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PIPE CRAWLING INSPECTION ROBOTS: AN OVERVIEW

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Abstract - Pipe Crawling Inspection Robots (PCIRs) are playing an important and expanding role in Remote Testing and Inspection of 4 in. to 8 ft. diameter pipe. PCIRs provide the power, process and pulp industries an economical and time-saving approach to inspection of insulated, buried or inaccessible pipe.

Three locomotive mechanisms of PCIRs, commonly-employed Non-Destructive Testing (NDT) Sensors and techniques, as well as field deployments are discussed in this paper.

INTRODUCTION

Robots can be thought of as computers equipped with sensors, instrumentation, and mobility to interact with the environment. Most current models crawl on treads or maneuver on wheels under the guidance of a human operator employing remote-control via a communications and power tether. Some are mobile underwater, while some are amphibious. Several emerging models even walk in a manner similar to the gait of insects.

Robots encompass several technologies, and will evolve as rapidly as advances occur in computer systems, electronics and motion controls. Miniaturization of cameras, high torque motors and integrated circuits allow designers to create very small-scale models.

Most of today's robots are used for inspection, surveillance, and monitoring tasks in utility work areas. Some current applications are listed below.

- Remove humans from potentially hazardous work situations;
- Allow inspection of inaccessible and/or hazardous equipment or work areas;
- Provide on-line inspection/maintenance without loss of equipment/plant availability;
- Provide information about the health and condition of critical plant components to facilitate decision-making regarding plant life management;
- Reduce equipment/plant downtime;
- Improve maintenance & inspection procedures through better coverage & documentations.

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Robots are being used successfully in nuclear and fossil power plants, and in electric and gas energy distribution. Significant resultant savings to users are often realized within one year or less of purchase.

Public Service Electric & Gas (PSE&G) Company reports $2 savings in O&M costs for every $1 spent on robotic hardware. Additionally, many users report savings of $50,000 or more for each robot purchase.

Tomorrow's advanced generation of robots will have more "brains on-board," with the ability to perform actual maintenance tasks. Designed with built-in artificial intelligence, they may prove invaluable to industry, being used throughout entire energy generation and delivery systems.

Interestingly, a recent survey of utility and robot vendors identified pipe crawling robots as one of the largest current applications. Of 192 areas surveyed, 33% were pipe inspection applications. (Figures 1 & 2). This paper discusses pipe crawling robots and highlights several new applications.

Robots and Pipe Systems

Every utility, whether electric or gas, hydro, nuclear or fossil fuel, has its share of piping systems. Regardless of the materials, fluids, or gases carried through them, piping systems have a limited life cycle. They are vulnerable to, and are often damaged by vibration, shock loading, thermal cycling, corrosion, cracking, pitting, joint failure, etc.

Equipment damage and plant outage costs resulting from the above can be minimized if (1) utility engineers can better anticipate failures or, (2) a method is available for more timely, comprehensive inspection of piping system interiors.

One method of pipe inspection involves insertion of a borescopic/fiber optic device linked to a TV camera to view a selected pipe area. Another involves insertion of push rods with a camera attached to the end for inspection of a longer length of pipe. Not long ago, small power plant workers even crawled into pipes for welding, grinding, cleaning, inspection, and retrieval.

These methods, while useful, are incomplete. With robots, inspections of entire piping systems are now possible, exposing previously undetected faults and potential problems.

Current technology allows robots to be built small enough to traverse pipes with diameters of 4 in. or greater. Advances in technology will soon enable robots to enter diameters as small as 2 to 3 inches. Micro-robots, like those under development at Massachusetts Institute of Technology and other academic centers, may, within ten years, traverse pipes as small as human arteries.

Most pipe crawling robots easily negotiate level pipe runs, and can climb and descend pipes with inclinations of 30 degrees or less. Vertical pipe runs are more difficult to achieve and few robots today perform this feat.

Robots may also have difficulty maneuvering through pipes with sharp 90 degree turns or those with "T" and "Y" sections. Often, the robot's shape and size is the most critical factor in determining maneuverability.

Properly-designed pipe crawling robots should include:

- a quality camera and TV for image viewing;
- variable lights to illuminate pipe interior;
- a reliable method of mobility;
- a communications and power tether;
- a fail-safe method of manual retrieval;
- videotaping capability of camera images; and
- a user-friendly control console for the human operator.

