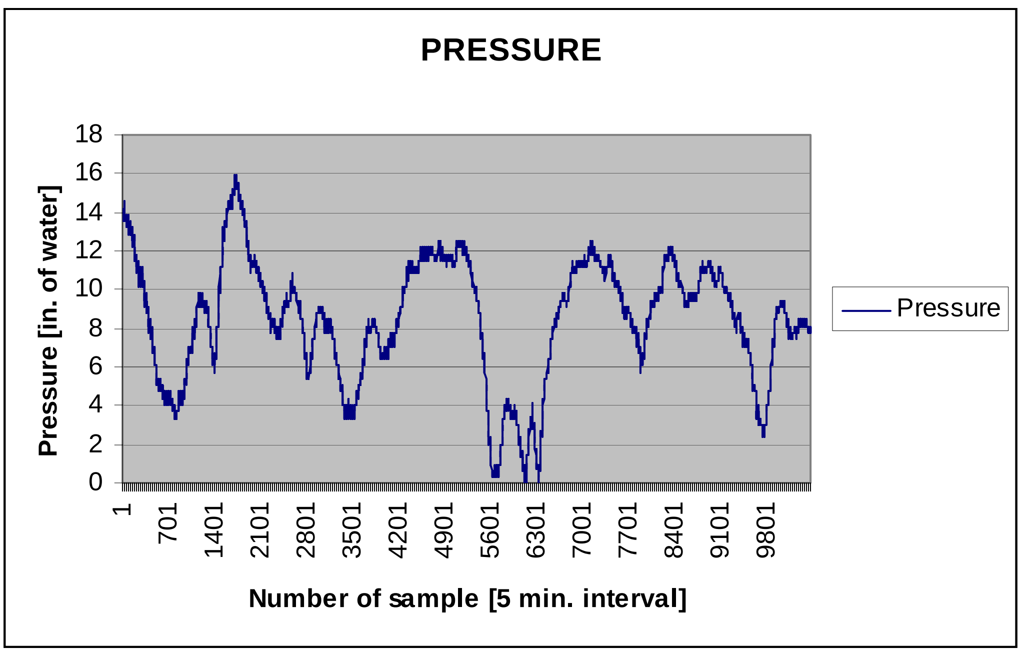


Figure II-34: Cast Iron Gas Main Pressure - Representative data-log plot

Notice the strong variability in magnitude over time, indicating a very clear demand/supply relationship usually not expected or observed at any instrumented station.

• Gas Water Content

Another interesting variable utilities will be monitoring is the net water-content of the gas as expressed in percentage by volume. This measurement was affected through a humidity sensor with a numerical conversion to water content. A typical log for one of the deployment sites is shown in Figure II-35.

