ISPIR

Intelligent System for Pipeline Infrastructure Reliability

Overall System Specifications

(Version 1.0)

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1 PURPOSE OF THIS SPECIFICATION

This document outlines the definitions, specifications and features of the ISPIR Intelligent System for Pipeline Infrastructure Reliability. It is a guideline to define and help to modularize the design for progressive implementation phases of the system. This first section presents an introduction to the system and its context**.** Subsequent sections are provided for each major system component including:

- Fiber-optic strain measuring systems
- Communications and knowledge-based data interpretation and pipeline condition diagnosis subsystem
- Corrosion monitoring subsystem

Each of these modules is described in separate sections of this overview document. A general survey of the status of inspection technologies is included in Section 5 of this report.

1.1 ISPIR Overview

ISPIR is a multifunctional system for monitoring pipelines in the field using currently available sensing and communications systems, including FOX-TEK fiber optic sensors, the CANMET Microbiologically Influenced Corrosion (MIC) sensor and chemical sensors to measure pH and CO_2 concentration. It incorporates an Internet-based communications system that provides the pipeline stakeholder community with instant information of the current status of the pipeline and alerts the operators of abnormal conditions. It also incorporates a knowledge-based data interpretation and condition diagnosis capability that integrates sensor data with operating context information for automated data interpretation and decision making.

This system will be integrated into a flexible and cost-effective fiber optics backbone. It adapts current technology for continuous pipeline monitoring to detect:

- Microbial activity
- Corrosion, including microbiologically influenced corrosion (MIC)
- Temperature changes
- Pressure changes
- Leaks
- Buckles
- Bends
- Cracks
- Pipe movement

ISPIR technologies are applicable to both oil and gas pipelines, old and new, transmission and production, large and small diameter, and will contribute significantly to the resolution of issues affecting critical infrastructure security. It is equally applicable to other process lines, slurry and tailing lines and water mains. The integrated ISPIR monitoring system monitors multiple types of strain and chemical sensors. Fiber-optic monitoring is immune to electromagnetic noise that affects electronic communications and sensing systems, and is low cost. The data returned by the system are rich in information and will be communicated to a data management system for interpretation and decision-making. The communication system will include the capability for data acquisition/management and decision-making based on data provided by these sensing systems.

The ISPIR system serves a community of users. Generally this community comprises a number of users within the owner/operator organization that operates the pipeline. In addition to the data input from ISPIR strain and corrosion sensors, ISPIR can accept parametric data from other sources in the owner/operator organization such as operating pressure and flow rate.

2 SIM-O-IP: STRUCTURAL INTEGRITY MONITORING OVER IP

This document outlines the definitions, specifications and features of the TISEC system for Structural Integrity Monitoring over IP (SIM-o-IP) system. It is a guideline to define and help to modularize the design for progressive implementation phases of the system. This chapter presents an introduction to the system and its context.

2.1 Scope of the SIM-o-IP Specification

This section defines the requirements and specifications for the TISEC SIM-o-IP system and its users. The intended audiences for this document are:

- The SIM-o-IP system users, so they may review and provide input into the requirements.
- The system design team, as this document will serve as the basis for system design.
- The test team, as this document will serve as the basis for system verification and validation.

In Section 2, a general description of the TISEC SIM-o-IP system is given. Section 3 describes the ConnectionAgent, an intelligent agent designed to perform all the functions required of SIM-o-IP. Section 4 describes system access and the Web-based communication system. Section 5 positions SIM-o-IP relative to other products and system for remote data acquisition and instrumentation control. Specific applications such as ISPIR and SWIM are described in their respective appendices. Detailed technical specifications for system components are also described in appendices.

This document also reviews the current status of the various SIM-o-IP components in its periodic updates.

2.2 Acronyms

DAS	Data Acquisition System
ISPIR	Intelligent Systems for Pipeline Infrastructure Reliability
KIF	Knowledge Interchange Format
KQML	Knowledge Query and Manipulation Language
SWIM	Stress Waves for Intelligent Manufacturing/Maintenance
IP	Internet Protocol
SIM-o-IP	Structural Integrity Monitoring over IP
UML	Unified Model Language
VPN	Virtual Private Network
P2P	Peer-to-Peer

2.3 General description

This section specifies the system capabilities and functions, identifies who the users are and outlines the general constraints of the overall system and the assumptions and dependencies considered for the system. The TISEC SIM-o-IP system meets a twofold requirement in new structural integrity inspection and monitoring systems:

- To more fully exploit the data generated by such systems
- To integrate more advanced interpretation and decision-making capabilities into the systems

An additional requirement in new systems is to acquire data by several means and to distribute these data as well as interpretations and decisions based on them to the parties involved in follow up actions, particularly in a systems maintenance context. It will also permit us to install and evaluate the system at field sites in the immediate future.

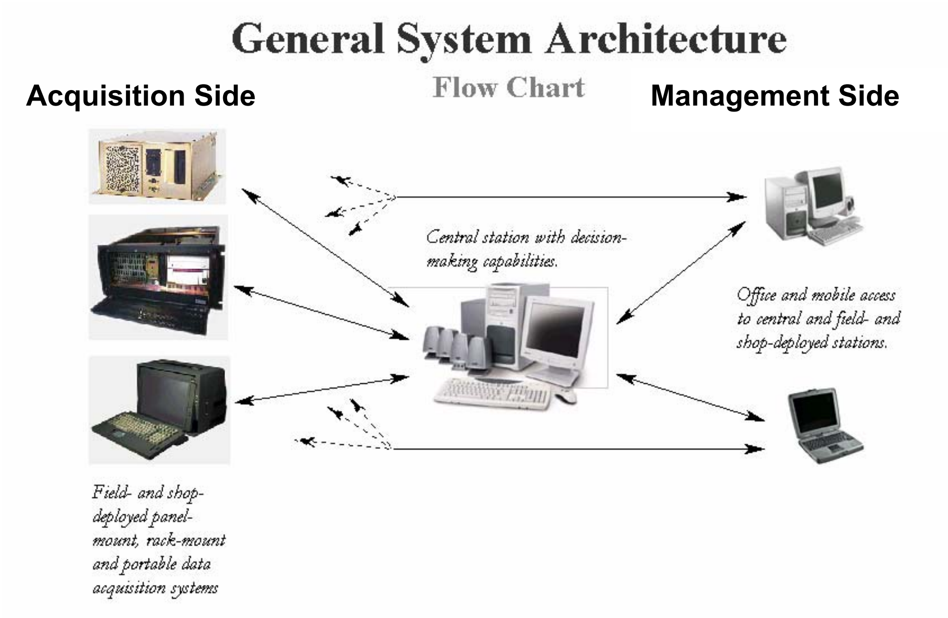
The SIM-o-IP system provides the communications component in this emerging inspection and monitoring environment and integrates it with artificial intelligence methods for data interpretation and decision making.

2.3.1 System capabilities

The requirement for remote communications with structural integrity monitoring systems is becoming widespread and almost universal. The SIM-o-IP system has two features that build upon unique TISEC expertise:

- Internet communications expertise ⇨ Intelligent Internet Interface
- Artificial intelligence expertise ⇨ Knowledge-Based Interpretation and Diagnosis

The general system architecture of the SIM-o-IP system is shown below with an ensemble of data acquisition devices serving a user group. A central station provides the system intelligence.



SIM-o-IP is a web-based real time, distributed computerized system to monitor and control remote on site testing with an intelligent capability for condition identification and fault diagnosis. The acquisition side can perform a variety of test services, including

- fiber-optic strain measurement
- corrosion monitoring
- ultrasonic thickness measurements
- flaw detection and weld inspection
- acoustic emission monitoring

The acquisition side sends

- current real-time data
- alerts of abnormal testing results

to the central station for processing and analyzing.

Customers at the management side can

- monitor the on site testing for current real-time data
- send instrumentation setup commands to the acquisition stations
- perform operational checks on acquisition side components and the communications network
- access the central station for decision support

The central station can

- provide basic system maintenance
- provide continuous monitoring
- send instrumentation setup commands to the acquisition stations
- perform operational checks on acquisition side components and the communications network
- provide decision support through data interpretation in its knowledge-based system

Access of each user will be controlled on a function-by-function basis by allocation of passwords.

2.3.2 System users

The system is accessible to several different levels and types of users. It assumes that all user groups have the required level of knowledge or training to navigate through Web pages or how to use this application software. The interfaces are developed in such a way that the system will be intuitive to use. Users with minimal familiarity with the Web will be able to navigate successfully through the system.

The users of the system are divided into following groups

1. General user
2. Owner/operator
3. Monitoring system contractor
4. System operator and monitor
5. Regulatory observers

General User

General users are those people that don't need a password to view the information in the web site. Actually, everyone who has access to Internet can be treated as "general user". Since information available from the data acquisition side and the central station will be proprietary and set up of the acquisition-side instrumentation limited to authorized users, general users will be blocked at the site welcome page through password-protected access. There may be public information at the site available to the General User.

Owner/Operator

The owner/operators of the system, structure or machine being monitored can access the system to monitor its current status, respond to alerts sent by the acquisition system, and to access condition and diagnostic reports and recommendations. Depending on the specific system, they may have access to the data acquisition system for set up and system control.

Monitoring System Contractor

Monitoring system contractors are the suppliers and installers of the data acquisition instrumentation. If their role extends to in-service system operation, the contractor will have access for system set up and control.

System Operator and Monitor

The system operator and monitor is a user responsible on-going operation of the system including maintenance and any manual interventions. This user monitors the running of the system and may be designated from either the owner/operator or monitoring system contractor user groups.

Regulatory Observers

During the project development phase, observers from regulatory agencies may participate and have access to the system to observe system performance and the type of information generated.

Within each user group the following type of interests can be accommodated:

- Structure owner/operator
  - ✓ Quality control personnel
  - ✓ Operations personnel
  - ✓ Maintenance personnel
  - ✓ Management personnel
- Monitoring system contractor
  - ✓ Field personnel
  - ✓ Engineering personnel
- Regulatory Observers
  - ✓ Engineering personnel
  - ✓ Management personnel

The user categories for specific projects are described in their respective appendices.

2.3.3 Acquisition-Side Configuration

Acquisition-side instrumentation is deployed at field and shop sites where structures and machines are being monitored. The instrumentation configurations may include

- Stand-alone bench-top instrumentation units
- Field- or shop-deployed panel-mount units
- Field- or shop-deployed rack-mount units
- Portable units

The back end of each acquisition unit is Internet-capable and PC-based operating under Windows. Data are stored digitally and available for access by the SIM-o-IP component placed on the acquisition unit. SIM-o-IP accommodates various modes of communication from land links to wireless including:

- Phone land line through dialup or continuous access
- Access through corporate LAN
- Phone cellular dialup access
- Phone satellite dialup access
- High-speed on-line access

In addition to establishing conventional remote access links, SIM-o-IP fetches specific data from the data acquisition system for transmission to the central station and other users. It also examines the data for trends and thresholds that serve as a basis for alerting users of abnormal conditions requiring attention. It provides conventional remote access capabilities for complete instrumentation control.

This is achieved by putting an intelligent agent designated as the *ConnectionAgent* on each computer in the network. The intelligence available at the acquisition side will monitor trends and thresholds and reduce the data storage and transmission requirements during continuous monitoring, particularly when the data link for continuous data transmission is prohibitively expensive.

In environments where a continuous link is feasible, acquisition-side instrumentation will be linked continuously to the central station and, on demand, to other users. Where continuous on-line connection is not feasible, the *ConnectionAgent* will detect trends and thresholds that correspond to anomalies that require decision support and will dial in to establish a connection. Once connected all normal interactions with the central station and other users will be available.

2.3.4 Management-side configuration

The link to from management-side users is made on demand using the standard ISP access mode normally used at the user organization. The management-side user can access and display current raw data from the acquisition instrument, alerts from the acquisition instrument and the central station and condition evaluation and diagnostic reports from the central station. The complete failure analysis knowledge base available at the central station is also accessible.

2.3.5 Central station configuration

In addition to the normal data display functions available at all user monitoring sites, the central station hosts the main functions that include

- a redundant self-checking and verification system to confirm warning signals and recommendations for maintenance follow ups
- knowledge-based condition evaluation and diagnostic tools
- the Web site

The SIM-o-IP knowledge-based component provides an "intelligent" capability to address potential data overflow resulting from continuous monitoring of structures. It also combines information rich data with complementary knowledge about the environment and operating conditions to assist in fully exploiting the data is applied to the interpretation. The control station has software for interrogating the data acquisition system and extracting information for potential system fault identification and necessary remedial action using thresholding and trend analysis. The central station is a standard PC that host data and knowledge management software for diagnosing potential long-term trends in the structural response of pipeline sections to permit early detection and risk analysis of potential failures. It is an interactive, open tool capable of interfacing with the sensing system and pipeline maintenance personnel.

The knowledge-based system accepts data from acquisition-side instruments and domain context information on the operating and external environment of the system being monitored. The system is built by formalizing knowledge representation and sharing using evolving ANSI and ISO standardization efforts to ensure compatibility with the current state of the art for future system expansion. System functions will be encapsulated in intelligent agents to facilitate system management and evolution. With this system architecture, the system can grow as in-service knowledge and experience accumulate.

The heart of the knowledge system is a core competence repository encoded using a virtual representation formality for capturing and storing the core competency. The competency seed core comprises engineering knowledge on the mechanical design, materials specifications, deterioration mechanisms, and codes and standards requirements for the application. Application-specific information consisting of operating, environmental and manufacturing and construction conditions are also entered into the system. Intelligent agent flexibility facilitates future evolutionary growth through use and maintenance of the system. The specific knowledge-based systems for fiber-optic, ultrasonic, acoustic emission and corrosion condition monitoring are described in their respective appendices to this document.

2.3.6 System component availability

The TISEC system has the following constraints:

- Acquisition-side instrumentation should be running on site at all times.
- The central station should be running at all times.
- Management side users access the system on demand

2.3.7 Assumptions and dependencies

The TISEC system has the following assumptions and dependencies:

- While the system operates on a peer-to-peer basis, it is conveniently envisaged as a central station hosting the intelligent component for condition identification and fault diagnosis
- acquisition side requirements could be quite different depending on whether fiber optics, ultrasonics, acoustic emission, corrosion condition monitoring or other sensing methods are used.
- the users can access the system through the Internet from office computers or mobile devices. Their computer or devices can be ordinary computers with low computational and process ability or can be powerful ones. In fact, the system shall be platform independent and accessible by any Java-enabled browser
- user Internet access can be quite different from dial-in to high-speed ADSL or VPN.
- there could be a firewall at the customer side
- there is a firewall at the central station.
- the central station should be able to cope when more than one acquisition system sends data to central station.
- the communication modes between the acquisition side and the central station can be quite different for different acquisition system; it can be dial up, wireless cellular or satellite links.

2.3.8 Attributes

Security The system is accessible via the Web. Main system functions are accessible only after the user has been authenticated. Important message can be encrypted before being transmitted among system components. The system use a data transfer method that can penetrate a firewall. The system shall keep a log file for all customers logging in.

Maintainability When the central station is down, the repair time is less than 1 hour. When the acquisition system is down, the repair time is less than 2 hours.

Usability Requirements The interfaces of the system should be designed to be clear, friendly and intuitive and use an end-user metaphor.

2.3.9 Design Constraints

Bandwidth The system should have enough bandwidth to support many customers to access TISEC system through Internet at a specific speed.

On-site testing sites The TISEC system should be able to support many testing on site simultaneously

Download time When access from browser, each page down load time shall less than 20 seconds.

Standard compliance The design will follow the UML notation, code shall comply with internationally accepted standards. The system uses KQML (Knowledge Query and Manipulation Language) as its open standard for exchanging knowledge and inter-agent communication with domain content representation languages such as KIF (Knowledge Interchange Format). These are compatible with the trends in ANSI/ISO standardization. The system shall support both Netscape Communicator and Microsoft Internet Explorer and, for DBMS, use Office XP containing Microsoft Access.

Service Requirements The system shall host a knowledge-based system for data interpretation and condition diagnosis. The system at the acquisition shall apply algorithm to identify “abnormal” data, so that only these data need to be transferred or so they can be used to trigger data transmission.

Error and exception handling The system shall log all errors and exceptions. The system shall identify all errors and exceptions. Network errors and ordinary circumstance seem the same to the central station.

Adaptability The system shall support different acquisition systems including strain gage, corrosion, acoustic emission, and ultrasonic sensing and different transmitting networks (VPN, satellite or dial in).

Flexibility The system shall be prepared to support voice and visual communication among the sites

2.4 ConnectionAgent

The ConnectionAgent is a smart agent to help the user to setup and carry out communication tasks. While the overall communication requirement in TISEC's Intelligent Internet Instrumentation could be quite complex, they can all be built on a small set of basic communication services.

The ConnectionAgent provides the following basic services

- Receive data/information from another system remotely
- Send data/information to another system remotely
- Control the field Data Acquisition System remotely
- Share data/information with peers

over different communication links. The ConnectionAgent will provide a set of unified application-programming interfaces (API) that will enable any application program to perform the tasks outlined above with minimal programming or interface effort. The ConnectionAgent should provide setup wizards to make the GUI more user-friendly and intelligent.

The ConnectionAgent will handle all the communication related setup, login, verification, encryption, hand shaking and data transmission. The ConnectionAgent is kind of a mini-server once started and it sits there and serves calls made by different programs to setup and handle the communication details.

2.4.1 ConnectionAgent - Functionalities

ConnectionAgent, as a SIM-o-IP component, acts as an interface between Data Acquisition System (DAS) and the central system hosting the intelligent component for condition identification and fault diagnosis or any peer system. It is the agent that communicates the data and control between these entities. It communicates remotely through communications media such as the Internet and thereby control and manage the remote Data Acquisition Systems (DAS). In adding remote data logging of a DAS data stream the simplest and preferred API is to just make a simple file open call and then write the entire AE data stream into it. ConnectionAgent can provide a special file handle that is linked to the target receiving machine and forward all the data write to this file handle and transmit it to the target machine without the end user worrying about how it is done. While we are not talking about using the file handle literally, nonetheless that is the kind of simple API that ConnectionAgent is supposed to provide.

Splitting the communication setup, data transfer handling, encryption and verification from the application program, provides a simple and clean interface from the application program's point of view. All the application program has to worry about is to call a function to open the communication channel and write to the open channel to send data or read from the channel to receive data. This is important, especially for the ISPIR project because many of the ISPIR partners have their own proprietary software and we don't want to get into the details of how they program their software. The simpler the ConnectionAgent API, the better for the end user.

2.4.2 ConnectionAgent - Requirements and specifications.

- Capabilities of sharing data between itself and Data acquisition System (DAS).
- Capabilities of sharing data between itself and central station or any peer system.
- Capabilities of supporting the TISEC assumptions and dependencies (2.7).
- Capabilities to act like a peer-to-peer
- Capabilities of supporting multi-connections

2.4.3 ConnectionAgent - Constraints

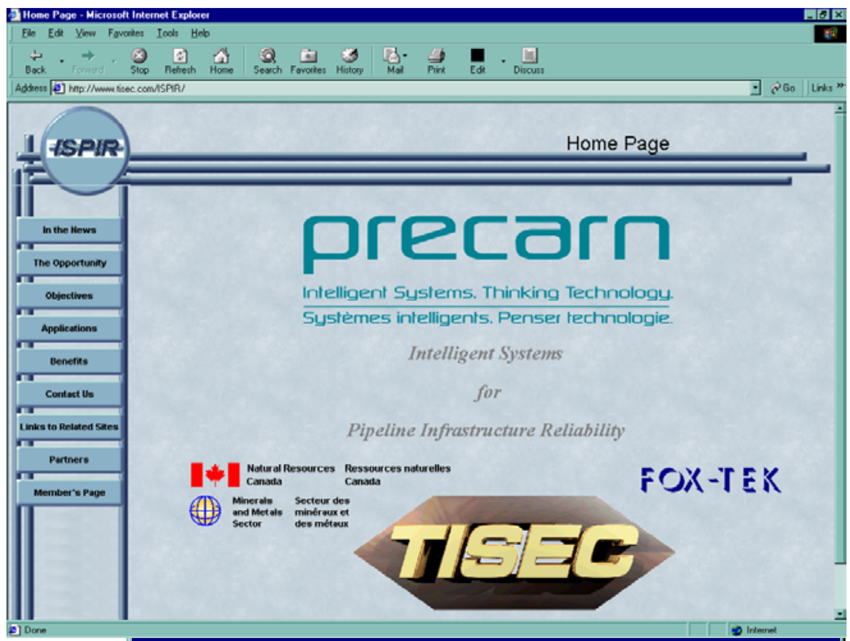
Field control and data monitoring can use different Data Acquisition System (DAS). To maintain this adaptability, the best ConnectionAgent will be a stand-alone executable application working with a specified, documented format of an accessible data/information file on the DAS. This strategy minimizes any need to modify the DAS, the central system or any peer system.

2.5 System access

2.5.1 Management-Side System Access

System access for General Users, Owner/Operators, Monitoring System Contractors, System Operators and Monitors and Regulatory Observers is through the main system portal through

- its own URL
- through links from relevant sites. These links include
  - ✓ tisec.com
  - ✓ wavesinsolids.com
  - ✓ supericepak.com
  - ✓ fox-tek.com
  - ✓ and an NRCan site



Links will direct the browsers to the main Web page for all systems being monitored at the central station. The main page for the a specific system such as the ISPIR fiber-optic monitoring system where access to pipeline monitoring applications is provided is shown below. Access to the protected part of the site is obtained by clicking on the "Member's Page" button on the left.

After entering the User Name and Password, the user accesses the Members or Users page. This page for the ISPIR system is shown below and provides access to background information on ISPIR and the ensemble of sites being monitored by ISPIR

The user selects the specific system to be queried such as an NRCan laboratory setup or a Syncrude, PanCanadian or Saudi Aramco field installation. Upon satisfying identification and password criteria, the management-side user accesses the monitoring system of interest. It contains general information for the user, this case project information, and a link to the system management page.

The system management page offers five options:

- Display current real-time data and status
- Display condition assessments, diagnoses and recommendations
- Set up or adjust instrument settings through the central station
- Set up or adjust instrument settings by direct access
- On-line help and user administration

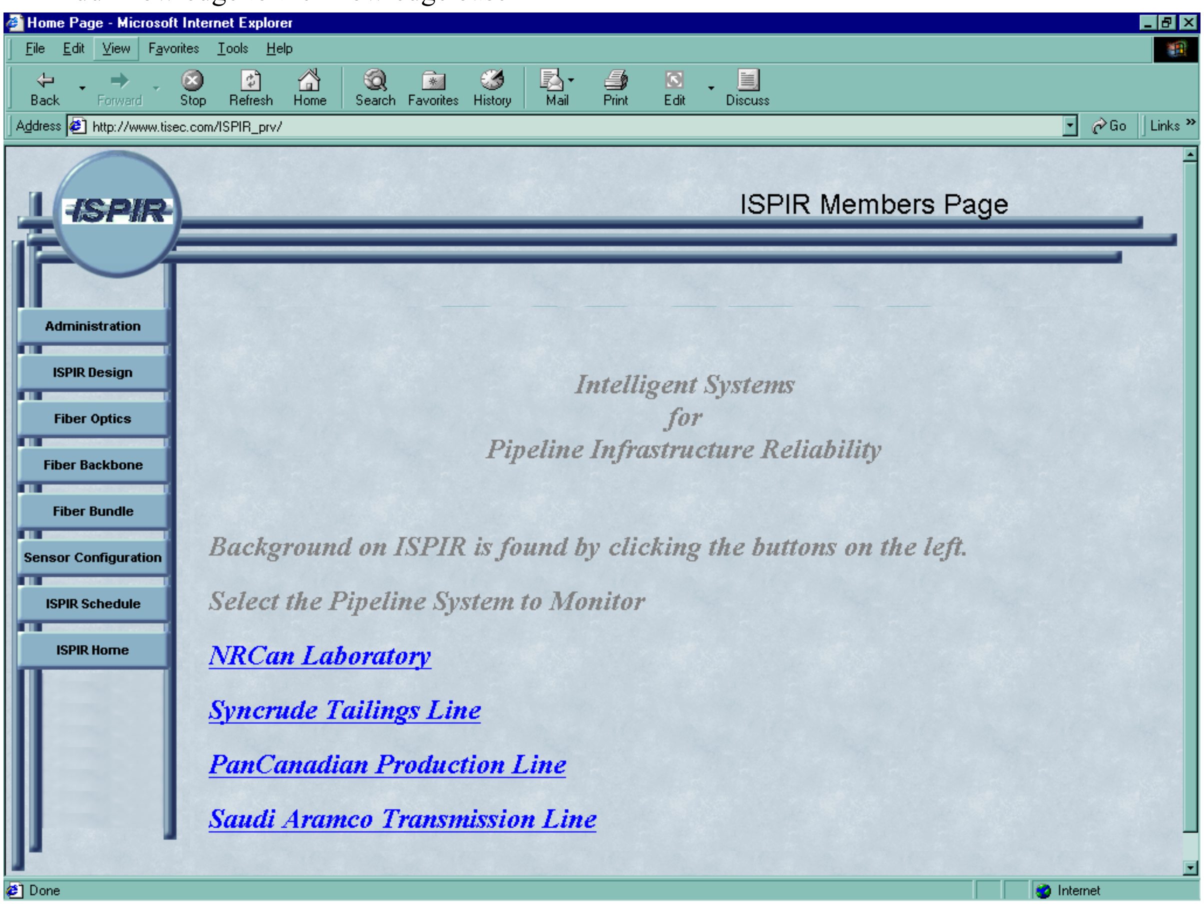
2.5.2 Central Station Access

The central station is accessed only at the host station by authorized users. For the system administrator the system provides the following functions:

- Add user account
- Modify or delete user account
- Monitor running of the system
- Set up and initialize connection

The knowledge engineer carries out the following functions:

- Add knowledge to the knowledge base



2.6 Positioning of ConnectionAgent

The ConnectionAgent has been designed to provide an enhanced capability for instrument interfacing over the Internet. Candidate commercial packages that perform some of the required functions required for TISEC systems were examined in detail to determine if they could meet TISEC requirements. Their essential features are outlined below. The products reviewed include:

- Traditional Client/Server model
- pcAnyWhere
- LapLink
- Timbuktu Pro
- WinVNC
- Windows XP professional
- Remote Desktop
- JINI
- GnuTella
- Freenet
- Others

2.6.1 Traditional Client/Server model

The Client/Server model is an application that make intensive used of the server. Any operation the client needs to be done on a remote DAS site must be passed by the server. It also does not have the possibility of directly contacting the remote DAS site without passing by the server. This method accumulates the data/information from all the remote DAS sites at the same place (i.e., the server). Later, the client can ask for data/information for its own use or the server can warn the clients that they have data/information to be fetched. The latter choice is more difficult to realize and implement because in the Client/Server method, the Server would normally wait for a request from Client and it is not really a true bidirectional communication.

2.6.2 pcAnyWhere

Symantec's pcAnywhere™ 10.5 supports all 32-bit Windows operating systems, including Windows XP. pcAnywhere lets you connect to office PCs or servers to transfer files or run applications. It's fast, secure, and provides easy remote access. pcAnywhere lets you control remote machines and manage servers remotely . With security features, including authentication methods, mandatory passwords, serialization, integrity checking, and enhanced logging tools, pcAnywhere can be safely deployed in any environment. A Web deployment tool and documentation and other popular deployment methods are included. Its design ensures high performance at any connection speed, across a wide range of connection methods-including standard modems, ISDN lines, TCP/IP and SPX networks, cable, and infrared connections.

2.6.3 LapLink

LapLink has much the same capability as pcAnyWhere as well as its PCsync 3, a file management utility that connects multiple computers. PCsync makes it easy to migrate settings, transfer files, synchronize folders, share files and even play multi-player games with another PC. PCsync 3 canremotely send and access documents on a PC from any Internet browser, via Surf Up. The Surf Up feature allows you to remotely access a computer's PCsync shared folder from any remote PC running Internet Explorer 4.0 or Netscape 6.0 or later versions.

2.6.4 Timbuktu Pro

Timkbuktu Pro for Windows 4.5 is cleaner, leaner, and more logically organized than pAnyWhere or LapLink. Timbuktu doesn't have the pcAnywhere or LapLink suite of controls, or its encryption and authentication features, but the Netopia features program can access a PC over the Net via the computer's primary e-mail address that works around a host's ISP s dynamic IP address assignment. With its Flash Notes (instant messaging) service, you can attach and send files to the other PC.

2.6.5 WinVNC

Developed by AT&T's U.K. research center for accessing in-house PCs, WinVNC is flexible, and stable, and its viewer can run on many different platforms. But it clearly wasn't written for the commercial market. Its own manual admits that it isn't very secure. You can't transfer items, sync files, or open a chat session. The program has a decent set of access and security controls, but you have to edit Registry keys to use some of them. It is not a commercial option.

2.6.6 Windows XP remote Desktop

Windows XP does have the build-in remote access mechanism called "remote Desktop". It works at some point like any other remote access software packages, but this implies that all of the machines run with this operating system.

2.6.7 Commercial Software Drawbacks

We can't rely on these proprietary software packages for development of our system because none has a programming extension that we can use to deal with TISEC's range of custom systems like ISPIR, TRADE, DynaDie and Helius. As a monitoring system domain, we need some intelligence on fetching data/information and making it available automatically to the concerned people for decision making. Since we will have to support multiplatform corporate networks this type of system will not meet the requirements. In addition, the Windows XP Remote Desktop has the additional inconvenience that all systems on the network may not be running XP.

2.6.8 JINI

JINI network technology provides a simple infrastructure for delivering services in a network and for creating spontaneous interaction between programs that use these services, regardless of their hardware and software implementation. JINI is a standard for services and devices to talk to each other primarily for a local area network (LAN). There are bridges in JINI to allow communication to a local network from another, but the path is usually to a specific service in the network. SIM-o-IP requires a technology that is less concerned with the network boundaries and less likely to target a specific device or computer. It should work locally and across the Web.

2.6.9 Gnutella

Gnutella was developed by AOL's Nullsoft division and was released as an open-source alternative to Napster. The project was canceled and AOL removed support. AOL could not support a system that allowed un-metered moving of copyrighted material. However, a community of developers outside AOL already had the source code and the project continued to grow, even spawning several commercial companies.

Gnutella was originally created as a tool to search for and transfer information. Gnutella is more of a collaboration application than it is a platform for P2P applications. Gnutella is being used to create P2P applications, but these are secondary to its original and more popular purpose of sharing files.

Gnutella compartmentalizes P2P services and each node is essentially identical. In SIM-o-IP, a peer can be a relay, a rendezvous, and/or provide a variety of network available services. This means that super nodes can be created that can optimize the bandwidth of the network. Gnutella suffers from the fact that the interconnected network causes all the peers to participate equally, even though peers vary in capacity and bandwidth. Gnutella's community is debating whether the network can scale because of these issues. SIM-o-IP needs to able to scale with configurable and specialized peers. In addition, SIM-o-IP will have to support protocols other than HTTP, such as TCP and IP broadcasting, whereas Gnutella uses only HTTP, to be able to choose the most efficient protocols for each situation.

2.6.10 Freenet

Freenet is a variation on file sharing using a peer-to-peer model. Freenet was created to implement the protocol described in Ian Clarke's paper "A Distributed Decentralized Information Storage and Retrieval System." Freenet claima that content can be published and read without fear of censorship because individual documents cannot be traced to their source. In addition, because of the distribution, it is also difficult to determine who is reading information. While Freenet is P2P, it is not a generalized platform for P2P applications. The design is dedicated to content and the idea that publishers and readers are anonymous.

2.6.11 Others

There are other incarnations of P2P networking. In addition to these more successful examples, other P2P protocols are appearing as well as self-contained P2P applications such as Morpheus and there will be others. Some use instant messaging platforms as a backbone for P2P communications. In fact, Microsoft's Hailstorm can use instant messenger. In the future, there may be more applications that use an instant messenger infrastructure because instant messaging platforms provide a platform that gets around firewalls.

2.6.12 ConnectionAgent

This comparison shows there are many different types of P2P platforms. Each was created with aspecific goal in mind. ConnectionAgent will handle a variety of applications as a generic multi-purpose networking tool supporting multi-platforms. It will be developed with JAVA to deploy a cross-platform interface for all of TISEC products. It will be developed as a set of open, generalized peer-to-peer (P2P) protocols, defined as XML messages, that allow any connected device on the network ranging from cell phones and wireless PDAs to PCs and servers to communicate and collaborate in a P2P manner. It is envisaged that many peers will not be PC based, but that they will be either enterprise systems or small instrument-based DASs. Its peers create a virtual network where any peer can interact with other peers and resources directly even when some of the peers and resources are behind firewalls and NATs or are on different network transports.

2.6.13 Connection Agent Functions

The first component of SIM-o-IP is the ConnectionAgent. This component, as its name implies, is central to all activities that would be managed by this project. Thus the initial effort on this part of the project has been concentrated on this particular module.

ConnectionAgent is planned to have the following properties:

1- Have the capability to communicate in the "peer-to-peer" fashion.
2- Support TCP/IP protocol.
3- Support HTTP protocol.
4- Have the capability to create a peer group "level 1".
5- Have the capability to create a peer group "level 2".
6- Have the capability to create a peer group "level 3".
7- Have the capability to control the behaviors of the remote Data Acquisition System (DAS).
8- Have the capability to send data to remote Data Acquisition System (DAS).
9- Have the capability to extract data from remote Data Acquisition System (DAS).
10- Have the capability to be platform independent.
11- Have the capability to communicate through firewall.
12- Have the capability to support the RS-232 communication protocol.
13- Have the capability to support the parallel port.
14- Have the capability to chat.
15- Have the capability to generate "Report".
16- Have the capability to print "Report".
17- Have the capability to send "Report" through e-mail.
18- Have the capability to login "to join group".
19- Have the capability to logout "to leave group".

20- Have the capability to set up the JXTA links through ConnectionAgent Interface.
21- Have the capability to have its own routers and relays.
22- Have the capability to run SIM-o-IP from WEB.
23- Have the capability to communicate with different Data Acquisition System (DAS) software packages.
24- Wireless communication capability.
25- Adaptability.

2.6.14 Functional Descriptions

Some of the functional item titles are self explanatory. Details on others are provided below.

Item #1 of ConnectionAgent Specifications:
Have the capability to communicate in the "peer-to-peer" fashion.
"Peer-to-peer" communication allows peers in the group to communicate in the "one to one" fashion. It means that communication between any two peers can be established without the intervention of the third medium like a centralized server that is used for the sake of authentication or whatever. For this reason, SIM-o-IP has adopted the "peer-to-peer" protocol as the mean of communication among its members through its ConnectionAgent module. By using "peer-to-peer" protocol, SIM-o-IP will identify its member as a peer. For this reason, we can interchangeably refer to SIM-o-IP's member as "***member***" or "***peer***". And also, SIM-o-IP's main purpose is to establish the communication with member that is usually a remote Data Acquisition System (DAS), we can refer to SIM-o-IP's member as "***member***" or "***peer***" or "***DAS***" in the subsequent discussion.

Item #2 of ConnectionAgent Specifications:
Support TCP/IP protocol.
SIM-o-IP does support TCP/IP protocol. It uses this protocol to establish the communication between any two members in the SIM-o-IP's group. This is a "one to one" communication.

Item #3 of ConnectionAgent Specifications:
Support HTTP protocol.
SIM-o-IP does support HTTP protocol. It uses this protocol to allow any member in the SIM-o-IP's group to communicate with other member(s). This is a "one to many" communication.

Item #4 of ConnectionAgent Specifications:
Have the capability to create a peer group "level 1".
SIM-o-IP has the capability of creating peer groups through its ConnectionAgent module. Each group, essentially, consists of a remote Data Acquisition System (DAS). This level has no private group, no sophisticated authentication, apart from "Name" and "Password".

Item #5 of ConnectionAgent Specifications:
Have the capability to create a peer group "level 2".
Create peer group in private network with enhanced authentication. In the immensity of the internet's world and specially "peer-to-peer" protocol, "Being part" of a group, takes a large sense for this capability. SIM-o-IP re-enforced this notion by having a more formalized and systematic way of submitting for membership. This little convenient assures to SIM-o-IP's memberships to exercise their rights of using SIM-o-IP with a group of people who have the same interests. SIM-o-IP lends itself as "application" for small groups. And small group in SIM-o-IP means speed and ease of membership's management.

Item #6 of ConnectionAgent Specifications:
Have the capability to create a peer group "level 3".
Create peer group in private network with data encryption. Like all applications that make use of internet, security is the criteria that should take into account. Not only it should help assuring data integrity during data transferring through internet, it also makes sure that the right person does receive the right information. SIM-o-IP implements "level 3" by using the contemporary technologies concerning "data encryption". And at the same time, SIM-o-IP leaves the door open for add-on technologies. Data encryption technologies like: MD5, RSA, RC4 and the combinations of these technologies are in the order.

Item #7 of ConnectionAgent Specifications:
Have the capability to control the behaviors of the remote Data Acquisition System (DAS).
SIM-o-IP has established its own communicate protocol to exchange information between its remote Data Acquisition System (DAS) through its ConnectionAgent module. This protocol has a generic pattern designed to support eventually different kinds of Data Acquisition System (DAS). For the time being, some patterns have been developed to support RS-232 protocol, some patterns have been developed to control the behavior of remote DAS. This is an incremental development along with SIM-o-IP.
The basic and generic commands for control DAS's fields consist of: INCR, DECR, FAST, SLOW, etc. SIM-o-IP keeps adding these capabilities through the use of "Command Pattern".

Item #8 of ConnectionAgent Specifications:
Have the capability to send data to remote Data Acquisition System (DAS).
This is one of the strength of SIM-o-IP. Any peer in SIM-o-IP group, have the capability to communicate to any other peer in the group and have the capability to send data to or extract data from that peer. It means that you can, from any peer, takes control of any other peer. At least two capabilities of data transferring were supported: file transferring, per-request transferring.

Item #9 of ConnectionAgent Specifications:
Have the capability to extract data from remote Data Acquisition System (DAS).
This is one of the strength of SIM-o-IP. Any peer in SIM-o-IP group, have the capability to communicate to any other peer in the group and have the capability to send data to or extract data from that peer. It means that you can, from any peer, takes control of any other peer. At least two capabilities of data transferring were supported: file transferring, per-request transferring.

Item #10 of ConnectionAgent Specifications:
Have the capability to be platform independent.
SIM-o-IP is developed with the objective of support different platforms. This is because DAS devices could be running in any operating system: WINDOWS, UNIX, LINUX, or any special equipments. For this reason, SIM-o-IP was developed with the tools that lend itself to these changes.

Item #11 of ConnectionAgent Specifications:
Have the capability to communicate through firewall.
SIM-o-IP does support HTTP protocol through its ConnectionAgent module. This is a high level language and is a WEB based language. Any application, that uses this protocol, can easily get through the firewall as this protocol will not be filtered by the firewall. And so does SIM-o-IP.

Item #12 of ConnectionAgent Specifications:
Have the capability to support the RS-232 communication protocol.
SIM-o-IP does support the RS-232 serial communication protocol through its ConnectionAgent module. This is one of the SIM-o-IP capabilities used to support any Data Acquisition System (DAS) that makes use of serial port as a medium to communicate data to SIM-o-IP.

Item #13 of ConnectionAgent Specifications:
Have the capability to support the parallel port.
SIM-o-IP does support parallel port. But, for the time being, this effort has been deferred to other higher priorities tasks.

Item #14 of ConnectionAgent Specifications:
Have the capability to chat.
This "chatting" capability allows SIM-o-IP to give an "online assistance". No extra phone line is necessary.

Item #15 of ConnectionAgent Specifications:
Have the capability to generate "Report".
Status: 0% completed

Item #16 of ConnectionAgent Specifications:
Have the capability to print "Report".

Item #17 of ConnectionAgent Specifications:
Have the capability to send "Report" through e-mail.

Item #18 of ConnectionAgent Specifications:
Have the capability to login "to join group".

Item #19 of ConnectionAgent Specifications:
Have the capability to logout "to leave group".

Item #20 of ConnectionAgent Specifications:
Have the capability to set up the links through ConnectionAgent Interface.

Item #21 of ConnectionAgent Specifications:
Have the capability to have its own routers and relays.

Item #22 of ConnectionAgent Specifications:
Have the capability to run SIM-o-IP from WEB.

Item #23 of ConnectionAgent Specifications:
Have the capability to communicate with different Data Acquisition System (DAS) software packages.
This is an important of SIM-o-IP capability. SIM-o-IP is a remote monitoring platform that unifies diverse Data Acquisition System (DAS) to be controlled and have data extracted through the used of contemporary technologies like TCP/IP and HTTP.

Item #24 of ConnectionAgent Specifications:
Wireless communication capability.
Status: 80%
As SIM-o-IP supports internet protocols, it takes all of the advantages that these technologies could provide and one of these advantages is "wireless communication". SIM-o-IP makes use of this available technology to fetch its NDT's data from the location where accessibility is reduced to minimum.

Item #25 of ConnectionAgent Specifications:
Adaptability.
Status: Open
SIM-o-IP is an application that lends itself easily to others systems due to its neutral applicability and its uses of standard communication protocols. Any specific Data Acquisition System (DAS) can be incorporated to SIM-o-IP with the minimum of time.

