# *ISPIR*

# Intelligent System for Pipeline Infrastructure Reliability

## Final Report


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Natural Resources Canada · Ressources naturelles Canada

TISEC

April 23, 2004

# ISPIR Fact Sheet

## Intelligent System for Pipeline Infrastructure Reliability

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|---|---|---|
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***Project Period:*** Start date: January 1, 2002
End date: March 31, 2004

***Project Objective:*** ISPIR investigated how the advantages of fiber-optic strain measurement and the detection and characterization of chemical and microbiological species detected using fiber-optic sensors could be brought to the applications in the pipeline and process industries.

***Accomplishments:*** Through a combination of field and laboratory experimental and demonstration work and engineering development a complete system for monitoring strain in pipeline and process equipment applications was developed. The system has the capability to detect and measure strain using fiber-optic sensors, control the instrumentation remotely, transmit data peer-to-peer or on a client/server basis and to interpret the data. Several variations on the system concept have been designed to accommodate a wide range of applications.

# *ISPIR*

## Intelligent System for Pipeline Infrastructure Reliability

# Executive Summary

Fiber-optic technologies are unique by enabling sensing of strain data in structural materials of construction and communication of the strain data in a single system component – the optical fiber. The availability of low-cost fiber optics developed for the communications industry makes fiber-optic sensing feasible technically and economically viable. Intelligent agent software design and standardization of knowledge representation also make it feasible to implement data interpretation, fault diagnosis and overall knowledge-based system management at reasonable cost. ISPIR investigated how the advantages of fiber-optic strain measurement and the detection of chemical and microbiological species using fiber-optic sensors could be brought to the applications in the pipeline and process industries.

While new pipelines could eventually be completely monitored, the technology at the end of the project is currently deployable to measure strain profiles and pipeline behavior at critical locations. Leak monitoring is a candidate operation while the detection of leak precursor events is a priority of the technology. These critical locations are areas of generalized corrosion/erosion including monitoring existing defects such as stress corrosion cracking and unstable slopes and other locations where ground movement or upheaval buckling cause excessive pipeline strain, particularly near road, river, and rail crossings. Similarly, areas where environmental damage could be critical and intrusion monitoring are candidates for this type of monitoring.

Progress was made in the areas of sensor design, instrumentation, communications and knowledge management and system operation was demonstrated from data acquisition through interpretation. Special prefabricated sensor designs integrate the fibers on a flexible mesh carrier to facilitate installation and make the sensor system much more robust. Knowledge-based technologies were developed and implemented for the specific cases such as generalized wall thinning and stress corrosion cracking detection and characterization. These software and hardware components are modular, thereby providing significant flexibility for the configuring the system for a wide range of applications. Field testing provided valuable information for industrial design of both transducers and measurement instrumentation and for development and design of the communications and interpretation software.

A number of system configurations were developed for industrial deployment. Some of these are available at the end of the project and others are expected within a year of project completion. It is expected that the project will continue by funding from first-adopter end users to implement prototype systems, from in-house funding by the project participants and through a public offering of shares in one of the project partners.

Advantages of fiber-optic sensors over conventional strain sensors include the fact that they are non-conductive, immune to EMI interference, and light weight & flexible. They are low line loss materials and can transmit signals over distances of the order of 30 km. Thus, they can be deployed with large gage lengths of the order of many tens of meters in one configuration and several tens of kilometers in another. This makes them more cost-effective than periodic inspection and provides real-time detection of fault conditions. In general, the project technology will improve the safety of the public in cases where the technology is used to monitor structures such as pipelines that come into close proximity to the public and reduce operating costs to pipelines and similar system operators by providing more timely and accurate data upon which to base maintenance decisions.

# Table of Contents

# ISPIR

## Intelligent System for Pipeline Infrastructure Reliability

# 1 PROJECT DESCRIPTION

### 1.1 Project Objectives

Fiber-optic technologies are unique by enabling sensing of strain data in structural materials of construction and communication of the strain data in a single system component – the optical fiber. The availability of low-cost fiber optics developed for the communications industry makes fiber-optic sensing feasible technically and economically feasible. Intelligent agent software design and standardization of knowledge representation also make it feasible to implement data interpretation, fault diagnosis and and overall knowledge-based system management at reasonable cost. ISPIR investigated how the advantages of fiber-optic strain measurement could be brought to the applications in the pipeline and process industries.

The project evaluated the technical feasibility of

- Specific applications
- Attachment technology
- Instrumentation technology
- Knowledge-based data interpretation and condition diagnosis

### 1.2 Project Scope

While new pipelines could eventually be completely monitored, the technology is currently deployable to measure strain profiles and pipeline behavior at critical locations. These critical locations include:

- Areas of generalized corrosion/erosion
- Monitor existing defects such as SCC
- Unstable slopes and other locations where ground movement or upheaval buckling cause excessive pipeline strain, particularly near road, river, and rail crossings, aboriginal reservations
- Areas where environmental damage could be critical
- Intrusion monitoring
- Leak detection

In addition to the strain measurement, fiber-optic means of detecting and measuring chemical and bio-chemical species that influence the corrosion environment were also investigated to identify pipeline locations where corrosion potential is high.

### 1.3 Advantages of Fiber Optic Sensors

Fiber-optic sensors have several advantages over conventional strain sensors. They are:

- Non conductive
- Immune to emi interference
- Light weight & flexible
- Low line loss materials and can transmit signals of the order of 30km

In certain application they provide:

- More cost-effective than periodic inspection
- Real-time detection of fault conditions
- Full and effective utilization of information-rich sensed data
- Productivity gains by delivering oil and gas more efficiently
- Increased safety and reliability
- Life extension

# 2 FIBER-OPTIC STRAIN MEASUREMENT TECHNOLOGIES

Two optical strain measurement technologies were used in the project. They included the Long Gage with a gage length in the range of 1 to 100 m and the Brillouin Gage whose gage length can range up to 25 km with a resolution of the order of several meters. The project focused on the Long Gage.