Future robotic devices will include:

- all-interior pipe terrain maneuverability;
- miniature tongs and grippers for material sampling;
- non-destructive testing probes;
- maneuverable camera angles; and
- work packages like welding/coating applications/grinding /machining/tooling, etc.

Today's and tomorrow's robots can survive prolonged immersion in fluids and/or high radiation fields.

Pipe Crawling Inspection Robots (PCIRs)

PCIRs are moderately complex machines, usually controlled remotely (tele-operated) via an umbilical cable. Since PCIRs are not autonomous, they do not fit the true scientific definition of a robot. However, the term "robot" has become more loosely interpreted as recently-developed machines fall into the grey area between remote tooling devices and the R2D2s we envision from Hollywood.

A generic PCIR consists of the following components:

- Sensor(s)
- End effector (tool)
- Vehicle
- Umbilical cable & take-up reel
- Control console

These component systems must be integrated and matched into a general purpose or application-specific PCIR. The design and engineering of PCIRs, therefore, consists of balancing size, weight, reliability, and cost and feature/benefit variables.

Figure 3 shows a typical pipe crawler designed for 12 in. and larger diameter pipe, weighing 75 lbs. with an 1100 ft. tether. This machine has been applied to numerous electric utility inspection applications.

Sensors and Camera Systems

The PCIR's primary objective is to deliver its on-board sensor into a pipe. Sensors vary from simple thermocouples to more advanced NDT probes, such as ultrasonic or eddy current devices.

Almost all PCIRs carry a miniature CCTV camera for real-time feedback of the robot's path to enable operators to navigate towards and locate the targeted inspection zone. The CCTV camera can also serve as the primary inspection device.

Current video technology, via the solid-state CCD (charge couple device), permits a broadcast quality (350 H lines) color camera, about the size of a roll of dimes, to be mounted on the robot.

Focusing is accomplished remotely with a small (10mm dia) D.C. motor and gear head attached to the cameras lens. On-board lighting is usually provided by several miniature halogen lamps from 4 to 35 watts each. By mounting the camera & light source on a pan & tilt mechanism, the robot can "look" up, down, left and right thereby increasing the inspection coverage. Figure 4 shows a miniature PCIR with full pan & tilt capability.

Important to note is that reflectivity of pipe I.D. wall surfaces varies considerably in both color and texture. These surfaces are often unpredictable and can change even within the same piping system. Obtaining high quality, color-correct video images from a pipe I.D. is contingent on adequate, directional light since color CCDs function poorly otherwise. Figures 5a, 5b, & 5c are photos of a monitor screen showing a pipe I.D. condition.

The first serious design compromise involves balancing lighting needs as a function of pipe diameter with size, wattage, heat, power requirements and tether/cable gage, size and weight.

Ultrasonic Sensors are now finding their way on board PCIRs. They can be applied to wall thickness profiling or flaw detection, such as crack detection in welds or base metal.

Because of the intricacies and pitfalls of performing remote ultrasonic testing (UT), in this area especially, robot designers must work closely with experienced NDT personnel. While mounting a UT probe on a robot is simple, making accurate, reliable thickness measurements remotely is not. Maintaining acoustic coupling, probe perpendicularity while having a smooth, clean surface to measure from are major pitfalls of remote UT thickness measurement. Those familiar with hands-on UT weld inspection know that performing this task remotely is difficult at best. Accurate positional feedback from the transducer coupled with the precision with which the probe must be controlled places tight demands on the robot.

Other Sensors can include, but are not limited to:

1. Eddy Current: Can help locate welds in pipe for further NDT.
2. Radiation: Can be used to plot radiation levels in a room or pipe prior to human access.
3. Temperature: Measure temperature in a pipe.
4. Humidity: Measure humidity in a pipe.
5. Pitch & Roll: Can help determine if a waste or drain pipe has sufficient pitch for gravity draining. A roll sensor can warn the operator of the vehicle tipping over.
6. Location Sondes: Transmits a low frequency sonic pulse which can serve to trace an underground pipe.

Remote tooling is a rapidly-expanding area of PCIR accessories. These attachments enhance the value and performance of robots and allow work-like operations to be performed, including:

- Welding, cutting, drilling
- Retrieval and material sampling
- Pipe relining or repair
- Pipe cleaning

A detailed discussion of these various sensors and tools is not included in this paper.