2.7 ISPIR User Category Assignments

In the ISPIR project, the following organizations are associated with each category:

TISEC Inc.	➢ Monitoring system contractor	✓ Field and engineering personnel
Fox-Tek	➢ Monitoring system contractor	✓ Field and engineering personnel
NRCan	➢ Monitoring system contractor	✓ Field and engineering personnel
University of Ottawa	➢ Monitoring system contractor	✓ Field and engineering personnel
Syncrude	➢ Structure owner/operator	✓ Quality control ✓ Operations ✓ Maintenance ✓ Management
PanCanadian	➢ Structure owner/operator	✓ Quality control ✓ Operations ✓ Maintenance ✓ Management
Saudi Aramco	➢ Structure owner/operator	✓ Quality control ✓ Operations ✓ Maintenance ✓ Management
U.S. DOT	➢ Project Participants	✓ Engineering personnel ✓ Management personnel

2.8 SIM-o-IP components

SIM-o-IP has two basic components, its communication and interface capability and its knowledge base. The communications system includes both the transmission of data, queries and decision-support information and the tools used by the user community to monitor and interpret data and to react to fault conditions. The knowledge base stores the competency required to diagnose pipeline condition and to develop recommendations for corrective actions. It is accessed through the communications system interface.

2.9 ISPIR data and information flow chart

The overall ISPIR system from sensor to decision support is shown in the figure below.

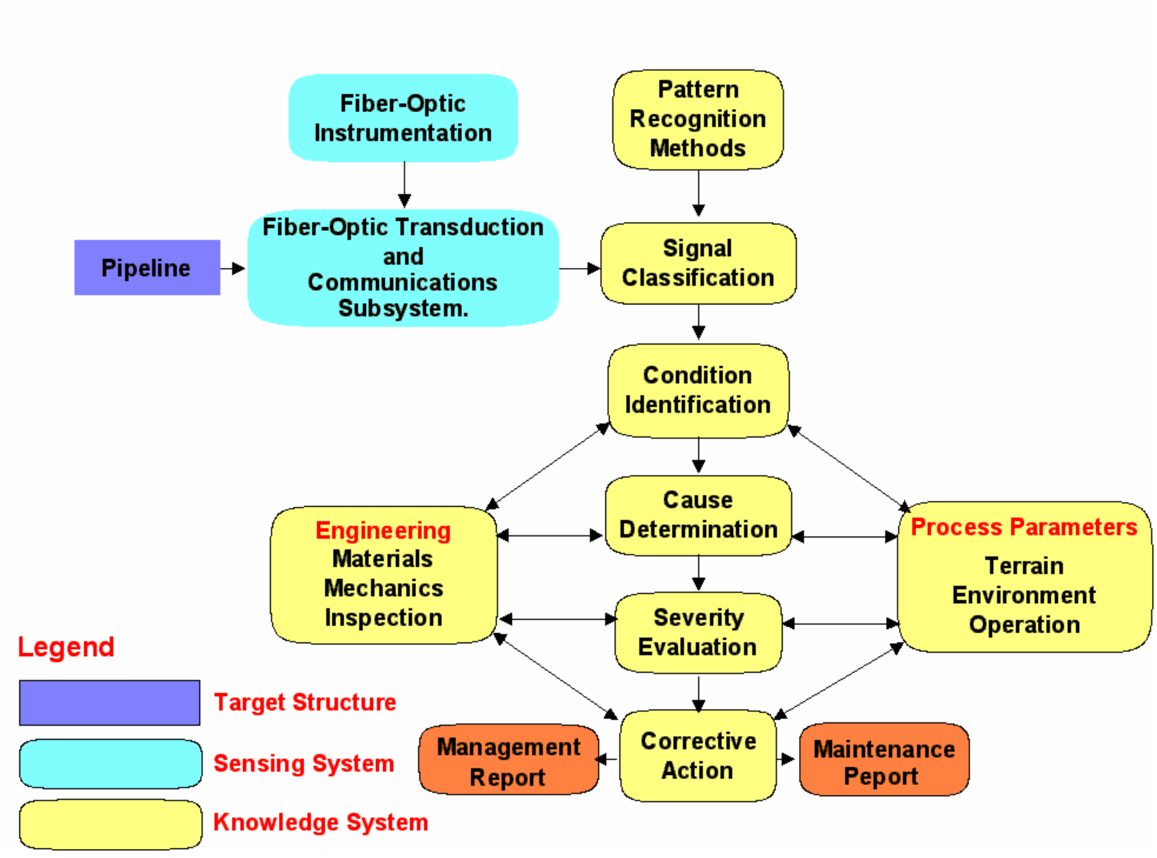


Figure 1. ISPIR System Diagram

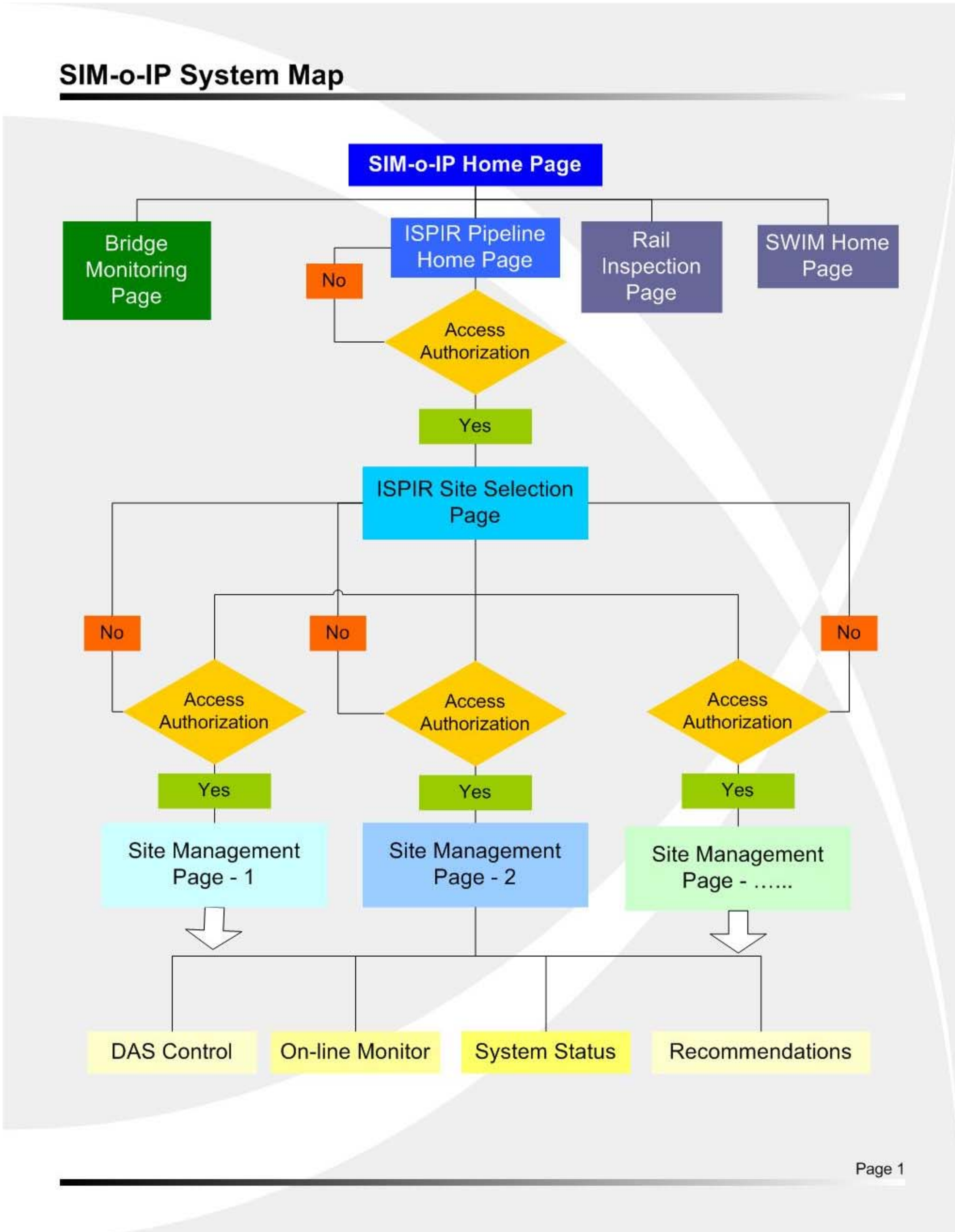
The fiber-optic monitoring system sends a time-stamped strain and temperature data stream to the knowledge system whose objectives are to

- ✓ Detect a fault condition
- ✓ Determine the cause of the condition and evaluate its severity
- ✓ Propose actions to correct the fault and/or to mitigate its effects.

This information is shared in a peer-to-peer, controlled-access community of users in the owner-operator community responsible for the structure. This community includes the on-site monitoring instrumentation and includes the Internet for communications.

2.10 SIM-o-IP System Map and Components

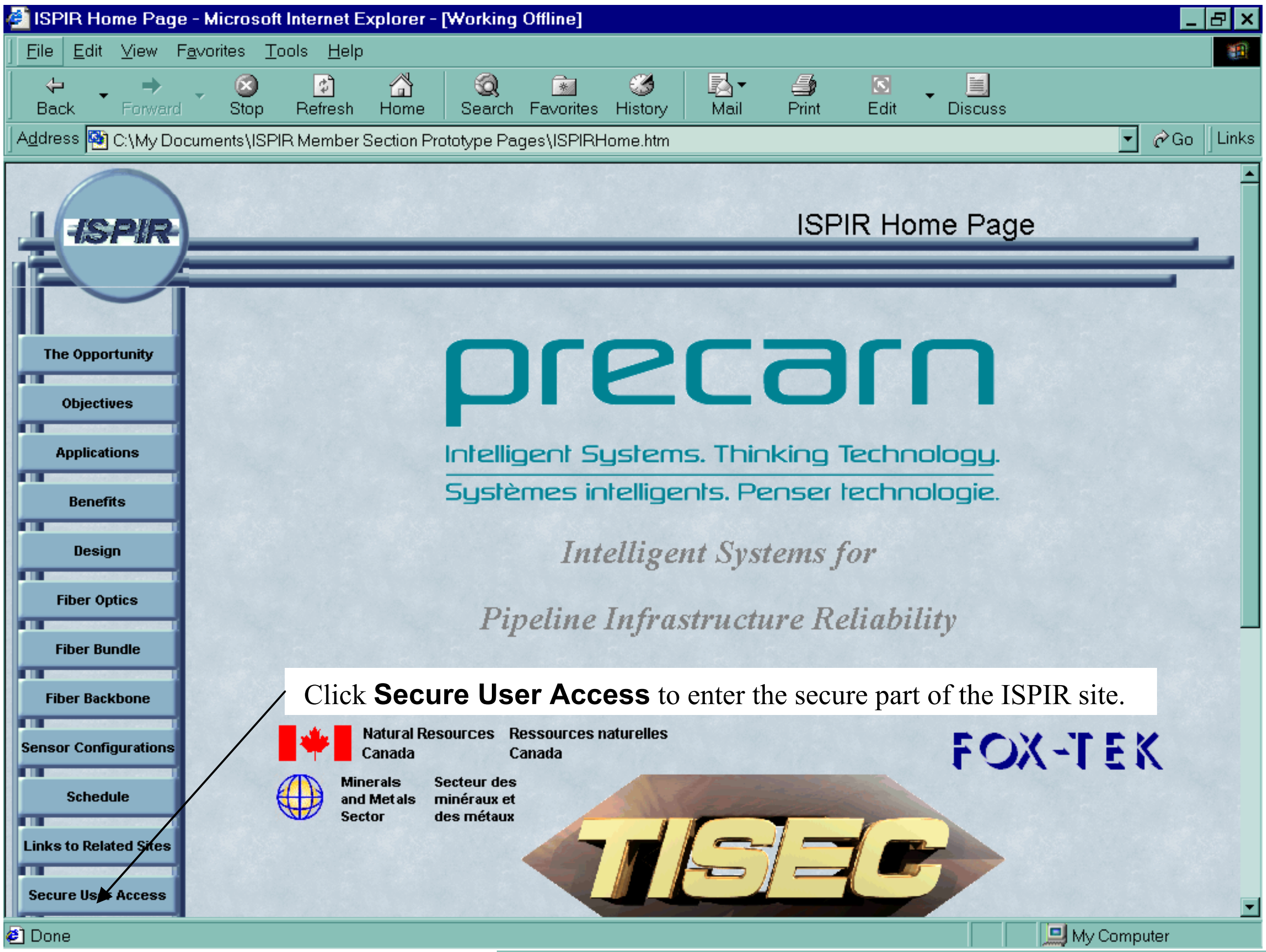
The SIM-o-IP System is designed to host an unlimited number of applications from bridge and railway rail monitoring to pipelines and the TISEC SWIM series of ultrasonic and acoustic emission applications. The system map below shows the system structure for the ISPIR pipeline monitoring system. This structure is replicated in the other applications.



2.11 SIM-o-Ip ISPIR Access

2.11.1 ISPIR Home Page

The ISPIR Home Page shown below is the ISPIR community portal from which secure user entry to the community is accessed. The user accesses the secure part of the site by clicking the Secure User Access button on the left. In addition, during the course of the project, this page will provide access to general project background and progress information. When the project is complete, this information will be consolidated into a background knowledge base.

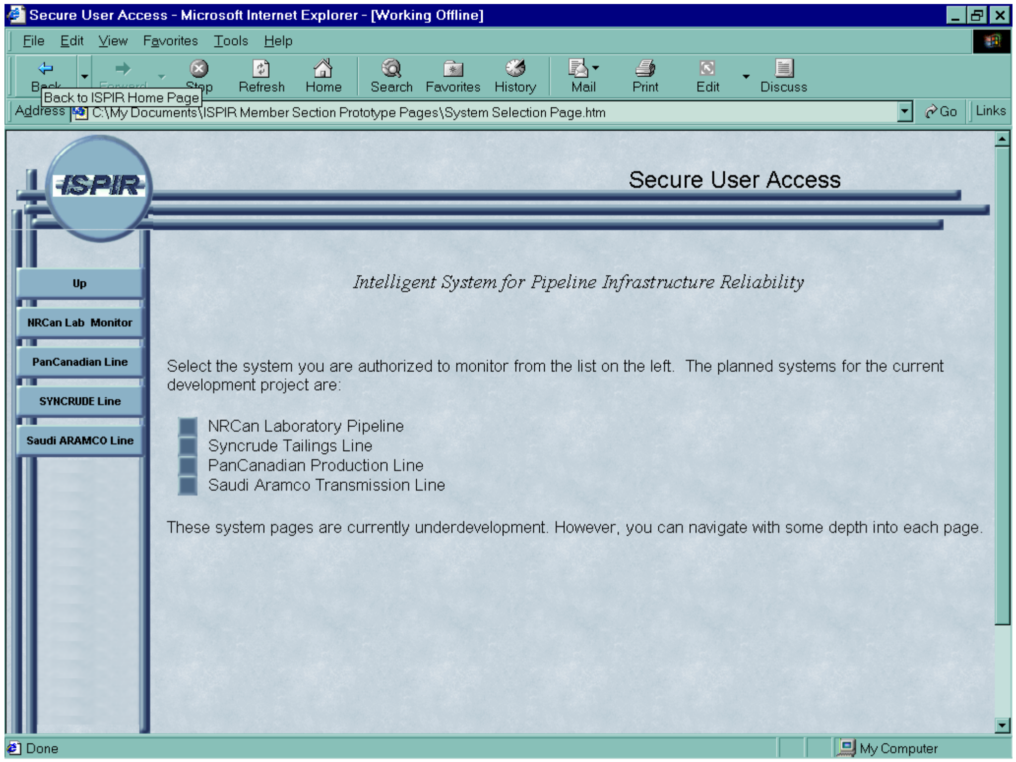


Clicking the Secure User Access button will take you to the ISPIR Sites Page shown on the next page. To proceed further from this page into the ISPIR Sites Page requires that a password be entered on the box that appears on the screen as shown on the right.

2.11.2 ISPIR Sites Page

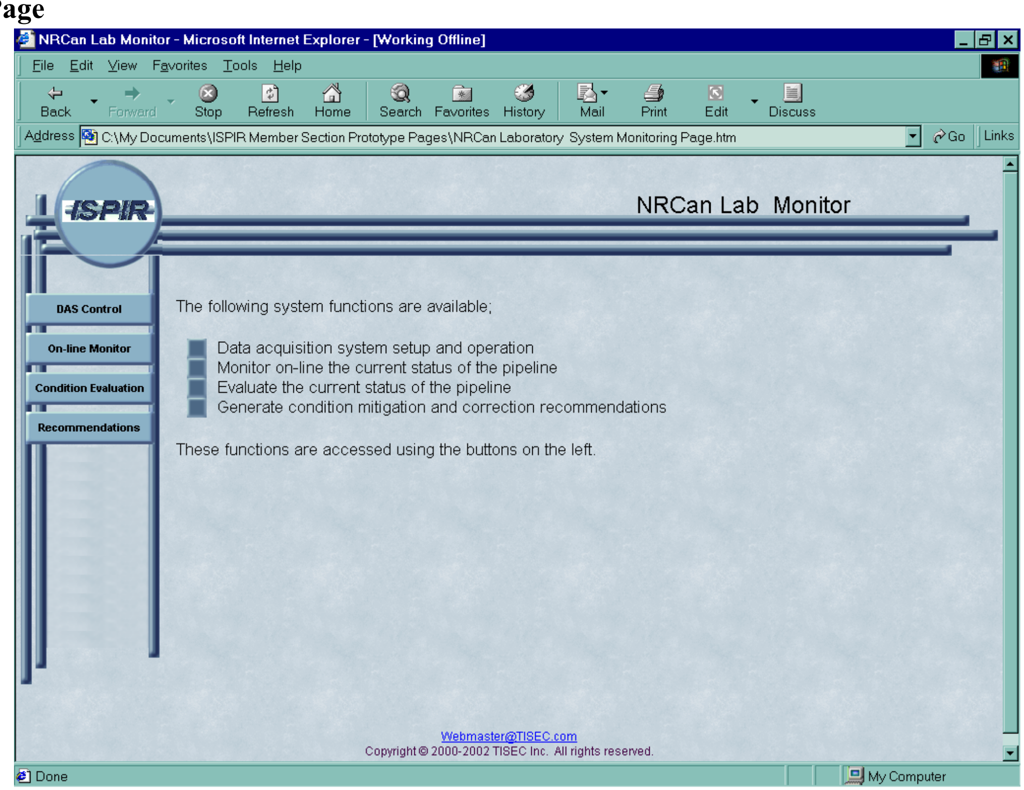
This ISPIR Sites page lists the systems that are currently being monitored by the SIM-o-IP system. Another level of security is provided that only permits access to those systems for which the user is authorized.

When the system to be worked on is selected, you get its main page as shown on the next page for the NRCan Laboratory pipe.



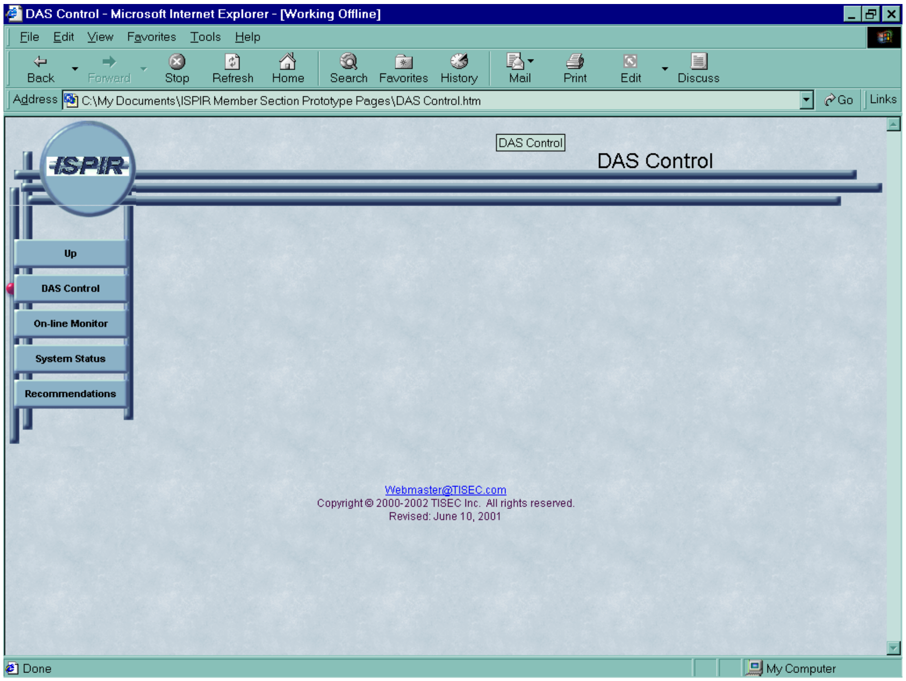
2.11.3 Site Home Page

Each site has its own home page that gives access to the four standard site functions shown in the figure below.



2.11.4 Data Acquisition System Control Page

The data acquisition system (DAS) control has four basic functions:

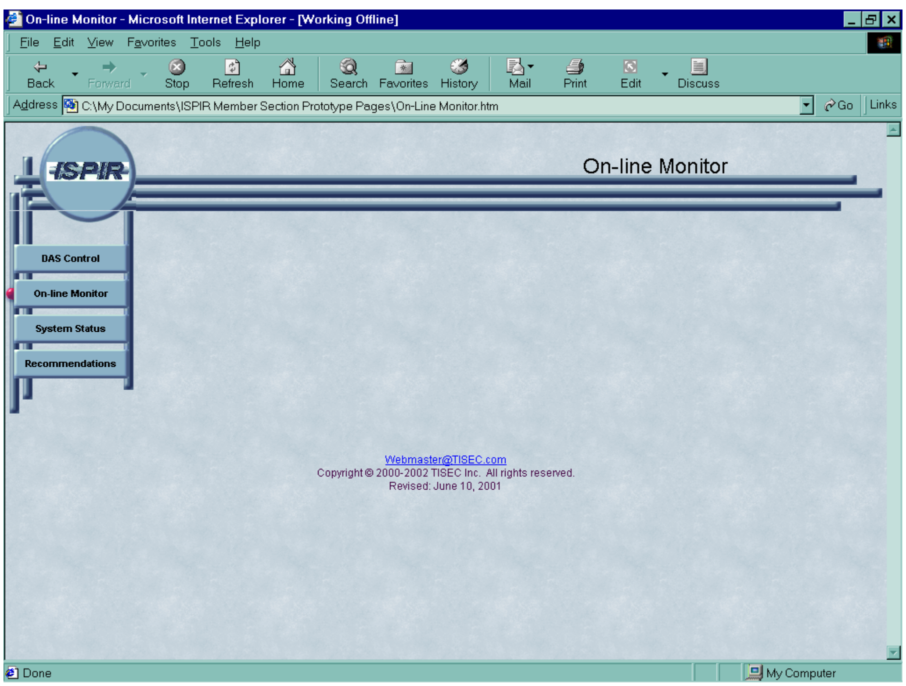


1. Set up and adjust DAS instrument settings before and during a test
2. Perform operational checks
3. Calibrate and perform calibration checks
4. Back up and archive data

The first three of these functions are carried out by the through a replication of the instrumentation interface at a remote site. The fourth function is performed by a system administrator at intervals and locations designated by the owner/operator.

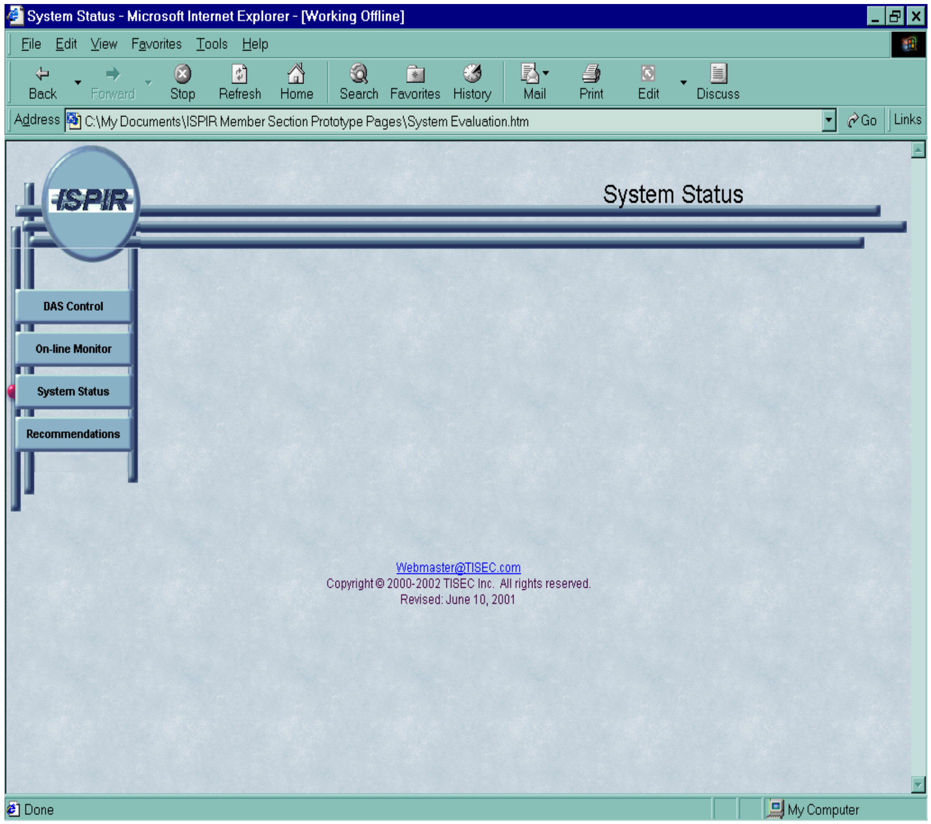
2.11.5 On-Line Monitor Page

The on-line monitor page will access the data base and construct real-time displays of temperature and stress as a function of time. This page will also have the ability to display, if available, parametric data such as operating pressure and flow rate for correlation with strain and temperature.



2.11.6 System Status Page

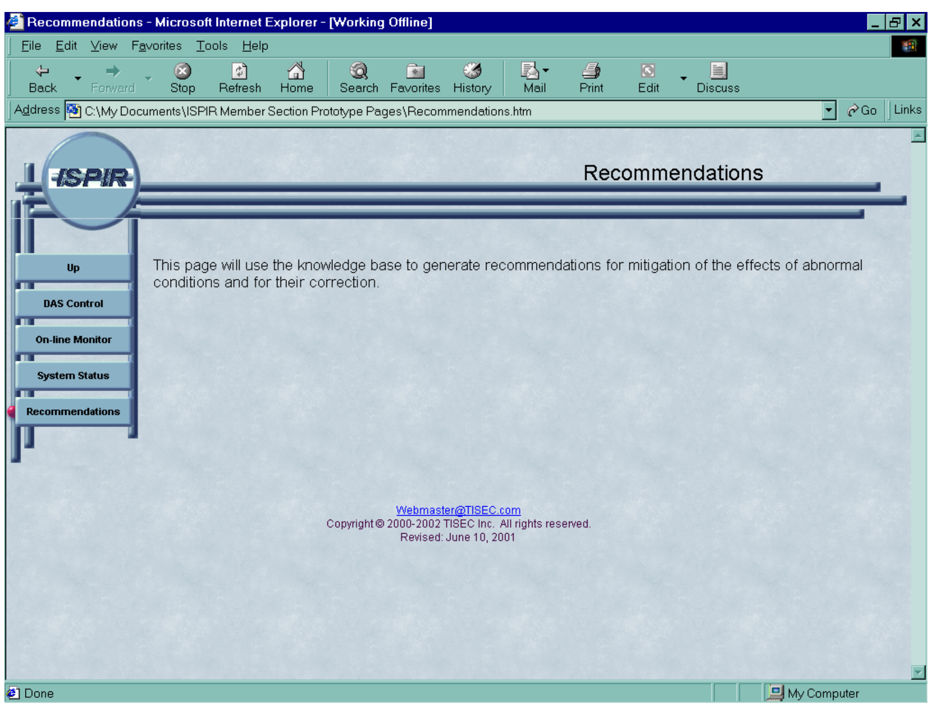
The system status page shows trending data, detection of thresholded variations, and correlations to parametric data. The system will first use the data obtained over time to establish a baseline pipeline operating status.. It will then use the sign and magnitude of deviations from baseline conditions as well as spatial and temporal distributions of the data to provide interpretations of the cause of the fault condition and its severity.



Threshold and excursions and temporal and spatial data distribution will be used along with operations and environmental context information from the knowledge base to diagnose the source of the fault condition.

2.11.7 Recommendations Page

Combining the raw sensor data, context information and fault diagnoses with maintenance knowledge and procedures from the knowledge base, the recommendations page will interact closely with the user to develop action recommendations. This page will also generate automatic alerts and send them to designated community users.



2.12 Knowledge Base

2.12.1 Interpretation Requirements

Since the sensing methods simply detect strain and temperature, supplementary information is required to identify which of the above conditions is causing the strain excursion. It is the objective of the knowledge-based component of the ISPIR system to provide such an interpretation and identification. Although not all of these will be detected in each application, the conditions to be identified by the fiber optic sensing system include:

- ✓ pressure loss
- ✓ pipe buckling
- ✓ pipe bending due to ground settling
- ✓ pipe wall rupture and leakage
- ✓ generalized pipe wall thinning due to corrosion and erosion
- ✓ discrete corrosion pitting

This subsystem will include certain modules that can be implemented algorithmically such as structural models that account for bending, wall thinning, buckling limits, thermal loading and the presence of cracks. These structural models, built into the software, provide a means of comparing incoming data with model analysis to alert the user to possible failure conditions. In addition, the system will include a set of logical and heuristic rules for data interpretation.

The knowledge base can use data provided by two different strain measurement technologies, the Long Gage and the Brillouin Gage. The algorithmic component for the Long Gage is shown below.

2.12.2 Long Gage Knowledge System

Fiber-optic strain gages can be mounted in several different configurations including axial, circumferential and spiral mountings. Of these, it is anticipated that the axial and spiral configurations will be most common for inspection of long lengths of pipe. Thus, this information must be supplied to the knowledge base for each monitoring site.

2.12.2.1 Algorithmic Component

To apply decision making theory to the sensor data, we need to establish the following inputs:

- ✓ Model equations for pipe phenomena:
  - external surface axial (X) and hoop (Y) strains for internal pressure
  - change in X and Y due to wall thinning
  - X and Y for axial compression loading
  - X and Y for axial compressive buckling of pipe
  - X and Y for bending moment loading
  - X and Y as a function of temperature of pipe, including gradients due to internal/ external temperature differences
  - X and Y for critical pitting hole sizes as a function of depth through wall.
- ✓ For given pipe material, geometry, corrosion/erosion depth and loads (thermal and physical), determine allowable values of X and Y under nominal acceptable limit conditions—these values become the threshold limits.
- ✓ For known values of the loads and pipe geometry, undertake tests in NRCan and the U. Alberta labs to correlate parameter changes as a function of load and geometry using different sensor configurations.

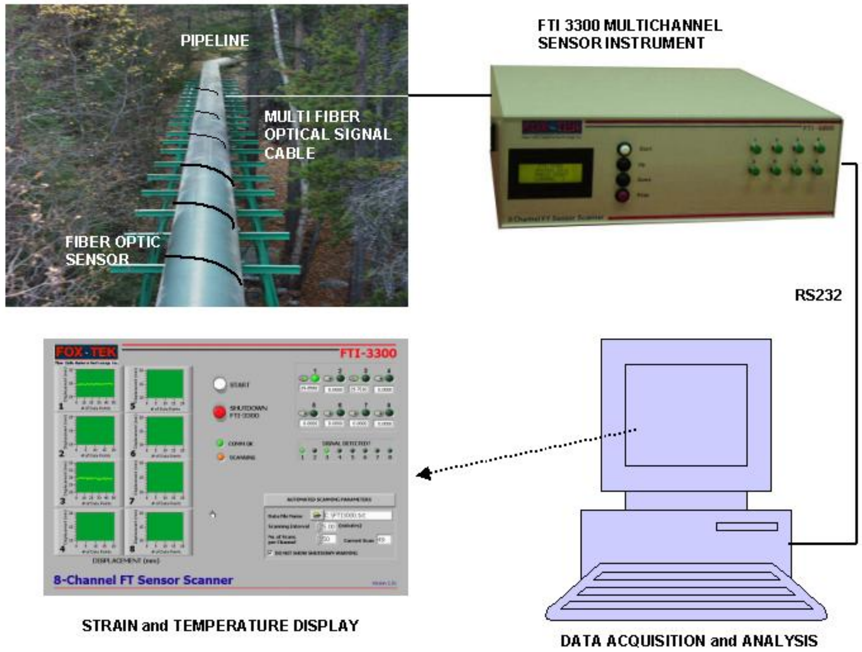
3 FIBER-OPTIC LONG-GAUGE STRAIN MEASUREMENT SYSTEM

3.1 System Elements

The major elements required to define a fiber optic sensor system for pipeline applications are:

- Fiber optic sensors
- Optical fiber backbone
- Installation procedures / sensors and backbone
- Sensor measuring instrument
- Communication link to DAQ
- Software for interpreting data
- Data Storage and Retrieval (Strain and Temperature)

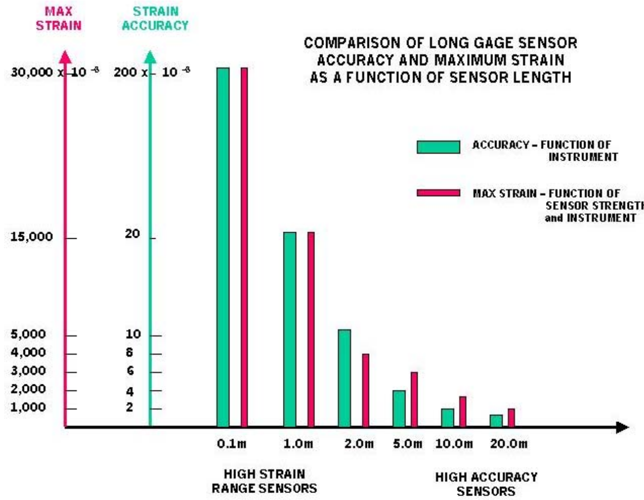
These elements are shown in the figure on the right.



3.2 Fiber-Optic Sensors

The FT sensors to be used on the pipeline are made from single mode standard telecom optical fiber, connected to single mode jacketed lead optical fiber as shown below. The interface (FT connector) is specially designed by FOX-TEK. The figure below shows a sensor assembly.

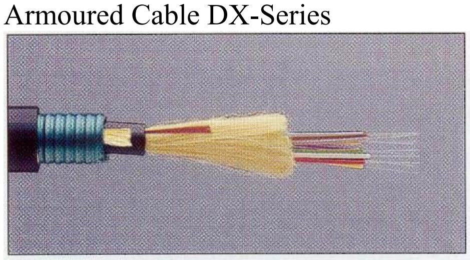
The strain resolution and strain range can be determined as a function of sensor length from the figure on the right.



3.3 Optical Fiber Backbone

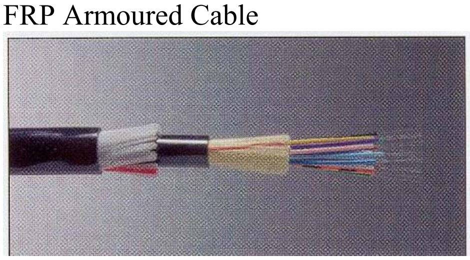
Three types of single mode multifiber cables will be used, depending on the application and requirement for protective jackets. These are described below (from Optical Cable Corp.):

Armoured Cable DX-Series



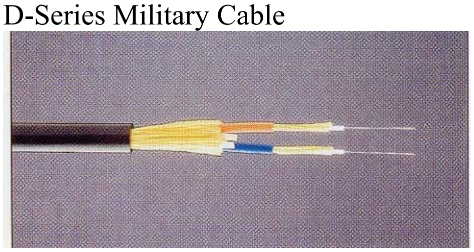
Direct burial and aerial applications
Corrugated steel tape – protects against rodents
Available in 8 – 24 colour coded strands
Flexible, rugged, good for long cable pulls
Weight: 8 strand = 33 kg/km

FRP Armoured Cable



Fiberglass rodent protection
For surface installation in conduits
Not for burial applications

D-Series Military Cable



Extra rugged, crush resistant, flexible
Excellent chemical resistance
Not for burial—surface installations

3.4 Installation Procedures

OPTICAL FIBER BACKBONE:

Buried Pipe: use Armoured Cable DX Series, with split outs to connect sensors at required locations along pipeline

Elevated Pipe: use FRP Armoured cable with split outs, mounted along bottom of pipe with flexible ties

External Pipe Sections in High Traffic Areas: use D-Series Military Cable

SENSOR CONFIGURATIONS:

Axial, hoop, spiral, combinations

Bare fiber or fiber enclosed in thin walled, flexible steel tubing

Fusion bond sensors to Optical Backbone Cable fibers (colour coded)

PIPE SURFACE PREPARATION:

Uncoated / Polymer Coated Pipe:

- Remove surface scale/contaminants/etc using steel brush or grinder
- De-grease and clean surface with solvent such as alcohol
- Re-coat pipe surface after sensor installation (for coated pipes)

ADHESIVE:

Tack bond bare fiber sensor ends with Loctite quick set epoxy, with sensor under prescribed pre-tension

AE 10 –for bonding bare fiber to uncoated steel pipe, and for polymer coated pipe

Spot Weld steel tubing tabs to steel pipe (for sensors enclosed in steel tubing)

SURFACE PROTECTION:

Silicon environmental protection overcoat on bare fibers after bond has cured

Option: use an overcoat of M-brace epoxy for crush protection if required

3.5 Sensor Measuring Instrument

For long gage sensors, the FTI 3300 8-channel instrument will be employed, as shown in the photograph below.

.

Detailed specifications for this instrument are given in the table below.

Number of Channels	8 standard
Sensor Length	0.1m, 1m, 2m, 5m, 10m, 20m, 30m standard, custom lengths (5cm – 100m) available
Scan Time	<15 sec. in Fast Scan Mode, 30 sec. in full scan mode (per channel)
Dimensions	17” x 17” x 5.5” (excluding mounting brackets) – 19” rackmount, 3U height
Weight	10kg
Measurement Range	±15mm or ±4000 microstrain, whichever is less
Resolution	±20 microns
Operating Temperature	0° – 40°C (32° - 104°F)
Storage Temperature	-10° - +65°C (14° - 149°F)
Power	110V/2A or 220V/1A, 50-60Hz
Fuse	250V, 2.5A (5x20mm – IEC type 60127-2 or UL248-14)
Computer Interface	RS232 or RS485 (RS232 default)

The FOX-TEK FTI-3300 instrument is designed to measure changes in displacement of the FT sensor, which is effectively a fiber optic extensometer. The instrument is equipped with 8 input channels, in a 19” rackmount configuration. The instrument will read any three of FOX-TEK’s suite of seven standard FT sensor lengths – 0.1m, 1m, 2m, 5m, 10m, 20m and 30m - as specified by the customer. The default configuration will read the 0.1m, 1m and 5m sensor lengths. A custom option is available to incorporate other sensor lengths (5cm to 100m) into the instrument if required.

The system operates by scanning the attached sensor for a change in the reflected intensity of light, and recording the location at which that signal was detected. Any changes in sensor length can be detected by the shift in the signal to a different displacement location, which is detected and recorded by the instrument.

3.6 Communications Link to Data Acquisition System

The FTI-3300 unit has two modes of operation – stand-alone, and PC controlled. In the stand-alone mode, the user controls the unit through the front panel buttons. In the remote control mode, a PC connected to the unit can be used to control the device using the FOX-Ware control software or a standard terminal program.

The FTI-3300 unit has a standard 9-pin RS-232 serial port for connecting to a PC. A standard serial cable is required to connect the unit to the monitoring computer. To ensure a successful connection, the serial (COM) port settings of the connected PC must be set to the following:

BAUD Rate	9600
Data Bits	8
Parity	N
Stop Bit	1
Flow Control	Xon/Xoff

3.6.1 Receiving Data and Saving Using a Terminal Program

Communication with the FTI-3300 is possible via a standard Windows-based terminal program (e.g. HyperTerm). Remote control of the unit using a terminal program is however not possible in the stand-alone operating mode, as only the front panel buttons are active. However, once the serial parameters are set correctly, it is possible to receive data from the unit in the stand-alone mode. To transfer data to the PC, press the data transfer key (Down key) at the appropriate time (when the result is displayed onscreen).

Result Display

Sending Data to PC

The FTI-3300 will send formatted ASCII data to the RS232 port, consisting of the active channel and the displacement, in the following format:

CHANNEL 4, DISPLACEMENT = 25764.4

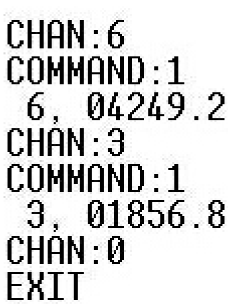
3.6.2 Remote Control Using a Terminal Program

The FTI-3300 uses a simple set of commands to operate in remote mode. *In remote mode, all front panel buttons (except the **STOP** button) are disabled, and the unit will only accept remote commands.*

To enable remote communications, connect the PC to the FTI-3300 unit using the supplied RS232 cable and launch the communications/terminal program. Power up the FTI-3300, wait until the power up tests are completed and press the **UP** button on the front panel when the "Remote/Front Panel" operating mode selection menu appears. When this selection (Remote) is made, the unit will then send a "**CHAN:**" prompt to the terminal screen, indicating that it is ready to receive commands.