## *2.1 Long Gauge*

The Long Gage is an economical means of monitoring areas of up to 100 meters in length. At the end of the project, it is a mature technology using commercial instrumentation. It is available for monitoring areas of extended corrosion/erosion and local defects.

The sensor is a length of fiber with a mirror at one end. It is attached to the structure to be monitored to track the strain. Strain sensing uses low coherence interferometry and a short coherence length source - a light emitting diode. The diode light is split in two, travels two different path lengths and is then recombined at a photodetector. The two recombined beams interfere with each other due to the low coherence of the source. This interference pattern is monitored by the photodetector and the peak of the interference pattern is a measurement of the average displacement over the gauge length.

Since the long gauge sensor is a flexible optical fiber, it can be used in many different configurations, for example: wrapped around a column or pipeline to measure circumferential strains, attached to long spans or strung across a crack to monitor crack growth. The system and sensors are well suited to monitor permanent long-term static deformation either from thermal or mechanical loading.

## *2.2 Brillouin Gauge*

The Brillouin Gage is a development particularly well-suited to monitoring of large structures such as pipelines. It is characterized by efficient monitoring over long distances with excellent spatial resolution. Brillouin scattering occurs in optical fibers when light is back-reflected due to refractive index modulation produced by acoustic waves in the fiber. The measurement is made when a pulsed laser beam interacts with a counter-propagating continuous laser beam at a higher frequency. At a particular location along the fiber, when the beat frequency between these lasers is within the “Brillouin” loss profile for the fiber, some power is transferred to the pulsed beam. Monitoring the continuous laser beam using optical time domain reflectometry (OTDR), one can determine the location of the sensed 'gauge length.' Knowing the Brillouin power spectrum and the frequency shift, both the temperature and strain can be determined as average values over the “gauge length”.

## *2.3 Technical Description*

The system specifications are outlined in Deliverable 1 “*Overall System Specifications”* and the details of a system delivered as part of the project are contained in Deliverable 2 *“Demonstration and Field Data Acquisition”*. Technical descriptions are also provided in Deliverable 5, *“System Specifications and Operations Manual”*.

# 3 PROJECT DEVELOPMENTS

## *3.1 Sensor Development*

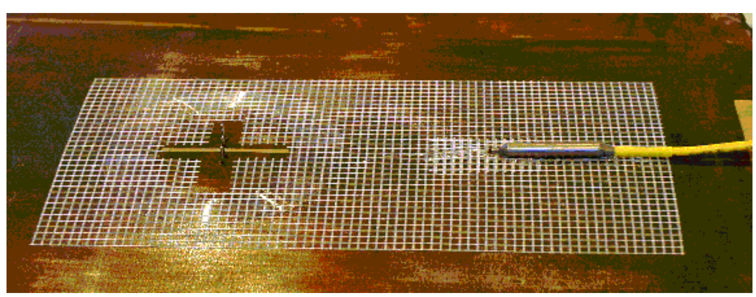
During the project, the sensor design evolved from simply gluing raw fiber to a prepared surface to prefabricated configurations that were assembled in the shop and bonded to the structure in the field. Two of the prefab configurations are the snake and spiral sensors. These are described in Deliverable 3 "*Sensor System and Performance Development".*

### 3.1.1 Prefab Snake Sensor

Optical fiber in the form of a snake configuration in this case is laid out on and bonded to an adhesive mesh. The mesh is rolled up, delivered to the site and laid out on the structure.


### 3.1.2 Prefab Patch Sensor

Optical fiber in the form of a spiral configuration in this case is laid out on and bonded to an adhesive mesh. This patch type of sensor is used in local areas to monitor wall thinning over local areas such as piping elbows and areas of stress corrosion cracking.

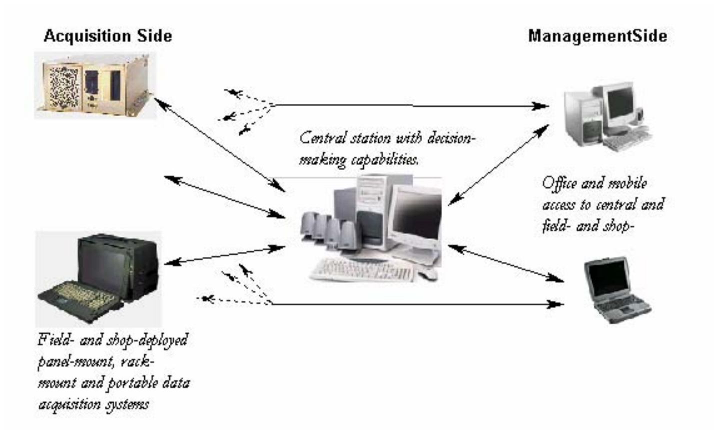


### 3.2 Knowledge-Based Interpretation System

The knowledge-based part of the ISPIR system has been designated as the Structural Integrity Monitoring over IP (SIM-o-IP) system. It is described in Deliverable 4 *"Interpretation, Fault Identification and Diagnosis"*. SIM-o-IP meets a twofold requirement in new structural integrity inspection and monitoring systems:

- ⌘ Data Interpretation and decision making
- ⌘ Communications

SIM-o-IP acquires data by several means and distributes these data as well as interpretations and decisions based on them to the parties involved in follow-up maintenance actions. SIM-o-IP provides the communications component in this inspection and monitoring environment.