<u>Vehicles</u>

Locomotion is accomplished through any one or combination of 3 ways:

1. Tractor/Truck type
2. Propulsion
3. Clamp & Pull

Each mechanism represents advantages and disadvantages and must therefore be selected on a per-case basis.

Tractor-type vehicles are the most common PCIRs and generally use 4-6 wheels or tank threads for traction/locomotion. In order to generate sufficient "pull" to drag the desired cable length, vehicle weight, power and speed must all be considered. Tractor-type vehicles are built to fit pipes of 4 in. ID and larger models capable of pulling several thousand feet of tether. Figures 3 and 4 are examples of tractive-locomotion PCIRs.

Propulsion- or propeller-driven PCIRs are used exclusively in submarine type vehicles or ROVs. Commercially available models fit into 24 in. ID or larger pipes with cable tethers up to 500 ft. Submarines can generate up to 10 lbs. of pull, but must be used in totally submerged pipe.

Water clarity is an important factor in the use of propeller-driven PCIRs in that floating particles and murky water render navigation and video inspection difficult to impossible. A typical submarine is shown in Figure 6.

Clamp and Pull devices are the newest class of PCIR. They can create the greatest amount of power inside pipe and can therefore pull the most cable. More complex than tractor or subs, they require more motion-control logic (Figure 7), are more application-specific, and cover a narrower range of pipe diameters.

Figure 8 shows a typical "Clamp & Pull" PCIR with color pan and tilt video and ultrasonic sensor for 12-24 in. diameter pipe. Some PCIRs contain more than one means of locomotion; e.g., submarines with tracks or clamping devices with tracks. Combining several features can improve versatility.

<u>Cable/Cable Reel</u>

Most PCIRs are powered and controlled via a tethered cable or umbilical, usually delivering the following functions:

1. Power (AC,DC, Pneumatic or hydraulic) to the PCIR for locomotion, sensors, video and lighting.
2. Control signals for speed, steering, focussing, pan and tilt, etc.
3. Sensor signals, eg RS-170 video and positional signals, back to the control console.
4. Safety tether or strength member to assist retrieving the PCIR in the event of power loss, control problems or mechanical jamming. A plastic protective jacket such as polyurethane is used generally to waterproof the cable and provide a smooth surface for dragging.

A typical cross-section of robot cable is shown in Figure 9. Proper cable design and fabrication is critical to successful performance of PCIRs. Variables such as jacketing material, hardness, thickness and weight, strength member sizing, and electrical shielding must all be considered. On long tether (>500 ft.) PCIRs, cable drag due to weight and friction must also be considered. Various electronic techniques such as multi-plexing signals and/or fiber-optics for data and control signals will help minimize diameter, weight and resultant cable drag.

Slip-ring type cable reels are essential for systems with cable length greater than several hundred feet. Slip-ring cable reels allow better cable management shipping and handling.

<u>Control Unit</u>

Most robot functions and sensor feedback are processed and controlled at the control console control unit. Joystick control for steering and diving is user-friendly and minimizes operator fatigue. Control units on larger more advanced PCIRs can have safety interlocks to prevent human error. PCs with motion control cards and software are also being applied as control consoles.

Field Deployments

Figure 10 shows variables and results of 14 separate field deployments from March 1990-March 1991.

Justification of a PCIR System

The use of PCIRs represents significant advantages, discussed below.

Mandated inspections of nuclear power plants usually require robotic inspection devices to minimize or eliminate radiation exposure to humans. Operated at safe distances from contaminated sites, robots effectively minimize radiation exposure. However, used in highly contaminated areas, they require special cameras and radiation-hardened electronics which can increase cost.

When performing hazardous inspections, personnel may be more concerned about personal safety than a thorough inspection. Due to the robot's small size and flexibility, many dangerous and previously uninspectable tasks can be performed.

Inspections also tend to be subjective. Repeated inspections, unless performed by the same person, may be difficult to compare. Video images produced by PCIRs can be viewed by inspection personnel in real time, or later in an office environment. Results of a critical inspection can then be jointly analyzed by a group. The video tape also provides a permanent record that can be reviewed and compared to future inspection results.

PCIRs also have the ability to retrieve lost parts. Manipulators can be attached to the robot for pickup of various objects. Its jaws can be made magnetic for ferrous objects. Serrated jaws can be used for odd shaped or soft objects. Retrieval tools are positioned with the aid of the video camera. Contaminated objects can also be retrieved with minimal human exposure.