The unit only has two prompts, "**CHAN:**", and "**COMMAND:**". CHAN prompts the user to input a channel number to be scanned, and COMMAND prompts the user input a command to either begin the scan or shutdown the system.

All inputs are in the form of simple integers, **with CHAN having a valid range of 0-8,** and **COMMAND having a valid input range of 0-1**. Any values entered outside these ranges will cause the unit to repeat the prompt until an acceptable value is input. Entering '0' as a value to either prompt will cause the system to perform a shutdown (similar to pressing the "**STOP**" button on the front panel of the unit). Entering a '1' as a response to COMMAND will initiate the scan on the unit. Once a scan is complete, the unit will output the result in the following form:



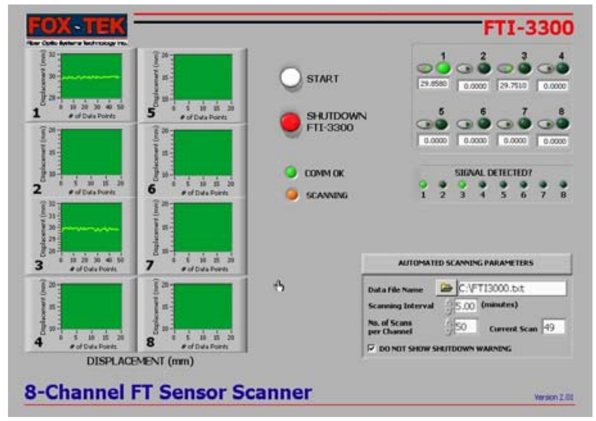
Channel #, Displacement (in microns)

When '0' is input and the system shuts down, the unit will output an "EXIT" message once the shutdown is complete. Power to the unit can then be disconnected.

The above shows a screen capture from a HyperTerm session with the unit in Remote mode. Note the repeated prompts for incorrect entry values. The results show a reading of 4249.2 µm on Channel 6, and a reading of 1856.8 µm on Channel 3.

3.7 FOX-Ware Remote Control and data Collection Software

FOX-Ware software is provided with the FTI-3300 unit to facilitate automated control and data collection using a Windows-based PC connected to the instrument. The software, of which the main screen is shown on the right, allows for automated scanning and data storage at specified intervals, to automate remote monitoring of structures with FT sensors. The software scans selected channels at specified intervals, storing the data in a text file for later analysis, as well as displaying the results on-screen in real time.



FOX-Ware allows unattended remote monitoring by using commercial off-the-shelf remote control software such as PC Anywhere, as long as there is a PC onsite connected to the FTI-3300 unit running FOX-Ware. Using the PC Anywhere program, the user can take remote control of the onsite PC (with FOX-Ware) and perform the monitoring and control tasks from his or her remote office location. However, the initial start-up communications test procedure must be done onsite with the local PC (as described in the following sections), before attempting remote communications.

3.7.1 Connecting with FOX-Ware

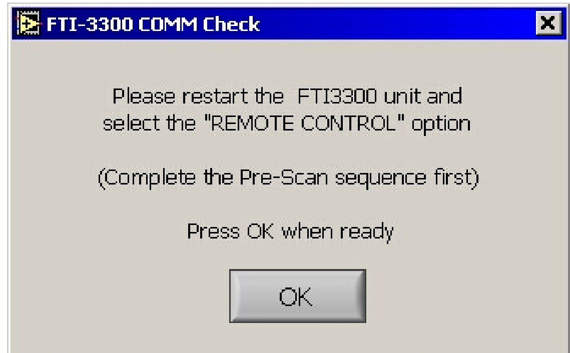
To ensure trouble free communications, FOX-Ware asks the user to follow certain procedures during the start-up phase of the FTI-3300 unit. The software sends certain commands to the instrument and analyzes the responses to ensure that proper communication has been established. The software has some pop-up screens that instruct the user to follow certain steps with the FTI-3300 unit as it proceeds through the communication checks. The basic system requirements for FOX-Ware are:

- ✓ Pentium II-300 or higher, running Windows 95, 98 or Windows 2000
- ✓ 64MB RAM
- ✓ 25MB free disk space (plus additional space as required for data storage)

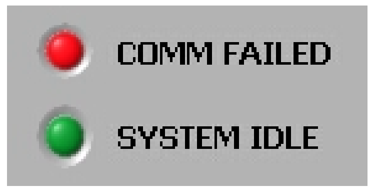
The initialization procedure for FOX-Ware is as follows:

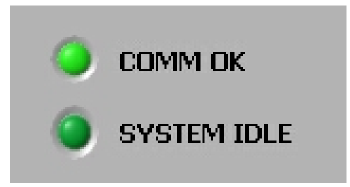
1. Connect the FTI-3300 to an available COM port on the PC using the supplied RS232 serial cable
2. Power up the FTI-3300, wait until the boot up screen on the right is displayed, and then press the **Stop** button immediately. Wait until the box displays **"Shutdown Complete – Turn System Off"**
3. Launch the FOX-Ware software (by double-clicking on the FOX-Ware icon). The software will then pop up the dialog box on the right.
4. Select the appropriate COM port (of the PC which is connected to the FTI-3300) on the **COMM Check** dialog box and then press **OK**
5. Select the appropriate COM port (of the PC which is connected to the FTI-3300) on the **COMM Check** dialog box and then press **OK**

6. The software will then pop up another dialog box shown on the right.
7. Restart the FTI-3300 unit, complete the Pre-Scan procedure and select the “Remote” option from the “Remote/Front Panel” menu (by pushing the **UP** button).
8. Press OK on the dialog box when the “Remote Control Active” message appears on the FTI-3300 display. This completes the communications handshaking procedure.



Once the communication check is over, the main FOX-Ware screen will be displayed. The communication status will be displayed by the COMM status indicator light on the screen as shown on the right. If the COMM Failed display is active, then the software was unable to communicate properly with the FTI-3300. If this occurs, please re-check the cable connecting the PC with the unit, exit FOX-Ware and repeat the above procedure from the start to ensure proper communication.



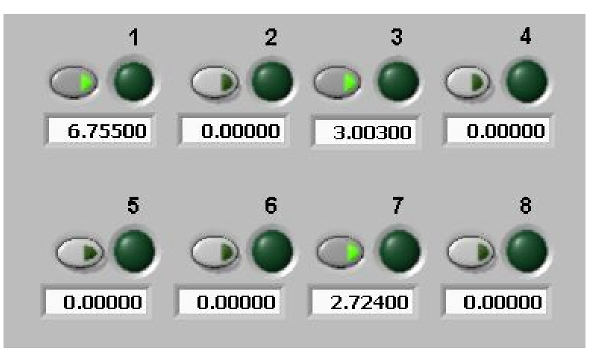


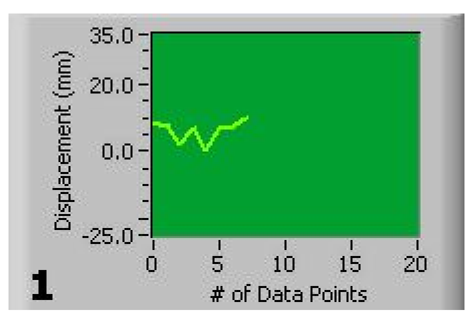
3.7.2 Operating with FOX-Ware

There are two main areas of the FOX-Ware screen where user input is required. It is important that all the necessary inputs to the software be completed before pressing the “Start” button to activate the scanning. Once the user has entered all the required information, the system can be set into automatic scanning mode by pressing the START button on the FOX-Ware main screen.

The first area is the channel selection section, where the channels to be scanned during each pass are selected. The required channels are selected by pushing the corresponding channel buttons next to the FOX-Ware channel indicators as shown below. The channel indicator light will activate when the system is scanning that particular channel, to give a visual indication of which channel in the pre-programmed scan cycle is active. Any combination of single or multiple channels can be selected for scanning. The digital display under each channel indicator will display the last scan reading for that channel. A complete history of the readings for that channel during each pre-programmed cycle will be displayed on the graphical display on the left hand side of the FOX-Ware main screen below).

The settings/values for the axes of the graphical displays can be edited during operation by clicking on (the text of) the axis values. The default values for the Y-axis (displacement) are 10 to 30mm. Changing the axes’ minima and maxima can help in better visualization of the data.





The second area of the FOX-Ware screen requiring user input is the "Automated Scanning Parameters" section on the right. These parameters include the filename in which FOX-Ware will store data, as well as the interval between scan cycles and the number of scan cycles to be repeated during the automated sequence. Each channel selected using the channel selector will be scanned during each scan cycle, so the total number of scans performed by the system during an automated session will be: No. of selected channels x No. of scans per channel. i.e. each complete scan cycle will scan through all the selected channels sequentially. The scanning interval determines the waiting period between successive scan cycles. There will be no waiting period between scans inside a single scan cycle, as each channel will be scanned as quickly as possible after the completion of the previous scan in that cycle. Default values for the parameters are:

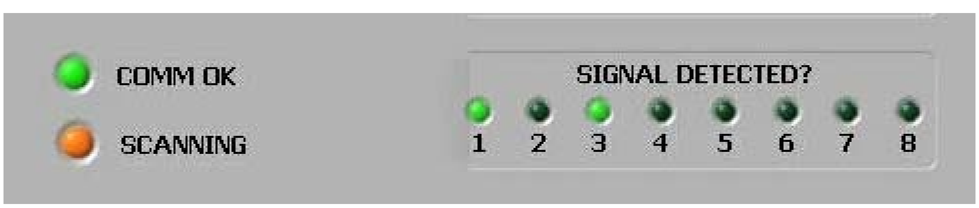
Data Filename: C:\FTI3300.TXT
Scanning Interval: 0.0 minutes (maximum: 1440 minutes, or once every 24 hours)
No. of Scans per channel: 1 (maximum: 1000 scans)

If required, the maximum limits can be changed to suit the user's operating requirements. Please contact FOX-TEK for further information regarding these modifications.

The FTI-3300 can also be operated in a 'scan on demand' fashion through FOX-Ware, with the added convenience of automatically recording data to disk. By setting the scan interval to zero and the number of scans to one (the default values), the system can be operated on demand by selecting individual channels on the channel selector and pressing the **START** button – similar to operating the instrument using the front panel.

Once all the parameters are entered, press the **START** button on the FOX-Ware front screen to initiate the preset series of scans. When the FTI-3300 begins a scan, a window with a progress bar will appear to indicate the system preparing to scan.

During the scan, the **SYSTEM IDLE** indicator will glow orange, and will read - **SCANNING**. The **SIGNAL DETECTED?** display to the right of the **SCANNING** indicator will light up once a signal is detected by the instrument during a scan. Once the scan is completed, the software updates the result on the graphical display as well as the digital readout below the selected channel. The **SIGNAL DETECTED?** indicators will stay lit after a scan to show which channels were scanned successfully (when a scan is active, the respective indicator will turn off again until a signal is detected). This feature provides a convenient visual indicator as to which channels are active on the instrument.



The "Current Scan" display in the Automated Scan Parameter box helps determine how many scans have been completed and how many scans remain in the pre-programmed cycle.

3.8 Data Storage and Retrieval (Strain and Temperature)

FOX-Ware stores data in a text file (specified in the front panel scanning parameters box), in a columnar, comma-separated format. The default filename for storage is C:\FTI3300.TXT unless this is changed by the user before pressing the **Start** button. If the filename is changed after scanning is initiated, then FOX-Ware saves the data to the new filename for all subsequent scanning runs, but the scan data up to the point of change will be saved to the old filename. This feature can be used to save data to different filenames to facilitate data archival and organization purposes, as well as to manage file sizes. A screen capture of a typical data file is shown below:

```
2001-08-29, 17:36:02, 1, 8.448000
2001-08-29, 17:36:34, 2, 4.861000
2001-08-29, 17:37:05, 6, 5.121000
2001-08-29, 17:37:48, 1, 7.587000
2001-08-29, 17:38:19, 0, 0.000000
2001-08-29, 17:38:50, 6, 0.000000
2001-08-29, 17:39:33, 1, 2.019000
2001-08-29, 17:40:04, 0, 0.000000
2001-08-29, 17:45:44, 1, 6.509000
2001-08-29, 17:46:16, 2, 5.691000
2001-08-29, 17:46:47, 3, 7.524000
2001-08-29, 17:47:31, 1, 0.000000
2001-08-29, 17:48:03, 1, 0.000000
2001-08-29, 17:59:08, 1, 6.598000
2001-08-29, 17:59:40, 2, 3.231000
2001-08-29, 18:00:24, 1, 7.191000
2001-08-29, 18:00:55, 2, 2.741000
2001-08-29, 18:01:39, 1, 9.792000
2001-08-29, 18:02:11, 2, 6.537000
```

The data are organized into the following format:

Date (yyyy-mm-dd)**, Time** (hh:mm:ss)**, Channel #, Displacement** (mm).
The data is in a standard comma-separated format, which makes it easy to import into any analysis software such as a spreadsheet or database program like Excel or Access.

Zero Results
A zero (0.00000) for the scan result indicates that a signal was not detected from that particular channel. While this would be obvious, and easy to check immediately when the system is in stand-alone operating mode (on-site front panel operation), when the system is operating in an unattended or remote location the situation is less clear. While a zero reading may occur occasionally due to various conditions at the site, a consistent zero reading on a particular channel is an indication of trouble with either the sensor or the port on the FTI-3300. If the sensor is not reading properly or has failed, then this usually indicates a problem with the underlying structure, and should be treated seriously. Therefore it is highly recommended that an on-site inspection and diagnosis be performed as soon as possible after the detection of such a problem.

4 FIBER OPTIC PH (FOpH) SENSOR SUBSYSTEM

4.1 INTRODUCTION

This document outlines the definitions, specifications and features of the CANMET pH system for integration with a fiber optic system to produce a fiber optic pH sensor (FOpH). It is a guideline to define and help to modularize the design for progressive implementation phases of the system. This appendix presents an introduction to the system and its context.

4.1.1 Purpose of This Specification

The purpose of this document is to define the requirements and specifications for the pH sensor and its integration to fiber optic transducer. The intended audiences for this document are:

- The FOpH users, so they may review and provide input into the requirements.
- The design team, as this document will serve as the basis for system design.
- The test team, as this document will serve as the basis for system verification and validation.

The structure of this appendix is based on Structural Integrity Monitoring Over IP - SIM-o-IP (Version 1.0) Specifications developed by TISEC on Monday, October 21, 2002. In Section 2, a general description of the CANMET FOpH system is given. Section 3 describes the sensing element development. Section 4 describes the fiber optic backbone system requirements for integrating the FOpH sensor. Section 5 positions FOpH relative to other sensors including $FOCO_2$ (Appendix IV) and FOMIC (Appendix V).

This document also reviews the current status of the development of FOpH sensor.

4.1.2 System Perspective

The CANMET FOpH system meets a twofold requirement: pH monitoring at discrete locations around the pipelines to:

- Integrate pH monitoring with other chemical (CO_2) and biochemical (SRB) changes
- Integrate pH changes with corrosion rates.

An additional requirement in new systems is to acquire data at several locations and to distribute these data as well as interpretations and decisions based on them to the parties involved in follow-up actions, particularly in a systems maintenance context. It will also permit us to install and evaluate the system at field sites in the future.

4.1.3 Acronyms

MIC	Microbiologically Influenced Corrosion
FOpH	Fiber optic pH sensor
$FOCO_2$	Fiber Optic Carbon Dioxide Sensor
FOMIC	Fiber Optic Microbiologically Influenced Corrosion Sensor
ISPIR	Intelligent Systems for Pipeline Infrastructure Reliability
SIM-o-IP	Structural Integrity Monitoring over Internet Protocol
SRB	Sulphate Reducing Bacteria
CO_2	Carbon Dioxide
SCC	Stress-Corrosion Cracking

4.2 GENERAL DESCRIPTION

This section specifies the system capabilities and functions, identifies who the users are and outlines the general constraints of the overall system and the assumptions and dependencies considered for the system.

4.2.1 System Capabilities

High-pH SCC occurs at pH in the range of 9 to 10 in the presence of a concentrated carbonate/ bicarbonate environment. In the case of near-neutral-pH SCC, the environment is a dilute ground-water containing carbon dioxide, essentially dilute carbonic acid. It is obvious that pH values determine the type of SCC. Therefore, online monitoring of pH will be very useful to develop strategies to mitigate corrosion and SCC.

FOpH is a real time sensor to monitor pH at various locations along the pipeline and to communicate through the fibre optic backbone. Fig. III.1 presents the flow-chart to develop FOpH.

- The sensor monitors the pH and communicates to the fiber optic backbone
- The transducer (fiber optic cables) transmits real-time data to the central station for processing and analyzing.

For management, it is possible to:

- monitor the on-site testing for current real-time pH data
- send instrumentation setup commands to the sensors
- perform operational checks on sensor components and the fiber optic network

4.2.2 System Users

All users of the system can access and/or activate the pH sensor through the fibre optic backbone.

4.2.3 Sensor Configuration

The sensors are attached to the fiber optic backbone at pipeline sites which are being monitored. The sensor configurations may include

- Immobilized sensing element(s) specific to hydrogen ion activity
- Anti-interference layer
- Rugged material(s) for protection of sensing element(s) and anti-interference layer
- A specific coloured casing or housing unit (specific colours for specific sensors)

The back end of each sensor unit is attached to the fiber optic backbone.

4.2.4 Management-Side Configuration

The link from sensors to the management-side users is made through fibre optic cables, developed and field tested by FOX-TEK.

4.2.5 Central Station Configuration

The central station will be established by TISEC Inc.

4.2.6 Sensor Component Availability

The CANMET FOpH sensor has the following requirements:

- Sensing element(s) are active and sensitive at all times.
- Sensing elements are attached at various locations on the fiber optic backbone

- The fiber optic backbone is capable of relaying the signal accurately and immediately from specific sensors to the central station
- The central station should be running at all times.
- Management side users access the system on demand

4.2.7 Assumptions and Dependencies

The CANMET FOpH sensor system has the following assumptions and dependencies:

- While the system monitors pH changes, it is conveniently envisaged that the fiber optic backbone is successfully field tested and accepted by the pipeline community as the mode for monitoring corrosion and stress-corrosion cracking.
- The fiber optic backbone is capable of relaying accurately the signals from different pH sensors and/or MIC or CO_2 sensors attached at various locations on the fiber
- Sensing elemement requirements could be quite different depending on whether fiber optics or electrochemical or other transducer is used .
- The users can access the sensor unit through the TISEC communication system

4.2.8 Attributes

Security	The security of the sensor unit will become part of the overall pipeline network security
Maintainability	When the sensor system is down or lost sensitivity, the unit should be easily replaced. Physical access to the site is required.
Useability Requirements	The interfaces of the environment/sensor and sensor/transducer should be designed for clear and error-free communication

4.2.9 Design Constraints

Sensitivity/Activity	The sensor system should have enough sensitivity and activity for long-term field monitoring
On-Site Testing Sites	A field operating protocol will be developed for routine inspection of sensors.
Standard Compliance	A standard operating procedure for sensor testing will be developed with some inbuilt standards. This procedure will be used to ensure the sensor meets the requirements.
Service Requirements	A host of possible interfering substances will be developed. The extent of their interference will be documented. The role of an anti-interference layer in discriminating the interfering substances will be documented.
Adaptability	The sensor shall be incorporated with fiber optic cables for transmission of data.
Flexibility	The sensor shall be prepared in a physical form recommended by the fiber optic cable supplier.

4.3 pH SENSING ELEMENT

The sensing element is a smart agent to help the user to monitor the pH and relay the signal to the fiber optic backbone. The sensing element unit provides the following basic services

- Senses pH changes
- Discriminates other events that might produce similar signals
- Relays the signal to the fiber optic backbone.
- The sensing element is housed in a rugged, coloured unit for field deployment and identification

4.3.1 Sensing Element - Functionalities

The sensing element acts as an interface between the environment and the fiber optic backbone for pH monitoring. It is actually the agent that is producing the data based on environmental change (i.e., pH) and communicating the data to the fibre optic cable.

4.3.2 Sensing Element - Requirements and Specifications

An Internet search was conducted using DialogWeb, a search engine providing online-based information services to organizations seeking competitive advantages in such fields as business, science, engineering, finance and law. DialogWeb offers organizations the ability to retrieve data from more than 800 million unique records, accessible via the Internet. DialogWeb is a well established information retrieval system.

The search was conducted using as its search parameters the keywords, ‘Fiber Optics’, ‘Carbon Dioxide Sensors’, ‘pH Sensors’ and synonyms for each of these terms. The search returned results from the following databases:

INSPEC (1969 - present),
BIOSIS Previews (1969 - present),
NTIS - National Technical Information Service,
EI Compendex, SciSearch - a Cited Science Database - 1990 -,
Inside Conferences,
EMBASE (1974 - present),
Wilson Applied Science & Technology Abstracts,
Energy Science and Technology,
Aerospace Database,
PASCAL,
MEDLINE (1966 - present),
Electric Power Database , and
Federal Research in Progress (FEDRIP).
The results of the search were then downloaded into a database filing system called Reference Manager®, and then the results were separated into those applicable to pH sensors and those applicable to carbon dioxide sensors. The list of references that apply to pH sensors are collected at the end of this Appendix.

The commercial availability of FOpH sensors has been determined. Table III.1 gives examples of some sensors that have been found.

Table III.1: Some Commercially Available FOpH Sensors

Analyte	Sensing Element	Sensing Method	Remarks
Hydrogen	Tungsten Oxide	Surface plasma resonant light absorption by thin sensing element	
Hydrogen	Pd-Coated fibers		0.2-0.6% gas within 20-30 s
Hydrogen	Pd-based system with a Bragg grating	Bragg wavelength shift by the stress on Pd film caused by hydrogen	

Candidate commercial FOpH that perform some of the required functions will be examined in detail to determine if they could meet the requirements. The specific requirements of the sensing element to be selected for CANMET FOpH sensors are:

- Capabilities to react selectively to pH
- Capabilities of relaying the signal to the fiber optic backbone
- Long-term stability
- Able to withstand rugged operations and rough field handling
- Capabilities to withstand pipeline operating conditions, i.e., temperature and pressure fluctuations

4.3.3 Sensing Element - Constraints

Field conditions fluctuate between wet and dry seasons, between snowy and rainy seasons. To maintain this adaptability, the best sensing element will be able to be executable under various climatic conditions.

4.4 SENSOR SYSTEM ACCESS AND SUPPORT

4.4.1 Management-Side System Access

System access for General Users, Owner/Operators, Monitoring System Contractors, System Operators and Monitors, and Regulatory Observers is through the fiber optic backbone and through the TISEC portal

4.4.2 Central Station Access

The central station is accessed only at the hot station by authorized users.

4.4.3 Sensor System Physical Support

The sensors will be physically incorporated and supported by the fiber optic cables. The fiber optic cables have the following requirements:

- Capable of interacting with the sensor unit
- Capable of physically supporting the sensor unit
- Capable of discriminating signals from various sensors (pH, CO_2, and MIC) at various positions on its backbone
- Has obtained the recognition by the pipeline community as a capable system for corrosion and/or stress-corrosion monitoring.

4.4.4 Sensor System Knowledge Support

CANMET will provide system support and will carry out the following functions:

- Source of knowledge on pH sensor
- Evaluation system performance

4.5 INTEGRATED FIBER OPTIC CHEMICAL SENSOR ARRAY

The sensing element described in this appendix has been designed to provide an enhanced capability for monitoring pH over large areas of pipeline. Figure III.1 presents the flow chart for FOpH sensor development. At the time of writing this report, the system specifications and literature survey for the pH sensor have been completed. The next step will be to investigate if any of the commercial sensors will meet the requirements of ISPIR and the fiber optic backbone. If the answer is yes, then the commercial sensor will be evaluated with standard pH solutions. If the answer is no, then based on the literature database, a suitable sensor will be fabricated.

Based on experimental results using standard solutions, the interfering elements, if any, will be investigated. After understanding the interfering elements, an anti-interference layer will be developed, and the sensor unit will be re-evaluated in the laboratory using standard solutions. If there are no interfering elements, there is no need to develop an anti-interference layer.

After successfully testing the FOpH sensor using standard solutions, the sensor will be evaluated using live fluids obtained from the field

After successfully evaluating the FOpH sensor using live fluids, a limited amount of field evaluation will be performed.

Simultaneously, $FOCO_2$ and FOMIC will be developed. Appendix IV and V, respectively, describe the system specifications for CO_2 and MIC monitoring.

After evaluating the FOpH, $FOCO_2$ and FOMIC individually, the sensors will be incorporated in a single fiber optic cable backbone and evaluated. The integrated sensors will be evaluated in the laboratory, first with standard solutions and, after developing the anti-interference layer, with live solutions, and field evaluated before commercialisation. Fig.III.2 presents the flow chart for the development of an integrated fiber optic chemical sensor array.

Fig.III.1: Specification for Fiber Optic pH (FOpH) Sensor Development

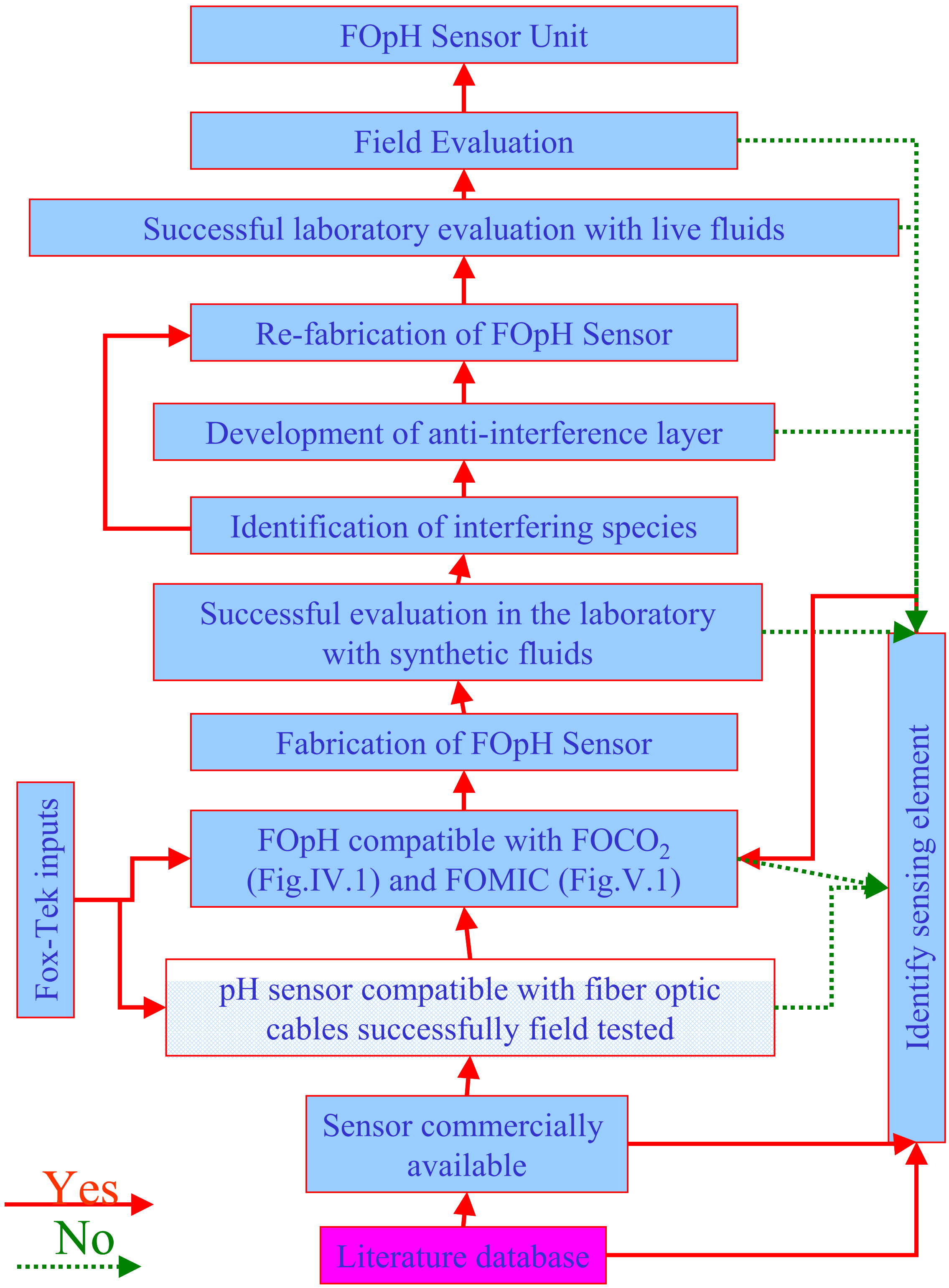
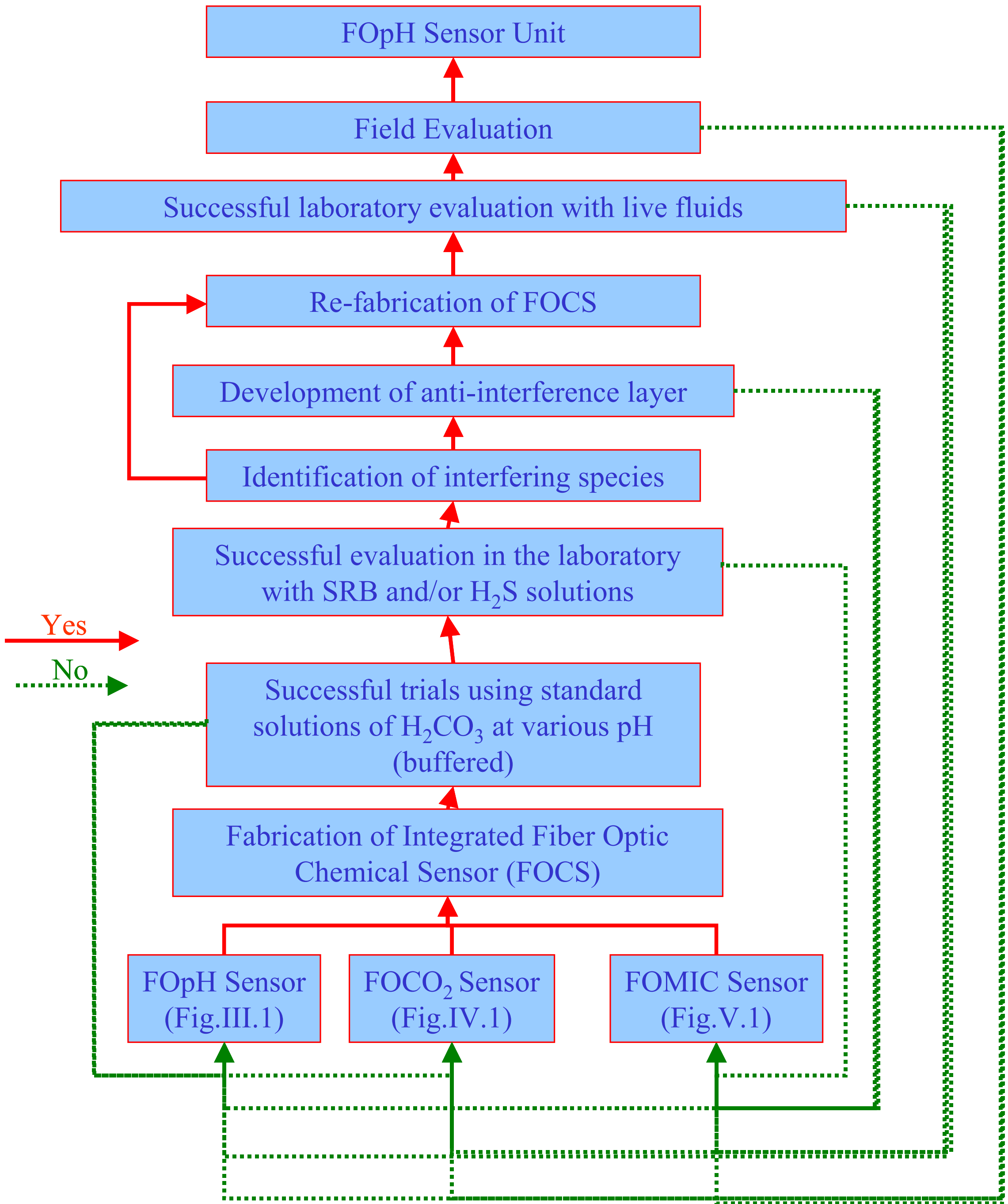


Fig.III.2: Specification for the Development of Integrated Fiber Optic Chemical Sensors for Pipeline Application



5 APPENDIX IV: SPECIFICATION FOR FIBER OPTIC CO_2 ($FOCO_2$) SENSOR

5.1 INTRODUCTION

This document outlines the definitions, specifications and features of the CANMET CO_2 system for integration with the fiber optic system to produce the fiber optic CO_2 sensor ($FoCO_2$) . It is a guideline to define and help to modularize the design for progressive implementation phases of the system. This appendix presents an introduction to the system and its context.

1.1. Purpose of this Specification

The purpose of this document is to define the requirements and specifications for the CO_2 sensor and its integration with the fiber optic transducer. The intended audiences for this document are:

- The $FOCO_2$ users, so they may review and provide input into the requirements.
- The design team, as this document will serve as the basis for system design.
- The test team, as this document will serve as the basis for system verification and validation.

The structure of this appendix is based on Structural Integrity Monitoring Over IP - SIM-o-IP (Version 1.0) Specifications developed by TISEC on Monday, October 21, 2002. In Section 2, a general description of the CANMET $FOCO_2$ system is given. Section 3 describes the sensing element development. Section 4 describes the fiber optic backbone system requirements for integrating with the $FOCO_2$ sensor. Section 5 positions $FOCO_2$ relative to other sensors including FOpH (Appendix III) and FOMIC (Appendix V).

This document also reviews the current status of the development of the $FOCO_2$ sensor.

1.2 System Perspective

The CANMET $FOCO_2$ system meets a twofold requirement: CO_2 monitoring at discrete locations around the pipelines.

- To integrate CO_2 monitoring with other chemical (pH) and biochemical (SRB) changes
- To integrate CO_2 changes with corrosion rates.

An additional requirement in new systems is to acquire data at several locations and to distribute these data as well as interpretations and decisions based on them to the parties involved in follow-up actions, particularly in a systems maintenance context. It will also permit us to install and evaluate the system at field sites in the future.

1.3 Acronyms

MIC	Microbiologically Influenced Corrosion
FopH	Fiber Optic pH Sensor
$FOCO_2$	Fiber Optic Carbon Dioxide Sensor
FOMIC	Fiber Optic Microbiological Influenced Corrosion Sensor
ISPIR	Intelligent Systems for Pipeline Infrastructure Reliability
SIM-o-IP	Structural Integrity Monitoring over Internet Protocol
SRB	Sulphate Reducing Bacteria
CO_2	Carbon Dioxide
SCC	Stress-Corrosion Cracking

5.2 GENERAL DESCRIPTION

This section specifies the system capabilities and functions, identifies who the users are and outlines the general constraints of the overall system and the assumptions and dependencies considered for the system.

5.2.1 2.1. System Capabilities

Pitting corrosion and stress-corrosion cracking (SCC) have caused pipeline failures and are significant threats to pipeline integrity. These phenomena depend on the environment at the pipe surface. It has been hypothesized that the quantity of chlorides, sulfates and CO_2 play a role in the severity of the environment that causes SCC and pitting.

Previous research has concluded that SCC cracks often initiate in corrosion pits, and both pitting and SCC have been observed in low (near-neutral) pH solutions. These environments have been attributed to a combination of low CP current and the presence of CO_2. Other research has suggested that the presence of free CO_2 in field electrolyte solutions creates a low pH, even in the presence of CP current, due to the equilibrium between carbonic acid and bicarbonate ions. It has also been suggested that CO_2 plays an important role in the generation and entry of diffusible hydrogen into steel, thus playing a major role in crack initiation and growth.

Since it is known that cracks often initiate at pits, in which a localized low pH environment exists due to the presence of CO_2, chlorides and sulfates, the role of these species in both corrosion pitting and SCC should be studied. In order to understand the role of the species, it is preferable to monitor the concentration of CO_2 online.

$FOCO_2$ is a real time sensor to monitor CO_2 at various locations along the pipeline and communicate through the fibre optic backbone. Fig. IV.1 presents the flow-chart to develop $FOCO_2$.

- The sensor monitors the CO_2 and communicates to the fiber optic backbone
- The transducer (fiber optic cable) transmits real-time data to the central station for processing and analyzing.

Customers at the management side can

- monitor the on site testing for current real-time CO_2 data
- send instrumentation setup commands to the sensors
- perform operational checks on sensor components and the fiber optic network

5.2.2 System Users

All users of the system can only access and/or activate the CO_2 sensor through the fibre optic backbone.

5.2.3 Sensor Configuration

The sensors are attached to the fiber optic backbone at pipeline sites which are being monitored. The sensor configurations may include

- Immobilized sensing element(s) specific to CO_2 concentration
- Anti-interference layer
- Rugged material(s) for protection of sensing element(s) and anti-interference layer
- A specific coloured casing or housing unit (specific colours for specific sensors)

The back end of each sensor unit is attached to the fiber optic backbone.

5.2.4 Management-Side Configuration

The link from sensors to the management-side users is made through fibre optic cables, developed and field tested by FOX-TEK.

5.2.5 Central Station Configuration

The central station will be established by TISEC Inc.

5.2.6 Sensor Component Availability

The CANMET FOCO$_2$ sensor has the following requirements:

- Sensing element(s) are active and sensitive at all times.
- Sensing elements are attached at various locations on the fiber optic backbone
- The fiber optic backbone is capable of relaying the signal accurately and immediately from specific sensors to the central station
- The central station should be running at all times.
- Management side users access the system on demand

5.2.7 Assumptions and Dependencies

The CANMET FOCO$_2$ sensor system has the following assumptions and dependencies:

- While the system monitors CO_2 changes, it is conveniently envisaged that the fiber optic backbone is successfully field tested and accepted by the pipeline community as the mode for monitoring corrosion and stress-corrosion cracking.
- The fiber optic backbone is capable of relaying accurately the signals from different CO_2 sensors and/or MIC or pH sensors attached at various locations on the fiber
- Sensing element requirements could be quite different depending on whether fiber optic or electrochemical or other transducer is used .
- The users can access the sensor unit through the TISEC communication system

5.2.8 Attributes

Security	The security of the sensor unit will become part of the overall pipeline network security
Maintainability	When the sensor system is down or lost sensitivity, the unit should be easily replaced. Physical access to the site is required.
Useability Requirements	The interfaces of the environment/sensor and sensor/transducer should be designed for clear and error-free communication

2.9 Design Constraints

Sensitivity/Activity	The sensor system should have enough sensitivity and activity for long-term field monitoring
On-Site Testing Sites	A field operating protocol will be developed for routine inspection of sensors.
Standard Compliance	A standard operating procedure for sensor testing will be developed with some inbuilt standards. This procedure will be used to ensure the sensor meets the requirements.
Service Requirements	A host of possible interfering substances will be developed. The extent of their interference will be documented. The role of an anti-interference layer in discriminating the interfering substances will be documented.

Adaptability	The sensor shall be incorporated with fiber optic cables for transmission of data.
Flexibility	The sensor shall be prepared in a physical form recommended by the fiber optic cable supplier.

5.3 CO_2 SENSING ELEMENT

The sensing element is a smart agent to help the user to monitor the CO_2 and relay the signal to the fiber optic backbone.

The sensing element unit provides the following basic services

- Senses CO_2 changes
- Discriminates other events that might produce similar signals
- Relays the signal to the fiber optic backbone.
- The sensing element is housed in a rugged, coloured unit for field deployment and identification

5.3.1 Sensing Element - Functionalities

Sensing element, acts as an interface between the environment and the fiber optic backbone for CO_2 monitoring. It is actually the agent that is producing the data based on environmental change (i.e., CO_2 concentration) and communicating the data to the fibre optic cable.

5.3.2 Sensing Element - Requirements and Specifications

An internet search was conducted using DialogWeb, a search engine providing online-based information services to organizations seeking competitive advantages in such fields as business, science, engineering, finance and law. DialogWeb offers organizations the ability to retrieve data from more than 800 million unique records, accessible via the Internet. DialogWeb is a well established information retrieval system. The search was conducted using as its search parameters the keywords, ‘Fiber Optics’, ‘Carbon Dioxide Sensors’, ‘pH Sensors’ and synonyms for each of these terms. The search returned results from the following databases:

INSPEC (1969 - present),
BIOSIS Previews (1969 - present),
NTIS - National Technical Information Service,
EI Compendex, SciSearch - a Cited Science Database - 1990 -,
Inside Conferences,
EMBASE (1974 - present),
Wilson Applied Science & Technology Abstracts,
Energy Science and Technology,
Aerospace Database,
PASCAL,
MEDLINE (1966 - present),
Electric Power Database , and
Federal Research in Progress (FEDRIP).