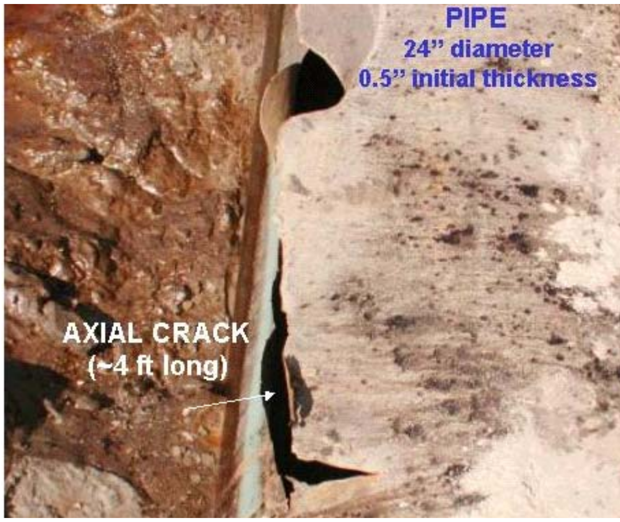


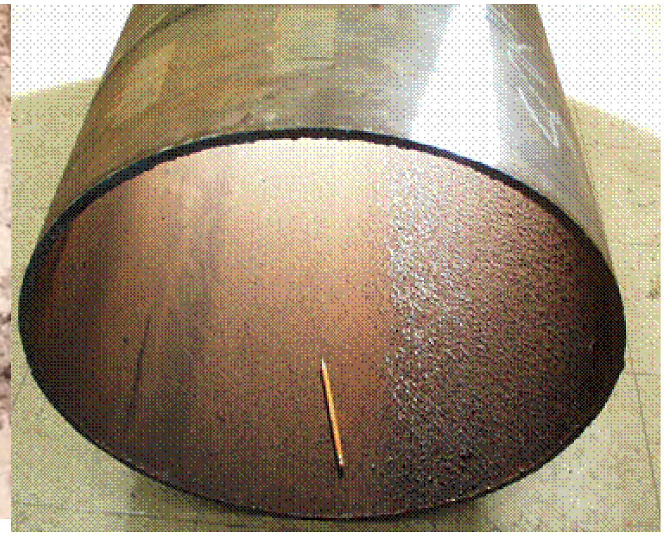

## 4 REPRESENTATIVE APPLICATIONS STUDIED IN THE PROJECT

### 4.1 Pipe Wall Thinning

This pipeline was provided by Syncrude and transports corrosive water with a high, coarse particulate content and operates at a nominal pressure of 300 psi, and a temperature of about 60C.

The purpose of installing fiber optic sensors in this pipeline application is to monitor continuously internal wall thinning of the pipe over a segment prone to rapid thinning.   A failed segment and a photo of the internally thinned wall are shown below.



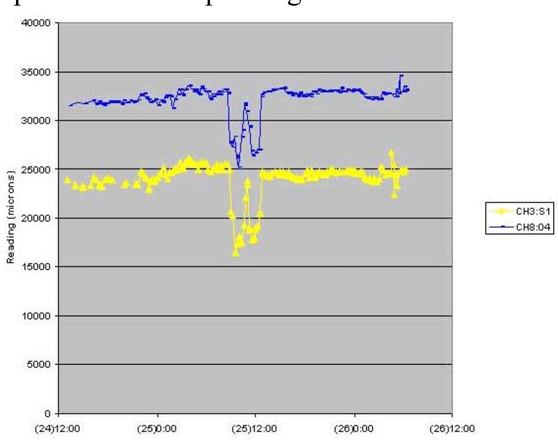
Sensors are mounted in a configuration that optimizes acquisition of data for the type of damage that occurs in the pipe.  In this case sensors were mounted in a spiral array (left photo) and a snake array (photo on the right) over an area with known wall thinning.

The fibers are handled in conduits much like electrical cables with the additional advantage of low cost and immunity to electromagnetic and other interference that make it difficult to use electronics in the plant and field environment.

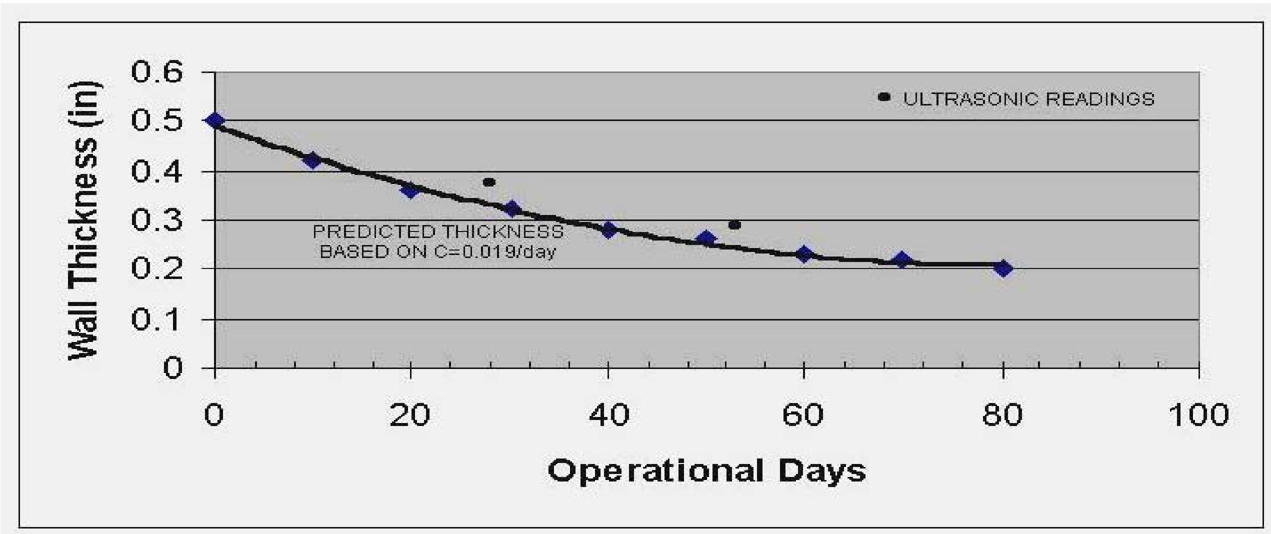

The long gage fiber optic sensors detect:

- wall thinning of the pipe wall due to erosion and corrosion
- pressure changes in the pipe
- temperature changes in the pipe wall

In this case, data were read over a wireless remote connection to the instrument every 15 minutes using TISEC's SIM-o-IP (Structural Integrity Monitoring over IP) system. A representative trace is shown on the left below for the hoop (blue) and snake (yellow) sensors. The drops in strain correspond to outages when the pipeline was not operating.