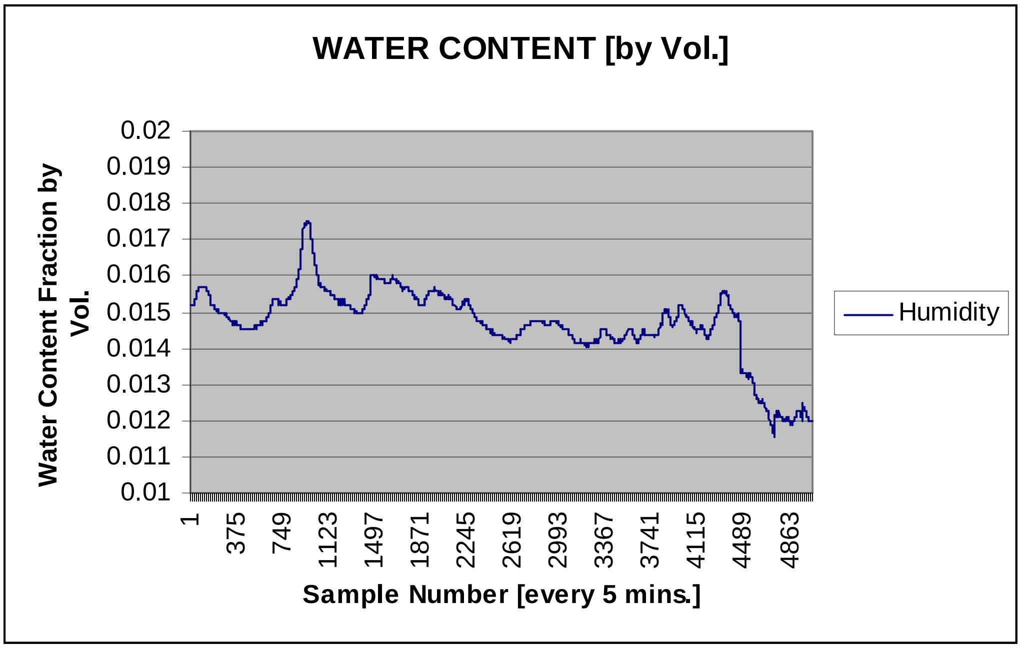


Figure II-35: Gas Main Water Content Data-Plot

As expected by the utility, the water content is rather low (between 1% and 2% by volume - not atypical for higher pressure gas), implying the gas was dry and thus containing saleable BTU-content for the customer. Variations over time are also apparent, even though the changes are small, they are visible and can help utilities better understand their BTU-value of customer-delivered natural gas.

• Gas Temperature

Utilities are also interested in the cool-down and mixing phenomenon of gas flows in distribution networks, when heated gas is mixed with colder gas to avoid internal freezing of any internal moisture content. Others are interested in knowing the impact of ground-temperature on the heat-transfer (positive or negative) into/from the gas for the additional reason of thermal expansion/ contraction especially for bell-and-spigot jointed gas mains. The fact that this occurs is known, but the variation over time and its distribution in space is not well understood. Towards that end a set of networked sensor data for temperature was plotted for the same pipe section with substantially-spaced nodes, with the resulting data shown in Figure II-36 on page 42.

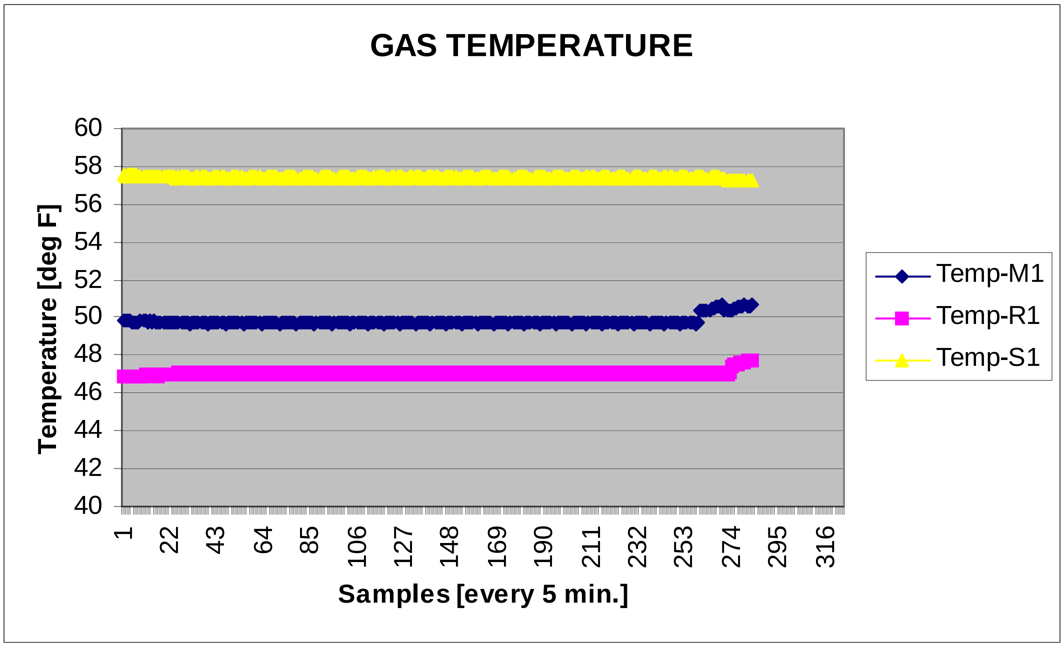


Figure II-36: Temperature data-log - Multi-node temperature distribution

Notice how the temperature varies very little over time, given just shy of a 20 hour monitoring window. However, the data shows dynamic response in a delayed (expected) fashion to a change in temperature at M1, with a delayed-reaction change to the downstream R1 and S1 sensors. This data clearly indicates mixing and heat-transfer phenomena. Hence this data can be us to generate or verify mixing and heat-transfer models and allow utilities to control regulators for appropriate mixing based on demand and ambient temperature (which are related).