The results of the search were then downloaded into a database filing system called Reference Manager®, and then the results were separated into those applicable to pH sensors and those applicable to carbon dioxide sensors. The list of references that apply to $FOCO_2$ sensors are attached at the end of this appendix.

The commercial availability of $FOCO_2$ sensors has been determined.

Candidate commercial $FOCO_2$ that perform some of the required functions will be examined in detail to determine if they could meet the requirements. The specific requirements of the sensing element to be selected for CANMET $FOCO_2$ sensors are:

- Capabilities to react selectively to CO_2
- Capabilities to relay the signal to fiber optic backbone
- Long-term stability
- Capability to withstand rugged operations and rough field handling
- Capabilities to withstand pipeline operating conditions, i.e., temperature and pressure fluctuations

5.3.3 Sensing Element - Constraints

Field conditions fluctuate between wet and dry seasons, between snowy and rainy seasons. To maintain this adaptability, the best sensing element will be executable under various climatic conditions.

5.4 SENSOR SYSTEM ACCESS AND SUPPORT

5.4.1 Management-Side System Access

System access for General Users, Owner/Operators, Monitoring System Contractors, System Operators and Monitors, and Regulatory Observers is through the fiber optic backbone and through the TISEC portal

5.4.2 Central Station Access

The central station is accessed only at the hot station by authorized users.

5.4.3 Sensor System Physical Support

The sensors will be physically incorporated and supported by the fiber optic cables. The fiber optic cables have the following requirements:

- Capable of interacting with the sensor unit
- Capable of physically supporting the sensor unit
- Capable of discriminating signals from various sensors (pH, CO_2, and MIC) at various positions on its backbone
- Obtained the recognition by the pipeline community as a system for monitoring corrosion and/or stress-corrosion.

4.3 Sensor System Knowledge Support

CANMET will provide system support and carries out the following functions:

- Source of knowledge on CO_2 sensor
- Evaluation of system performance

5.5 INTEGRATED FIBER OPTIC CHEMICAL SENSOR ARRAY

The sensing element described in this appendix has been designed to provide an enhanced capability for monitoring CO_2 over large areas of pipeline. Figure III.1 presents the flow chart for $FOCO_2$ sensor development. At the time of writing this report, the system specifications and literature survey for CO_2 sensors has been completed. The next step will be to investigate if any of the commercial sensors will meet the requirements of ISPIR and the fiber optic backbone. If the answer is yes, then the commercial sensor will be evaluated with standard CO_2 solutions. If the answer is no, then based on the literature database, a suitable sensor will be fabricated.

Based on experimental results using standard solutions, the interfering elements, if any, will be investigated. After developing an understanding of the interfering elements, a suitable anti-interference layer will be developed. The sensor unit will be re-evaluated in the laboratory using standard solutions. If there are no interfering elements, there is no need to develop an anti-interference layer.

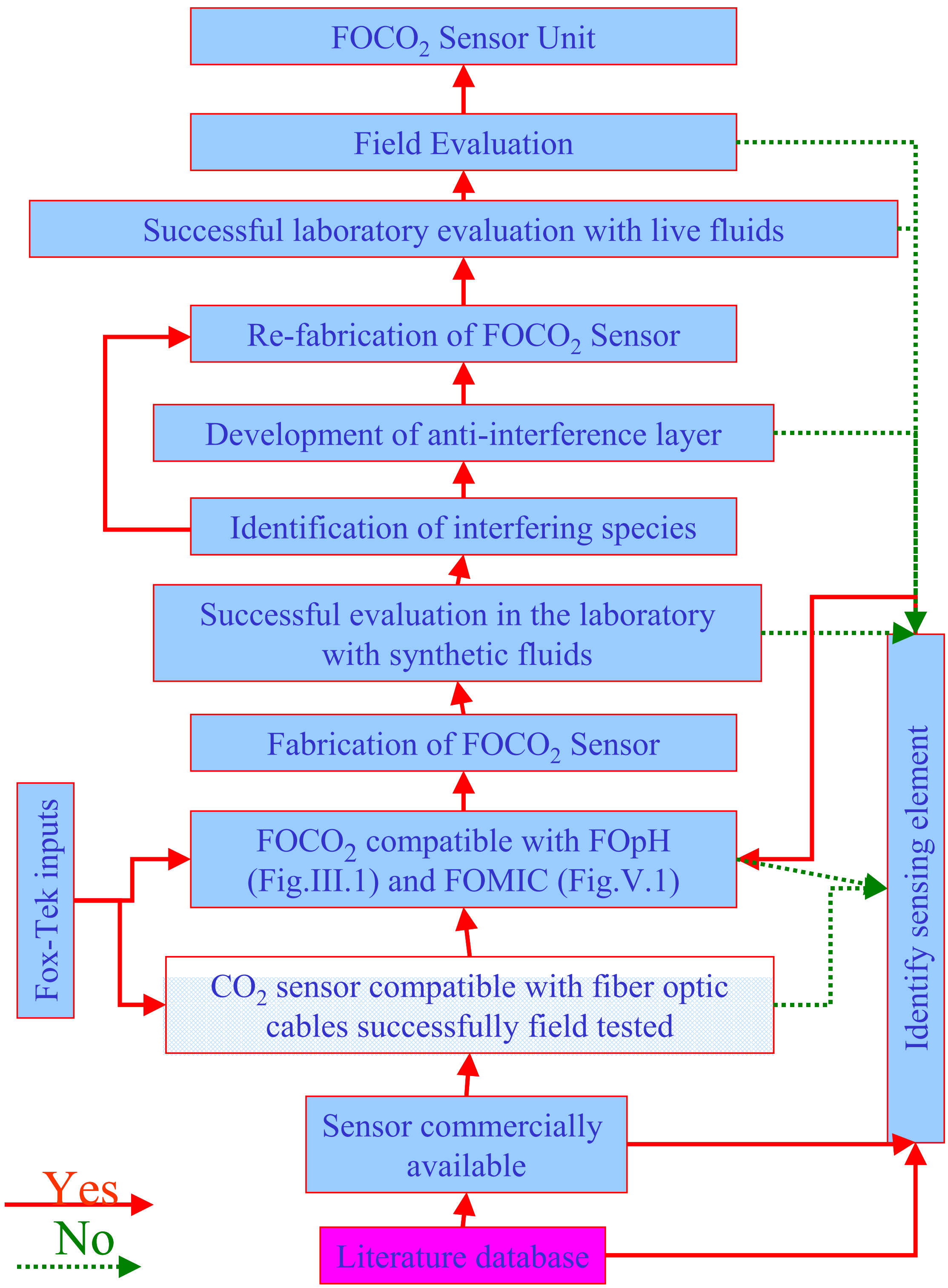
After successfully testing the $FOCO_2$ sensor using standard solutions, the sensor will be evaluated using live fluids obtained from the field

After successfully evaluating the $FOCO_2$ sensor using live fluids, a limited amount of field evaluation will be performed.

Simultaneously, FopH and FOMIC will be developed. Appendices III and V, respectively, describe the system specifications for pH and MIC monitoring.

After evaluating the FopH, $FOCO_2$ and FOMIC individually, the sensors will be incorporated in a single fiber cable backbone and evaluated. The integrated sensors will again be evaluated in the laboratory, first with standard solutions and, after developing the anti-interference layer, with live solutions, and field evaluated before commercialisation. Fig.III.2 presents the flow chart for development of the integrated fiber optic chemical sensor array.

Fig.IV.1: Specification for Fiber Optic CO_2 ($FOCO_2$) Sensor Development



6 SPECIFICATION FOR FIBER OPTIC MIC (FOMIC) SENSOR

6.1 Introduction

This document outlines the definitions, specifications and features of the CANMET MIC system for integration with a fiber optic system to produce fiber optic MIC sensor (FOMIC) . It is a guideline to define and help to modularize the design for progressive implementation phases of the system. This appendix presents an introduction to the system and its context.

6.1.1 Purpose of this Specification

The purpose of this document is to define the requirements and specifications for the MIC sensor and its integration to the fiber optic transducer. The intended audiences for this document are:

- The FOMIC users, so they may review and provide input into the requirements.
- The design team, as this document will serve as the basis for system design.
- The test team, as this document will serve as the basis for system verification and validation.

The structure of this appendix is based on Structural Integrity Monitoring Over Internet Protocol - SIM-o-IP (Version 1.0) Specifications developed by TISEC on Monday, October 21, 2002. In Section 2, a general description of the CANMET FOMIC system is given. Section 3 describes the sensing element development. Section 4 describes fiber optic backbone system requirements for integrating FOMIC sensor. Section 5 positions FOMIC relative to other sensors including FOpH (Appendix III) and $FOCO_2$ (Appendix IV).

This document also reviews the current status of the development of the FOMIC sensor.

6.1.2 System Perspective

The CANMET FOMIC system meets a twofold requirement for monitoring MIC at discrete locations at and near pipelines:

- To integrate MIC monitoring with other chemical (pH) and chemical (CO_2) changes
- To integrate MIC changes with corrosion rates.

An additional requirement in new systems is to acquire data at several locations and to distribute these data as well as interpretations and decisions based on them to the parties involved in follow-up actions, particularly in a systems maintenance context. It will also permit us to install and evaluate the system at field sites in the future.

6.1.3 Acronyms

MIC	Microbiologically Influenced Corrosion
FopH	Fiber Optic pH Sensor
$FOCO_2$	Fiber Optic Carbon Dioxide Sensor
FOMIC	Fiber Optic Microbiologically Influenced Corrosion (MIC) Sensor
ISPIR	Intelligent Systems for Pipeline Infrastructure Reliability
SIM-o-IP	Structural Integrity Monitoring over Internet Protocol
SRB	Sulphate Reducing Bacteria
CO_2	Carbon Dioxide
SCC	Stress-Corrosion Cracking

6.1.4 Current System Status

A literature search on the fiber optic MIC sensors has been completed. System specification for the development of FOMIC has been outlined. "Biological Activity Probe" US Patent: Application No: US09/809,108 (Filed on March 16, 2001) and Canadian Patent filed in March 2002. A sensing element for monitoring SRB has been identified. Work on bacterial culture to develop the sensors is being started.

Because the several steps involved, including culture, growth, harvest, isolation, purification, determination of bacterial growth, growth curve, immobilization and activity of immobilized bacteria, may take some time, it is envisaged that the development of FOMIC may take about another 9-12 months.

6.2 General Description

This section specifies the system capabilities and functions, identifies who the users are and outlines the general constraints of the overall system and the assumptions and dependencies considered for the system.

6.2.1 System Capabilities

Since the discovery of sulphate-reducing bacteria (SRB) by the Dutch microbiologist Wilhelm Bijerninck[1] in 1905, the question of what is now referred to as microbiologically influenced corrosion (MIC) has been a subject of extensive research and interest. MIC has been documented for metals exposed to seawater, fresh water, demineralized water, process chemicals, foods, aircraft fuels, human plasma, and sewage.

Despite the evidence that a number of different groups of microorganisms are capable of accelerating corrosion, and the recognition that most MIC[2] occurs in the presence of consortia of bacteria[3], SRB have received the most attention as the causative agents of MIC for several reasons:

- Historically, SRB have been thought to be the most common causative group of microorganisms involved in microbial corrosion[4];
- The first corrosion mechanism to explain the anaerobic corrosion of iron and steel involved SRB;
- They are ubiquitous and, in anaerobic, sulphate-containing environments, they produce hydrogen sulphide, which can react with iron, copper, and nickel alloys;
- The metabolic processes of SRB that involve hydrogen utilization and hydrogen sulfide production make them obvious candidates to accelerate corrosion of metals under anaerobic conditions;
- SRB were one of the first microorganisms that were identified as being capable of promoting corrosion of metals under anaerobic conditions;
- Discovery and identification of the genus *Desulfovibrio*;
- The ability of SRB to convert sweet production to sour production (containing hydrogen sulphide);
- The development of much valuable information on the identification and cultivation of oilfield microorganisms; and
- Microbiological plugging that reduces flow injection rates.

Despite the recognized involvement of SRB in microbial corrosion, analytical methods have restricted the application of microbial assessment to pipeline reliability[1-21]. In particular, the lack of a direct correlation between numbers of SRB and the likelihood that corrosion has or will occur has limited the ability to assess risk. Based on a 30-month study of electrochemical, weight-loss, water chemistry, and microbiological data for an oilfield water flood operation which produced brine was injected to displace oil from the reservoir, no correlation was established between corrosion measurements and microbial numbers[5]. A 2-year study of MIC in natural gas pipeline facilities failed to establish a relationship between numbers of SRB and MIC in carbon steel[6].

Microorganisms can accelerate the electrochemical processes of corrosion by assisting in the establishment of electrochemical cells, or by stimulating the anodic and cathodic reactions. Microorganisms are not restricted to one form of corrosion. Instead, the presence and activities of microorganisms can cause pitting, crevice corrosion, selective dealloying, and differential aeration cells, in addition to enhanced galvanic and erosion corrosion. MIC does not produce a totally unique type of localized corrosion. However, there are some morphological descriptions that are often associated with MIC, such as nonuniform pitting[7], pits filled with black corrosion product[8], rounded pits under tubercles on carbon steel[9], and pinholes at the surface leading to large subsurface cavities on stainless steel.

As a consequence of the absence of definitive indicators, identification of MIC is often complicated by misconceptions. Furthermore, there are no definite tests that can be used to detect MIC. Diagnosis requires sophisticated microbiological, surface analytical, and electrochemical techniques. The reason for the inconsistency of knowledge can be related directly to the lack of methods for monitoring MIC.

Based on 3 years of extensive in-house R&D, CANMET applied for a patent (US 09/809,108), "CANMET Bio-Corrosion Probe (CBC-Probe)" that can be used "in-situ" to monitor both corrosion and SRB activity simultaneously.

The CANMET Bio-Corrosion Probe characterising MIC has the following unique features:

- Because it is generally recognised that the most common cause of MIC is SRB activity, the device can be used to detect SRB activity within a biofilm.
- The device can be used to differentiate the corrosion rate caused by microbial activity and by non-microbial activity.
- The measurements of SRB activity and corrosion rate are online and instantaneous.
- The device will detect the activity of SRB which are active only under anaerobic conditions, but the probe can potentially function under aerobic conditions as well.

The CANMET Bio-Corrosion Probe has two parts: 1. SRB activity monitoring and 2. Corrosion monitoring. Both SRB and corrosion monitoring are performed by electrochemical methods.
An electrochemical method for on-line monitoring of biofilm activity has been developed for continuous monitoring of biofilm formation without the need for excessive involvement of plant personnel[19-21]. Stainless steel or titanium discs are exposed to the plant environment. One set of discs is polarized (relative to the other set) for a short period of time each day. The electrodes are connected through a shunt the remainder of the time. Biofilm activity is monitored by tracking changes in the applied current (i.e., when the external potential is on) and the generated current (when the potential is off). The onset of biofilm formation on the probe is indicated when either of these independent indicators deviates from the baseline level. The level of biofilm activity is also measured by the amount of variation from the baseline. On-line monitoring of biofilm using silver electrodes plated onto platinum electrodes is also available[22].

Change in potential or current can occur for several reasons, including formation of surface films, solid deposition, biofilm deposition and microbiological activities[23,24]

MIC is a form of localised corrosion. Standard and specialised corrosion monitors have been developed that provide an alert that the system being monitored (or an accelerated and disposable simulation of the system) is corroding, how it is corroding, and at what rate. The corrosion monitor provides qualitative information on MIC rate. The commonly used electrochemcial methods for corrosion monitoring include galvanic probes; electrical resistance probes; linear polarisation resistance (LPR); electrochemical impedance spectroscopy (EIS); and electrochemical noise (EN).

FOMIC, on the other hand, is a real time sensor to monitor MIC at various locations along the pipeline and communicate through the fibre optic backbone; i.e., both SRB and corrosion monitoring are performed by fiber optics. Fig. V.1 presents the flow-chart to develop $FOCO_2$.

- The sensor monitors MIC and communicates to the fiber optic backbone
- The transducer (fiber optic cables) transmits real-time data to the central station for processing and analyzing.

Customers on the management side can

- Monitor the on-site testing for current real-time MIC data
- Send instrumentation setup commands to the sensors
- Perform operational checks on sensor components and the fiber optic network

6.3 System Users

All users of the system can access and/or activate the MIC sensor through the fibre optic backbone only.

6.3.1 Sensor Configuration

The sensors are attached to the fiber optic backbone at pipeline sites which are being monitored. The sensor configurations may include

- Immobilized sensing element(s) specific to MIC causing SRB
- Anti-interference layer
- Rugged material(s) for protection of sensing element(s) and the anti-interfernce layer
- A specific coloured casing or housing unit (specific colours for specific sensors)

The back end of each sensor unit is attached to the fiber optic backbone.

6.3.2 Management-Side Configuration

The link from sensors to the management-side users is made through fibre optic cables, developed and field tested by FOX-TEK.

6.3.3 *Central Station Configuration*

The central station will be established by TISEC Inc.

6.3.4 Sensor Component Availability

The CANMET FOMIC sensor has the following characteristics:

- Sensing element(s) are active and sensitive at all times
- Sensing elements are attached at various locations on the fiber optic backbone
- The fiber optic backbone is capable of relaying the signal accurately and immediately from specific sensors to the central station
- The central station should be running at all times.
- Management side users access the system on demand

6.3.5 Assumptions and Dependencies

The CANMET FOMIC sensor system has the following assumptions and dependencies:

- While the system monitors SRB activities, it is envisaged that the fiber optic backbone will be successfully field tested and accepted by the pipeline community as the mode for monitoring corrosion and stress-corrosion cracking.
- The fiber optic backbone is capable of relaying accurately the signals from different CO_2 sensors and/or MIC or pH sensors attached at various locations on the fiber
- Sensing element requirements could be quite different depending on whether fiber optics or electrochemical or other transducer is used .
- The users can access the sensor unit through the TISEC communication system

6.3.6 Attributes

Security	The security of the sensor unit will become part of the overall pipeline network security
Maintainability	When the sensor system is down or sensitivity has been lost, the unit should be easily replaced. Physical access to the site is required.
Usability Requirements	The interfaces of the environment/sensor and sensor/transducer should be designed for clear and error-free communication

2.9 Design Constraints

Sensitivity/Activity	The sensor system should have enough sensitivity and activity for long-term field monitoring
On-Site Testing Sites	A field operating protocol will be developed for routine inspection of sensors.
Standard Compliance	A standard operating procedure for sensor testing will be developed with inbuilt standards. This procedure will be used to ensure that the sensor meets the requirements.
Service Requirements	A host of possible interfering substances will be developed. The extent of their interference will be documented. The role of the anti-interference layer in discriminating the interfering substances will be documented.
Adaptability	The sensor shall be incorporated with fiber optic cables for transmission of data.
Flexibility	The sensor shall be prepared in a physical form recommended by the fiber optic cable supplier.

6.4 MIC Sensing Element

The sensing element is a smart agent to help the user to monitor the MIC and relay the signal to the fiber optic backbone.

The sensing element unit provides the following basic services

- Senses MIC activities
- Descriminates other events that produce similar signals
- Relays the signal to the fiber optic backbone.
- The sensing element is housed in a rugged, coloured unit for field deployment and identification

6.4.1 Sensing Element - Functionalities

The sensing element acts as an interface between the environment and the fiber optic backbone for MIC monitoring. It is actually the agent that produces the data based on environmental change (i.e., MIC activity) and communicating the data to the fibre optic cable.

6.4.2 Sensing Element - Requirements and Specifications

The specific requirements of sensing element to be selected for CANMET FOMIC sensors are:

- Capabilities of selectively reacting to MIC activity
- Capabilities of relaying the signal to the fiber optic backbone
- Long-term stability
- Capacity to withstand rugged operation and rough field handling
- Capabilities to withstand pipeline operating conditions, i.e., temperature and pressure fluctuations

6.4.3 Sensing Element - Constraints

Field conditions fluctuate between wet and dry seasons, between snowy and rainy seasons. To maintain this adaptability, the best sensing element will be executable under various climatic conditions.

6.5 Sensor System Access and Support

6.5.1 Management-Side System Access

System access for General Users, Owners/Operators, Monitoring System Contractors, System Operators and Monitors, and Regulatory Observers is through the fiber optic backbone and through the TISEC portal.

6.5.2 Central Station Access

The central station is accessed only at the hot station by authorized users.

6.5.3 Sensor System Physical Support

The sensors will be physically incorporated and supported by the fiber optic cables. The fiber optic cables have the following requirements:

- Capable of interacting with the sensor unit
- Capable of physically supporting the sensor unit
- Capable of discriminating signals from various sensors (pH, CO_2, and MIC) at various positions on its backbone
- Recognized by the pipeline community for monitoring corrosion, including stress-corrosion cracking.

6.5.4 Sensor System Knowledge Support

CANMET will provide system support and will carry out the following functions:

- Source of knowledge on MIC sensor
- Evaluation of system performance

6.6 Integrated Fiber Optic Chemical Sensor Array

The sensing element described in this appendix has been designed to provide an enhanced capability for monitoring MIC activity over large areas of pipeline. Figure V.1 presents the flow chart for FOMIC sensor development. At the time of writing this report, the system specifications and literature survey for the FOMIC sensor has been completed. Work on the bacterial culture to develop the sensors is being started.

Based on experimental results using standard solutions, the interfering elements, if any, will be investigated. After developing an understanding of the interfering elements, an anti-interference layer will be developed, and the sensor unit will be re-evaluated in the laboratory using standard solutions. If there are no interfering elements, there will be no need to develop an anti-interference layer.

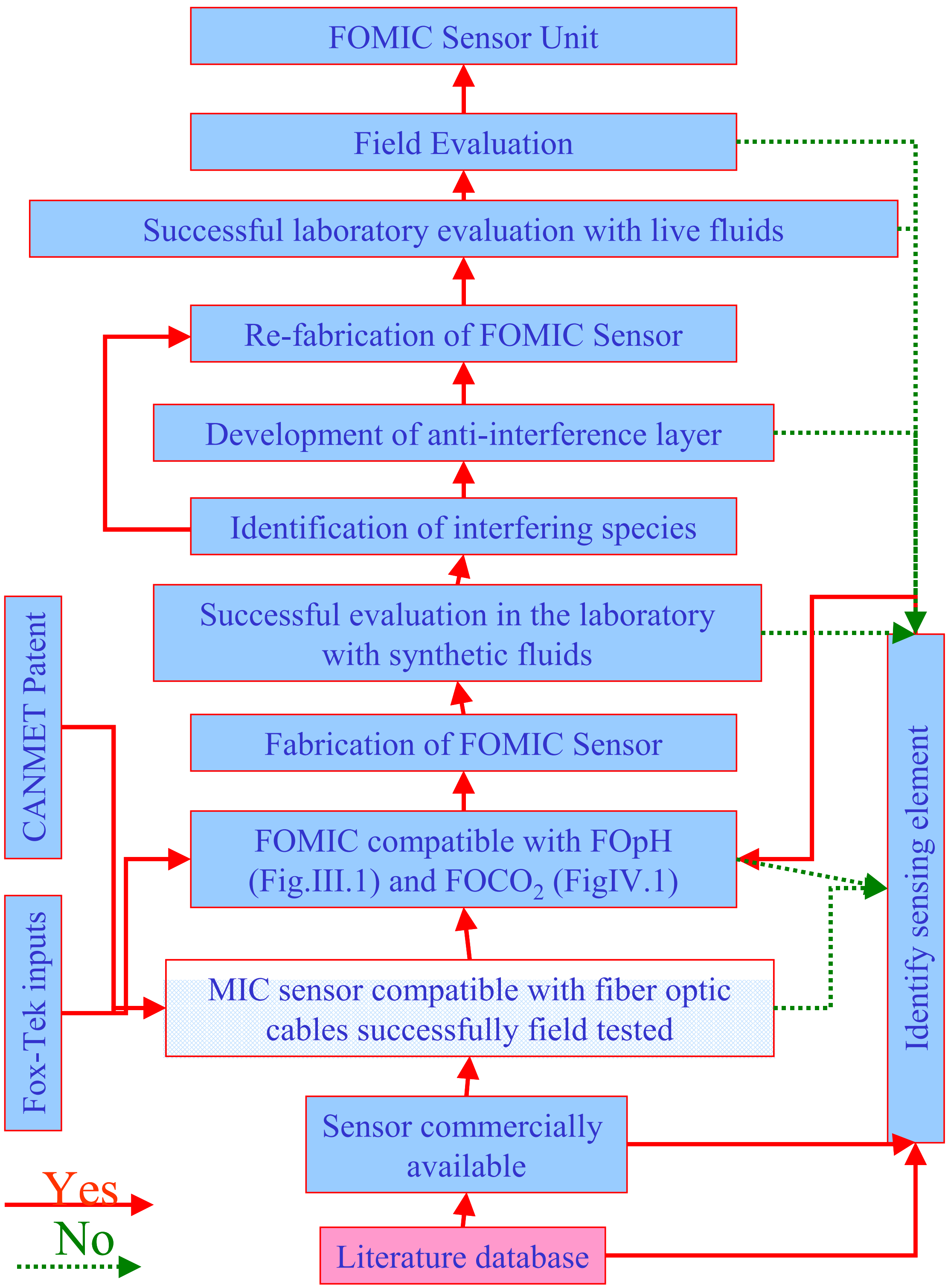
After successfully testing the FOMIC sensor using standard solutions, the sensor will be evaluated using live fluids obtained from the field.

After successfully evaluating the FOMIC sensor using live fluids, a limited amount of field evaluation will be carried out.

The several steps involved, including culture, growth, harvest, isolation, purification, determination of bacterial growth, growth curve, immobilisation, and activity of immobilized bacteria, may take some time. It is envisaged that the development of FOMIC may take about 9 to 12 months. FOpH and $FOCO_2$ will be developed. Appendix III and IV, respectively, describe the system specifications for monitoring pH and CO_2.

After evaluating the FopH, $FOCO_2$ and FOMIC individually, the sensors will be incorporated in a single fiber optic cable backbone and evaluated. The integrated sensors will again be evaluated in the laboratory, first with standard solutions and, after developing the anti-interference layer, with live solutions. Field evaluated will be carried out before commercialisation. Fig.III.2 presents the flow chart for development of the integrated fiber optic chemical sensor array.

Fig.V.1: Specification for Fiber Optic MIC (FOMIC) Sensor Development



7 APPENDIX I: PICON SURVEY

7.1 Survey Demographics

To collect the information on various techniques that are currently being used in the pipeline industry, an online survey was posted at: http://www.nrcan.gc.ca/PICon in April 2002. By the time the survey was completed in October 2002, 47 persons had responded to it. This section presents the analysis of the survey.

A total of 47 persons have responded to the survey, including most sectors of the pipeline industry -- coating manufacturers, coating applicators, coating users, pipeline companies, R&D performers, academicians, and consultants (Table VI.1). About 83 % of the responders were from North America, whereas the remaining 17 % were from Argentina, Australia, Belgium, India, Iran, South Korea, South Africa, and Venezuela. The majority of responses to the survey came from personnel interested in gas production (68%), oil and gas production (59%), gas transmission (59%), oil transmission (58%) and oil production pipelines (43%). One response each came from respondent.

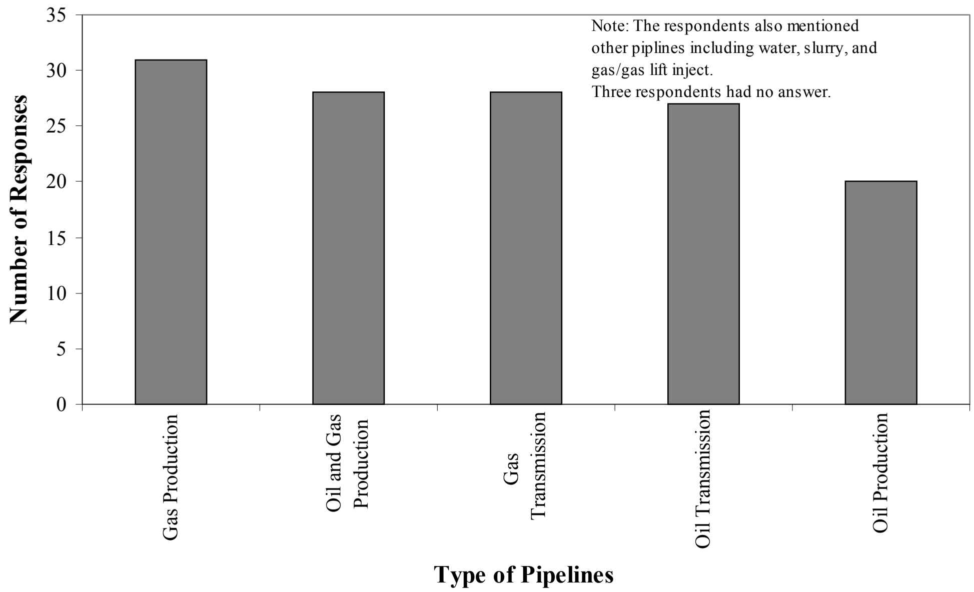


Figure VI.2 presents the pipeline corrosion type the industry is interested in. About 60% of the respondents are interested both in internal and external corrosion. The remaining persons were interested either in internal corrosion (20%), or external corrosion (10%) only, or skipped this question (10%). Figure VI.3 presents the various concerns that affect pipeline performance. The following paragraphs discuss various techniques that pipeline companies use to monitor the features that concern pipeline performance. The techniques can be broadly classified into:

- Physical Techniques
- Electrochemical Techniques
- Non-Intrusive Techniques
- On-Line Monitoring Techniques
- MIC Monitoring Techniques
- Off-Line Monitoring Techniques
- ILI Techniques
- New Techniques

Figure VI.2: Companies Major Interest with Respect to Corrosion

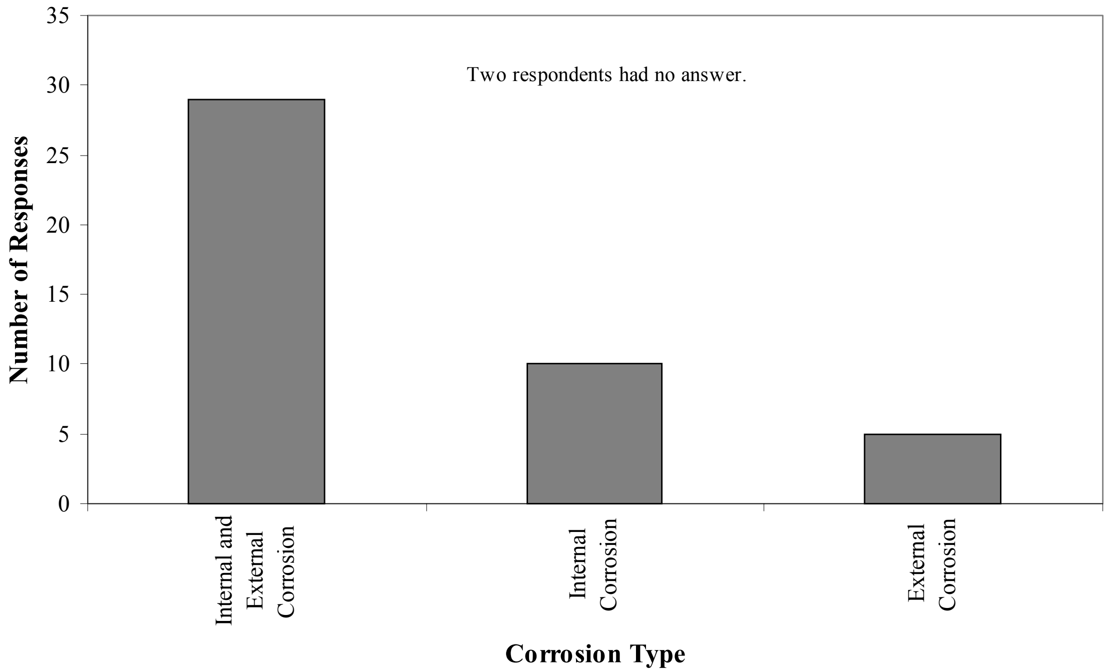
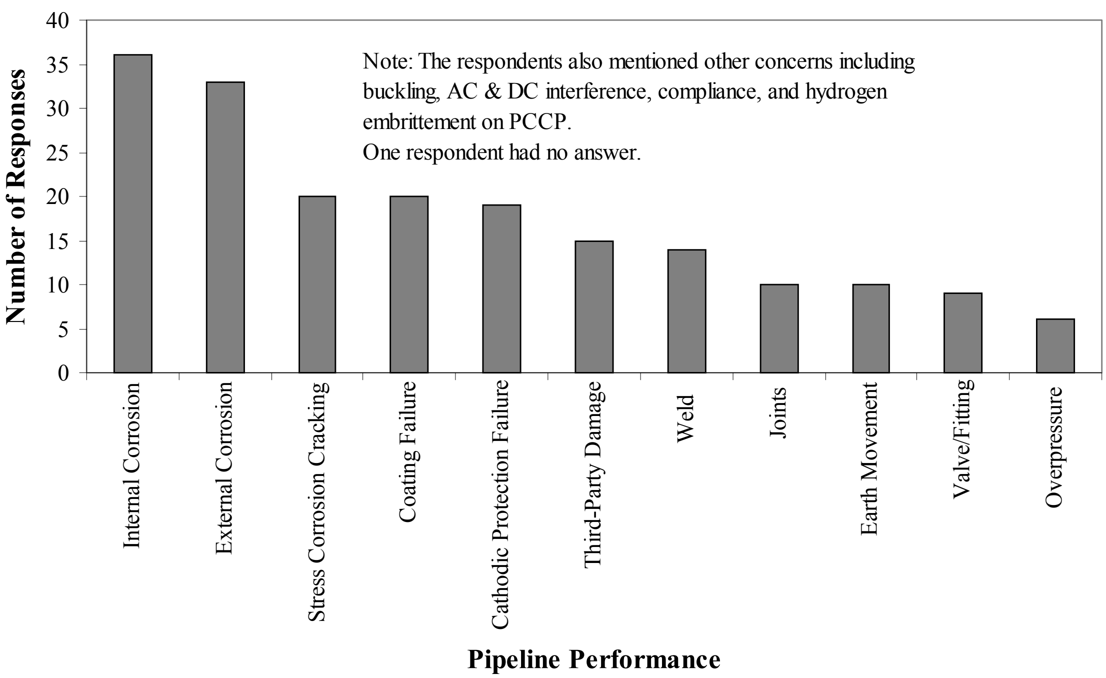


Figure VI.3: Companies Major Concerns for Pipeline Performance



7.2 PHYSICAL TECHNIQUES

Figures VI.4, VI.5, and VI.6, respectively, present the physical techniques the companies use, prefer to use, and their reliability. By far the most preferred technique is ILI, both in terms of usage and preference. The following paragraphs discuss individually the merits and demerits of the techniques as observed by the participants.

Visual Inspection (Internal and External Corrosion)

Advantages:

- It is not a unique technique, but is simply the means by which one obtains information when examining the pipe visually following excavation.

Disadvantages

- Small area inspected. It does not give the full picture
- Easily misleading. It is not an on-line tool
- The nature of external corrosion in the soil in the environment makes conditions extremely variable from one section to the next and therefore unpredictable.
- Doesn't give good results
- Usually, one cannot make a scientific judgment by using visual inspection

Electrical Resistance (ER) (Internal Corrosion)

Advantages

- The response capacity and its accuracy are good
- Proven technology, easy, resistant to fouling
- It has established a place in pipeline monitoring

Disadvantages

- Lack of care and maintenance, loss of data
- Frequent equipment failure
- Non-utility in sour service
- Probes and coupons can only assess corrosivity of the media. Generally, an assumption is made that the pipe wall will behave virtually the same way, which may or may not be true.
- Provides information only on corrosion at the site where the device is located.

Mass Loss (Internal Corrosion)

Advantages

- Don't have to shut down, inexpensive
- Commonly used by pipeline operators
- The coupons present a visual representation of the form of attack
- It is the real weight loss, whereas in ER one may obtain a false reading.

Disadvantages

- Often the coupons are not correctly installed, and the analysis of the data is not performed correctly.
- Differences in chemical composition and metallurgical characteristics of coupons *vs.* real materials; differences in service conditions among the coupons in the line.
- Mass-loss coupons are sensitive to locations and give data for one location only.

Close-Interval Survey (External Corrosion)

Advantages

- Provides a relatively detailed profile of the pipe-to-soil potential over the line. Differences between the on and off potentials infer ground current flow to the pipe at the measuring point. Areas of non-compliance with criteria can be marked on the surface
- Gives indication of potential problem at low cost
- The best way to combat external corrosion problems
- Most valuable to pipeline operator trying to address pipeline integrity concerns on the largest sector of pipelines. This is applicable to nearly all pipelines, because all pipelines have CP, and still have external corrosion occurring

Disadvantages

- Coating surveys are often conducted by inexperienced technicians and oversold to be capable of finding corrosion. Coating failures only become an integrity concern if CP and soil conditions are conducive.

FSM (Internal Corrosion)

Advantages

- Fast response, good coverage of the pipe surface.
- It can be applied over long distances of pipe

DCVG (External Corrosion)

Advantages

- Excavation is not required, detects, dimensions and ranks failure severity.
- It is the only method that gives the pipeline operator an accurate assessment of whether the pipeline is cathodically protected or corroding.

ILI

Advantages

- In Line Inspection (ILI) results in data for most of the pipeline and can indicate locations needing special attention.
- Covers the entire line
- Ability to monitor actual corrosion (location and severity) on the pipeline
- Comprehensive coverage of internal, external as well as geometrical features
- Wall thickness readings along the entire length of the pipeline
- Only real method which gives actual condition of the entire pipeline.
- UT is an direct measurement of wall thickness as opposed to MFL, which is an indirect measurement of change in wall thickness.
- The combination of tools to use is critical to a correct assessment of integrity.