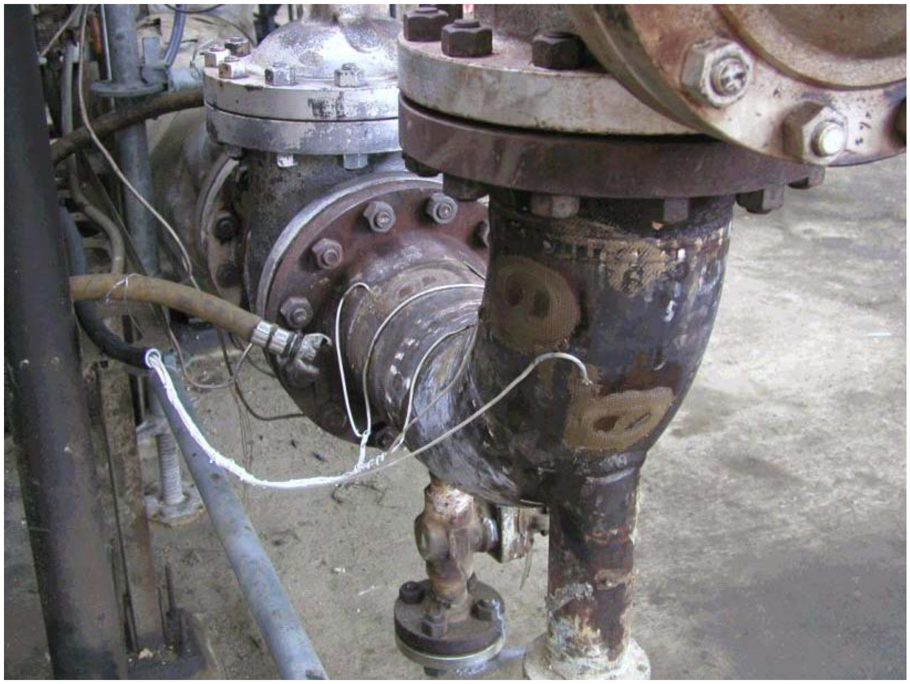
The SIM-o-IP intelligent component accounts for downtime and compensates for temperature. The wall thickness change predicted by the system based on optical thickness measurements early in the life of the structure is shown below and compared to ultrasonic thickness measurements. Fiber-optic sensors combined with SIM-o-IP for data interpretation provide a basis for both real-time detection of materials deterioration and as a valuable input to maintenance planning.




### *4.2 Process Piping - Hot Elbow Monitoring*

In any oil refinery, there are large numbers of elbow joints. Many of these elbows are operated at very high temperatures, ranging from 230-370°C (450-700°F). This "hot elbow" monitoring application used oval shaped coil sensors on 8-inch L/R 90° pipe.

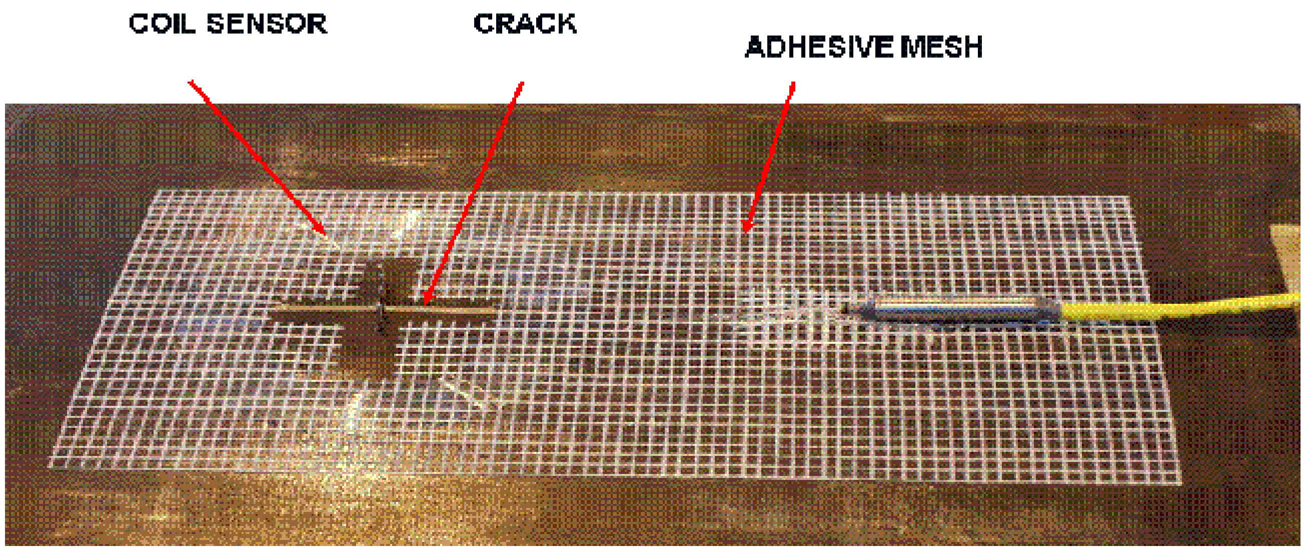
This elbow was monitored because of wall corrosion problems and its critical role in the plant process operations.