9.2 Data Evaluation Summary

Based on the data collected and the on-site evaluation of the data-validity and -trends, the following summary observations were made (in no particular order of importance) by the AI contractor team, which were corroborated by the on-site utility representatives:

1. The gas flow behavior was noted to be the most interesting in terms of its dynamics and temporal behavior, which can not be extracted form a Stoner model and could possibly reveal important trends. Better understanding of the warm-up and oscillatory node behavior will be needed to extract more accurate flow-data.
2. As expected, the water-content of both low and high-pressure natural gas these days is very low, and found to be between 1% and 2% by volume for a particular utility's high-pressure gas system for a particular location.
3. Pressure sensors seemed to indicate that pressures are along nominal lines, and within acceptable variability bounds. Variations are substantial enough to warrant further investigation by the utilities as to how to best use this data for more sophisticated regulator control.
4. Temperature was as expected fairly steady, but its longer-term behavior though an entire winter-season will be valuable to log and understand, to better understand potential leakage-contribution due to freeze/thaw induced motions at the bell-and-spigot joints. Additionally, the variation of temperature to demand- and ambient factors can also be studied in the future.
5. As was discovered in previous efforts, the vibration data collected was not telling of any phenomena and was thus not presented here.
6. As was seen with previous phases' data, the current data contained far more dynamic behavior with unexpected trends and oscillatory behaviors (flow) than would have been expected, leading one to conclude that a better understanding could be important to utility operations.

10.0 Project Summary

The development effort for a prototype ***GasNet^{TM}*** system can be deemed to have been successful overall. The main technologies, ranging from sensing, communications, software and display to in-filed installation and safety-design considerations were completed, resulting in the installation and ongoing operation of multi-dozen units in the field. Utility representatives are logging data and will be processing and evaluating it well beyond the end of this program in order to guide a potential commercialization effort to make the GasNet system commercially available.

The design for live low-/no-blow installation in low-/high-pressure distribution mains (cast-iron/ steel) of multi-sensory probes (using existing commercial tools and methods), coupled with external data-sampling, -collection, -storage and -communication software and hardware was proven to be a very viable approach for instrumenting critical distribution network sections. The flexibility of he design to include the ability to tailor the system to local datalogging with wired/ wireless data-dump, and the ability set up pipe-internal communication networks and cellular real-time data-links for real-time monitoring proved to be technically feasible. Critical areas of safety-design, logistics and system-modularity were addressed successfully in this program, resulting in multi-dozen units currently installed and operational in the field.

The selected sensors and the distributed microprocessor system were shown in the lab and field to perform as expected, in both low-pressure (sub-atmospheric) and high-pressure (up to 85 psig - limited by pressure-sensor saturation) environments. The wireless communications link was also shown to work in a dynamic network setting, with varying operational modes implemented in software (emergency, monitor, datalogger, alarm, etc.). The modularity of the system allowed it to be configured in a variety of models (datalogger, slave, master, repeater, etc.), with multiple data-interfaces (batch-log, bluetooth-dump, cellular-relay, memory-card exchange) and various external power-options (battery, solar-cell, AC-drop). Each of these options was implemented and is in one combination or another installed in the field. For the real-time cellular-relay, the graphical user interface (GUI), was developed for flexible data-display, -conversion and data-storage in an accessible database for each utility. Said GUI is also used to collect and store data collected in the field (via bluetooth PDA or memory-card exchange) into the same database for later access and processing.

Field installations included low-pressure cast-iron datalogger nodes with PDA-based bluetooth data-collection interfaces, spider-/star-networked master/repeater/slave networks in higher-pressure steel mains with cellular data-relay and remote GUI display of quasi real-time data, as well as stand-alone cellular relay and AC/solar powered nodes for critical node monitoring. A total of six (6) utilities were assigned a set of nodes, with five (5) of them having installed nodes and currently collecting data on their distribution networks. Additional modifications for a proprietary SCADA data-interface to GasNet for a particular utility is currently in the planning phases.

Experimental field-testing showed that low-pressure cast-iron mains could be monitored and data logged, collected and visualized as expected, proving the viability of the GasNet system. Establishing pipe-internal networks in bell-and-spigot cast-iron networks was experimentally determined to not be possible beyond $^{1}/_{4}$-mile inter-node spacings. Nodes installed in high-pressures (welded or flange-bolted) steel mains proved to also be viable, resulting in local and relayed data from pipe-internal wireless multi-node networks. Different patterns of networks were shown to be feasible, with quasi real-time data being viewable at a remote site using cellular networks. The extent of inter-node spacings was controlled by pipe-diameter, pipe-junction losses, and any other non-conductive pipe-inserts; distances of multi-thousand feet were however possible as long as electrical continuity was guaranteed.