Figure VI.4: Physical Techniques Companies Use in Pipeline Monitoring/Inspection

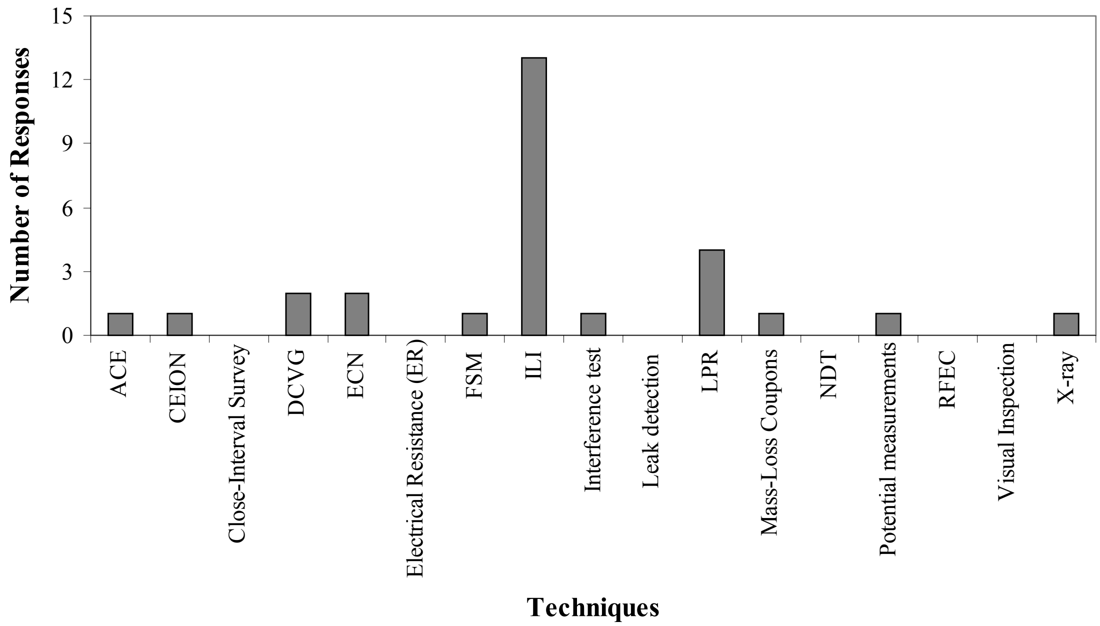


Figure VI.5: Physical Techniques Companies Prefer to Use in Pipeline Monitoring/Inspection

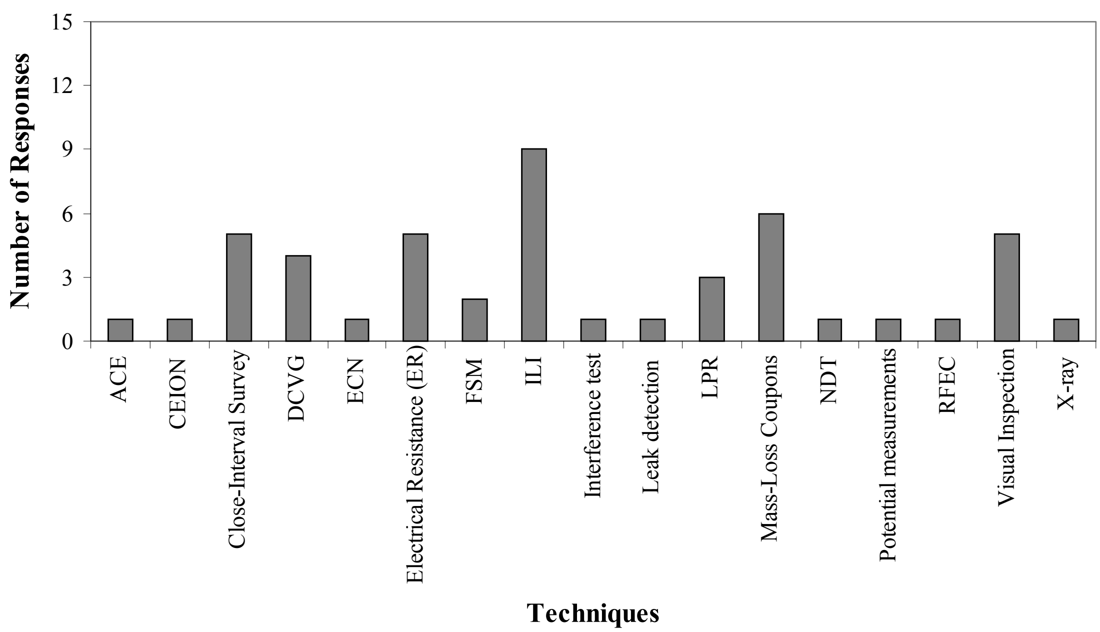
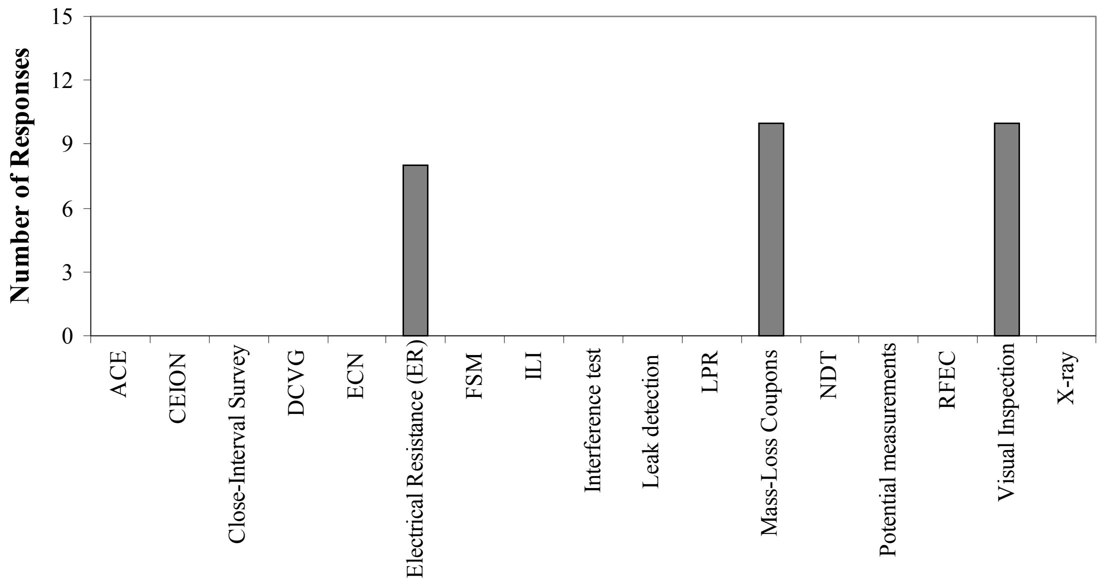


Figure VI.6: Physical Techniques Companies Find Unreliable in Pipeline Monitoring/Inspection



7.3 Electrochemical Techniques

Because corrosion is electrochemical in nature, several electrochemical techniques are used to monitor it. Figures VI.7, VI.8, and VI.9, respectively, present the electrochemical techniques the companies use, prefer to use, and their reliability. By far the most preferred technique is LPR, both in terms of usage and preference. Electrochemical noise technique is the second most preferred and used technique. The industry is still not comfortable in using ECN, as this technique is identified as the most unreliable technique.

The following paragraphs discuss individually the merits and demerits of the techniques as observed by the participants.

LPR (Internal Corrosion)

Advantages

- Quick response times, if correctly located
- Fast response, but requires free water
- Simple and straightforward
- Relatively easy to use by field technicians

Potentiodynamic Polarization (Internal and External Corrosion)

Advantages

- This technique gives an indication of the effect of cathodic protection

Disadvantages

- There is a lot of interference from previous runs and condition, i.e., repeat monitoring can not be performed.
- It produces sensor damage and is subject to probe malfunction in short time. No track record.
- Polarization away from E_{corr}

Figure VI.7: Electrochemical Techniques the Companies use for Pipeline Monitoring

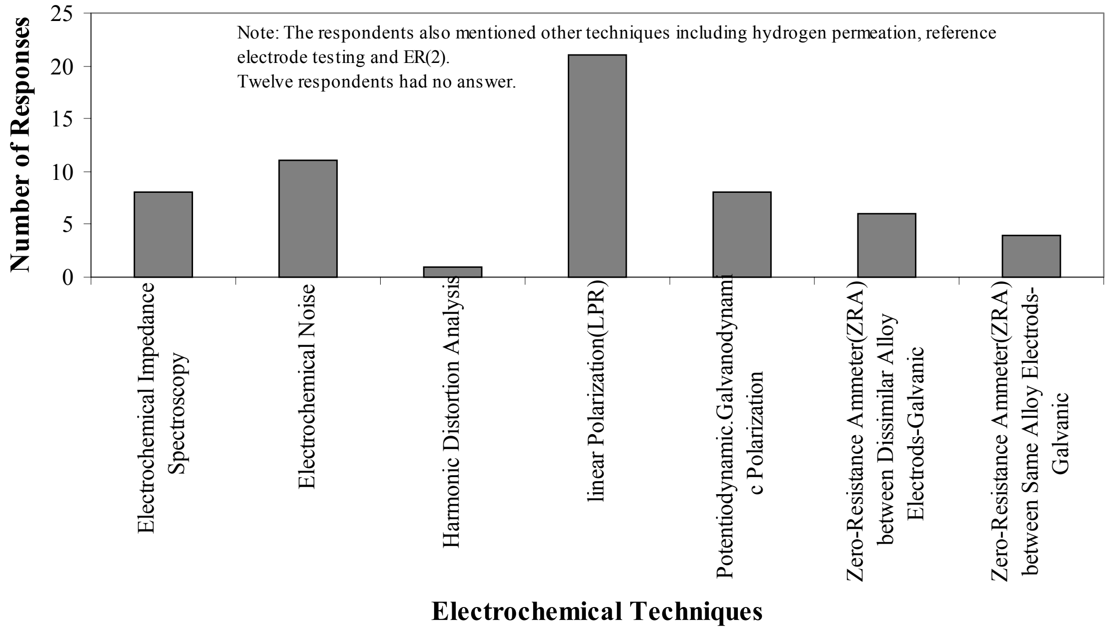


Figure VI.8: Electrochemical Techniques Companies Prefer to Use for Pipeline Monitering

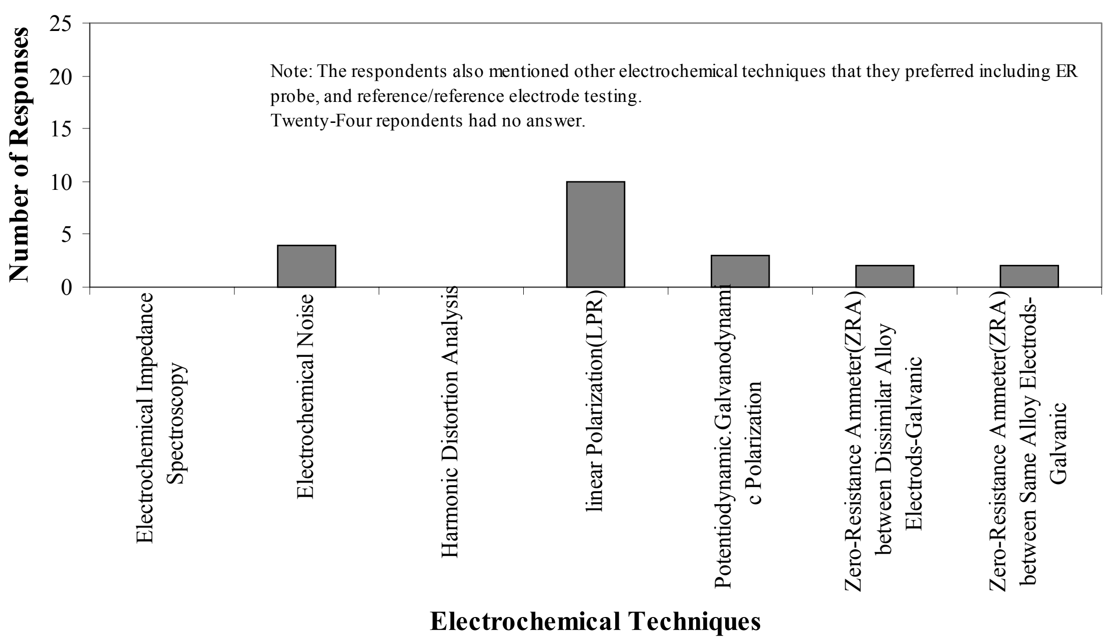
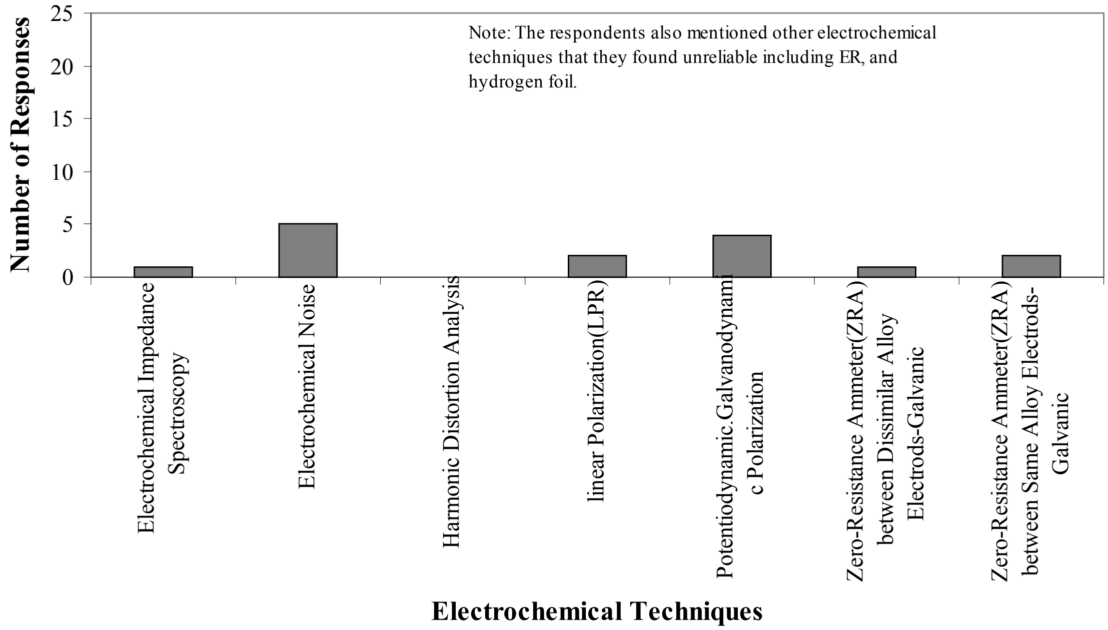


Figure VI.9: Electrochemical Techniques Companies Find Unreliable in Pipeline Monitering



ECN

Advantages

- Its accuracy to determine the mode of attack.
- Possibilities for discriminating general and localized corrosion; it is non-perturbative, i.e., it does not send any external signals (e.g., current or potential) into the system.

Disadvantages

- Very difficult analysis
- Poor probe design, confusing data, can foul, too expensive, lack of experience and too much hype for a 30-year-old techniques that keeps getting reinvented.
- Data interpretation
- Difficult to interpret
- No information to back it up

7.4 Non-Intrusive Techniques

Because pipelines are typically operated under pressure and production pipelines contain poisonous (H_2S) and/or greenhouse (CO_2) gases, the companies prefer to use non-intrusive techniques to monitor the status of the pipelines. Figures VI.10, VI.11, and VI.12, respectively, present the nonintrusive techniques that the companies use, prefer to use, and their reliability.

Ultrasonic measurements and magnetic flux methods are extensively used in the field. None of the techniques are preferred nor are they considered unreliable.

The following paragraphs discuss individually the merits and demerits of the techniques as observed by the participants.

Ultrasonic

Advantages

- Accurate
- It provides wall thickness measurements in addition to defect detection.
- Ease of application and use
- Provides a direct measure of metal loss
- Easy to do once you have the line exposed and you could also see if there is any internal metal loss

Disadvantages

- Don't detect cracks
- Variability between operators.
- Most non-destructive technicians are not properly trained.
- It is possible to miss a point defect easily.

Magnetic Flux

Advantages

- Capability of crack detection
- Accurate results
- It works in gas service
- Can usually prove anomalies by confirmation dig and then accept the log as true. Some tools not reliable though.
- Provides information on entire pipeline

Disadvantages

- Not widely used as an outside device
- It is not a direct measure of metal loss.
- Tool accuracy not good.
- Very dependent on calibration to actual field pitting corrosion aspect ratio.

Electromagnetic Eddy Current

Advantages

- Lots of history about it, old product

Disadvantages

- Not wide range of applications
- Cannot size defects, only detects them.

Electromagnetic Remote Field Technique

Advantages

- More measurement parameters - phase and log amplitude as well as x,y components of EM signals.

Radiography

Advantages

- Permanent record; fast, reliable, can be proved up with ultrasonics.

Disadvantages

- Subject to operator interpretation, I have seen too many errors made and any information has always had to be confirmed using other techniques.
- Looks at a small section of the pipe
- Difficult to really see defects

Electric Field Mapping

Advantages

- Electric Field Mapping

Disadvantages

- Not able to understand data

Ultrasonics (Flaw Detection and Sizing)

Advantages

- Of all the techniques, this one gives fairly reliable information at a reasonable cost.
- A direct read-out of the remaining wall thickness and size of the flaw is obtained.
- It is a direct measurement of wall thickness as opposed to MFL, which provides an indirect measurement of change in wall thickness
- Quick and accurate when used by a qualified technician.
- Able to detect cracks

Disadvantages

- Data interpretation difficult
- Variable interpolation

Guided Wave Ultrasonics

Advantages

- Able to inspect non-piggable lines with this technique for both internal and external corrosion

Table VI.10: Direct Nonintrusive Measurement Techniques the Companies Use for Pipeline Monitering

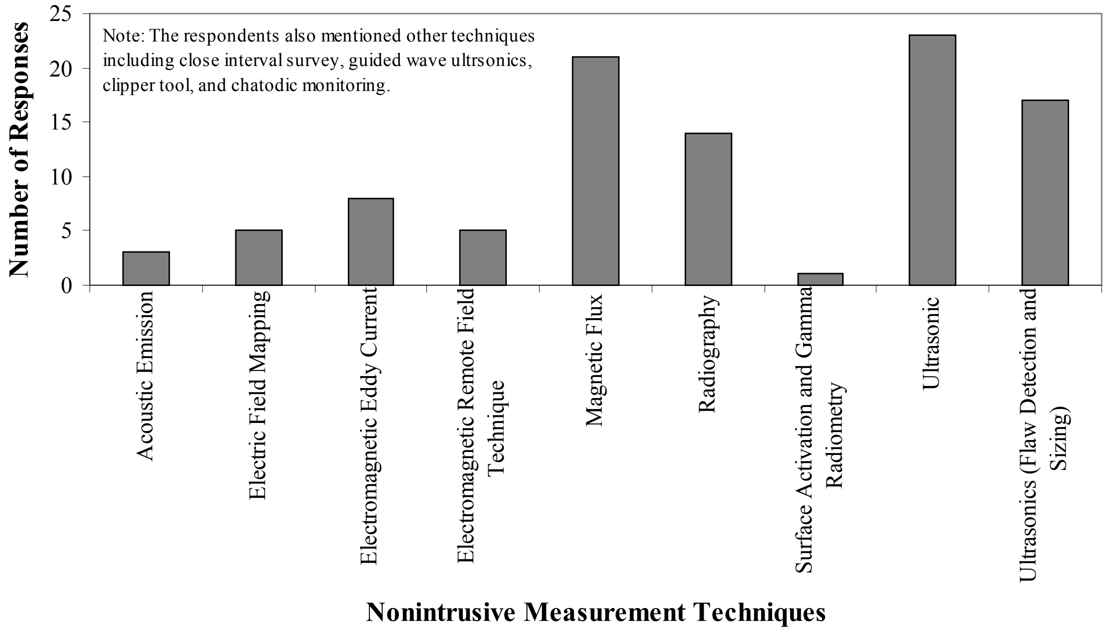


Figure VI.11: Nonintrusive Measurement Techniques Companies Prefer to Use for Pipeline Monitering

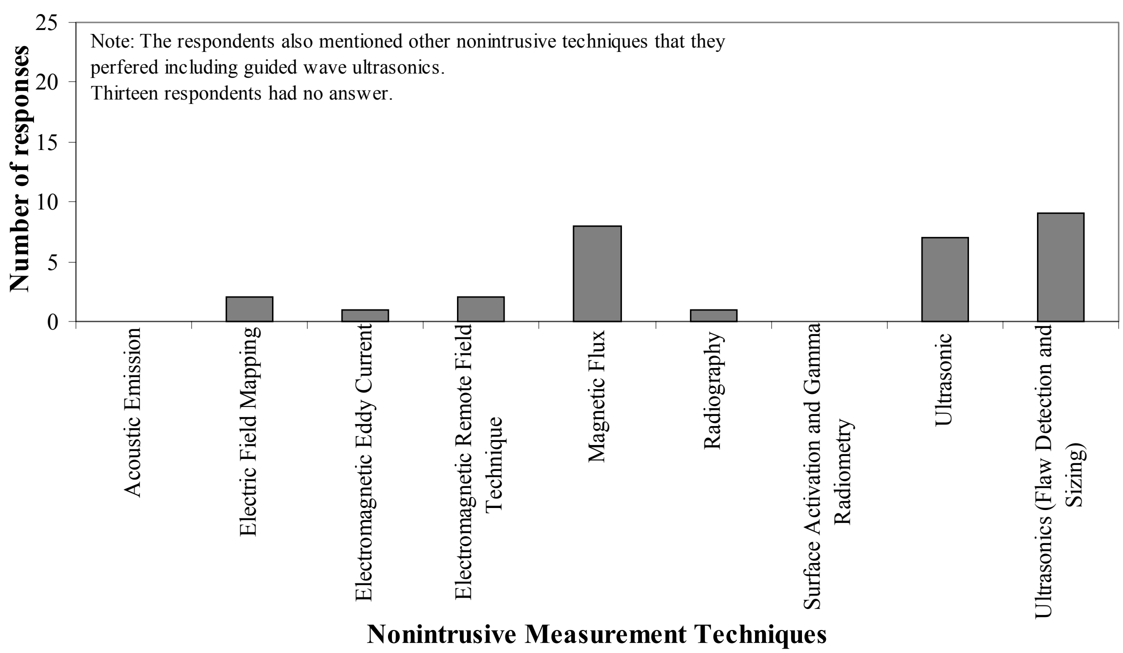
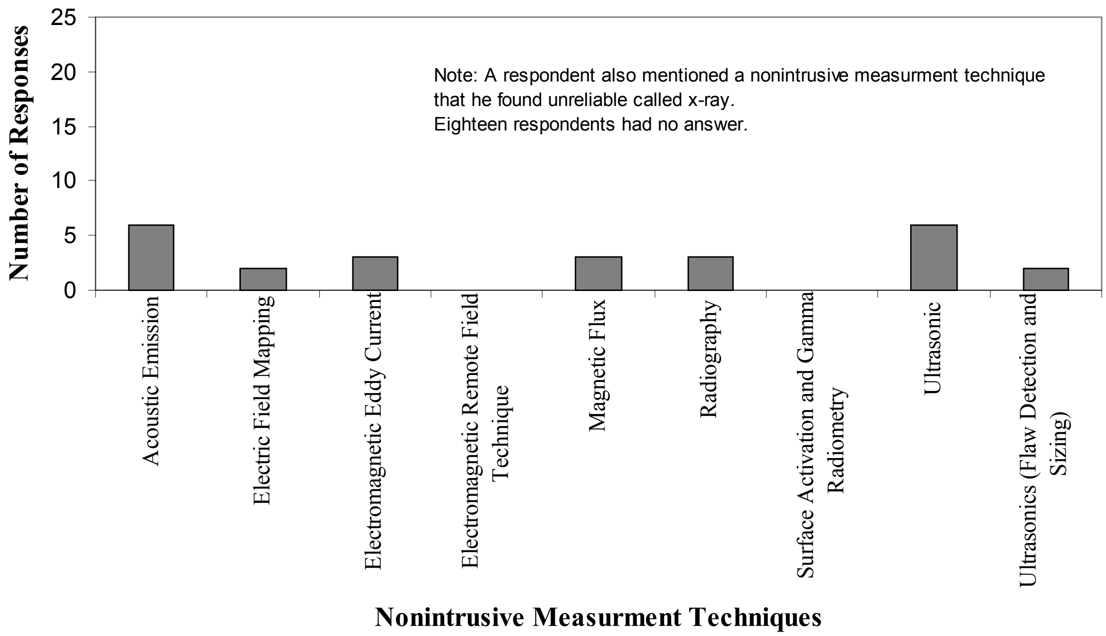


Figure VI.12: Nonintrusive Measurement Techniques Companies Consider Unrelaible to Use for Pipeline Monitering



7.5 Direct Online Monitoring

During regular operation of pipelines, several measurements are made, all or some of which can be used to determine the susceptibility to corrosion. Figures VI.13, VI.14, and VI.15, respectively, present the on-line measurements the companies use, prefer to use, and their reliability. The pH is measured because of its important influence on corrosivity of fluids.

The following paragraphs discuss individually the merits and demerits of the techniques as observed by the participants.

Corrosion Potential

Advantages

- Very direct measurement
- Valuable information at low cost
- It provides an indication of the effect of several other parameters and direct data on the integrity of the pipeline.
- Indication of corrosion integrity.

Hydrogen Permeation (Pressure)

Advantages

- Historically it has worked

Disadvantages

- If you get a positive result you know that corrosion is going on, if you get a negative result you do not know if you picked the wrong spot or if corrosion is going on elsewhere.
- Leakage, no good correlation to rate.

pH

Advantages

- You cannot just use one parameter; pH gives you a corrosion potential

Disadvantages

- What does it really tell you? The information alone has little value. It must always be used with other information to draw conclusions and often times, techniques used in the field are not terribly accurate.
- Depending on the calibration, sometimes it is not calibrated correctly or the way the experiment is conducted.
- If you are dealing with gas lines you don't have pH

Hydrogen Monitoring(Electrochemical)

Disadvantages

- Very difficult technique
- Trouble with meters
- Poor correlation
- It depends on the system

Oxidation Reduction (Redox) Potential (ORP)

Advantages

- It is easy to perform and reliable, allowing to know the pipeline integrity and the CP condition

Conductivity

Disadvantages

- In sour systems does not work. Do not believe there is reliable equipment

Flow Regime

Advantages

- It identifies areas of higher corrosion potential

Pressure

Advantages

- Pressure tells of what is happening with the line. Blocked valve, no pressure, fouling of pipe, etc.

Disadvantages

- Pressure can't tell how much a gas release or hydrocarbon spill

Dewpoint

Advantages

- Easiest, no water, no corrosion.
- Provides indication of free water in the pipeline, which is directly related to the corrosivity of the gas along with the gas composition.
- Gas below liquid water temperature, no corrosion

Disadvantages

- During upset conditions, small period of time, accumulation of water can occur

Fouling

Disadvantages

- It does not give idea of the corrosion situation straightforward.
- There is no baseline for this measurements and can be used only as an indicator of possible damage.
- Hard to measure, very subjective to opinion of analyst. If using millipore, great errors occur as a result of technique/procedure followed.

Table VI.13: Direct On-Line Measurment Techniques the Companies Use for Pipeline Monitoring

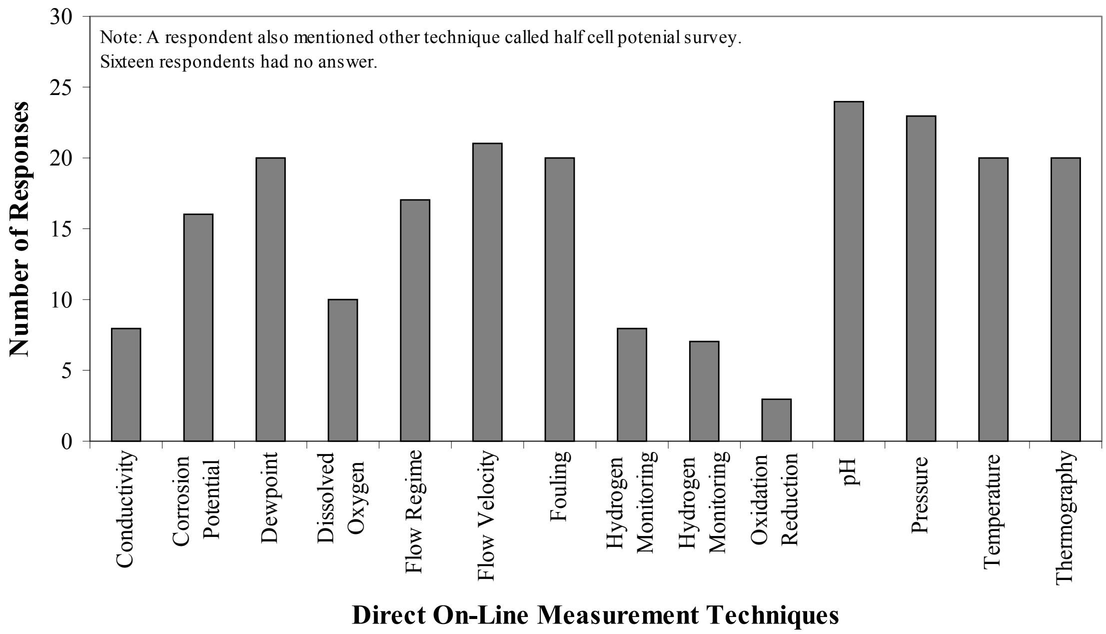


Figure VI.14: Direct On-Line Measurement Techniques Companies Prefer to Use for Pipeline Monitering

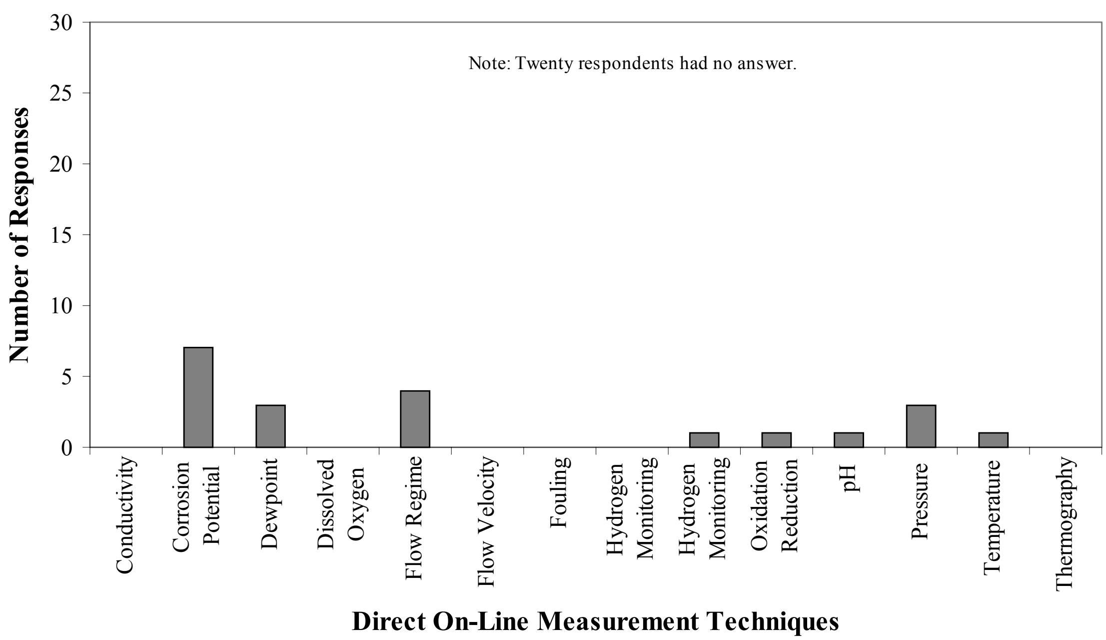
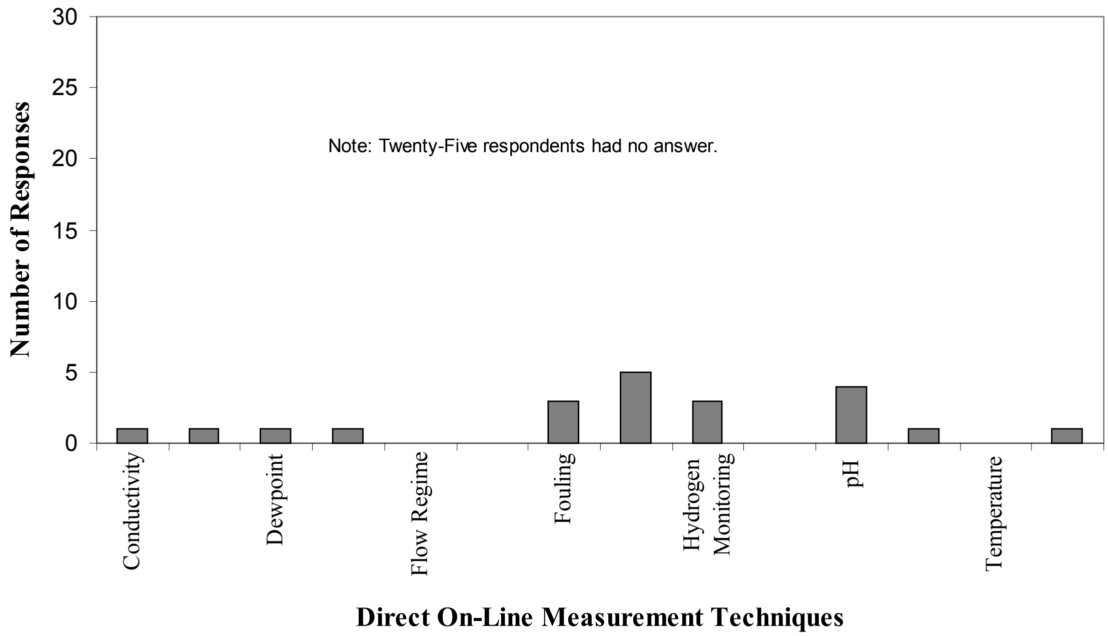


Figure VI.15: Direct On-Line Measurement Techniques Companies Consider Unrelaible to Use for Pipeline Monitering



7.6 MIC Monitoring

Presence and activity of microbes both inside and outside the pipeline, may potentially lead to corrosion. To control microbes inside, biocides are added. Figures VI.16, VI.17, and VI.18, respectively, present the nonintrusive techniques the companies use, prefer to use, and their reliability.

The following paragraphs discuss individually the merits and demerits of the techniques as observed by the participants.

Culturing Method - Broth Bottles

Advantages

- Easy, accepted, considering you have a lot of potential bacteria it would rather be important to treat than monitor to death
- It can be easily done, and reliable
- Easy, simple, quick and reliable
- Provides an idea of the quantity of bacteria in the fluid

Culturing Method - Agar Deeps

Advantages

- The method is quick and a reliable indicator of the level of biological activity

Disadvantages

- Contamination during sampling

Direct Method - APS Reductase Antibody

Advantages

- Quick, very selective for SRBs

Direct Method - Epifluorescence/cell Surface Antibody

Advantages

- Easy to use and proven success.

Figure VI.16: The Microbiologically Influenced Corrosion (MIC) Measurment/Monitor Techniques the Companies Use

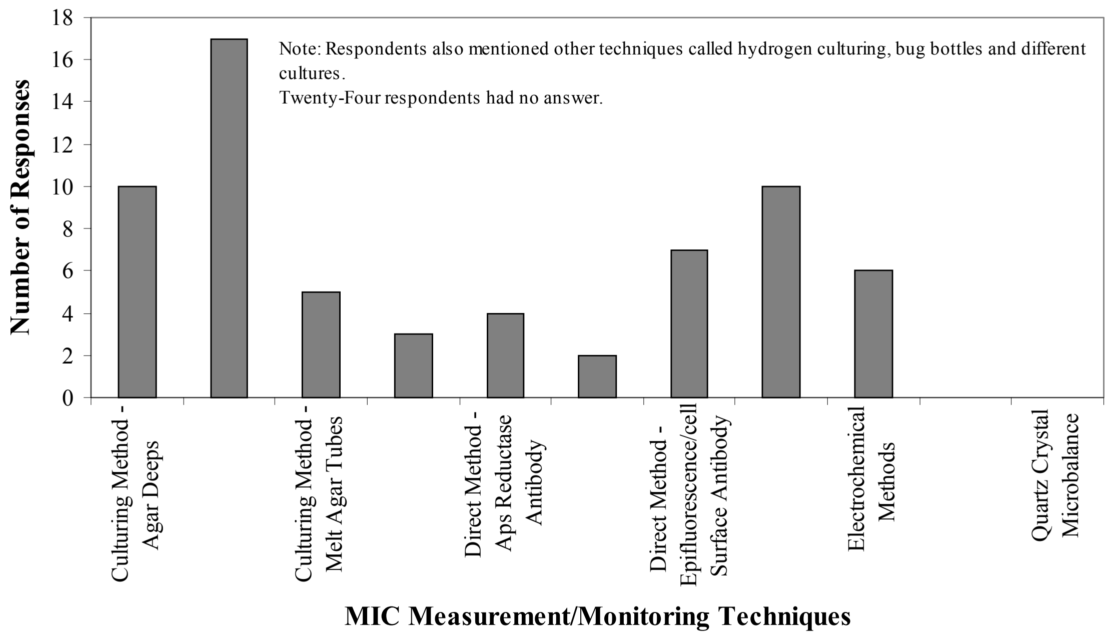


Figure VI.17: MIC Measurement/Monitoring Techniques Companies Prefer

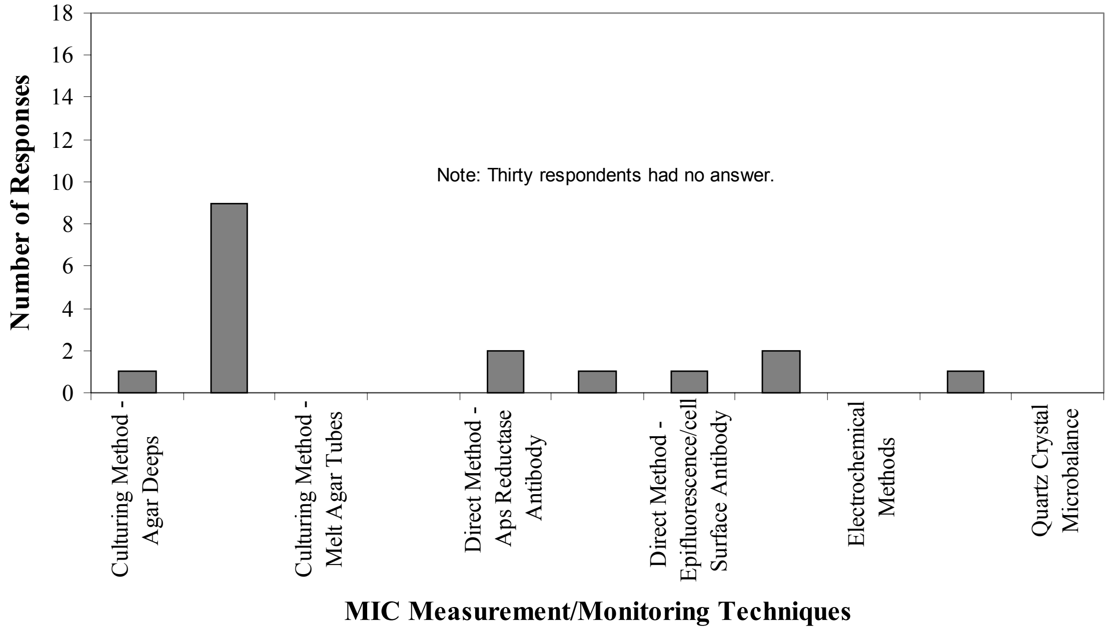
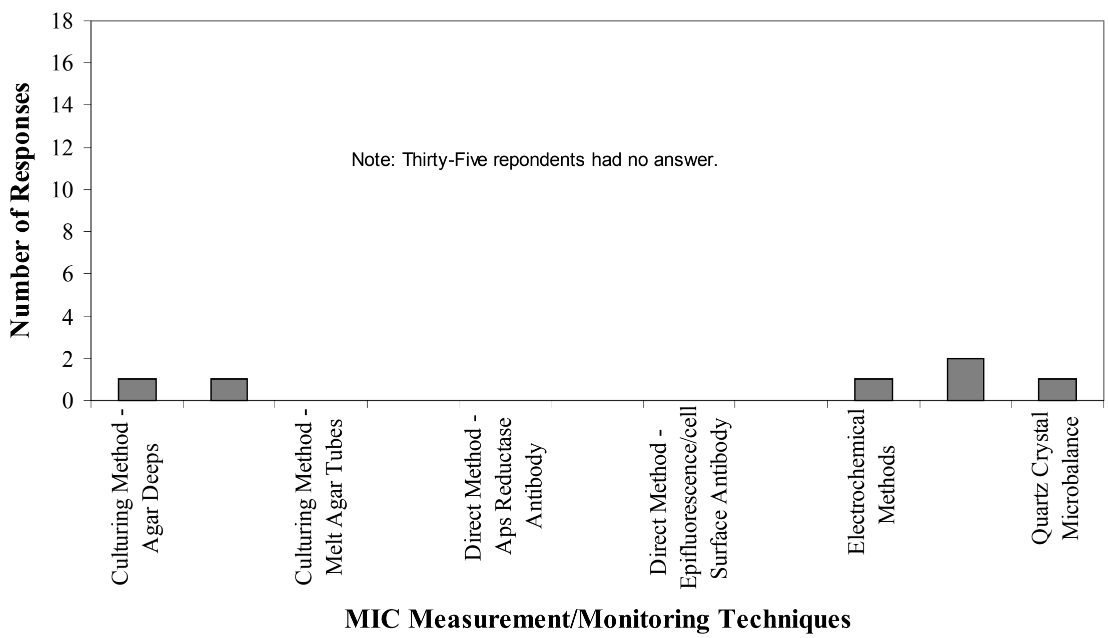


Figure VI.18: MIC Measurement/Monitoring Techniques Companies Consider Unrelaible



7.7 Off-Line Monitoring

Routine analysis of products, fluids, and other parameters are carried out. Some of the data can be used indirectly for developing corrosion control strategies. Figures VI.19, VI.20, and VI.21, respectively, present the nonintrusive techniques the companies use, prefer to use, and their reliability.