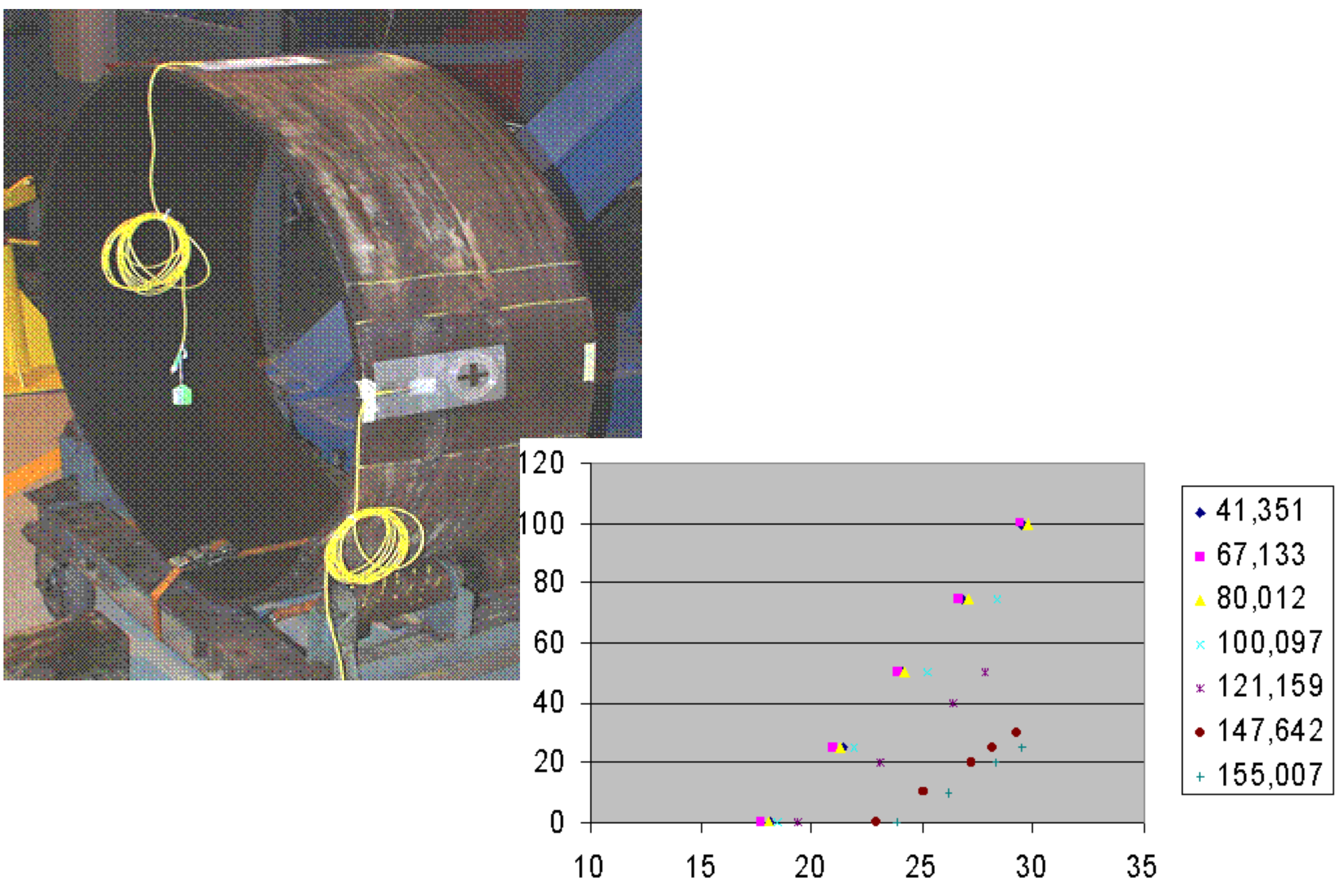
One major challenge in this test was to employ a high temperature adhesive and specially coated polyimide optical fiber. This innovation was required because the elbow was in a line that operated at a temperature of nominally 260°C (500°F). In addition, knowledge of the local pressure and temperature fluctuations was also needed to discriminate the wall thinning effect.

### *4.3 Stress corrosion cracking measurement*

The coil sensor was also used for monitoring stress corrosion crack growth as shown below.



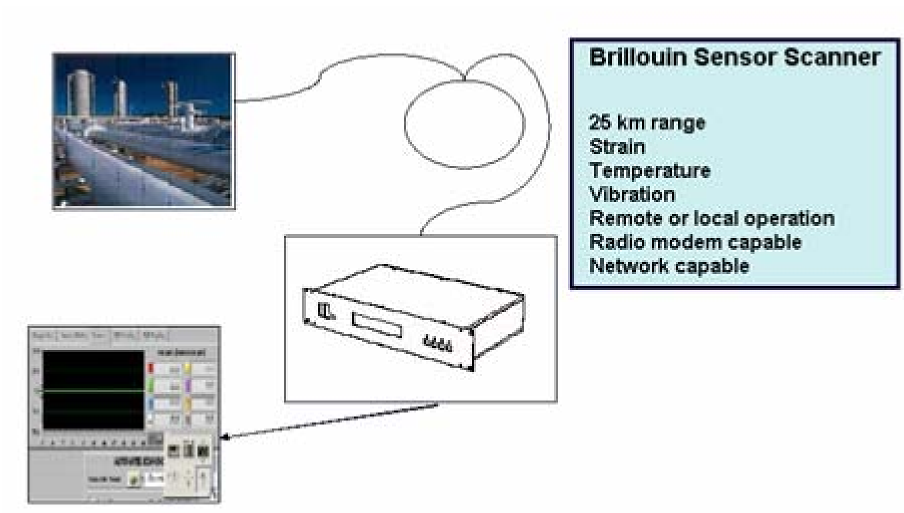

To calibrate the coil sensor in this type of application, an artificial crack was machined into a pipe segment and covered with a patch sensor. A reference patch sensor was also installed on uncracked material. The crack was extended in fatigue and the compliance change is shown in the figure below.