The limited data sets collected during the installation period of the nodes, again verified that the gas flow rates exhibit highly dynamic and oscillatory behavior varying widely across the pipe run in terms of amplitude (flow-rate) and flow-direction as a function of time-of-day. Pressure measurements showed that pressures were in the statically-predicted range, with variations due to consumption, ambient temperature and regulator settings. Gas temperature was found to be extremely steady, with higher temperatures of the gas flow than ambient, and correlated to daytime temperature fluctuations, preheated-gas mixing ratios and conductive cooling due to the surrounding soil as a function of distance travelled; these are critical measurements to better understand freeze/thaw impact on cast-iron mains as well as avoiding regulator freeze-up due to water-content freeze up in the main. Water content was found to be extremely low and measured at less than 1% by volume. Mechanical pipe-wall vibration measurements proved to only be possible within the vicinity of an instrumented pipe-section due to the segmented and isolating nature of the cast-iron bell-and-spigot design; measurements did however show that road-traffic could be ignored, while road-surface jack hammering was readily detected, as were impact-loads as small as a hammer-strike on the pipe-wall.

Data-collection by all participating utilities is still ongoing as of this point in time to asses the utility and needs for commercialization for the GasNet system beyond the current prototype units.

11.0 Conclusions and Recommendations

Based on all phases, but in particular the Phase III results, the following conclusions were drawn by the AI contractor team in different areas, which are reflective of the entire multi-phase development effort:

• Sensing Systems

- *Flow-rate*
  * Magnitude and <u>direction</u> of flow based on flow-speed continue to be extremely valuable and can be accomplished with a flow-speed sensor for both high and low flow conditions (pressure-dependent).
- *Gas Pressure*
  * Pressure measurements were found to be reliable at pressure up to 85 psig using the exchangeable pin-compatible low/high pressure sensor.
- *Gas Temperature*
  * Temperature was found to be extremely reliable and useful
- *Humidity/water-content*
  * Measurements were found to be very low and with variability.
- *Pipe Vibration*
  * Vibration in cast-iron is only a useful measure in cast-iron at a very local level.
  * More testing is recommended to validate the measure's utility in welded/bolted continuous steel pipe mains.
- *Third-party sensing*
  * The ability to interface an external sensor should be considered for other external sensors such as seismic (intrusion detection), corrosion (pipe-potential), temperature (freeze/thaw heave), etc.

• Wireless Communications

- *Wireless communications*
  * Range in cast-iron was corroborated to $^1/_4$ miles using network analyzers and adaptive/dynamic channel-selection for cast-iron mains.
  * Range in steel pipes was found to be highly dependent on pipe diameter, junction-types and frequency, as well as presence of non-conductive pipe-segments. More in-field experimentation and data-collection and -evaluation is necessary to clearly identify and quantitatively model the impact of each of these.
- *Wireless In-Pipe Networks*
  * Multi-unit serial (flattened network topology) master-repeater-slave architecture proved itself to work very well thereby validating the architecture and protocols developed for this application in this phase.

• Packaging and Operational Logistics

- *Live Installation*
  * Low-blow installation in cast-iron mains was found to be rather straightforward, repeatably accurate requiring no additional tools beyond the standard tapping and completion tools used by utilities.
  * Higher-pressure no-blow installation was accomplished using standard tools with modified adapters and procedures well established in the industry.
- *Safety*
  * The safety-design implemented in this program showed that the system could be installed safely and left in-situ buried without interference without causing safety concerns.

• User Interface

- *The user interface design and data-representation was modified and improved and proved to be extremely useful and provide novel insight into the (now known) dynamic nature of gas mains variables (flow, etc.)*

The above conclusions resulted in a set of recommendations by the AI contractor team to both NGA and DoE, primarily for consideration of implementation in a commercialization effort, and can best be summarized (in no particular order of importance) in varied categories, as follows:

• Sensing Systems

- *Flow-rate*
    * Understanding of oscillatory behavior due to electronics, mechanical oscillations and flow-alignment needs to be better understood.
    * Limitations of sensor based on pressure and flow-rate needs to be better understood through more extensive testing and calibration in a metering test-facility.
    * If MEMS-baed flow-technology is found to not be reliable, the inclusion of a vortex-based (or other) flow meter may need to be considered.
- *Gas Pressure*
    * Future versions should consider using different PCB-mountable pressure sensors with more sensitivity in the sub-one-psi range (low-pressure cast-iron mains) and a higher range (up to 125 psig) for the higher-pressure steel mains.
- *Water Content*
    * Additional calibration experiments should be performed to ensure the accuracy of the current measurements and calibration/conversion formulae.
    * Longer-term monitoring should be performed to determine the utility and variability of this variable, especially during times of water-intrusion in the winter-time and gas cool-down (freeze/thaw).
- *Third-party sensing*
    * Introduction of an acoustic monitoring system (e.g. geophone) for ultra-low frequency soil-vibration monitoring may also be useful to monitor and detect third-party intrusion.
- *Pipe Vibration*
    * Mechanical wall vibration experimentation should be considered in a bolted/welded steel network segment to predict whether such a measurement is useful in the field.
- *Other*
    * The sensors for pressure, temperature and humidity should be used to generate trend-data and used for follow-on testing to see if water-intrusion and freeze-thaw cycles can be detected/predicted.

• Wireless Communications

- *Wireless communications range*
    * The impact on range in steel mains with real field-conditions (junctions, bends, etc.) should be studied further through a focussed measurement program.
- *Pipe Discontinuities*
    * The impact of PE plastic-pipe cutouts and insulation-joints on RF signal-transmission characteristics should be explored further.

• Design for Installation

- *Wand Design*
    * The wand-unit should be improved to allow for a more rigid unit, especially in

larger-diameter pipes where flow-measurements at the center of the pipe are required.

- **Packaging and Operational Logistics**
  - *Other No-blow methods/tools*
    * The ability to extend the (plug- and adapter) design(s) to utilize TDW tools should be explored.
  - *Long-term performance*
    * The current design should be evaluated in light of long-term deployment (months to year) and its compliance with required sealing and fail-safe requirements based on utility and regulatory requirements.
  - *Power-source*
    * Additional effort should be considered in providing additional safety features for the solar/battery power systems to achieve a Class I Div.2 rating (minimally) for buried installations.
  - *Data Relaying*
    * Additional consideration should be given for data-relaying using not just cellular but also leased phone line access due to relay-delay and cost issues found with cellular modems.

- **User Interface**
  - *Extensions and Improvements*
    * The user interface should be improved based on feedback from the utility users and reprogrammed to better interface with existing graphing and database software in both the commercial and utility sector.
    * A more streamlined approach for field-collected and wirelessly-relayed data needs to be developed through a more generalized user interface program.
  - *Other interfaces*
    * SCADA interfaces should be explored to ensure that future interfacing is possible, by using a form of standardized data- and file-formats (or even real-time communication protocols).

- **Commercialization**
  - *Improvements Feedback*
    * A formalized process should be put in place to ensure all utility feedback is collected, sorted, filtered and weighted in order to provide a complete picture of the good and bad points of the design, installation, operation and usage of the GasNet data by utilities beyond the end of this program.
  - *Next Steps*
    * It is suggested that a commercialization-model, -path and -partner be identified to take this technology to market. Utility feedback and support will be critical to see this step succeed.
  - *Certification*
    * The selected commercializer or team will need to consider taking the system through certification (UL, FM, CSA, TUV, etc.) in order to enable national and international availability and sales.