Additionally, PCIRs have the special ability to function in an on-line working environment. Constant monitoring can be performed whether the robot is in a pipe with flowing water or an operational reactor drywell.

Finally, additional telemetry or sensor systems placed on the PCIR can monitor various sections of the pipe concurrently. Movement of valves and other internal parts can be viewed during normal operation.

CONCLUSIONS

PCIRs, though still in early development stages, have proved invaluable to inspection of plant equipment and piping at nuclear, fossil and hydroelectric power stations. PCIRs offer more comprehensive inspection, improved safety and plant reliability, and help solve maintenance and operation problems economically.

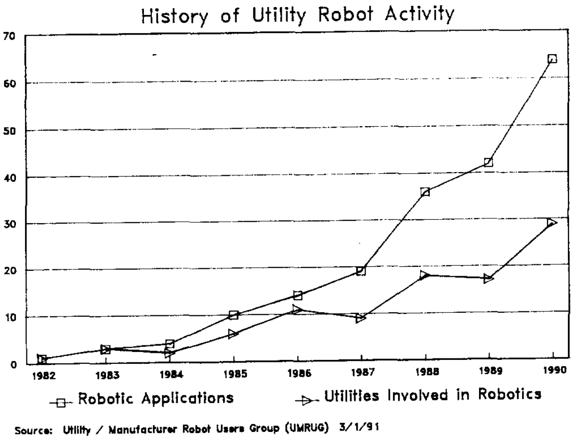

Figure 1

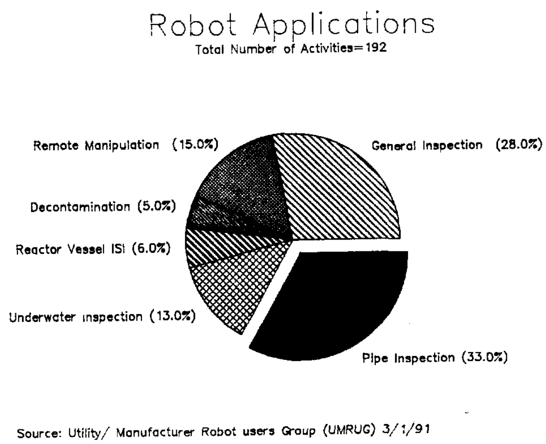

Figure 2

Figure 3: Track-type PCIR with monitor & VCR.

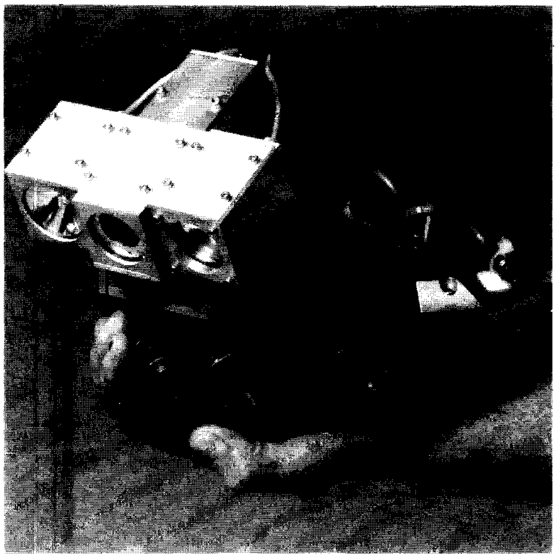

Figure 4: Miniature PCIR with Pan & Tilt feature

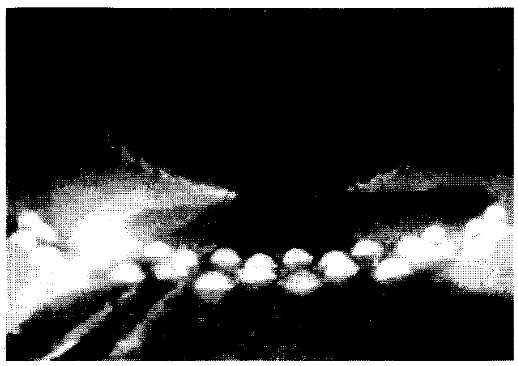

Figure 5a: Monitor display of 8 ft. diameter hydro-electric penstock.

Figure 5b: Cement-lined service water line.