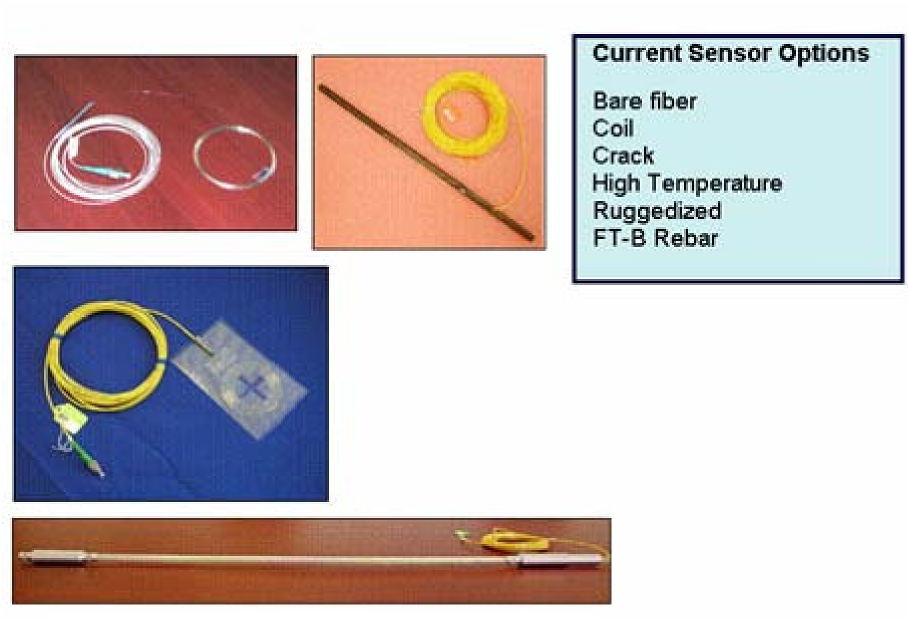


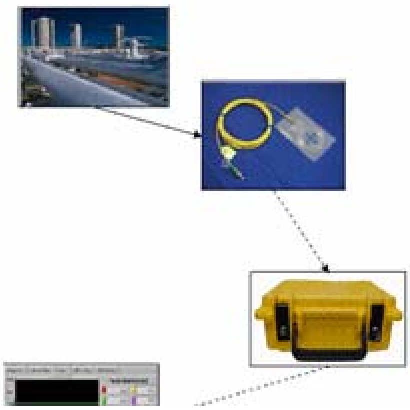
# 5 PRODUCTS DEVELOPED

### *5.1 Hardware Products*

A number of sensor configurations were developed and they are shown below. They range from the bare fiber to complete sensor and transmission line assemblies. For the patch-type gages, a high-temperature version was developed. In addition to the sensors, a number of system configurations were developed and they are shown on the next page. These configuration concepts are in various stages of development and a table with their availability status follows the graphical outlines.

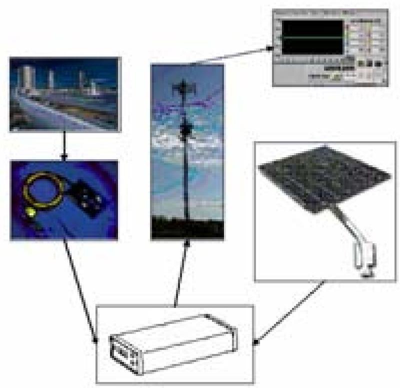




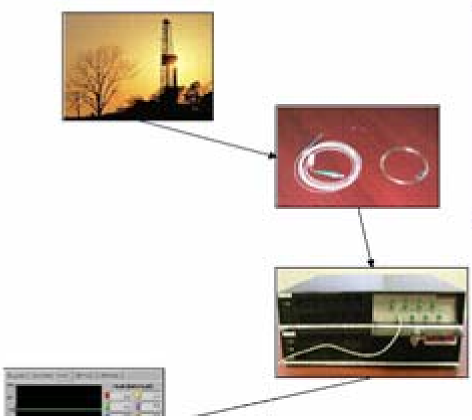
**Portable Sensor Scanner**

FT sensors (4+)
Battery powered
Rugged field design
Onboard data storage



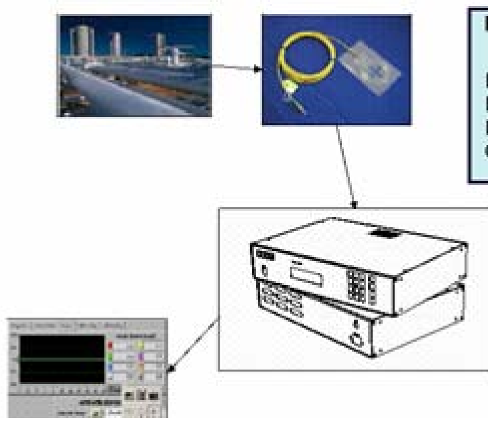
**Remote Sensor Scanner**

25 km range
Strain
Temperature
Vibration
Remote or local operation
Radio modem capable
Network capable



**Bragg Sensor Scanner**

Serial Bragg sensors
WDM system
Multi-channel design
Static & dynamic
Instrumentation room use
Remote or local operation
Network capability