III. APPENDICES

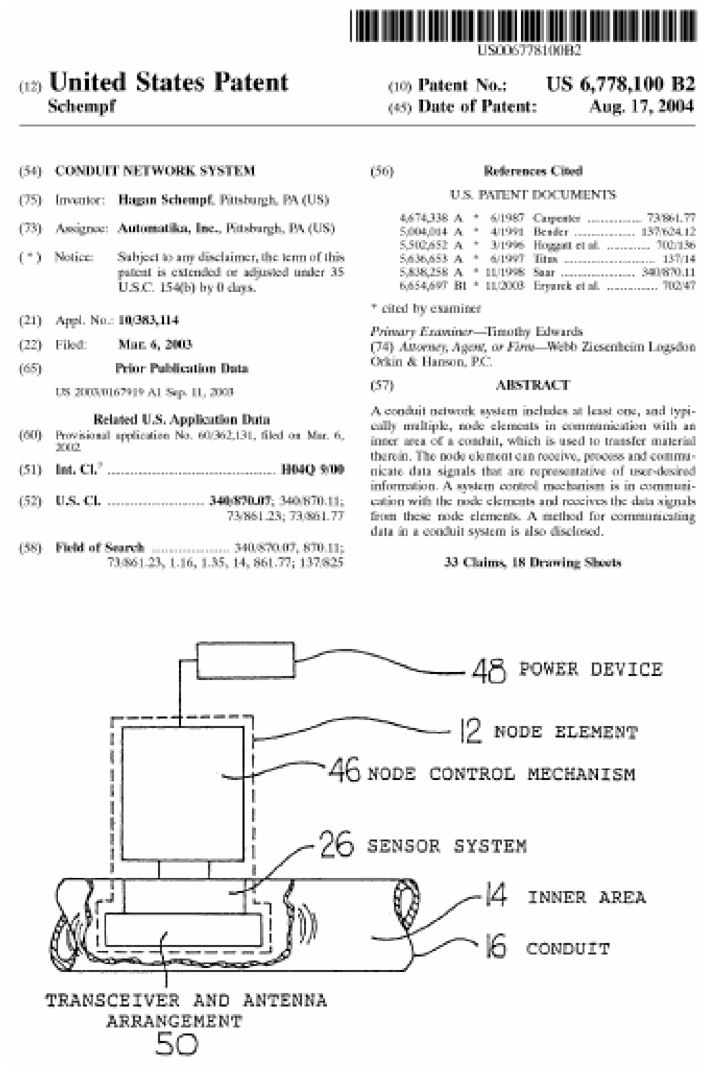
1.0 Acknowledgements

AI wishes to acknowledge the support of DoE-NETL's SCNG through co-funding this work under contract #DEFC26-02NT41320. In addition, we also wish to thank NGA for co-funding this effort through NYSEARCH under a separate fund-matching (cash and in-kind) contract.

Special thanks go to (a) ConEd and Mr. Anthony Hranicka, (b) Keyspan Energy, Inc. and Mr. Joseph Vitelli and (c) Niagara Mohawk (now National Grid) and Mr. Joe Santaro and Mr. Thomas Picciott for facilitating, managing and supervising the extended field-trial of the ***GasNet™*** system.

2.0 Patenting

The ***GasNet™*** system concept was filed with the USPTO and under the PCT. The USPTO has issued a patent, filed as No.# 6,778,100 (see Figure III-37). Worldwide patent protection is still pending, with a european patent issued (EP# 1373783 B1), but not yet published.



US006778100B2

(12) **United States Patent**
Schempf

(10) **Patent No.:** **US 6,778,100 B2**
(45) **Date of Patent:** **Aug. 17, 2004**

(54) **CONDUIT NETWORK SYSTEM**

(75) Inventor: **Hagan Schempf**, Pittsburgh, PA (US)

(73) Assignee: **Automatika, Inc.**, Pittsburgh, PA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **10/383,114**

(22) Filed: **Mar. 6, 2003**

(65) **Prior Publication Data**

US 2003/0167919 A1 Sep. 11, 2003

Related U.S. Application Data

(60) Provisional application No. 60/362,131, filed on Mar. 6, 2002.

(51) **Int. Cl.**[7] **H04Q 9/00**

(52) **U.S. Cl.** **340/870.07**; 340/870.11; 73/861.23; 73/861.77

(58) **Field of Search** 340/870.07, 870.11; 73/861.23, 1.16, 1.35, 14, 861.77; 137/825

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,674,338 A * 6/1987 Carpenter 73/861.77
5,004,014 A * 4/1991 Bender 137/624.12
5,502,652 A * 3/1996 Hoggatt et al. 702/136
5,636,653 A * 6/1997 Titus 137/14
5,838,258 A * 11/1998 Saar 340/870.11
6,654,697 B1 * 11/2003 Eryurek et al. 702/47

* cited by examiner

Primary Examiner—Timothy Edwards
(74) *Attorney, Agent, or Firm*—Webb Ziesenheim Logsdon Orkin & Hanson, P.C.

(57) **ABSTRACT**

A conduit network system includes at least one, and typically multiple, node elements in communication with an inner area of a conduit, which is used to transfer material therein. The node element can receive, process and communicate data signals that are representative of user-desired information. A system control mechanism is in communication with the node elements and receives the data signals from these node elements. A method for communicating data in a conduit system is also disclosed.

33 Claims, 18 Drawing Sheets

Figure III-37: GasNet Patent #6,778,100 Cover Page