Figure 5c: Gap in reinforced concrete pipe joint

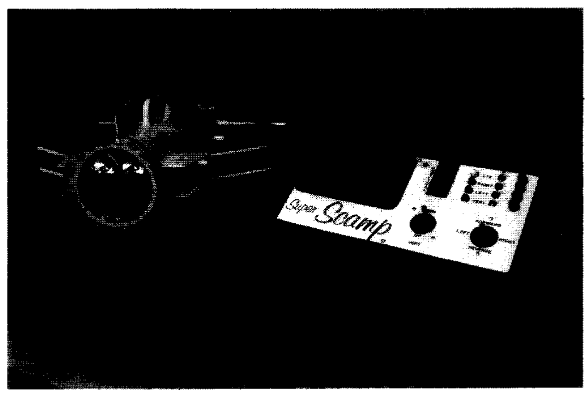

Figure 6: Typical propulsion driven submarine

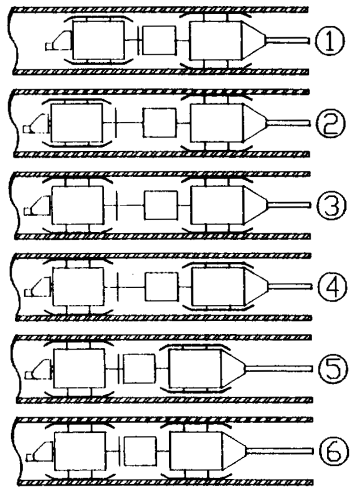

Figure 7

1) Rear clamp engages with pipe wall & front clamp releases.

2) Drive piston extends the vehicle 1"-5" with up to 500 lbs. of force.

3) Front clamp unit engages with pipe wall.

4) Rear clamp unit releases.

5) Drive piston contracts vehicle to

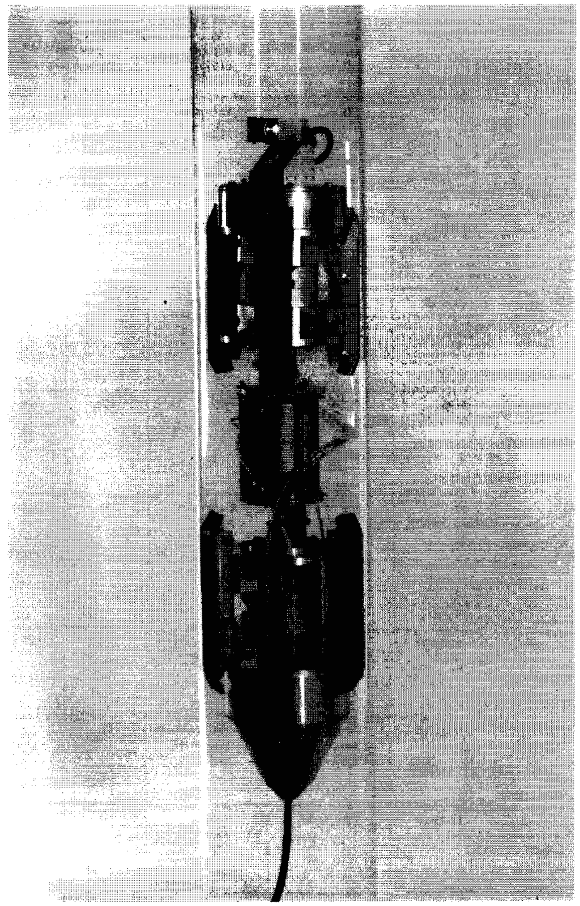

Figure 8: Vertical PCIR

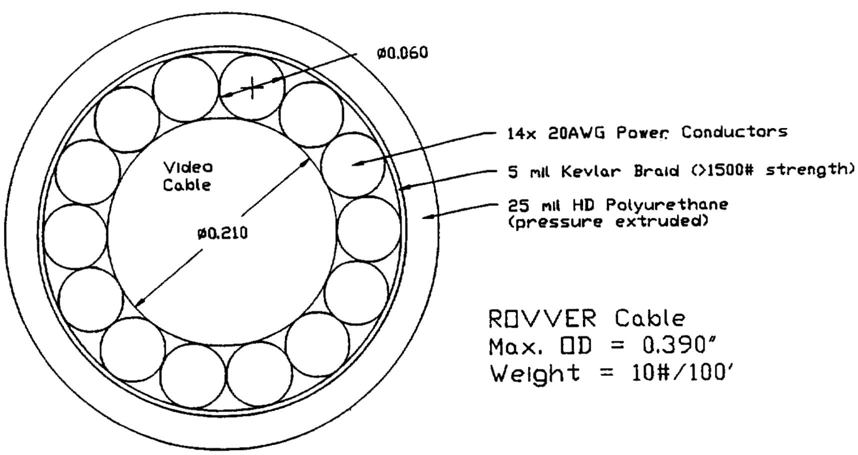

Figure 9: Typical PCIR tether cable.