**Portable Sensor Scanner**

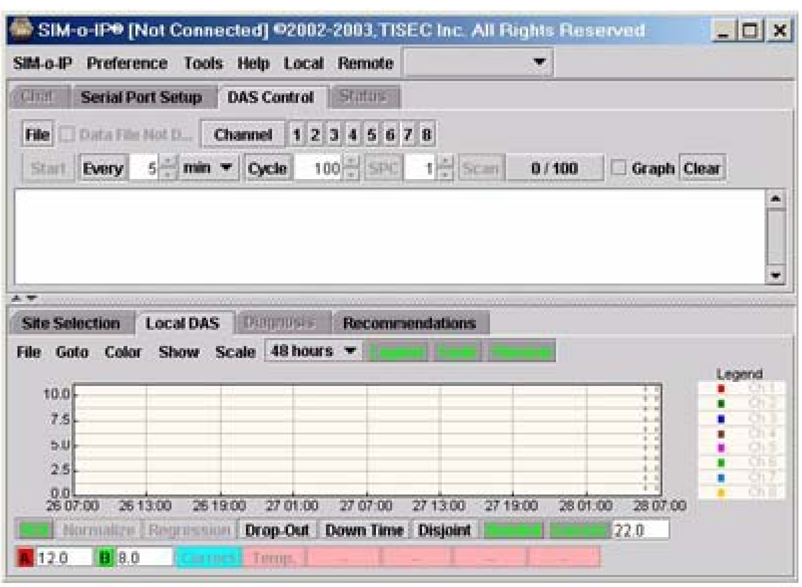
FT sensors (4+)
Battery powered
Rugged field design
Onboard data storage

## Availability

| Technology | Oil and Gas Application | Availability |
|---|---|---|
| FT Sensors | **Refineries**<br>■ hot elbow corrosion monitoring<br>■ temp and pressure monitoring<br>**Offshore Platforms**<br>■ splash zone monitoring<br>■ touchdown area fatigue crack monitoring<br>**Pipelines**<br>■ stress corrosion tracking and monitoring<br>■ ground movement detection<br>■ temp and pressure monitoring | Available now |
| Fiber Bragg Sensors | **Refineries**<br>■ temperature, strain, vibration monitoring<br>**Offshore Risers**<br>■ temperature, strain, vibration monitoring<br>**Pipelines**<br>■ hot tap detection | 3 months<br>■ Acquire test lasers<br>■ Update design<br>■ Build/test prototype<br>■ Build field deployable unit |
| Brillouin Sensors | **Pipelines**<br>■ 3rd party intrusion/damage detection<br>■ leak detection<br>■ ground movement detection<br>**Offshore Deep Water Risers**<br>■ temperature and strain profiling | 6 – 9 months<br>■ Investigate/acquire low cost light source<br>■ Upgrade processing/acquisition components<br>■ Integrate into single package<br>■ Build field deployable unit |