Table VI.19: The Indirect Off-Line Measurement Techniques the Companies Use

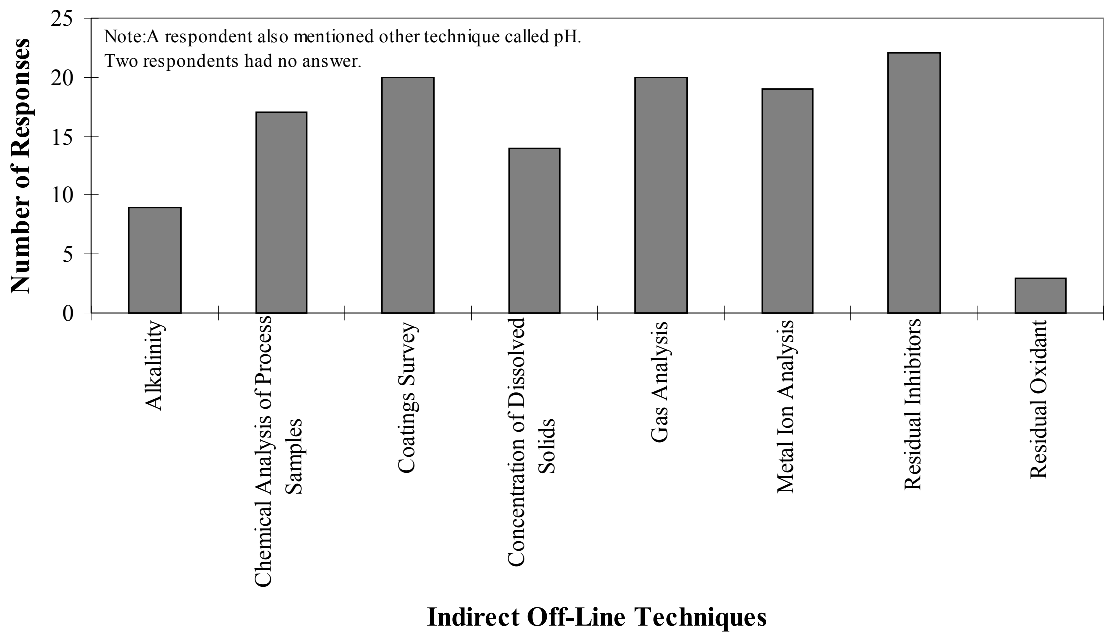


Figure VI.20: Indirect Off-Line Techniques Companies Perfer to Use

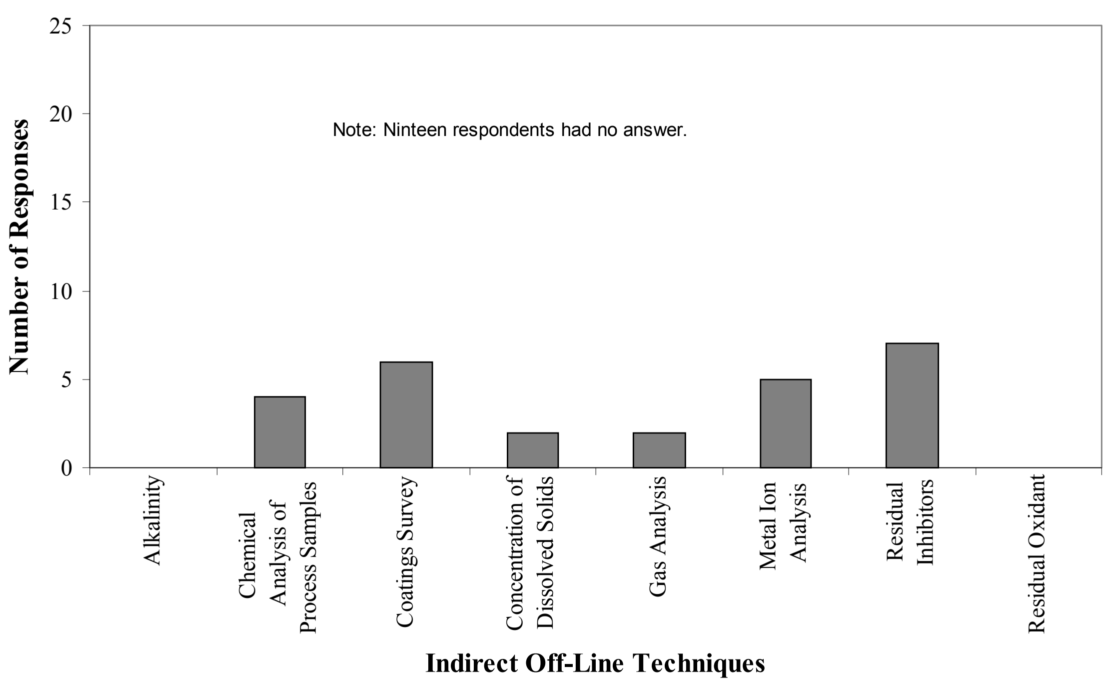
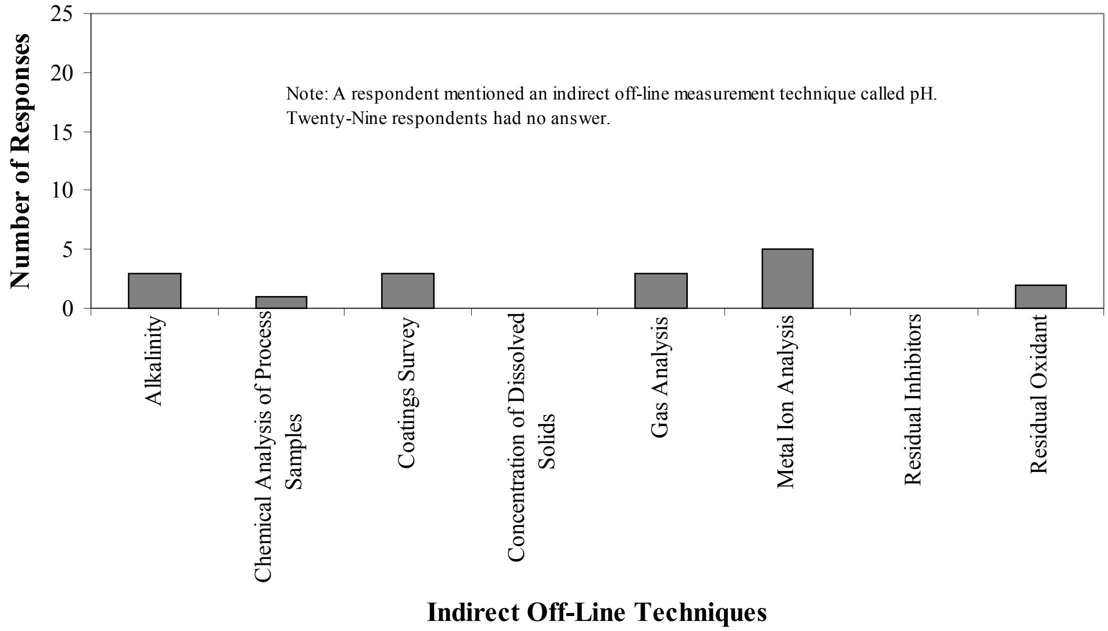


Figure VI.21: Indirect Off-line Measurement techniques Companies Consider Unreliable



The following paragraphs discuss individually the merits and demerits of the techniques as observed by the participants.

<u>Residual Inhibitors (Internal corrosion)</u>

<u>Advantages</u>

- One can follow the performance of the inhibitor
- Most important in making sure the corrosion process is capable of being controlled
- Measure alteration in process parameters.
- Assuming we are monitoring an inhibited system, it is a must

<u>Disadvantages</u>

- Not much of use

<u>Metal Ion Analysis</u>

<u>Advantages</u>

- Looking at iron and manganese you can relate them to actual corrosion rates.
- It tells how much iron lost, early indicator
- Uniqueness from one source
- It is reliable and easy to perform and also not expensive

<u>Disadvantages</u>

- The metal ion not only comes from oxidation of the pipe
- Iron count may be due to localised pitting, and not generalised corrosion.
- It gives only a very rough guide
- Prone to sampling errors and is greatly misused in sour systems.

Coating Survey (External Corrosion)

Advantages
- Valuable information at a reasonable cost.
- Works best and most cost-effective

Disadvantages
- External only, internal coatings do not work well although each year someone comes out with a new one.
- Not a direct measurement of the corrosivity of the pipeline

Gas Analysis

Advantages
- It is not unique but it is the first one to use and gives you your first indication of potential for corrosion. Inhibitor residuals is a good one too.
- Provides CO_2 and H_2S content

Chemical Analysis

Advantages
- Accurate
- Can see what contributing chemicals actually present

ILI Techniques

One of the common and reliable methods of determining the status of the pipeline is ILI technique. The major requirement of this measurement is to be able to send an ILI tool inside the pipeline. The companies frequently use ILI tools to determine leaks, dents (geometric inspection), defects and its size, metal loss (or gain), 3D mapping, route survey, bend and strain (Fig.VI.22).

Figures VI.23, VI.24, and VI.25, respectively, present the nonintrusive techniques the companies use, prefer to use, and their reliability.

The following paragraphs discuss individually the merits and demerits of the techniques as observed by the participants.

High-Resolution Magnetic Flux Leakage(MFL)

Advantages
- The lowest price with crack detection capability
- Good overall information on pipeline integrity.
- It has good resolution and gives accurate results
- Information on metal loss
- Provides information on defect size and length which enable you to determine possible failure pressure.
- Good track record

Table VI.22: The Main Use of In-Line Inspection in the Companies

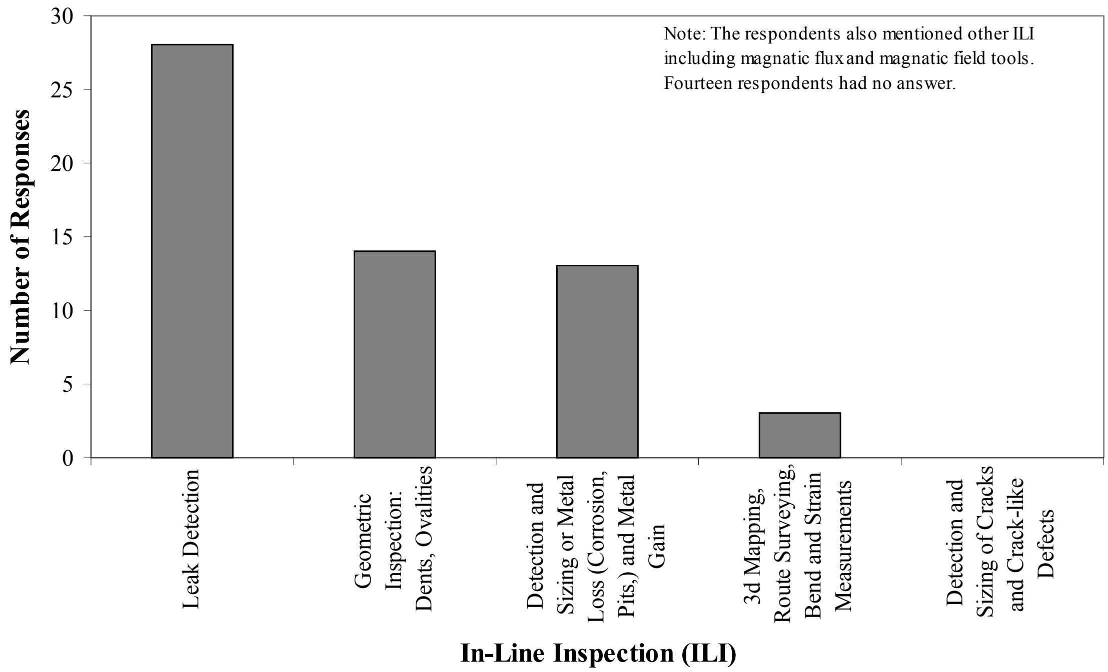


Figure VI.23: ILI Measurment Techniques the Companies Use

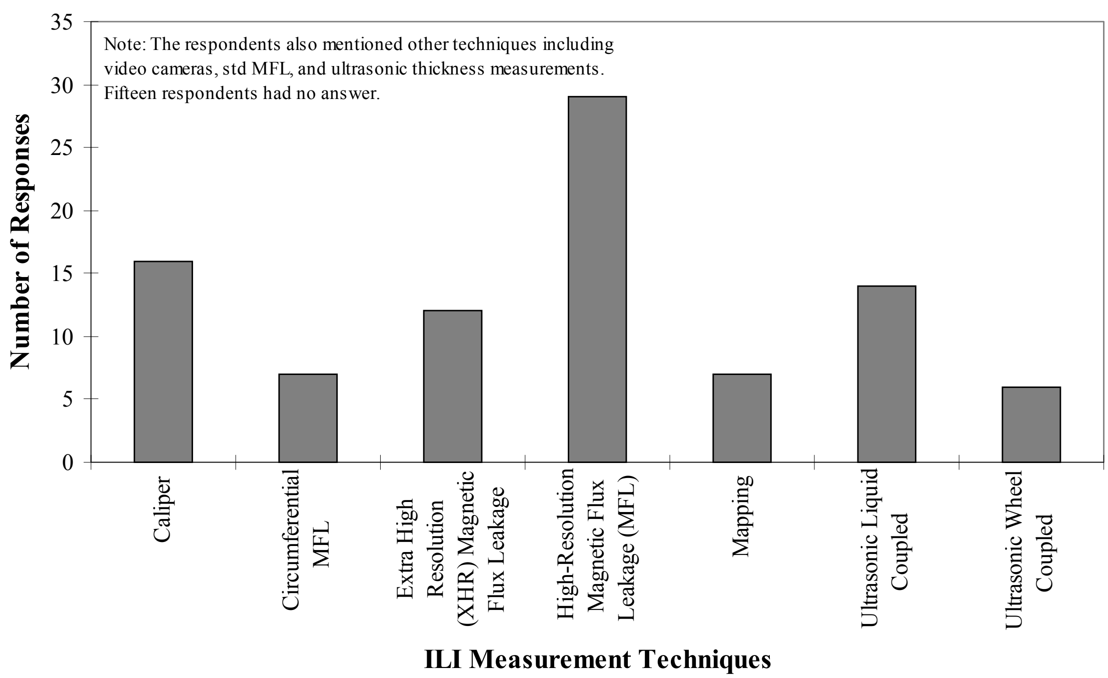


Figure VI.24: ILI Measurements Techniques Companies Perfer to Use

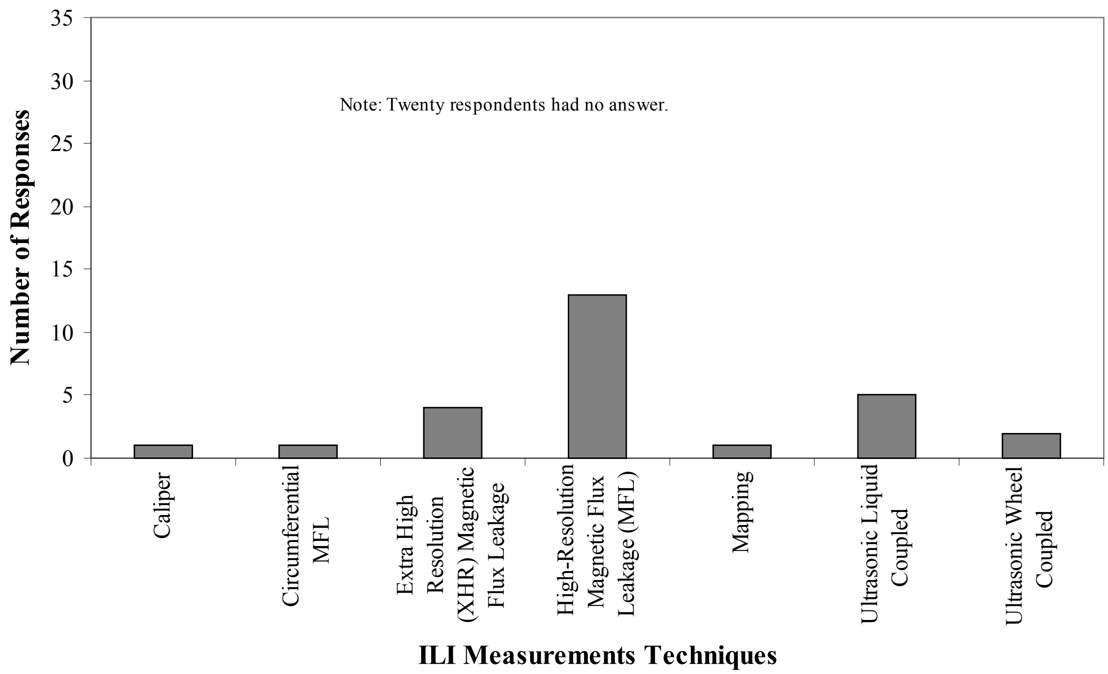
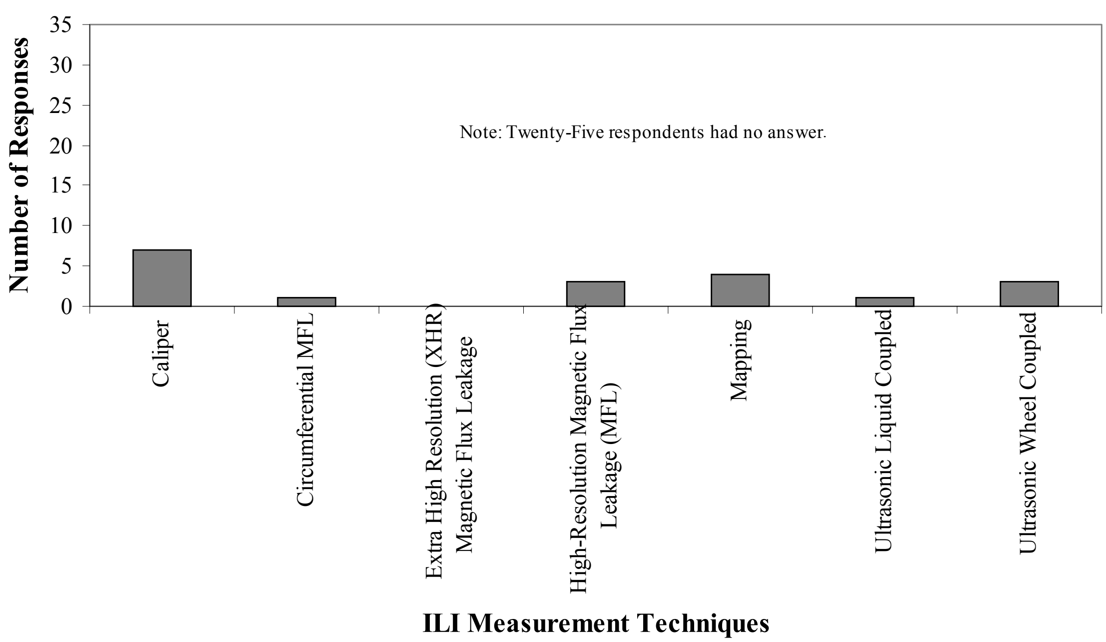


Figure VI.25: ILI Measurements Techniques Companies Consider Unreliable



Disadvantages

- Not a direct measure of metal loss
- Tolerances of MFL - the tool logs the response of a phenomenon to a specific anomaly - not a direct measurement. Several factors and considerations need to be addressed before the technique can be used reliably - but it is the cheapest!
- Ran both ultrasonic and high resolution pig and the UT pig picked up more anomalies than the high resolution pig did

Extra High Resolution(XHR) Magnetic Flux Leakage

Advantages

- Accurate, tethered tool, short line segments

Ultrasonic Liquid Coupled

Advantages

- It provides data on the actual wall thickness and size of the loss.
- Most accurate and sensitive for the broadest range of anomalies - cracks through wall loss and dents.
- Excellent results

Disadvantages

- Impurities would make an error

Ultrasonic Wheel Coupled

Disadvantages

- There are still some technical problems with this method
- It won't give external corrosion measurements

Circumferential MFL

Advantages

- The flux field is directly affected by axially oriented metal loss

Disadvantages

- Previous experience has indicated inconclusive results

Caliper

Advantages

- Obtain a view of mechanical damage on the pipe wall.

Disadvantages

- Easy to miss anomalies
- Only gives you some internal defect information and ovality and dent information, but does not tell you anything about general wall metal loss, or external corrosion defects.
- It needs many "fingers" to get accurate readings
- Probably miss what you are looking for
- Open to misuse/ misinterpretation

Visual Video

Disadvantages

- Misinterpretation because of shadows and misinterpretation when internal surfaces have scale or coating.

New Techniques

About a quarter of the respondents indicated that they are aware of new techniques that are on the horizon, including fiber optics (25%) and acoustics (about 20%) (Fig.VI.26). The factors (Fig.VI.27) that influence the companies' decision for selecting appropriate monitoring techniques are: reliability of the techniques (75%), adaptability to the existing operating conditions (53%), cost benefit (47%), user-friendly operation (25%). The responders emphasized that many operating factors will affect the performance of measuring/monitoring techniques. The factors, which are of equal importance, include: temperature fluctuation, pressure fluctuation, environmental variation, and loss of ruggedness during installation/operation (Fig.VI.28)

Figure VI.26: The Influences that effect the Companies Decision Making When Selecting Appropriate Techniques

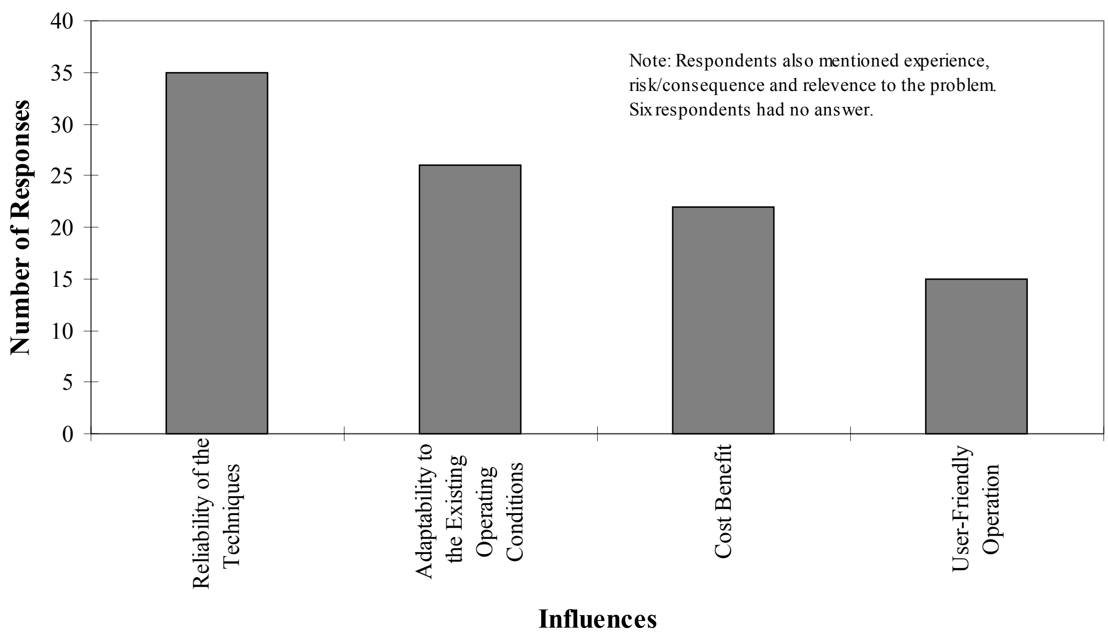


Figure VI.27: Companies Awearness of New Pipeline Monitering Techniques

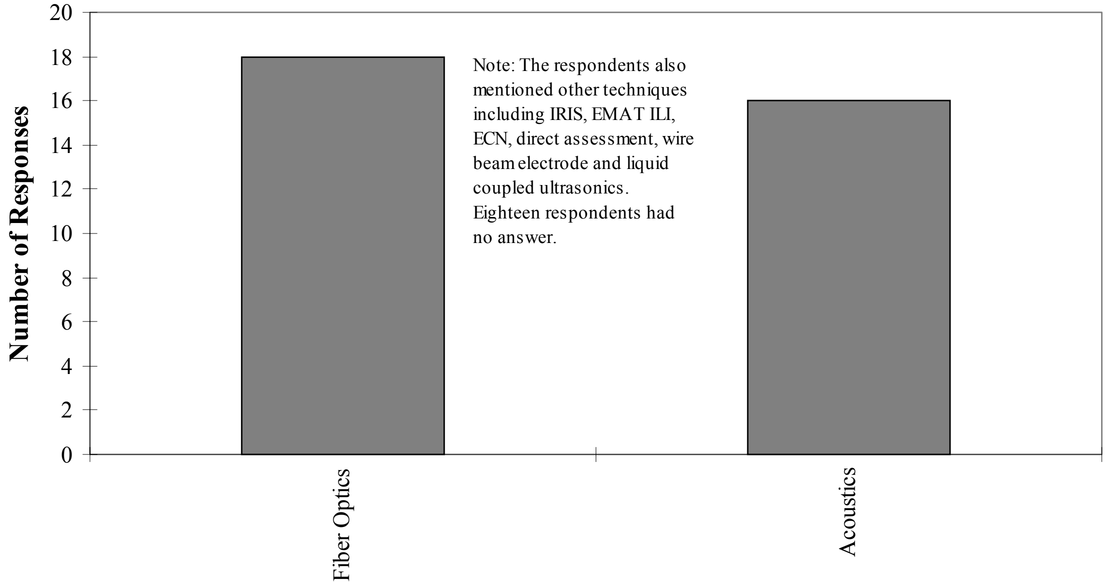
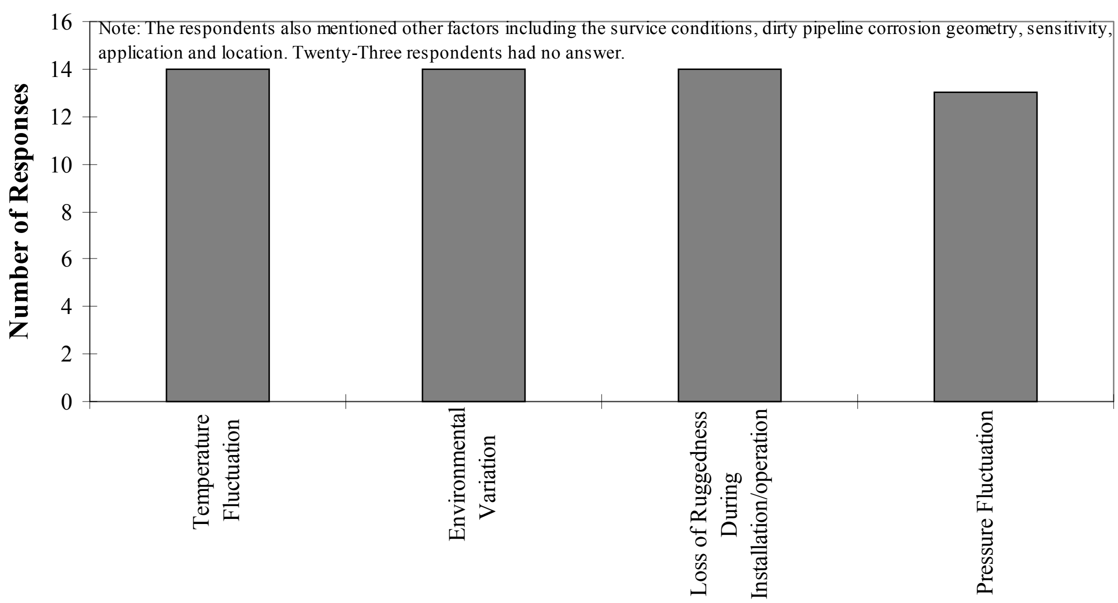


Figure VI.28: The Companies Opinions on What Factors Affect the Performance of Measuring/Monitoring Techniques



7.8 Database

The importance of the development of databases and data management is very well understood in the pipeline industry. About 50% of the companies indicate that their respective companies have a database/data management system (Fig.VI.29). The use of a knowledge-based system to integrate and analyze the data is not frequently used (Fig.VI.30); however, the companies use commercial and/or in-house software for integrity management (Fig.VI.31). The importance of training field operators is not well recognized in the industry. Less than 40% of the companies have a formal training program for pipeline evaluation and maintenance (Fig.VI.32).

Figure VI.29: Companies that Use Data Management to Archive the Data Vs. the Companies that Don't

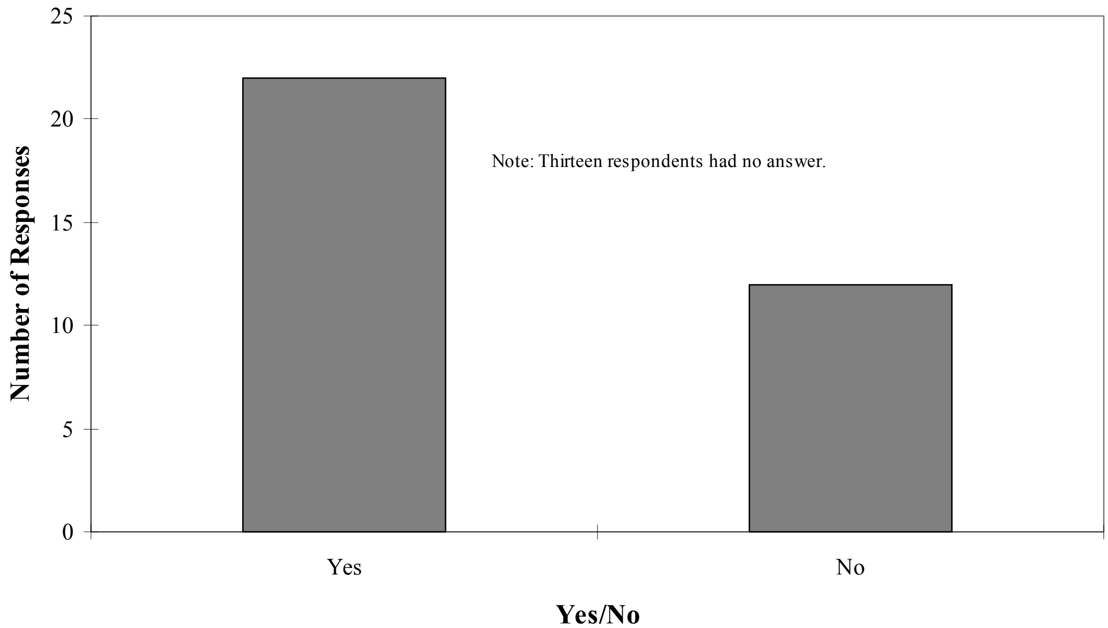


Figure VI.30: Companies that use knowledge-based System to Integrate and Analyze Data Vs. the Companies that Doesn't

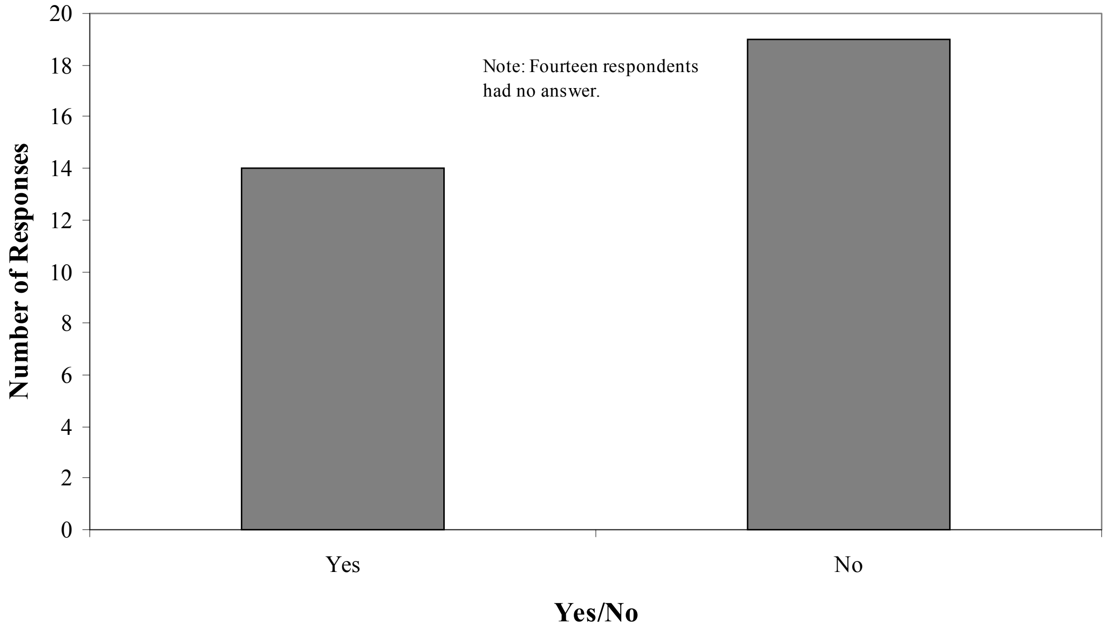


Figure VI.31: Companies that Use Software for Integrity Management Vs. the Companies that Don't

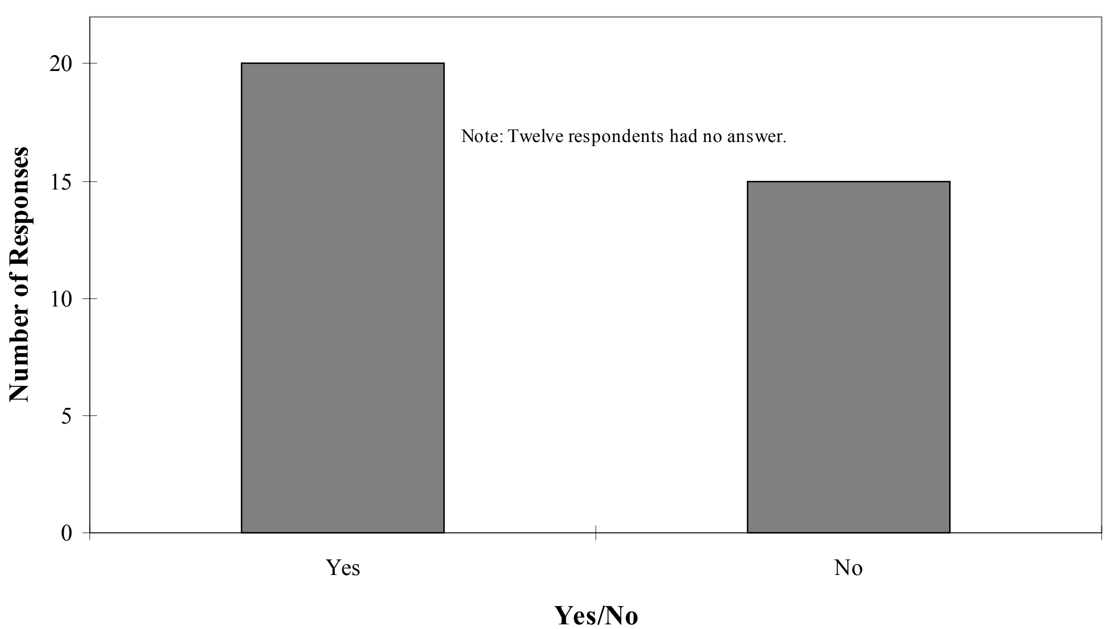
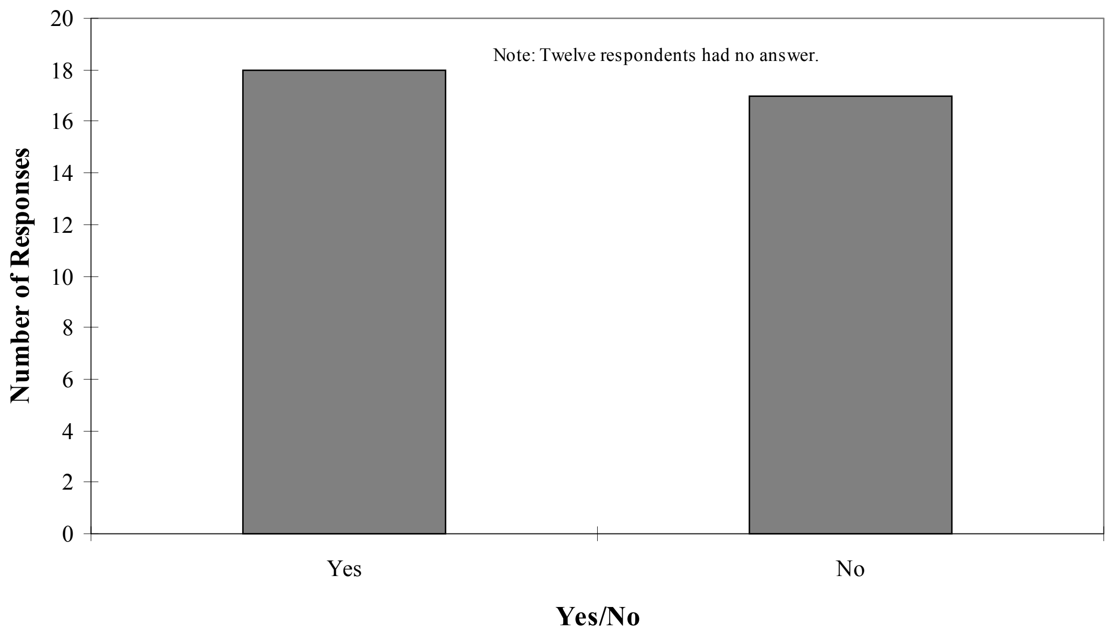


Figure VI.32: Companies that have Training Program for Pipeline Evaluation and Maintenance Vs. Companies that Don't



8 BIBLIOGRAPHY

8.1 Chemical Sensors

S. Thomas Lee, B. Aneeshkumar, P. Radhakrishnan, C. P. G Vallabhan, and V. P. N Nampoori. A microbent fiber optic pH sensor. *Optics Communications* 205 (4-6):253-256, 2002.

T. S. Lee, G. Jose, C. M. Manju, B. Joseph, M. S. John, P. Radhakrishnan, V. P. N Nampoori, C. P. G Vallabhan, and N. V. Unnikrishnan. A fiber Optic pH sensor with dye doped multi-layer sol-gel coatings. *Proceedings of the SPIE - The international society for Optical* 4417:546-554, 2001.

B. D Gupta and N. K. Sharma. Fabrication and characterization of U-shaped fiber-optic pH probes. *Sensors and Actuators B(chemical)* B82 (1):89-93, 2002.

A. L. Chaudhari and A. D. Shaligram. Development of fiber optic pH meter based on colorimetric principle. *Indian journal of pure and applied physics* 40 (2):132-136, 2002.

N. Kaval and W. R. Seitz. Aminated poly(vinylbenzylchloride-co-2,4,5-trichlorophenyl acrylate) microspheres for optical pH sensing. *Proceedings of the SPIE - The international society for Optical Engineering* 3860:224-231, 1999.

H. Wang and W. R. Seitz. pH sensor based on swellable poly(3-nitro-4-hydroxystyrene) microspheres in a hydrogel. *Proceedings of the SPIE - The international society for Optical Engineering* 3856:224-231, 1999.

Wang Chi-Cheng. Studies of optical fiber biosensors. *1999 IEEE Engineering in Medicine and Biology 21st annual conference (Cat.No.99ch37015)* 2:827, 1999.

P. Kronenberg, B Culshaw, and S. Pierce. Development of a novel fiber optic sensor for humidity monitoring. *Proceedings of the SPIE - The international society for Optical Engineering* 3670:480-485, 1999.

U. H. Manyam, M. R. Shahriari, and M. J. Morris. A complete spectrum fiber optic pH sensor based on a novel fluorescent indicator doped porous sol-gel material. *Proceedings of the SPIE - The international society for Optical Engineering* 3540:10-18, 1999.

A. Dybko, W. Wroblewski, E. Rozniecka, and K. Pozniakb. Assessment of water quality based on multiparameter fiber optic probe. *Sensors and Actuators B(chemical)* B51 (1-3):208-213, 1998.

B. D Gupta and N. K. Sharma. A long-range fiber optic pH sensor prepared by dye doped sol-gel immobilization technique. *Optics Communications* 154 (5-6):282-284, 1998.

D. Flannery, S. W. James, R. P. Tatam, G. J. Ashwell, D. W. Allen, and Xing Li. Chemical sensing using Langmuir-Blodgett waveguide overlays on single mode optical fibers. *Proceedings of the SPIE - The international society for Optical Engineering* 3105:144-153, 1997.

D. A. Nivens, M. V. Schiza, and S. M. Angel. Multilayer fiber-optic chemical sensors employing organically modified SiO/sub 2/ and mixed TiO/sub 2//SiO/sub 2/ sol-gel membranes. *Proceedings of the SPIE - The international society for Optical Engineering* 3105:52-60, 1997.

D. Flannery, S. W. James, R. P. Tatam, and G. J. Ashwell. Fiber optic pH sensors using thin-film Langmuir-Blodgett overlay
waveguides on single-mode optical fibers. *Proceedings of the SPIE - The international society for Optical Engineering* 3133:264-272, 1997.

A. Dybko, K. Pozniak, W. Wroblewski, J. Maciejewski, R. Romaniuk, and Z. Brzozka. LabWindows-tool and environment for sensor design. *Proceedings of the SPIE - The international society for Optical Engineering* 3189:122-128, 1997.

B. D Gupta and N. K. Sharma. Evanescent wave absorption based fiber optic pH sensor prepared by
dye doped sol-gel immobilization technique. *Optics Communications* 140 (1-3):32-35, 1997.

A. Dybko, W. Wroblewski, J. Maciejewski, R. Romaniuk, and Z. Brzozka. Efficient reagent immobilization procedure for ion-sensitive
optomembranes. *Sensors and Actuators B(chemical)* B39 (1-3):207-211, 1997.

H. Lehmann, G. Schwotzer, P. Czerney, and R. Willsch. Low-cost intrinsic fiber optic pH sensor using sol-gel immobilized
NIR dyes. *Eleventh International Conference on Optical Fiber Sensors -Advanced Sensing Photonics* 1:426-429, 1996.

C. Egami, Y. Suzuki, O. Sugihara, H. Fujimura, and N. Okamoto. Wide range pH fiber sensor with congo-red- and methyl-red-doped
poly(methyl methacrylate) cladding. *japanese Journal of Applied Physics* 36 (5a):2902-2905, 1997.

D. Flannery, S. W. James, R. P. Tatam, and G. J. Ashwell. pH sensor using Langmuir-Blodgett overlays on polished optical
fibers. *Optics Letters* 22 (8):567-569, 1997.

C. Egami, K. Takeda, M. Isai, and M. Ogita. Evanescent-wave spectroscopic fiber optic pH sensor. *Optics Communications* 122 (4-6):122-126, 1996.

S. Motellier, M. H. Noire, H. Pitsch, and B. Dureault. pH determination of clay interstitial water using a fiber-optic
sensor [HLW disposal site selection]. *Sensors and Actuators B(chemical)* B29 (1-3):345-352, 1995.

F. J. Arregui, C. Fernandez-Valdivielso, I. Ilundain, and I. R. Matias. pH sensor made using cellulosic coating on a biconically tapered
singlemode optical fiber. *Proceedings of the SPIE - The international society for Optical Engineering* 4185 2000 (57952), 2000.