Date	Customer	Site	Pipe Dia.	Length	# of Elbows	Findings / Results	Inspection Device	Plant Type
3-29-90	Commonwealth Edison	Zion Nuclear Power Plant	16" access way	20'	—	Remote Visual Inspect. of reactor head CRD canopy seal welds.	ROVVER	EN
4-21-90	TVA	Lexington, Tennessee	18"	450	1-45°	Inspection of a water main buried underneath an earthen dam. The cast iron pipe appeared to be in good condition.	SPOT	W
4-30-90	LILCO	Northport	4"	12'	2-180°	Remote Visual Inspect. of main steam control valves to confirm proper operation.	ROVVER	EF
7-13-90	Brooklyn Union Gas.	Maspeth LNG Facility	8"	50'	2-180°	Inspection of L.N.G fire system pumphouse loops. Looking for break-down of concrete lining.	ROVVER	G
9-90	PSE&G*	Hudson	14"	25'	—	Inspection of high voltage gas insulated bus duct. The robot was able to navigate under the center conductor.	ROVVER	EF
10-4-90	Law Environ.	Commercial Building	18"	3500' done in 500' intervals	—	Inspection of a buried concrete drain pipe. A location finder was used to track the robot because depth and direction of the pipe was unknown.	SPOT	E
10-16-90	Duquesne Light	Beaver Valley Nuclear Power Plant	14"	55'	2-90° 1-45°	Inspection of heat exchanger tube sheet. ROVVER navigated two 90° and one 45° elbows to gain access to the tube sheet.	Pan & Tilt ROVVER	EN
10-22-90	Consumers Power	J.H. Campbell West Olive, MI	10"	25'	3-90°	Remote Visual Insp. of feedwater heater valves. Erosion was found on the valve seat area.	ROVVER	EF
10-23-90	Duke Power	McGuire Nuclear Station	12"	400'	1-180° 1-90°	Inspection of air inlets to check for blockages and proper operation of remotely operated check valves.	ROVVER	EN
11-1-90	Pennsylvania Power & Light	Wallenpaupack Station	8'	500' (60-70°) Downward grade	1-45°	Rivets on the inner pipe dia were inspected, as well as general pipe conditions. Previously, a man with a safety harness was lowered.	SPOT	
11-7-90	Longview Inspection*	Baton Rouge Mississippi River X-ing	40"	520	1-45°	Inspection of Gasoline pipe to look for damage to pipe. A buckle in the pipe was found approx. 500' in. Damage occurred during installation.	SPOT	G
11-26-90	Caroline Power & Light	Brunswick Nuclear Power Plant	24"	70'	2-90°	Inspection of concrete lined service water line. No problems were found in the inspected area.	SPOT	EN
1-10-91	Virgin Island Water & Power	St. Croix Station	24"	180'	—	Remote Visual Inspect. of storm drains. Axial cracking and blockages were found.	SPOT	EF
3-15-91	Con Edison	Indian Point Station II	22"	Two pipes 300' & 139'	2-3	Inspection of concrete lined service water line. A damaged section of pipe was remotely repaired with a Remote Pan & Tilt camera system supplied by VIT.	SPOT & RPT-200	EN

Plant Type Legend
E - Environmental
EF - Electric Utility - Fossil
EH - Electric Utility - Hydro
EN - Electric Utility - Nuclear
G - Gas Utility
W - Water Utility

Figure 10

BIOGRAPHY

Bruce A. Pellegrino was born in Paterson, NJ on December 10, 1955. He attended New Jersey Institute of Technology in Newark NJ from 1976 - 1979.

From 1979 - 1983 he worked as a technical field representative for Panametrics Inc, Waltham MA. in the area of Ultrasonics for NDT applications. From 1984-85 he was Engineering Manager for Diaguide Inc, A Subsidiary of Mitsubishi Cable Co. in the area of radiation resistant fiberoptics. In 1985 Mr. Pellegrino co-founded Visual Inspection Technologies, Inc. (VIT) as an NDT company specializing in remote viewing, field services and robot development.