P. A. Wallace, N. Elliott, M. Uttamlal, A. S. Holmes-Smith, and M. Campbell. Development of a quasi-distributed optical fibre pH sensor. *Proceedings of the SPIE - The international society for Optical Engineering* 4185 2000 (57952), 2000.

T. S. Lee, J. Gin, V. P. N Nampoori, C. P. G Vallabhan, N. V. Unnikrishnan, and P. Radhakrishnan. A sensitive fibre optic pH sensor using multiple sol-gel coatings. *Journal of Optics A: Pure and applied Optics* 3 (5):355-359, 2001.

P. A. Wallave, N. Elliott, M. Uttamlal, A. S. Holmes-Smith, and M. Campbell. Development of a quasi-distributed optical fibre pH sensor using a covalently bound indicator. *Measurement Science and Technology* 12 (7):882-886, 2001.

P. R. Coulet and N. Jaffrezic-Renault. 5th European Conference on Optical Chemical Sensors and Biosensors, Europt(r)ode V: Opt(r)ode 2000. *Sensors and Actuators B(chemical)* 74 (1-3):211, 2001.

A. Iobnik, N. majcen, K. Niederreiter, and G. Uray. Optical pH sensor based on the absorption of antenna generated europium luminescence by bromothymolblue in a sol-gel membrane. *Sensors and Actuators B(chemical)* 74 (1-3):200-206, 2001.

P. T. Sotomayor, I. M. Raimundo, A. J. G. Zarbin, J. J. R. Rohwedder, G. O. Neto, and O. L. Alves. Construction and evaluation of an optical pH sensor based on polyaniline-porous Vycor glass nanocomposite. *Sensors and Actuators B(chemical)* 74 (1-3):157-162, 2001.

Z. Jin, Y. Su, and Y. Duan. Improved optical pH sensor based on polyaniline. *Sensors and Actuators B(chemical)* 71 (1-2):118-122, 2000.

N. Elliott, P. A. Wallace, M. Uttamlal, A. S. Holmes-Smith, and M. Campbell. Quasi-distributed pH sensor. *Proceedings of the SPIE - The international society for Optical Engineering* 3860:460-466, 1999.

Thorsten de Vries, Ralf Paetzold, Kai Jantos, Eberhard Voss, and Angelika Anders. Mobile multi sensor system for environmental monitoring. *Proceedings of the SPIE - The international society for Optical Engineering* 3853:249-253, 1999.

L. H. Garcia-Rubio, M. L. Janowiak, H. Huang, and S. Chang. Development of a fiber optic pH sensor for on-line control. *American Chemical Society, Polymer Priprints, Division of Polymer Chemistry* 40 (2):1260-1261, 1999.

W. Xu, J. Mehlmann, J. Rice, J. E. Collins, C. L. Fraser, J. N. Demas, B. A. DeGraff, and M. Bassetti. pH sensors based on luminescent ruthenium(II) alpha -diimine complexes with diethylaminomethyl sensing groups. *Proceedings of the SPIE - The international society for Optical Engineering* 3534:456-465, 1999.

G. Vishnoi, T. C. Goel, and P. K. C Pillai. pH-optrode for the complete working range. *Proceedings of the SPIE - The international society for Optical Engineering* 3538:319-325, 1999.

J. Bourilkov, M. Belz, W. Boyle, and K. Grattan. Electrical pH control in aqueous solutions. *Proceedings of the SPIE - The international society for Optical Engineering* 3538:268-277, 1999.

R. A. Lieberman. Proceedings of the 1998 Chemical, Biochemical, and Environmental Fibers Sensors X. *Proceedings of the SPIE - The international society for Optical Engineering* 3540 1999, 1999.

S. J. Glenn, B. M. Cullum, J. C. Carter, R. B. Nair, D. A. Nivens, C. J. Murphy, and S. M. Angel. Development of a lifetime-based fiber-optic imaging sensor to study water transport in thin Nafion**T**M membranes. *Proceedings of the SPIE - The international society for Optical Engineering* 3540:235-245, 1999.

S. M. Angel, M. V. Schiza, D. A. Nivens, F. P. Milanovich, and Ang. Characterization of mixed TiO//2 and SiO//2 sol-gel membranes for
volatile organochloride sensing. *Proceedings of the SPIE - The international society for Optical Engineering* 3540:164-174, 1999.

F. Baldini, L. Ciaccheri, A. Falai, A. G. Mignani, J. Rayss, and G. Sudolski. Thymol blue immobilized on tapered fibres as an optical transducer
for pH sensing. *Proceedings of the SPIE - The international society for Optical Engineering* 3540:28-33, 1999.

F. Baldini. Critical review of pH sensing with optical fibres. *Proceedings of the SPIE - The international society for Optical Engineering* 3540:2-9, 1999.

C. M. Santegoeds, A. Schramm, and D. de Beer. Microsensors as a tool to determine chemical microgradients and
bacterial activity in wastewater biofilms and flocs. *Biodegradation* 9 (3-4):159-167, 1998.

W. Fabianowski, M. Roszko, and W. Brodzinska. Optical sensor with active matrix built from
polyelectrolytes-smart molecules mixture. *Thin Solid Films* 327-329:743-747, 1998.

W. Wroblewski, E. Rozniecka, A. Dybko, and Z. Brzozka. Cellulose based bulk pH optomembranes. *Sensors and Actuators B(chemical)* B48 (1-3):471-475, 1998.

M. N. Taib and R. Narayanaswamy. Multichannel calibration technique for optical-fibre chemical
sensor using artificial neural network. *Sensors and Actuators B(chemical)* B39 (1-3):365-370, 1997.

Z. Xu, A. Rollins, R. Alcala, and R. E. Marchant. Novel fiber-optic pH sensor incorporating carboxy SNAFL-2 and
fluorescent wavelength-ratiometric detection. *Journal of Biomedical Materials Research* 39:9-15, 1998.

Y. Takahashi, T. Takeda, K. Suzuki, A. Maeda, K. Kojima, and H. Ohta. Optical pH sensing properties of coumarin-4-doped sol-gel coating
film. *japanese Journal of Applied Physics* 36 (9A):5751-5752, 1997.

J. Katsifolis, P. N. Moar, S. T. Huntington, L. W. Cahill, K. A. Nugent, and A. Roberts. Modelling, fabrication and testing of tapered optical fiber
evanescent wave devices. *Pacific Rim Conference on Lasers and Electro-Optics* 1997:306-307, 1997.

S. McCulloch and D. Uttamchandani. Development of a fibre optic micro-optrode for intracellular pH
measurements. *IEE Proceedings Optoelectronics* 144 (3):162-167, 1997.

A. M. Rollins, Z. Xu, R. Alcala, and J. A. Izatt. Novel wide range single fiber optic fluorescence pH sensor. *Conference Proceedings - Lasers and Electro-Optics Society Annual Meeting* 11 (1997):183-184, 1997.

M. R. Shortreed, S. Dourado, and R. Kopelman. Development of a fluorescent optical potassium-selective ion sensor with ratiometric response for intracellular applications. *Sensors and Actuators B(chemical)* B38 (1-3):8-12, 1997.

B. G. Healey and D. R. Walt. Fast temporal response fiber-optic chemical sensors based on the photodeposition of micrometer-scale polymer arrays. *Analytical Chemistry* 69 (11):2213-2216, 1997.

R. Blue and G. Stewart. Optical pH sensor for the alkaline region. *Electronics Letters* 33 (6):526-528, 1997.

H. H. Weetall and M. F. McCurley. Proceedings of the 1996 6th International Meeting on Chemical Sensors. *Sensors and Actuators B(chemical)* B35 (1-3):261, 1996.

C. A. Browne, D. H. Tarrant, and M. S. Olteanu. Intrinsic sol-gel clad fiber optic sensors with time resolved detection. *Analytical Chemistry* 68 (14):2289-2295, 1996.

M. Shortreed, E. Bakker, and R. Kopelman. Miniature sodium-selective ion-exchange optode with fluorescent pH chromoionophores and tunable dynamic range. *International Journal of Computer Vision* 18 (3):2656-2662, 1996.

A. Bromberg, J. Zilberstein, and S. Riesemberg. Optical-fibre sensors for blood gases and pH, based on porous glass tips. *Sensors and Actuators B(chemical)* B31 (3):181-191, 1996.

R. Blue and G. Stewart. Fibre-optic evanescent wave pH sensing with dye doped sol-gel films. *International Journal of Optoelectronics* 10 (3):211-222, 1995.

Y. Yang, P. A. Wallace, and M. Campbell. Distributed optical fiber chemical sensor. *Proceedings of the SPIE - The international society for Optical Engineering* 2594, 1996.

M. N. Taib and R. Narayanaswamy. Novel technique to improve optical fibre sensor's response for industrial applications. *IEE Colloquium (digest)* 1995 (232):13-1-13/6, 1995.

A. Rumphorst, S. Seeger, and H. Duschner. Immobilized fluorescent dyes for sensitive pH measurements on enamel surfaces with fiber optics. *Proceedings of the SPIE - The international society for Optical Engineering* 2629:119-128, 1996.

T. M. Butler, B. D. MacCraith, D. Brian, and C. M. McDonagh. Development of an extended-range fiber optic pH sensor using evanescent wave absorption of sol-gel-entrapped pH indicators. *Proceedings of the SPIE - The international society for Optical Engineering* 2508:168-178, 1995.

Y. Yang, Y. Yang, and M. Campbell. Toward a distributed optical fiber chemical sensor. *Proceedings of the SPIE - The international society for Optical Engineering* 2508:36-40, 1995.

H. Lehmann, G. Schwotzer, P. Czerney, and G. J. Mohr. Fiber-optic pH meter using NIR dye. *Sensors and Actuators B(chemical)* B29 (1-3):392-400, 1995.

M. E. J. Baker and R. Narayanaswamy. Modelling and control of the pH response of an immobilised
indicator. *Sensors and Actuators B(chemical)* B29 (1-3):368-373, 1995.

E. A. Mendoza, A. N. Khalil, Z. Sun, D. Robinson, S. J. Syracuse, C. O. Egalon, M. F. Gunther, and R. A. Lieberman. Embeddable distributed moisture and pH sensors for nondestructive
inspection of aircraft lap joints. *Proceedings of the SPIE - The international society for Optical Engineering* 2455, 1995.

C. Mueller, B. Hitzmann, F. Schubert, and T. Scheper. pH-based fiber optic biosensors for use in clinical and
biotechnological applications. *Proceedings of the SPIE - The international society for Optical Engineering* 2388:558-567, 1995.

S. Zhang, S. Tanaka, Y. A. B. D. Wickramasinghe, and P. Rolfe. Fibre-optical sensor based on fluorescent indicator for monitoring
physiological pH values. *Medical & Biological Engineering & Computing* 33 (2):152-156, 1995.

A. A. Panova, P. Pantano, and D. R. Walt. In situ fluorescence imaging of localized corrosion with a
pH-sensitive imaging fiber. *Corrosion/97* p 4, Paper 314 (CONF-970332), 1997.

R. J. Lynch and M. D. Bolton. A low cost fiber optic pH sensor for the in-situ measurement of
groundwater. *SPIE proceedings series* 2835:221-227, 1996.

T. S. Lee, B. Aneeshkumar, P. Radhakrishnan, C. P. G Vallabhan, and V. P. N Nampoori. A microbent fiber optic pH sensor. *Optics Communications* 205 (4-6):253-256, 2002.

Y. Clarke, X Wenying, J. N. Demas, and B. A. DeGraff. Lifetime-based pH sensor system based on a polymer-supported
ruthenium(II) complex. *Analytical Chemistry* 72 (15):3468-3475, 2000.

L. Jie and L. Dong. An optical pH sensor with a linear response over a broad range. *Analytica Chimica Acta* 408 (1-2):49-55, 2000.

D. A. Nivens, Z. Yunke, and S. M. Angel. A fiber-optic pH sensor prepared using a base-catalyzed organo-silica
sol-gel. *Analytica Chimica Acta* 376 (2):235-245, 1998.

M. A. dePaoli and W. Alves deOliveira. Fiber-optic pH sensor based on poly(o-methoxyaniline). *Analytica Chimica Acta* 353 (2-3):275-280, 1997.

Z. Zhang, Z. Shakhsher, W. R. Seitz, and O. S. Wolfbeis. Aminated polystyrene membranes for a fiber optic pH sensor based on
reflectance changes accompanying polymer swelling
Electrochemical and optical chemical sensors. *Mikrochimica acta* 121 (1-4):41-50, 1995.

K. S. Bronk, K. L. Michael, P. Pantano, and D. R. Walt. Combined imaging and chemical sensing using a single optical imaging
fiber. *Analytical Chemistry* 67 (17):2750-2757, 1995.

Francisco J. Arregui, Carlos Fernandez-Valdivielso, Inaki Ilundain, and Ignacio R. Matias. pH sensor made using cellulosic coating on a biconically tapered singlemode optical fiber. 4185 2000.:464-467, 2000.

Artur Dybko, Michal Chudy, and Wojciech Wroblewski. New flow-cell for fiber optic chemical sensors. *Proceedings of SPIE - The International Society for Optical Engineering* 4185 2000.:460-463, 2000.

P. A. Wallace, N. Elliott, M. Uttamlal, A. S. Holmes-Smith, and M. Campbell. Development of a quasi-distributed optical fibre pH sensor. *Proceedings of SPIE - The International Society for Optical Engineering* 4185 2000.:456-459, 2000.

Antony S. Jeevarajan, Sundeep Vani, Thomas D. Taylor, and Melody M. Anderson. Continuous pH monitoring in a perfused bioreactor system using an optical pH sensor. *Biotechnology and Bioengineering* 78 (4):467-472, 2002.

S. Thomas Lee, B. Aneeshkumar, P. Radhakrishnan, C. P. G. Vallabhan, and V. P. N. Nampoori. A microbent fiber optic pH sensor. *Optics Communications* 205 (4-6):253-256, 2002.

B. D. Gupta and Navneet K. Sharma. Fabrication and characterization of U-shaped fiber-optic pH probes. *Sensors and Actuators, B: Chemical* 82 (1):89-93, 2002.

S. T. Lee, J. Gin, V. P. N. Nampoori, C. P. G. Vallabhan, N. V. Unnikrishnan, and P. Radhakrishnan. A sensitive fibre optic pH sensor using multiple sol-gel coatings. *Journal of Optics A: Pure and applied Optics* 3:355-359, 2001.

P. A. Wallave, N. Elliott, M. Uttamlal, A. S. Holmes-Smith, and M. Campbell. Development of a quasi-distributed optical fibre pH sensor using a covalently bound indicator. *Measurement Science and Technology* 12:882-886, 2001.

P. R. Coulet and N. Jaffrezic-Renault. 5th European Conference on Optical Chemical Sensors and Biosensors, Europt(r)ode V: Opt(r)ode 2000. *Sensors and Actuators, B: Chemical* 74 (1-3):211, 2001.

A. Iobnik, N. majcen, K. Niederreiter, and G. Uray. Optical pH sensor based on the absorption of antenna generated europium luminescence by bromothymolblue in a sol-gel membrane. *Sensors and Actuators, B: Chemical* 74 (1-3):200-206, 2001.

P. T. Sotomayor, I. M. Raimundo, A. J. G. Zarbin, J. J. R. Rohwedder, G. O. Neto, and O. L. Alves. Construction and evaluation of an optical pH sensor based on polyaniline-porous Vycor glass nanocomposite. *Sensors and Actuators, B: Chemical* 74 (1-3):157-162, 2001.

Sheila A. Grant, Kerry Bettencourt, Peter Krulevitch, Julie Hamilton, and Robert Glass. In vitro and in vivo measurements of fiber optic and electrochemical sensors to monitor brain tissue pH. *Sensors and Actuators, B: Chemical* 72:174-179, 2001.

Zhe Jin, Yongxuan Su, and Yixiang Duan. Improved optical pH sensor based on polyaniline. *Sensors and Actuators, B: Chemical* 71 (1-2):118-122, 2000.

Sheila A. Grant, Kerry Bettencourt, Peter Krulevitch, Julie Hamilton, and Robert Glass. Development of fiber optic and electrochemical pH sensors to monitor brain tissue. *Critical Reviews in Biomedical Engineering* 28 (1 2000.):159-163, 2000.

Christopher G. Cooney and Brace C. Towe. Miniaturized pH and pCO//2 intravascular catheter using optical monitoring and a dual concentric-flow microdialysis approach. *Sensors and Actuators, B: Chemical* 62 (3 2000):177-181, 2000.

N. Elliott, P. A. Wallace, M. Uttamlal, A. S. Holmes-Smith, and M. Campbell. Quasi-distributed pH sensor. *Proceedings of SPIE - The International Society for Optical Engineering* 3860 1999:460-466, 1999.

Necati Kaval and W. Rudolf Seitz. Aminated poly(vinylbenzylchloride-co-2,4,5-trichlorophenyl acrylate) microspheres for optical pH sensing. *Proceedings of SPIE - The International Society for Optical Engineering* 3860 1999.:224-231, 1999.

Thorsten de Vries, Ralf Paetzold, Kai Jantos, Eberhard Voss, and Angelika Anders. Mobile multi sensor system for environmental monitoring. *Proceedings of SPIE - The International Society for Optical Engineering* 3853 1999.:249-253, 1999.

Hongming Wang and W. Rudolf Seitz. pH sensor based on swellable poly(3-nitro-4-hydroxystyrene) microspheres in a hydrogel. *Proceedings of SPIE - The International Society for Optical Engineering* 3856 1999.:224-231, 1999.

Chi Cheng Wang. Studies of optical fiber biosensors. *Annual International Conference of the IEEE Engineering in Medicine and Biology - Proceedings* 2 1999.:827, 1999.

L. H. Garcia-Rubio, M. L. Janowiak, H. Huang, and S. Chang. Development of a fiber optic pH sensor for on-line control. *American Chemical Society, Polymer Priprints, Division of Polymer Chemistry* 40 (2 1999.):1260-1261, 1999.

Pascal Kronenberg, Brian Culshaw, and Gareth Pierce. Development of a novel fiber optic sensor for humidity monitoring. *Proceedings of SPIE - The International Society for Optical Engineering* 3670 1999.:480-485, 1999.

Wenying Xu, John Mehlmann, Jason Rice, James E. Collins, Cassandra L. Fraser, J. N. Demas, B. A. DeGraff, and Mauro Bassetti. pH sensors based on luminescent ruthenium(II) alpha -diimine complexes with diethylaminomethyl sensing groups. *Proceedings of SPIE - The International Society for Optical Engineering* 3534 1999.:456-465, 1999.

Gargi Vishnoi, T. C. Goel, and P. K. C. Pillai. pH-optrode for the complete working range. *Proceedings of SPIE - The International Society for Optical Engineering* 3538 1999.:319-325, 1999.

Jordan Bourilkov, Mathias Belz, William Boyle, and Kenneth Grattan. Electrical pH control in aqueous solutions. *Proceedings of SPIE - The International Society for Optical Engineering* 3538 1999.:268-277, 1999.

R. A. Lieberman. Proceedings of the 1998 Chemical, Biochemical, and Environmental Fibers Sensors X. *Proceedings of SPIE - The International Society for Optical Engineering* 3540 1999.

Susan J. Glenn, Brian M. Cullum, J. ChanceA Carter, Delana A. Nivens, Catherine J. Murphy, and S. Michael Angel. Development of a lifetime-based fiber-optic imaging sensor to study water transport in thin Nafion**T**M membranes. *Proceedings of SPIE - The International Society for Optical Engineering* 3540 1999.:235-245, 1999.

Sunil Dourado and Raoul Kopelman. Development of fluorescent fiber-optic single polymer membrane sensors for simultaneous ratiometric detection of oxygen and carbon dioxide in biological systems. *Proceedings of SPIE - The International Society for Optical Engineering* 3540 1999.:224-234, 1999.

Maria V. Schiza, Delana A. Nivens, Fred P. Milanovich, and S. Michael Angel. Characterization of mixed TiO//2 and SiO//2 sol-gel membranes for volatile organochloride sensing. *Proceedings of SPIE - The International Society for Optical Engineering* 3540 1999.:164-174, 1999.

Francesco Baldini, Leonardo Ciaccheri, Alida Falai, Anna Grazia Mignani, Jan Rayss, and Grzegorz Sudolski. Thymol blue immobilized on tapered fibres as an optical transducer for pH sensing. *Proceedings of SPIE - The International Society for Optical Engineering* 3540 1999.:28-33, 1999.

Zoe Chen-Esterlit, Jonathan W. Aylott, and Raoul Kopelman. Development of oxygen and pH optical sensors using phase modulation technique. *Proceedings of SPIE - The International Society for Optical Engineering* 3540 1999.:19-27, 1999.

U. H. Manyam, M. R. Shahriari, and M. J. Morris. Complete spectrum fiber optic pH sensor based on a novel fluorescent indicator doped porous sol-gel material. *Proceedings of SPIE - The International Society for Optical Engineering* 3540 1999.:10-18, 1999.

Francesco Baldini. Critical review of pH sensing with optical fibres. *Proceedings of SPIE - The International Society for Optical Engineering* 3540 1999.:2-9, 1999.

Artur Dybko, Wojciech Wroblewski, Ewa Rozniecka, Krzysztof Pozniakb, Janusz Maciejewski, Ryszard Romaniuk, and Zbigniew Brzozka. Assessment of water quality based on multiparameter fiber optic probe. *Sensors and Actuators, B: Chemical* B51 (1-3):208-213, 1998.

Cecilia M. Santegoeds, Andreas Schramm, and Dirk de Beer. Microsensors as a tool to determine chemical microgradients and bacterial activity in wastewater biofilms and flocs. *Biodegradation* 9 (3-4 1998.):159-167, 1998.

W. Fabianowski, M. Roszko, and W. Brodzinska. Optical sensor with active matrix built from polyelectrolytes-smart molecules mixture. *Thin Solid Films* 327-329:743-747, 1998.

B. D. Gupta and Sonu Sharma. Long-range fiber optic pH sensor prepared by dye doped sol-gel immobilization technique. *Optics Communications* 154 (5-6):282-284, 1998.

Wojciech Wroblewski, Ewa Rozniecka, Artur Dybko, and Zbigniew Brzozka. Cellulose based bulk pH optomembranes. *Sensors and Actuators, B: Chemical* B48 (1-3 pt 4):471-475, 1998.

M. N. Taib and R. Narayanaswamy. Multichannel calibration technique for optical-fibre chemical sensor using artificial neural network. *Sensors and Actuators, B: Chemical* B39 (1-3 pt 2):365-370, 1997.

A. Dybko, W. Wroblewski, J. Maciejewski, R. Romaniuk, and Z. Brzozka. Efficient reagent immobilization procedure for ion-sensitive optomembranes. *Sensors and Actuators, B: Chemical* B39 (1-3 pt 2):207-211, 1997.

C. Muller, B. Hitzmann, F. Schubert, and T. Scheper. Optical chemo- and biosensors for use in clinical applications. *Sensors and Actuators, B: Chemical* B40 (1):71-77, 1997.

Sheila A. Grant and Robert S. Glass. Sol-gel based fiber optic sensor for local blood pH measurements. *Sensors and Actuators, B: Chemical* B45:35-42, 1997.

Zhong Xu, Andrew Rollins, Ricardo Alcala, and Roger E. Marchant. Novel fiber-optic pH sensor incorporating carboxy SNAFL-2 and fluorescent wavelength-ratiometric detection. *Journal of Biomedical Materials Research* 39:9-15, 1998.

Yoshihiro Takahashi, Takayuki Takeda, Kazuyuki Suzuki, Akinori Maeda, Kenzo Kojima, and Hiroshi Ohta. Optical pH sensing properties of coumarin-4-doped sol-gel coating film. *Japanese Journal of Applied Physics, Part 1: Regular Papers & Short Notes & Review Papers* 36 (9A):5751-5752, 1997.

Jim Katsifolis, P. Moar, S. T. Huntington, L. W. Cahill, K. A. Nugent, and A. Roberts. Modelling, fabrication and testing of tapered optical fiber evanescent wave devices. *Pacific Rim Conference on Lasers and Electro-Optics, CLEO -Technical Digest* 1997.:306-307, 1997.

S. McCulloch and D. Uttamchandani. Development of a fibre optic micro-optrode for intracellular pH measurements. *IEE Proceedings Optoelectronics* 144:162-167, 1997.

Andrew M. Rollins, Zhong Xu, Ricardo Alcala, and Joseph A. Izatt. Novel wide range single fiber optic fluorescence pH sensor. *Conference Proceedings - Lasers and Electro-Optics Society Annual Meeting-CLEO* 11 1997.:183-184, 1997.

Michael R. Shortreed, Sunil Dourado, and Raoul Kopelman. Development of a fluorescent optical potassium-selective ion sensor with ratiometric response for intracellular applications. *Sensors and Actuators, B: Chemical* B38 (1-3 pt 1):8-12, 1997.

B. D. Gupta and D. K. Sharma. Evanescent wave absorption based fiber optic pH sensor prepared by dye doped sol-gel immobilization technique. *Optics Communications* 140 (1-3):32-35, 1997.

Chikara Egami, Yoshiki Suzuki, Okihiro Sugihara, Hisashi Fujimura, and Naomichi Okamoto. Wide range pH fiber sensor with congo-red- and methyl-red-doped poly (methyl methacrylate) cladding. *Japanese Journal of Applied Physics, Part 1: Regular Papers & Short Notes & Review Papers* 36 (5A):2902-2905, 1997.

Brian G. Healey and David R. Walt. Fast temporal response fiber-optic chemical sensors based on the photodeposition of micrometer-scale polymer arrays. *Analytical Chemistry* 69 (11):2213-2216, 1997.

D. Flannery, S. W. James, R. P. Tatam, and G. J. Ashwell. pH sensor using Langmuir-Blodgett overlays on polished optical fibers. *Optics Letters* 22 (8):567-569, 1997.

R. Blue and G. Stewart. Optical pH sensor for the alkaline region. *Electronics Letters* 33 (6):526-528, 1997.

H. H. Weetall and M. F. McCurley. Proceedings of the 1996 6th International Meeting on Chemical Sensors. Part 1. *Sensors and Actuators, B: Chemical* B35 (1-3 pt 1):261, 1996.

Deepak Uttamchandani and Scott McCulloch. Optical nanosensors - towards the development of intracellular monitoring. *Advanced Drug Delivery Reviews* 21 (3):239-247, 1996.

Chi Cheng Wang and Xi Jin. Studies of noninvasive blood gases patient monitor. *Proceedings of SPIE - The International Society for Optical Engineering* 2887 1996..:227-232, 1996.

Clarice A. Browne, Darcy H. Tarrant, Marta S. Olteanu, Joseph W. Mullens, and Eric L. Chronister. Intrinsic sol-gel clad fiber optic sensors with time resolved detection. *Analytical Chemistry* 68 (14):2289-2295, 1996.

Michael Shortreed, Eric Bakker, and Raoul Kopelman. Miniature sodium-selective ion-exchange optode with fluorescent pH chromoionophores and tunable dynamic range. *International Journal of Computer Vision* 18:2656-2662, 1996.

Kevin J. Kuhn and James T. Dyke. Renewable-reagent fiber-optic sensor for measurement of high acidities. *Analytical Chemistry* 68 (17):2890-2896, 1996.

Avraham Bromberg, Judith Zilberstein, Salomon Riesemberg, Eyal Benori, Ernesto Silberstein, Joseph Zimnavoda, Gad Frishman, and Amnon Kritzman. Optical-fibre sensors for blood gases and pH, based on porous glass tips. *Sensors and Actuators, B: Chemical* B31:181-191, 1996.

Robert Blue and George Stewart. Fibre-optic evanescent wave pH sensing with dye doped sol-gel films. *International Journal of Optoelectronics* 10 (3):211-222, 1995.

Yatao Yang, Peter A. Wallace, and Michael Campbell. Distributed optical fiber chemical sensor. *Proceedings of SPIE - The International Society for Optical Engineering* 2594 1996.:233-242, 1996.

M. N. Taib and R. Narayanaswamy. Novel technique to improve optical fibre sensor's response for industrial applications. *IEE Colloquium (digest)* (232 1995.):13-1-13/6, 1995.

A. Rumphorst, Stefan Seeger, and H. Duschner. Immobilized fluorescent dyes for sensitive pH measurements on enamel surfaces with fiber optics. *Proceedings of SPIE - The International Society for Optical Engineering* 2629 1996.:119-128, 1996.

C. Egami, K. Takeda, M. Isai, and M. Ogita. Evanescent-wave spectroscopic fiber optic pH sensor. *Optics Communications* 122 (4-6):122-126, 1996.

Christopher W. Brown, Chi Shi Chen, and Yue Li. Near- and mid-infrared chemical and biological sensors. *Proceedings of SPIE - The International Society for Optical Engineering* 2528 1995.:243-250, 1995.

Thomas M. Butler, Brian D. MacCraith, and Colette M. McDonagh. Development of an extended-range fiber optic pH sensor using evanescent wave absorption of sol-gel-entrapped pH indicators. *Proceedings of SPIE - The International Society for Optical Engineering* 2508 1995.:168-178, 1995.

Peter A. Wallace, Yatao Yang, and Michael Campbell. Toward a distributed optical fiber chemical sensor. *Proceedings of SPIE - The International Society for Optical Engineering* 2508 1995.:36-40, 1995.

F. Baldini. Proceedings of the 2nd European Conference on Optical Chemical Sensors and Biosensors, EUROPT(R)ODE II. *Sensors and Actuators, B: Chemical* B29 (1-3):432, 1995.

H. Lehmann, G. Schwotzer, P. Czerney, and G. J. Mohr. Fiber-optic pH meter using NIR dye. *Sensors and Actuators, B: Chemical* B29 (1-3):392-400, 1995.

M. E. J. Baker and R. Narayanaswamy. Modelling and control of the pH response of an immobilised indicator. *Sensors and Actuators, B: Chemical* B29 (1-3):368-373, 1995.

S. Motellier, M. H. Noire, H. Pitsch, and B. Dureault. pH determination of clay interstitial water using a fiber-optic sensor. *Sensors and Actuators, B: Chemical* B29 (1-3):345-352, 1995.

Eden J. Netto, John I. Peterson, Michael McShane, and Victoria Hampshire. Fiber-optic broad-range pH sensor system for gastric measurements. *Sensors and Actuators, B: Chemical* B29 (1-3):157-163, 1995.

Andre Holobar, Roman Benes, Bernhard H. Weigl, Paul O'Leary, Peter Raspor, and Otto S. Wolfbeis. Fiber optic and non-fiber optic double-beam pH sensors for use in a flow-through cell. *Analytical Methods and Instrumentation* 2 (2 1995.):92-100, 1995.

Edgar A. Mendoza, Albert N. Khalil, Zongjian Sun, Daniel Robinson, Steven J. Syracuse, Claudio O. Egalon, Michael F. Gunther, and Robert A. Lieberman. Embeddable distributed moisture and pH sensors for nondestructive inspection of aircraft lap joints. *Proceedings of SPIE - The International Society for Optical Engineering* 2455 1995.:102-112, 1995.

Bruno J. C. Deboux, Elfed Lewis, Patricia J. Scully, and Robert Edwards. Novel technique for optical fiber pH sensing based on methylene blue adsorption. *Journal of Lightwave Technology* 13:1407-1414, 1995.

Cord Mueller, Bernd Hitzmann, Florian Schubert, and Thomas Scheper. pH-based fiber optic biosensors for use in clinical and biotechnological applications. *Proceedings of SPIE - The International Society for Optical Engineering* 2388 1995.:558-567, 1995.

Sylvia H. Chang, S. L. Druen, and Luis H. Garcia-Rubio. Modeling and analysis of fiber optic pH sensors: effect of the ionic strength. *Proceedings of SPIE - The International Society for Optical Engineering* 2388 1995.:540-551, 1995.

Edward J. A. Pope. Fiber-optic microsensors using porous, dye-doped silica gel microspheres. *Hollow and Solid Spheres and Microspheres: Science and Technology Associated with their Fabrication and Application Materials Research Society Symposium Proceedings* 372 1995.:253-262, 1995.

S. Zhang, S. Tanaka, Y. A. B. D. Wickramasinghe, and P. Rolfe. Fibre-optical sensor based on fluorescent indicator for monitoring physiological pH values. *Medical & Biological Engineering & Computing* 33:152-156, 1995.

Z. Shakhsher, W. R. Seltz, and K. D. Legg. Single fiber-optic pH sensor based on changes in reflection accompanying polymer swelling. *Analytical Chemistry* 66 (10):1731-1735, 1994.

Joshua Samuel, Allina Strinkovski, Shmuel Shalom, Klony Lieberman, Michael Ottolenghi, David Avnir, and Aaron Lewis. Miniaturization of organically doped sol-gel materials: A microns-size fluorescent pH sensor. *Materials Letters* 21 (5-6):431-434, 1994.

Karen S. Bronk and David R. Walt. Simultaneous imaging and pH measurments with a single fiber optic imaging bundle. *Proceedings of SPIE - The International Society for Optical Engineering* 2068 1994.:56-58, 1994.

Venetka I. Agayn and David R. Walt. Monitoring of fermentation parameters with fiber optics. *Proceedings of SPIE - The International Society for Optical Engineering* 2068 1994.:179-184, 1994.

Jialing Yao, Daniel McStay, Peter J. Quinn, and Alan J. Rogers. pH sensor based on a dielectric optical waveguide. *Proceedings of SPIE - The International Society for Optical Engineering* 2068 1994.:353-360, 1994.

Luis H. Garcia-Rubio and Sylvia H. Chang. Modeling of fiber optic-based pH sensors. *Proceedings of SPIE - The International Society for Optical Engineering* 2068 1994.:11-22, 1994.

Sifu Zhang, Peter Rolfe, and Yapa A. Wickramasinghe. Optical pH sensor for physiological pH measurement. *Proceedings of SPIE - The International Society for Optical Engineering* 2085 1994.:22-28, 1994.

Artur Dybko, Janusz Maciejewski, Ryszard S. Romaniuk, and Wojciech Wroblewski. Colorimetric sensor based on two optical fiber couplers. *Proceedings of SPIE - The International Society for Optical Engineering* 2085 1994.:131-136, 1994.

Francesco Baldini. Optical fiber chemical sensors at IROE for medical applications. *Proceedings of SPIE - The International Society for Optical Engineering* 2085 1994.:104-108, 1994.

A. Sansubrino and M. Mascini. Development of an optical fibre sensor for ammonia, urea, urease, and IgG. *Biosensors & Bioelectronics* 9 (3 1994.):207-216, 1994.

F. Baldini, S. Bracci, F. Cosi, P. Bechi, and F. Pucciani. Controlled-pore glasses embedded in plastic optical fibers for gastric pH sensing purposes. *Applied Spectroscopy* 48:549-552, 1994.

A. A. Panova, P. Pantano, and D. R. Walt. In situ fluorescence imaging of localized corrosion with a pH-sensitive imaging fiber. *Analytical Chemistry* 69:1635-1641, 1997.

P. Dress and H. Franke. Increasing the accuracy of liquid analysis and pH-value control using a liquid-core waveguide. *Review of Scientific Instruments* 68:2167-2171, 1997.

D. A. Holman, G. D. Christian, and J. Ruzicka. Titration without mixing or dilution: sequential injection of chemical sensing membranes. *Analytical Chemistry* 69:1763-1765, 1997.

A. Song, S. Parus, and R. Kopelman. High-performance fiber-optic pH microsensors for practical physiological measurements using a dual-emission sensitive dye. *Analytical Chemistry* 69:863-867, 1997.

H. Hisamoto, M. Tsubuku, and T. Enomoto. Theory and practice of rapid flow-through analysis based on optode detection and its application to pH measurement as a model case. *Analytical Chemistry* 68:3871-3878, 1996.

T. L. Blair, J. R. Allen, and S. Daunert. Potentiometric and fiber optic sensors for pH based on an electropolymerized cobalt porphyrin. *Analytical Chemistry* 65:2155-2158, 1993.

K. S. Bronk and D. R. Walt. Fabrication of patterned sensor arrays with aryl azides on a polymer-coated imaging optical fiber bundle. *Analytical Chemistry* 66:3519-3520, 1994.

Christopher W. Brown, Z. Ge, and L. Sun. Fiber-optic pH sensor based on evanescent wave absorption spectroscopy. *Analytical Chemistry* 65:2335-2338, 1993.

J. W. parker, O. Laksin, and C. Yu. Fiber-optic sensors for pH and carbon dioxide using a self-referencing dye. *Analytical Chemistry* 1993:2329-2334, 1993.

J. B. Puschett, B. S. Rao, B. M. Karandikar, and K. Matyjaszewski. INDICATOR CHARACTERISTICS OF BROMOTHYMOL BLUE DERIVATIVES. *talanta* 38 (3):335-338, 1991.

G. Serra, A. Schirone, and R. Boniforti. FIBER-OPTIC PH SENSOR FOR SEA WATER MONITORING USING A SINGLE DYE. *Analytica Chimica Acta* 232 (2):337-344, 1990.

W. R. Seitz. TRANSDUCER MECHANISMS FOR OPTICAL BIOSENSORS PART 1. THE CHEMISTRY OF TRANSDUCTION. *Comput.Methods Program Biomed.* 30 (1):9-20, 1989.

O. S. Wolfbeis, H. E. Posch, and M. J. P. Leiner. TOWARDS A GASTRIC PH SENSOR AN OPTRODE FOR THE PH 0-7 RANGE. *Fresenius Z Anal.Chem.* 334 (2):162-165, 1989.

R. Czolk, E. Gantner, and H. J. Ache. FIBER OPTICAL PH-SENSOR BASED ON LASER-INDUCED FLUORESCENCE. *GBF Monographs, Biosensors International Workshop 1987* 10:307-308, 1987.

T. J. takach, L. R. Glassman, E. R. Rodriguez, J. T. Falcone, V. J. Ferrans, and R. E. Clark. ACUTE REJECTION AFTER CARDIAC TRANSPLANTATION DETECTION BY INTERSTITIAL MYOCARDIAL PH. *Ann.Thorac.Surg.* 42 (6):619-626, 1986.

G. A. Tait, R. B. Young, G. J. Wilson, D. J. Steward, and D. C. MacGregor. MYO CARDIAL PH DURING REGIONAL ISCHEMIA EVALUATION OF A FIBER OPTIC PHOTOMETRIC PROBE. *Am.J.Physiol.* 243 (6):H1027-H1031, 1982.

D. T. Link, J. P. Willging, C. K. Miller, R. T. Cotton, and C. D. Rudolph. Pediatric laryngopharyngeal sensory testing during flexible endoscopic evaluation of swallowing: feasible and correlative. *Annals of Otology, Rhinology, and Laryngology* 109 (10 pt1):899-905, 2000.

K. L. Michael and D. R. Walt. Combined imaging and chemical sensing of fertilization-induced acid release from single sea urchin eggs. *Analytical biochemistry* 273 (2):168-178, 1999.

J. E. Aviv, T. Kim, J. E. Thomson, S. Sunshine, S. Kaplan, and L. G. Close. Fiberoptic endoscopic evaluation of swallowing with sensory testing (FEESST) in healthy controls. *Dysphagia* 13 (2):87-92, 1998.

J. E. Aviv. Sensory discrimination in the larynx and hypopharynx. *Otorlaryngology--head and neck surgery: Official journal of American Academy of Otolaryngology - Head and Neck Surgery* 116 (3):331-334, 1997.

J. I. Peterson and S. R. Goldstein. A miniature fiberoptic pH sensor potentially suitable for glucose measurements. *Diabetes Care* 5 (3):272-274, 1982.

G. A. Tait, R. B. Young, G. J. Wilson, D. J. Steward, and D. C. MacGregor. Myocardial pH during regional ischemia: evaluation of a fiber-optic photometric probe. *American journal of physiology* 243 (6):H1027-H1031, 1982.

P. Judeinstein and J. Livage. Sol-Gel Nano-Porous Silica-Titania Thin Films With Liquid Fill for Optical Interferometric sensors. *Proceedings of the SPIE - The international society for Optical Engineering* 1328 (AD-A249 986):352-363, 1990.

J. Lin and D. Liu. An optical pH sensor with a linear response over a broad range. *Analytica Chimica Acta* 2000 (408/1-2):49-55, 2000.

B. A. McKinley and B. D. Butler. Comparison of skeletal muscle POinf 2, PCOinf 2, and pH with gastric tonometric PCOinf 2 and pH in hemorrhagic shock. *Critical Care Medicine* 27 (9):1869-1877, 1999.

B. A. McKinley, C. L. Parmley, and B. D. Butler. Skeletal muscle POinf 2, PCOinf 2, and pH in hemorrhage, shock, and resuscitation in dogs. *Journal of Trauma-Injury, Infection and Critical Care* 44 (1):119-127, 1998.

E. E. Roupie, L. Brochard, and F. J. Lemaire. Clinical evaluation of a continuous intra-arterial blood gas system in critically ill patients. *Intensive Care Medicine* 22 (11):1162-1168, 1996.

B. A. McKinley, W. P. Morris, C. L. Parmley, and B. D. Butler. Brain parenchyma POinf 2, PCOinf 2, and pH during and after hypoxic, ischemic brain insult in dogs. *Critical Care Medicine* 24 (11):1858-1868, 1996.

S. A. Halbert. Intravascular monitoring: Problems and promise. *Clin.Chem.* 36 (8 II):1581-1584, 1990.

F. J. Bondurant, H. B. Cotler, R. Buckle, P. Miller-Crotchett, and B. D. Browner. The medical and economic impact of severely injured lower extremities. *Journal of Trauma* 28 (8):1270-1273, 1988.

T. Vo-Dinh, R. A. Lieberman, and G. V. Vurek. Biomedical sensing, imaging, and tracking technologies II; Proceedings of the Meeting, San Jose, CA, Feb. 11-13, 1997. *Society of Photo-Optical Instrumentation Engineers (SPIE Proceedings)* 2976:390, 1997.

R. A. Lieberman. Chemical, biochemical, and environmental fiber sensors V; Proceedings of the Conference, Boston, MA, Sept. 7-9, 1993. *Society of Photo-Optical Instrumentation Engineers (SPIE Proceedings)* 2068:374, 1994.

A. C. Smith. Fiber optic sensors for corrosion detection. *American Society for Engineering Education (ASEE) Summer Faculty Fellowship Program*:179-182, 1993.

Z. M. Hale. Fibre-optic sensors using adiabatically tapered single-mode fibres. *Ph.D.Thesis Air Force Inst.of Tech., Wright-Patterson AFB, OH.*:45, 1992.

M. L. Janowiak, H. Huang, S. Chang, and L. H. Garcia-Rubio. Development of a Fiber Optic pH Sensor for On-Line Control. *ACS SYMPOSIUM SERIES* 2001 (795 P):195-210, 2001.

S. T. Lee, C. M. Manju, B. Joseph, G. Jose, M. S. John, P. Radhakrishnan, V. P. N Nampoori, C. P. G Vallabhan, and N. V. Unnikrishnan. A Fiber Optic pH Sensor With Multi-Layer Sol-Gel Coatings. *INTERNATIONAL CONFERENCE ON FIBER OPTICS AND PHOTONICS* 1:351-354, 2000.

Z. Y. Shi and R. Kopelman. Fiber Optic HPTs pH Sensor's Fabrication and Application. *ANNUAL MEETING- FEDERATION OF ANALYTICAL CHEMISTRY AND SPECTROSCOPY SOCIETIES , 1995* 22:180, 1995.

J. I. Peterson and Eden J. Netto. A Fiber-Optic Broad-Range pH Sensor System for Gastric Measurements. *EUROPEAN CONFERENCE ON OPTICAL CHEMICAL SENSORS AND BIOSENSORS , 1994;* 2:94, 1994.

Sheila A. Grant and Robert Glass. Development of sensors to monitor stroke patients. *The 6th international meeting on chemical sensors* p 1 (paper 17):313, 1996.

J. N. Fisher. Development of photopolymerization for the fabrication of optically sensitive polymers for pH measurements. *Science and engineering Research Semester (SERS) symposium* paper 5:245, 1994.

D. McCrae and E. Saaski. Optical fiber pH sensors for high temperature water. Final report. *Electric power Research Inst.Palo Alto CA* Nov 1994:44, 1994.

W. Tan. Nanofabrication and applications of subwavelength optical probes: Chemical and biological sensors, light sources and exciton probes. *Ph.D.Thesis Michigan University*, 1993.

R. A. Lieberman. Chemical, biochemical, and environmental fiber sensors IV; Proceedings of the Meeting, Boston, MA, Sept. 8, 9, 1992. *Proceedings of the SPIE - The international society for Optical Engineering* 1796:422, 1993.

Wang Chi-Cheng and Xi Jin. Studies of blood gas determination and intelligent image. *Proceedings of the SPIE - The international society for Optical Engineering* 1993:142-145, 1992.

S. M. Angel and M. A Northrup. Stability of a fiber optic pH sensor at 100[degree]F. *Electric power Research Inst.Palo Alto CA* Feb. 1993:24, 1993.

T. Weihong, S Zhongyou, and K. Raoul. Development of submicron chemical fiber optic sensors. *Analytical Chemistry* 64 (23), 1992.

M. H. Michels and B. Dureault. Fiber-optic pH sensor for in-situ applications. *EUROPEAN CONFERENCE ON OPTICAL CHEMICAL SENSORS AND BIOSENSORS , 1992;* 1992:21, 1992.

L. C. Baylor and P. E. O'Rourke. Fiber-optic pH sensors. *American Chemical Society (ACS) General Meeting* 1991 (NUCL 89):26-27, 1991.

T. P. Jones. Development, characterization, and applications of optical pH sensors supported at cellulosic film. *Ph.D.Thesis Ames Lab., IA* 1990:152, 1990.

M. A Northrup, K. Langry, and S. M. Angel. Stability of a pH-sensitive polymer matrix. *SPIE optics, electro-optics and laser applications in science and engineering conference and exhibition* 1990:10, 1990.

M. D. Porter, T. P. Jones, C. Laikwan, and S. M. Stole. Approaches to the construction of optical sensors with porous polymer films. *Symposium on chemical sensors and microinstrumentation* 1988:84-85, 1988.

S. M. Angel and J. F. Poco. High-temperature optical-fiber pH sensor: Final report. *Lawrence Livermore National Lab., CA* Jun 1989:31, 1989.

S. Zhang, P. Rolfe, and Y. A. B. D. Wickramasinghe. Evaluation of fluorescent dyes for vivo pH measurement. *Medical & Biological Engineering & Computing* 32 (2):224-227, 1994.

Z. M. Hale and F. P. Payne. Fluorescent sensors based on tapered single-mode optical fibres. *Sensors and Actuators, B: Chemical* B17 (3):233-240, 1994.

G. Frishman and G. Gobor. Surface characteristics of optical chemical sensors. *Sensors and Actuators, B: Chemical* B17 (3):227-232, 1994.

F. Baldini, S. Bracci, and F. Cosi. Extended-range fibre-optic pH sensor. *Sensors and Actuators, A: Physical* 37-38 (2):180-186, 1993.

M. H. Maher and M. R. Shahriari. Fiber optic chemical sensor for measurement of groundwater pH. *Journal of Testing and Evaluation* **21** (5):448-452, 1993.

C. Takahashi, A. Kaneko, Y. Komata, S. Yokoyama, and T. Fujie. Studies of body fluids with optical fiber sensors. *Sensors and Actuators, B: Chemical* B14 (1-3):756-757, 1993.

N. Yamazoe, M. Aizawa, S. Yamauchi, and M. Egashira. Proceedings of the Fourth International Meeting on Chemical
Sensors. *Sensors and Actuators, B: Chemical* B14 (1-3):491-759, 1993.

T. Hao, X. Xing, and C-C Liu. pH sensor constructed with two types of optical fibers: the configuration and the initial results. *Sensors and Actuators, B: Chemical* B10 (2):155-159, 1993.

C. Milo and B. W. Atwater. Luminescent fiber optic sensor for the measurement of pH. *Proceedings of the SPIE - The international society for Optical Engineering* 1796 (1993):188-201, 1993.

R. Kopelman, W. Tan, and Z. Y. Shi. Nanometer optical fiber pH sensor. *Proceedings of the SPIE - The international society for Optical Engineering* 1796 (1993):157-162, 1993.

R. A. Lieberman. Chemical, Biochemical, and Environmental Fiber Sensors IV. *Proceedings of the SPIE - The international society for Optical Engineering* 1796 (1993):424, 1993.

S. Motellier, M. H. Michels, B. Dureault, and P. Toulhoat. Fiber-optic pH sensor for in situ applications. *Sensors and Actuators, B: Chemical* B11 (1-3):467-473, 1993.

M. Busch, F. Gutberlet, W. Hoebel, J. Polster, H.-L. Schmidt, and M. Schwenk. Application of optodes in FIA-based fermentation process control using the software package FIACRE. *Sensors and Actuators, B: Chemical* B11 (1-3):407-412, 1993.

B. D. MacCraith. Enhanced evanescent wave sensors based on sol-gel derived porous glass coatings. *Sensors and Actuators, B: Chemical* B11 (1-3):29-34, 1993.

D. Cui, Q. Cao, J. Han, J. Cai, Y. Li, and Z. Zhu. Optical-fibre pH sensor. *Sensors and Actuators, B: Chemical* B12 (1):29-32, 1993.

G. L. Mitchell, J. C. hartl, D. McCrae, R. A. Wolthuis, E. W. Saaski, and K. C. Garcin. Fiber optic pH measurement using azo indicators: optics development. *Proceedings of the SPIE - The international society for Optical Engineering* 1587 (1992):81-85, 1992.

F. Baldini, S. Bracci, and M. Bacci. Fiber optic pH sensor using acid-base indicators covalently bound on controlled pore glasses. *Proceedings of the SPIE - The international society for Optical Engineering* 1587 (1992):67-73, 1992.

T. Hao, X. Xing, and C-C Liu. Fiber optic chemical sensor constructed with different types of optical fiber. *Proceedings of the SPIE - The international society for Optical Engineering* 1587 (1992):2-3, 1992.

C-C Liu and W. H. Ko. Third International Meeting on Chemical Sensors. *Sensors and Actuators, B: Chemical* B5 (1-4):263, 1991.

R. Wolthuis, D. McCrae, E. Saaski, J. Hartl, and G. L. Mitchell. Development of a medical fiber-optic pH sensor based on optical absorption. *IEEE Transactions on Biomedical Engineering* 39 (5):531-537, 1992.

J. Y. Ding, M. R. Shahriari, and G. H. Sigel Jun. Fibre optic pH sensors prepared by sol-gel immobilisation technique. *Electronics Letters* 27 (17):1560-1562, 1991.

A. J. Martin and M. Green. Sol-gel nano-porous silica-titania thin films with liquid fill for optical interferometric sensors. *Proceedings of the SPIE - The international society for Optical Engineering* 1328 (1990):352-363, 1990.

B. S. Rao, J. B. Puschett, and K. Matyjaszewski. Preparation of pH sensors by covalent linkage of dye molecules to the surface of polystyrene optical fibers. *Journal of Applied Polymer Science* 43 (5):925-928, 1991.

F. Baldini, M. Bracci, and S. Bracci. Analysis of acid-base indicators covalently bound on glass supports. *Proceedings of the SPIE - The international society for Optical Engineering* 1368 (1991):210-217, 1991.

F. Baldini. Recent progress in fiber optic pH sensing. *Proceedings of the SPIE - The international society for Optical Engineering* 1368 (1991):184-190, 1991.

M. A Northrup, K. Langry, and S. M. Angel. Stability studies of a pH-sensitive polymer matrix. Applications to fiber optic pH sensors. *Proceedings of the SPIE - The international society for Optical Engineering* 1201 (1990):368-374, 1990.

S. M. Barnard and D. R. Walt. Fiber optic sensors based on time release polymers. *Proceedings of the SPIE - The international society for Optical Engineering* 1201 (1990):362-367, 1990.

R. A. Lieberman and M. T. Wlodarczyk. Chemical, Biochemical, and Environmental Fiber Sensors II. *Proceedings of the SPIE - The international society for Optical Engineering* 1368 (1991):274, 1991.

P. Poscio, C. Depeursinge, G. Vorin, B. Sheja, and O. Parriaux. Realization of a miniaturized optical sensor for biomedical applications. *Sensors and Actuators, A: Physical* 23 (1-3):1092-1096, 1990.

A. Katzir. BIOMEDICAL FIBER OPTIC SENSORS. *Optical Fiber Sensors* 2 (1988 parts 1-2), 1988.

D. R. Walt, C. Munkholm, P. Yuan, S. Luo, and D. R. Walt. FIBER OPTIC BIOSENSORS FOR IN VIVO AND IN VITRO MEASUREMENTS OF CLINICALLY IMPORTANT SPECIES. *9th Publ by IEEE* (1987):802-803, 1987.

M. Bacci, F. Baldini, M. Brenci, G. Conforti, and R. Falciai. MODEL FOR AN OPTICAL FIBER pH SENSOR. *Proceedings of the SPIE - The international society for Optical Engineering* 713 (1987):88-92, 1987.

M.-R. S. Fuh, L. W. Burgess, and G. D. Christian. SINGLE FIBER-OPTIC FLUORESCENCE ENZYME-BASED SENSOR. *Analytical Chemistry* 60 (5):433-435, 1988.

K. T. V. Grattan, Z. Mouaziz, and A. W. Palmer. DUAL WAVELENGTH OPTICAL FIBRE SENSOR FOR pH MEASUREMENT. *Biosensors* 3 (1):17-25, 1987.

J. W. Attridge, K. D. Leaver, and J. R. Cozens. DESIGN OF A FIBRE-OPTIC pH SENSOR WITH RAPID RESPONSE. *Journal of Physics E: Scientific Instruments* 20 (5):548-553, 1987.

H. M. Hochberg and F. W. Hetzel. TISSUE pH MONITORING IN OBSTETRICS. *Publ by Assoc for the Advancement of Medical Instrumentation* (1984), 1984.

R. F. Colvile. ON-LINE pH MEASUREMENT AND CONTROL. *Measurement and Control* 18 (10):396-399, 1985.

S. R. Goldstein, J. I. Peterson, and R. V. Fitzgerald. MINIATURE FIBER OPTICS pH SENSOR FOR PHYSIOLOGICAL USE. *Journal of Biomechanical Engineering* 102 (2):141-146, 1980.

S. T. Lee, B. Aneeshkumar, P Radhakrishnan , C. P. G. Vallabhan, and V. P. N. Nampoori. A microbent fiber optic pH sensor. *Optics Communications* 205 , (4-6 (MAY 1) ,):253-256

A. L. Chaudhari and A. D. Shaligram. Development of fiber optic pH meter based on colorimetric principle. *INDIAN JOURNAL OF PURE & APPLIED PHYSICS* 40 , (2 (FEB) ,):132-136, 2002.

A. Dybko. Influence of temperature on performance of chemical sensors. *CHEMIA ANALITYCZNA* 47 , (1 ,):65-74, 2002.

G. Knichwitz, T. Brussel, P. Reinhold, F. Schaumann, K. D. Richter, and H. VanAken. Early onset of regional intestinal ischemia can be detected with carbon dioxide tension measurement inside the peritoneal cavity. *ANESTHESIA AND ANALGESIA* 91 , (5 (NOV) ,):1182-1187, 2000.

J. Lin. Recent development and applications of optical and fiber-optic pH sensors. *TRAC-TRENDS IN ANALYTICAL CHEMISTRY* 19 , (9 (SEP) ,):541-552, 2000.

W. H. Tan, B. A. Thorsrud, C. Harris, and R. Kopelman. Real time pH measurements in the intact rat conceptus using ultramicrofiber-optic sensors. *UNIV MICHIGAN,DEPT ENVIRONM & IND HLTH, TOXICOL PROGRAM/ANN ARBOR//MI/48109* 690:266-272, 1998.

W. R. Seitz, M. T. V. Rooney, E. W. Miele, H. M. Wang, N. Kaval, L. Zhang, S. Doherty, S. Milde, and J. Lenda. Derivatized, swellable polymer microspheres for chemical transduction. *Analytica Chimica Acta* 400 (SI (NOV) ,):55-64, 1999.

B. A. McKinley and B. D. Butler. Comparison of skeletal muscle P-O2, P-CO2, and pH with gastric tonometric P-CO2 and pH in hemorrhagic shock. *Critical Care Medicine* 27 , (9 (SEP) ,):1869-1877, 1999.

D. A. Nivens, Y. K. Zhang, and S. M. Angel. A fiber-optic pH sensor prepared using a base-catalyzed organo-silica sol-gel. *Analytica Chimica Acta* 376 , (2 (DEC 11) ,):235-245, 1998.

R. A. Potyrailo and G. M. Hieftje. Spatially resolved analyte mapping with time-of-flight optical sensors. *TRAC-TRENDS IN ANALYTICAL CHEMISTRY* 17 , (10 (NOV-DEC) ,):593-604, 1998.

G. Knichwitz, J. Rotker, T. Mollhoff, K. D. Richter, and T. Brussel. Continuous intramucosal PCO2 measurement allows the early detection of intestinal malperfusion. *Critical Care Medicine* 26 , (9 (SEP) ,):1550-1557, 1998.

R. A. Potyrailo and G. M. Hieftje. Distributed fiber-optic chemical sensor with chemically modified plastic cladding. *Applied Spectroscopy* 52 (8 (AUG)):1092-1095, 1998.

A. Safavi and H. Abdollahi. Optical sensor for high pH values. *Analytica Chimica Acta* 367 (1-3 (JUL 3)):167-173, 1998.

B. D. Gupta and S. K. Khijwania. Experimental studies on the response of the fiber optic evanescent field absorption sensor. *FIBER AND INTEGRATED OPTICS* 17 (1):63-73, 1998.

B. A. McKinley, C. L. Parmley, and B. D. Butler. Skeletal muscle PO2, PCO2, and pH in hemorrhage, shock, and resuscitation in dogs. *JOURNAL OF TRAUMA-INJURY INFECTION AND CRITICAL CARE* 44 (1 (JAN)):119-127, 1998.

M. D. T. Sotomayor, M. A. dePaoli, and W. A. deOliveira. Fiber-optic pH sensor based on poly(o-methoxyaniline). *Analytica Chimica Acta* 353 (2-3 (OCT 30)):275-280, 1997.

J. L. H. Jiwan and J. P. Soumillion. A halogen anion sensor based on the hydrophobic entrapment of a fluorescent probe in silica sol-gel thin films. *JOURNAL OF NON-CRYSTALLINE SOLIDS* 220 (2-3 (NOV)):316-322, 1997.

O. BenDavid, E. Shafir, I. Gilath, Y. Prior, and D. Avnir. Simple absorption optical fiber pH sensor based on doped sol-gel cladding material. *CHEMISTRY OF MATERIALS* 9 (11 (NOV)):2255-2257, 1997.

D. B. Papkovsky, G. V. Ponomarev, and O. S. Wolfbeis. Protonation of porphyrins in liquid PVC membranes: Effects of anionic additives and application to pH-sensing. *JOURNAL OF PHOTOCHEMISTRY AND PHOTOBIOLOGY A-CHEMISTRY* 104 (1-3 (APR)):151, 1997.

J. Lin and C. W. Brown. Sol-gel glass as a matrix for chemical and biochemical sensing. *TRAC-TRENDS IN ANALYTICAL CHEMISTRY* 16 (4 (APR)):200-211, 1997.

M. Campbell, Y. T. Yang, P. A. Wallace, and A. S. HolmesSmith. A multipoint quasi-distributed optical fiber pH sensor. *OPTICAL REVIEW* 4 (1A (JAN-FEB)):111-113, 1997.

M. Holzinger, J. Maier, and W. Sitte. Potentiometric detection of complex gases: Application to CO2. *SOLID STATE IONICS* 94 (1-4 (FEB)):217-225, 1997.

Y. N. Shi and C. J. Seliskar. Optically transparent polyelectrolyte-silica composite materials: Preparation, characterization, and application in optical chemical sensing. *CHEMISTRY OF MATERIALS* 9 (3 (MAR)):821-829, 1997.

W. E. Hoffman, F. T. Charbel, G. Edelman, and J. I. Ausman. Brain tissue cases and pH during arteriovenous malformation resection. *NEUROSURGERY* 40 (2 (FEB)):294-300, 1997.

E. D. S. Kerslake and C. C. Wilson. Pharmaceutical and biomedical applications of fiber optic biosensors based on infra red technology. *Advanced Drug Delivery Reviews* 21 (3 (OCT 11)):205-213, 1996.

B. A. McKinley, W. P. Morris, C. L. Parmley, and B. D. Butler. BRAIN PARENCHYMA PO2, PCO2, AND PH DURING AND AFTER HYPOXIC, ISCHEMIC BRAIN INSULT IN DOGS. *Critical Care Medicine* 24 (11 (NOV)):1858-1868, 1996.

Z. J. ZHANG, Z. Shakhsher, and W. R. Seitz. AMINATED POLYSTYRENE MEMBRANES FOR A FIBER OPTIC PH SENSOR-BASED ON REFLECTANCE CHANGES ACCOMPANYING POLYMER SWELLING. *Mikrochimica acta* 121 (1-4):41-50, 1995.

C. A. Browne, D. H. Tarrant, M. S. Olteanu, J. W. MULLENS, and E. L. CHRONISTER. INTRINSIC SOL-GEL CLAD FIBEROPTIC SENSORS WITH TIME-RESOLVED DETECTION. *Analytical Chemistry* 68 (14 (JUL 15)):2289-2295, 1996.

D. B. Papkovsky, G. V. Ponomarev, W. TRETTNAK, and P. OLEARY. PHOSPHORESCENT COMPLEXES OF PORPHYRIN KETONES -OPTICAL- PROPERTIES AND APPLICATION TO OXYGEN SENSING. *Analytical Chemistry* 67 (22 (NOV 15)):4112-4117, 1995.

S. Motellier, M. H. Noire, H. Pitsch, and B. Dureault. PH DETERMINATION OF CLAY INTERSTITIAL WATER USING A FIBEROPTIC SENSOR. *SENSORS AND ACTUATORS B-CHEMICAL* 29 (1-3 (OCT)):345-352, 1995.

E. J. NETTO, J. I. Peterson, M. MCSHANE, and V. HAMPSHIRE. A FIBEROPTIC BROAD-RANGE PH SENSOR SYSTEM FOR GASTRIC MEASUREMENTS. *SENSORS AND ACTUATORS B-CHEMICAL* 29 (1-3 (OCT)):157-163, 1995.

M. D. MARAZUELA, M. C. M. BONDI, and G. ORELLANA. ENHANCED PERFORMANCE OF A FIBEROPTIC LUMINESCENCE CO2 SENSOR USING CARBONIC-ANHYDRASE. *SENSORS AND ACTUATORS B-CHEMICAL* 29 (1-3 (OCT)):126-131, 1995.

H. SZMACINSKI and J. R. LAKOWICZ. FLUORESCENCE LIFETIME-BASED SENSING AND IMAGING. *SENSORS AND ACTUATORS B-CHEMICAL* 29 (1-3 (OCT)):16-24, 1995.

M. F. CHOI and P. HAWKINS. NOVEL DYE-SOLVENT SOLUTIONS FOR THE SIMULTANEOUS DETECTION OF OXYGEN AND CARBON-DIOXIDE. *Analytical Chemistry* 67 (21 (NOV 1)):3897-3902, 1995.

W. H. Tan, Z. Y. Shi, and R. Kopelman. MINIATURIZED FIBEROPTIC CHEMICAL SENSORS WITH FLUORESCENT DYE-DOPED POLYMERS. *SENSORS AND ACTUATORS B-CHEMICAL* 28 (2 (AUG)):157-163, 1995.

L. LI and D. R. Walt. DUAL-ANALYTE FIBEROPTIC SENSOR FOR THE SIMULTANEOUS AND CONTINUOUS MEASUREMENT OF GLUCOSE AND OXYGEN. *Analytical Chemistry* 67 (20 (OCT 15)):3746-3752, 1995.

I. KLIMANT, V. MEYER, and M. KUHL. FIBEROPTIC OXYGEN MICROSENSORS, A NEW TOOL IN AQUATIC BIOLOGY. *LIMNOLOGY AND OCEANOGRAPHY* 40 (6 (SEP)):1159-1165, 1995.

K. S. Bronk, K. L. Michael, P. Pantano, and D. R. Walt. COMBINED IMAGING AND CHEMICAL SENSING USING A SINGLE OPTICAL IMAGING FIBER. *Analytical Chemistry* 67 (17 (SEP 1)):2750-2757, 1995.

D. W. LUBBERS. OPTICAL SENSORS FOR CLINICAL MONITORING. *ACTA ANAESTHESIOLOGICA SCANDINAVICA* 39 (S104):37-54, 1995.

Y. J. XU, Q. J. XIE, M. Q. HU, L. H. NIE, and S. Z. YAO. SIMULTANEOUS UV-VISIBLE SPECTROELECTROCHEMICAL AND QUARTZ-CRYSTAL MICROGRAVIMETRIC MEASUREMENTS DURING THE GROWTH OF POLY(1-NAPHTHYLAMINE) FILM. *JOURNAL OF ELECTROANALYTICAL CHEMISTRY* 389 (1-2 (JUN 1)):85-90, 1995.

M. Uttamlal and D. R. Walt. A FIBEROPTIC CARBON-DIOXIDE SENSOR FOR FERMENTATION MONITORING. *BIO-TECHNOLOGY* 13 (6 (JUN)):597-601, 1995.

G. A. CASAY, F. MEADOWS, N. DANIELS, A. ROBERSON, and G. PATONAY. FIBER OPTIC PROBE APPLICATIONS USING NEAR-INFRARED COMPOUNDS - DETERMINATION OF NAOH. *SPECTROSCOPY LETTERS* 28 (3):301-326, 1995.

G. E. BADINI, K. T. V. Grattan, and A. C. C. TSEUNG. IMPREGNATION OF A PH-SENSITIVE DYE INTO SOL-GELS FOR FIBER OPTIC CHEMICAL SENSORS. *ANALYST* 120 (4 (APR)):1025-1028, 1995.

S. Zhang, S. Tanaka, Y. A. B. D. Wickramasinghe, and P. Rolfe. FIBEROPTIC SENSOR-BASED ON FLUORESCENT INDICATOR FOR MONITORING PHYSIOLOGICAL PH VALUES. *Medical & Biological Engineering & Computing* 33 (2 (MAR)):152-156, 1995.

A. FONG and G. M. Hieftje. NEAR-INFRARED MEASUREMENT OF RELATIVE AND ABSOLUTE-HUMIDITY THROUGH DETECTION OF WATER ADSORBED ON A SILICA-GEL LAYER. *Analytical Chemistry* 67 (6 (MAR 15)):1139-1146, 1995.

M. F. CHOI and P. HAWKINS. RESPONSE OF FLUORESCEIN TO CARBON-DIOXIDE IN DIMETHYL SULFOXIDE-WATER MIXTURES. *JOURNAL OF THE CHEMICAL SOCIETY-FARADAY TRANSACTIONS* 91 (5 (MAR 7)):881-885, 1995.

V. V. COSOFRET, E. LINDNER, T. A. JOHNSON, and M. R. NEUMAN. PLANAR MICRO SENSORS FOR IN-VIVO MYOCARDIAL PH MEASUREMENTS. *talanta* 41 (6 (JUN)):931-938, 1994.

8.2 CO_2 Sensors

M. V. Schiza, M. P. Nelson, M. L. Myrick, and S. M. Angel. Hyperspectral imaging sensors using a novel 2D to 1D fiber array. *Proceedings of the SPIE - The international society for Optical Engineering* 3860:317-325, 1999.

S. M. Angel, M. V. Schiza, D. A. Nivens, F. P. Milanovich, and Ang. Characterization of mixed TiO//2 and SiO//2 sol-gel membranes for volatile organochloride sensing. *Proceedings of the SPIE - The international society for Optical Engineering* 3540:164-174, 1999.

F. Baldini. Critical review of pH sensing with optical fibres. *Proceedings of the SPIE - The international society for Optical Engineering* 3540:2-9, 1999.

C. M. Santegoeds, A. Schramm, and D. de Beer. Microsensors as a tool to determine chemical microgradients and bacterial activity in wastewater biofilms and flocs. *Biodegradation* 9 (3-4):159-167, 1998.

A. Bromberg, J. Zilberstein, and S. Riesemberg. Optical-fibre sensors for blood gases and pH, based on porous glass tips. *Sensors and Actuators B(chemical)* B31 (3):181-191, 1996.

Christopher G. Cooney and Brace C. Towe. Miniaturized pH and pCO//2 intravascular catheter using optical monitoring and a dual concentric-flow microdialysis approach. *Sensors and Actuators, B: Chemical* 62 (3 2000):177-181, 2000.

Maria V. Schiza, Matthew P. Nelson, M. L. Myrick, and S. Michael Angel. Hyperspectral imaging sensors using a novel 2D to 1D fiber array. *Proceedings of SPIE - The International Society for Optical Engineering* 3860 1999.:317-325, 1999.

Sunil Dourado and Raoul Kopelman. Development of fluorescent fiber-optic single polymer membrane sensors for simultaneous ratiometric detection of oxygen and carbon dioxide in biological systems. *Proceedings of SPIE - The International Society for Optical Engineering* 3540 1999.:224-234, 1999.

Maria V. Schiza, Delana A. Nivens, Fred P. Milanovich, and S. Michael Angel. Characterization of mixed TiO//2 and SiO//2 sol-gel membranes for volatile organochloride sensing. *Proceedings of SPIE - The International Society for Optical Engineering* 3540 1999.:164-174, 1999.

Francesco Baldini. Critical review of pH sensing with optical fibres. *Proceedings of SPIE - The International Society for Optical Engineering* 3540 1999.:2-9, 1999.

Cecilia M. Santegoeds, Andreas Schramm, and Dirk de Beer. Microsensors as a tool to determine chemical microgradients and bacterial activity in wastewater biofilms and flocs. *Biodegradation* 9 (3-4 1998.):159-167, 1998.

Chi Cheng Wang and Xi Jin. Studies of noninvasive blood gases patient monitor. *Proceedings of SPIE - The International Society for Optical Engineering* 2887 1996..:227-232, 1996.

Avraham Bromberg, Judith Zilberstein, Salomon Riesemberg, Eyal Benori, Ernesto Silberstein, Joseph Zimnavoda, Gad Frishman, and Amnon Kritzman. Optical-fibre sensors for blood gases and pH, based on porous glass tips. *Sensors and Actuators, B: Chemical* B31:181-191, 1996.

Venetka I. Agayn and David R. Walt. Monitoring of fermentation parameters with fiber optics. *Proceedings of SPIE - The International Society for Optical Engineering* 2068 1994.:179-184, 1994.

M. D. DeGrandpre, M. M. Baehr, and T. R. Hammar. Calibration-free optical chemical sensors. *Analytical*

Chemistry 71 (6):1152-1159, 1999.

X. He and G. A. Rechnitz. Linear response function for fluorescence-based fiber-optic CO2 sensors. *Analytical Chemistry* 67:2264-2268, 1995.

J. W. parker, O. Laksin, and C. Yu. Fiber-optic sensors for pH and carbon dioxide using a self-referencing dye. *Analytical Chemistry* 1993:2329-2334, 1993.

W. R. Seitz. TRANSDUCER MECHANISMS FOR OPTICAL BIOSENSORS PART 1. THE CHEMISTRY OF TRANSDUCTION. *Comput.Methods Program Biomed.* 30 (1):9-20, 1989.

E. E. Roupie, L. Brochard, and F. J. Lemaire. Clinical evaluation of a continuous intra-arterial blood gas system in critically ill patients. *Intensive Care Medicine* 22 (11):1162-1168, 1996.

N. Yamazoe, M. Aizawa, S. Yamauchi, and M. Egashira. Proceedings of the Fourth International Meeting on Chemical Sensors. *Sensors and Actuators, B: Chemical* B14 (1-3):491-759, 1993.

H. H. Miller and T. B. Hirschfeld. FIBER OPTIC CHEMICAL SENSORS FOR INDUSTRIAL AND PROCESS CONTROL. *Proceedings of the SPIE - The international society for Optical Engineering* 718 (1987):39-45, 1987.

D. R. Walt, C. Munkholm, P. Yuan, S. Luo, and D. R. Walt. FIBER OPTIC BIOSENSORS FOR IN VIVO AND IN VITRO MEASUREMENTS OF CLINICALLY IMPORTANT SPECIES. *9th Publ by IEEE* (1987):802-803, 1987.

M. V. Schiza, M. P. Nelson, M. L. Myrick, and S. M. Angel. Use of a 2D to 1D dimension reduction fiber-optic array for multiwavelength imaging sensors. *Applied Spectroscopy* 55 , (2 (FEB) ,):217-226, 2001.

G. Knichwitz, T. Brussel, P. Reinhold, F. Schaumann, K. D. Richter, and H. VanAken. Early onset of regional intestinal ischemia can be detected with carbon dioxide tension measurement inside the peritoneal cavity. *ANESTHESIA AND ANALGESIA* 91 , (5 (NOV) ,):1182-1187, 2000.

J. Lin. Recent development and applications of optical and fiber-optic pH sensors. *TRAC-TRENDS IN ANALYTICAL CHEMISTRY* 19 , (9 (SEP) ,):541-552, 2000.

B. A. McKinley and B. D. Butler. Comparison of skeletal muscle P-O2, P-CO2, and pH with gastric tonometric P-CO2 and pH in hemorrhagic shock. *Critical Care Medicine* 27 , (9 (SEP) ,):1869-1877, 1999.

G. Knichwitz, J. Rotker, T. Mollhoff, K. D. Richter, and T. Brussel. Continuous intramucosal PCO2 measurement allows the early detection of intestinal malperfusion. *Critical Care Medicine* 26 , (9 (SEP) ,):1550-1557, 1998.

B. A. McKinley, C. L. Parmley, and B. D. Butler. Skeletal muscle PO2, PCO2, and pH in hemorrhage, shock, and resuscitation in dogs. *JOURNAL OF TRAUMA-INJURY INFECTION AND CRITICAL CARE* 44 (1 (JAN)):119-127, 1998.

M. Holzinger, J. Maier, and W. Sitte. Potentiometric detection of complex gases: Application to CO2. *SOLID STATE IONICS* 94 (1-4 (FEB)):217-225, 1997.

W. E. Hoffman, F. T. Charbel, G. Edelman, and J. I. Ausman. Brain tissue cases and pH during arteriovenous malformation resection. *NEUROSURGERY* 40 (2 (FEB)):294-300, 1997.

B. A. McKinley, W. P. Morris, C. L. Parmley, and B. D. Butler. BRAIN PARENCHYMA PO2, PCO2, AND PH DURING AND AFTER HYPOXIC, ISCHEMIC BRAIN INSULT IN DOGS. *Critical Care Medicine* 24 (11 (

NOV)):1858-1868, 1996.

X. Y. HE and G. A. Rechnitz. PLANT TISSUE-BASED FIBEROPTIC PYRUVATE SENSOR. *Analytica Chimica Acta* 316 (1 (NOV 20)):57-63, 1995.

M. D. MARAZUELA, M. C. M. BONDI, and G. ORELLANA. ENHANCED PERFORMANCE OF A FIBEROPTIC LUMINESCENCE CO2 SENSOR USING CARBONIC-ANHYDRASE. *SENSORS AND ACTUATORS B-CHEMICAL* 29 (1-3 (OCT)):126-131, 1995.

M. F. CHOI and P. HAWKINS. NOVEL DYE-SOLVENT SOLUTIONS FOR THE SIMULTANEOUS DETECTION OF OXYGEN AND CARBON-DIOXIDE. *Analytical Chemistry* 67 (21 (NOV 1)):3897-3902, 1995.

I. KLIMANT, V. MEYER, and M. KUHL. FIBEROPTIC OXYGEN MICROSENSORS, A NEW TOOL IN AQUATIC BIOLOGY. *LIMNOLOGY AND OCEANOGRAPHY* 40 (6 (SEP)):1159-1165, 1995.

X. Y. HE and G. A. Rechnitz. LINEAR-RESPONSE FUNCTION FOR FLUORESCENCE-BASED FIBEROPTIC CO2 SENSORS. *Analytical Chemistry* 67 (13 (JUL 1)):2264-2268, 1995.

M. F. CHOI and P. HAWKINS. INVESTIGATION OF THE RESPONSE OF DYE-NONAQUEOUS SOLVENT SOLUTIONS TO CARBON-DIOXIDE. *Analytica Chimica Acta* 309 (1-3 (JUN 20)):27-34, 1995.

M. Uttamlal and D. R. Walt. A FIBEROPTIC CARBON-DIOXIDE SENSOR FOR FERMENTATION MONITORING. *BIO-TECHNOLOGY* 13 (6 (JUN)):597-601, 1995.

M. F. CHOI and P. HAWKINS. RESPONSE OF FLUORESCEIN TO CARBON-DIOXIDE IN DIMETHYL SULFOXIDE-WATER MIXTURES. *JOURNAL OF THE CHEMICAL SOCIETY-FARADAY TRANSACTIONS* 91 (5 (MAR 7)):881-885, 1995.

8.3 MIC Sensors

1. M.W. Beijerink, Archives of Exact and Natrual Sciences (Dutch Journal) Haarlem, Series II, (1904) p.131.
2. Little, B., Wagner, P., Mansfeld, F. 1991. Int. Mat. Rev. 36:253-272
3. G.B.Farquhar, "A Review of Trends in MIC", Materials Performance, January 1993, p.53.
4. Hamilton, w.A. 1985. Sulphate-reducing bacteria and anaerobic corrosion. Ann. Rev. Microbiol.39:195-217. Booth,G.H. 1964. J.Appl. Bact.27:174-81
5. T.R.Jack, E.Rogoz, B.Bramhill, P.R.Roberge, "The Characterisation of Sulphate Reducing Bacteria in Heavy Oil Waterflood Operations", in: Microbiologically Influenced Corrosion Testing, J.R. Kearns, B.J.Little, eds. (West Conshohocken, PA: ASTM, 1994), p.108.
6. D.H.Pope, T.P.Zintel, A.K.Kuruvilla, O.W.Siebert, "Organic Acid Corrosion of Carbon Steel: A mechanism of Microbiologically Influenced Corrosion", CORROSION/88, Paper number 79 (Houston, TX: NACE 1988).
7. R.E. Tatnall and D.H.Pope, 1993. Identification of MIC, Part I. In A Practical Manual on Microbiologically Influenced Corrosion, G. Kobrin (ed.) p.65-78, NACE International, Houston,TX.
8. Borenstein, 1993. Identification of MIC, Part II. In A Practical Manual on Microbiologically Influenced Corrosion, G. Kobrin (ed.) p.79-82, NACE International, Houston,TX.
9. J.D.A. Miller and K.Tiller 1970. Microbial corrosion of buried and immersed metal. In Microbial aspects of metallurgy, J.D.A. Miller (ed.), p. 61-105. New York, Elsevier.
10. API Recommended Practice for Biological Analysis of Subsurface Injection Waters, American Petroleum Institute, Washington, D.C., March 1982.
11. L.A. Rossmoore, J.W.Wireman, and H.W.Rossmoore, Rapid Field Method for the Detection and Enumeration of Sulphate Reducers, Biodeterioration 6, United Kingdom, 1986.

12. R.E.Tatnall, K.M.Stanton, and R.C.Ebersole, “Testing for the Presence of Sulphate-Reducing Bacteria”, MaterialS Performance, August 1988, p.71.
13. E.S.Littmann, Oil Field Bactericide Parameters as Measured by ATP Analysis, Inernational Symposium of Oil Field Chemistry of the Soiety of Petrolium Engineers of AIME, Paper No. 5312, Dallas, TX, 1975.
14. D.H.Pope, Discussion of Methods for the Detection of Microorganisms, Involved in Microbiologically Influenced Corrosion, Biologically Induced Corrosion, NACE-8, S.C.Dexter, Ed., NACE, Houston, 1985, p.275.
15. Patent Application ICR 7780-USSN 946,547: Sulphate-Reducing Bacteria Detection, Du Pont Co. by J.M.Odom, L.J.Gawel, and T.K.Ng, 1987.
16. J.Boivin, E.J.Lashley, R.Bryant, J.W.Costerton, “A New Test for Microbial Corrosion” presented at NACE Canadian Region Western Conference, Vancouver, 1989.
17. B.J.Little and P.A.Wagner, “Advances in MIC Tetsing”, in “Microbiologically Influenced Corrosion Testing” J.R.Kearns and B.J.Little, (Ed.) ASTM Publication Code Number (PCN) 04-012320-27, ASTM STP 1232, Philadelphia, PA.
18. G.G.Geesey, P.J.Bremer, “Evaluation of Biofilm Microorganisms in Copper Corrosion” Microbially Influenced Corrosion and Biodeterioration, Ed. By N.J.Dowling, M.W.Mittleman, J.C.Danko, 1990, 1-19.
19. G.J.Licina, G.Nekoksa, R.L.Howard, “:An Electrochemical Method for On-Line Monitoring of Biofilm Activity in Cooling Water Using the GeorgeTM Probe”, Microbiologically Influenced Corrosion Testing” Ed. By J.F.Kearns, B.J.Little, ASTM STP-1232, ASTM, 1993, 118.
20. G.J.Licina, G.Nekoksa, “The Influence of Water Chemistry and Biocide Additions on the Response of an On-Line Biofilm Monitor”, CORROSION/95, Paper No. 527, NACE International, 1995, Houston, TX.
21. G.J.Licina, “Monitoring Biofilm Formation in a Brackish Water Cooled Power Plant Environment”, CORROSION/97, Paper No. 222, NACE International 1997, Houston, TX.
22. D.J.Blackwood, J.L.deRome, D.L.Oakly, A.M.Pritchard, “Novel Sensors for On-Line Detection of MIC, CORROSION/94, Paper No.254, NACE International 1994, Houston, TX.
23. H.Kurosawa, T.Hirano, K.Nakamura and Y.Amano; Appl. Microbiol. Biotechnol 41, 1994, P.556.
24. B.J.Little, R.I.Ray, and R.K.Pope, “Relationship between corrosion and the biological sulphur cycle: A Review, Corrosion, 56, No.4. 2000, P.433.