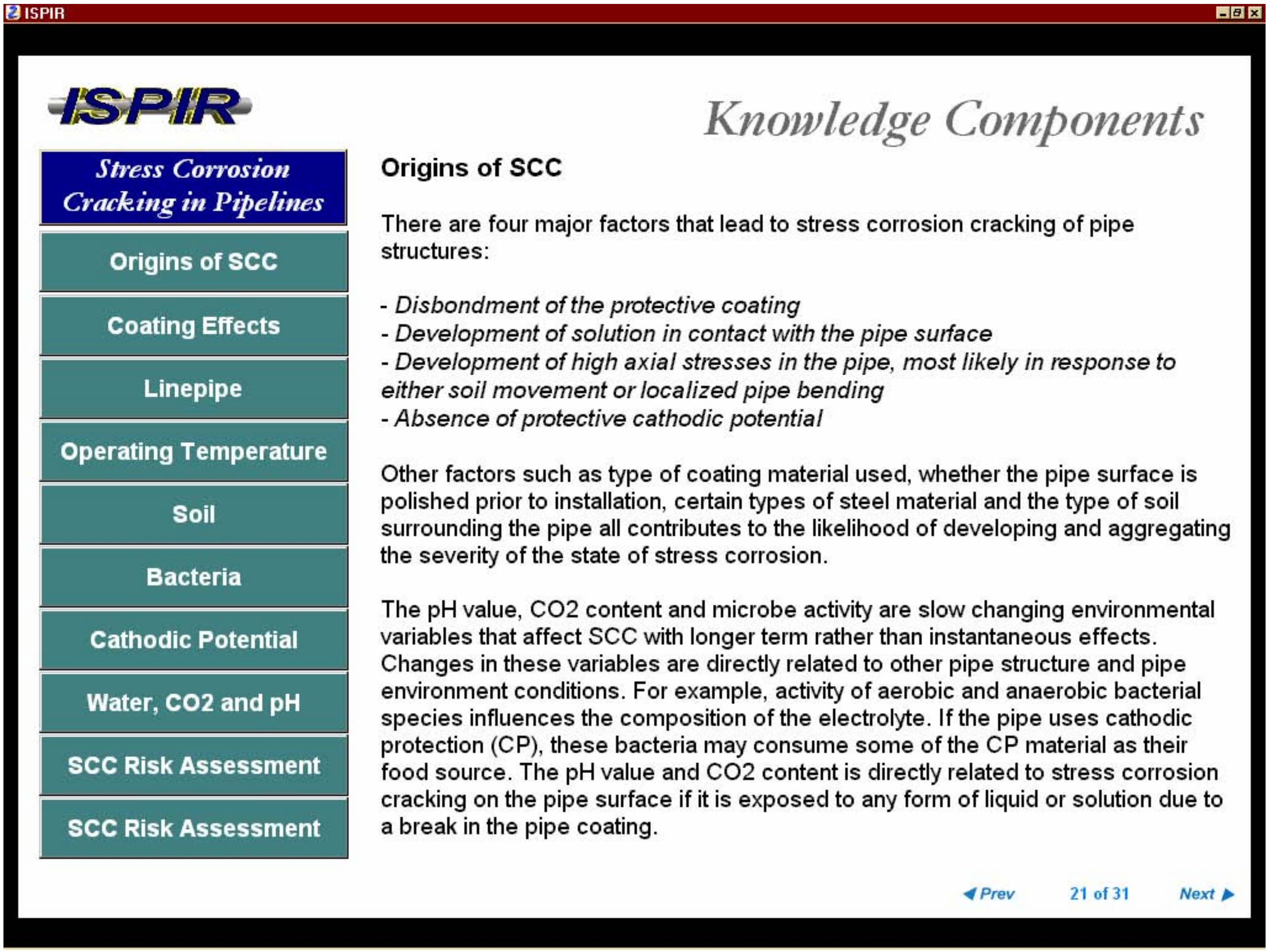
### *5.2 Software Products*

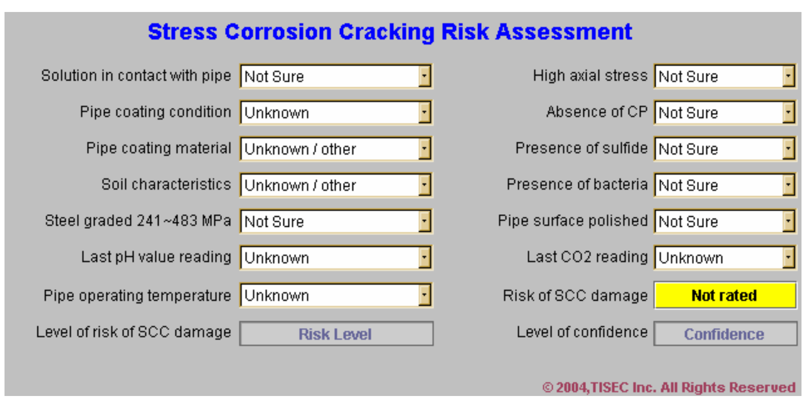
The project software is embodied in the SIM-o-IP system. This has been modularized to permit SIM-o-IP to be configured adaptively not only for pipeline monitoring but also as a flexible generic tool for structural integrity monitoring using a variety of sensor technologies in addition to fiber optics. SIM-o-IP is organized into three types of intelligent agents. The first is the real-time communications, control and display window shown below.




In this view, the upper part of the window contains the communications components and utilities for remote access and control of the data acquisition instrumentation. The lower part of the window provides a display of the monitored data. Other views provide data correction utilities for such parameters as temperature, off line conditions, and for calculations of crack growth rates.

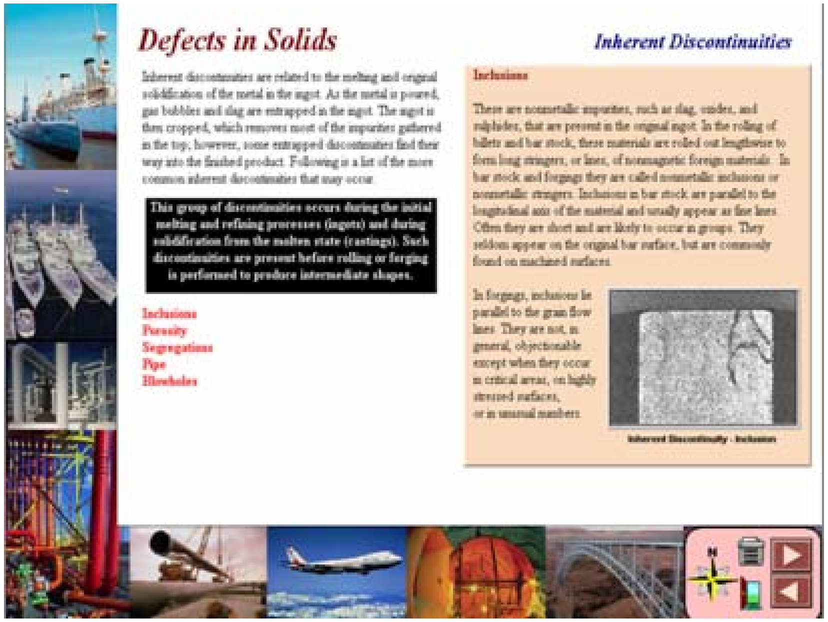
This SIM-o-IP module operates in either a peer-to-peer or client-server mode and provides effective communications independent of all corporate firewalls encountered to date. The second SIM-o-IP module is a diagnostic system for assessing the susceptibility of a pipeline to stress corrosion cracking. The diagnostic system is deployed inside SIM-o-IP but is also deployed on the Web and on CD ROM. In the latter format, it provides interactive content as outlined below and the dynamic interface for the diagnostic system is shown at the bottom of this page.

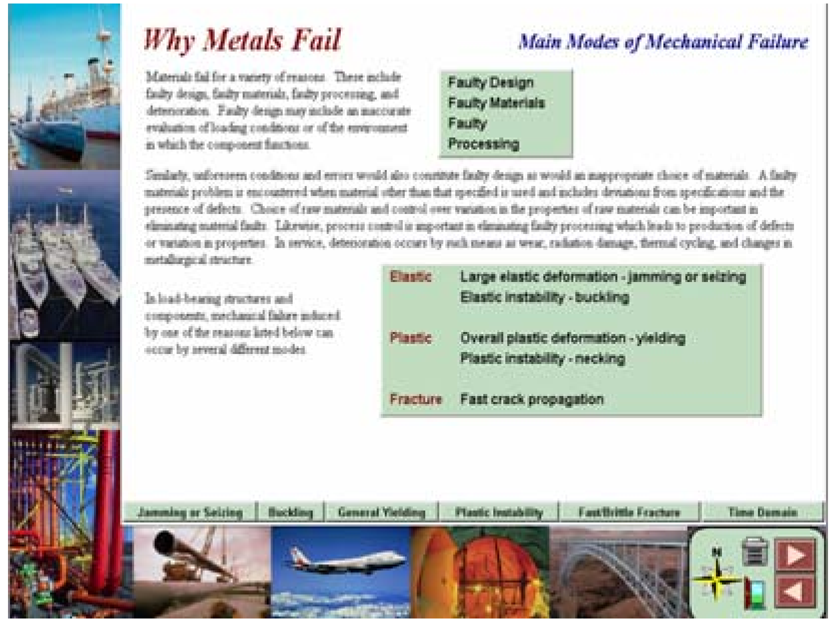


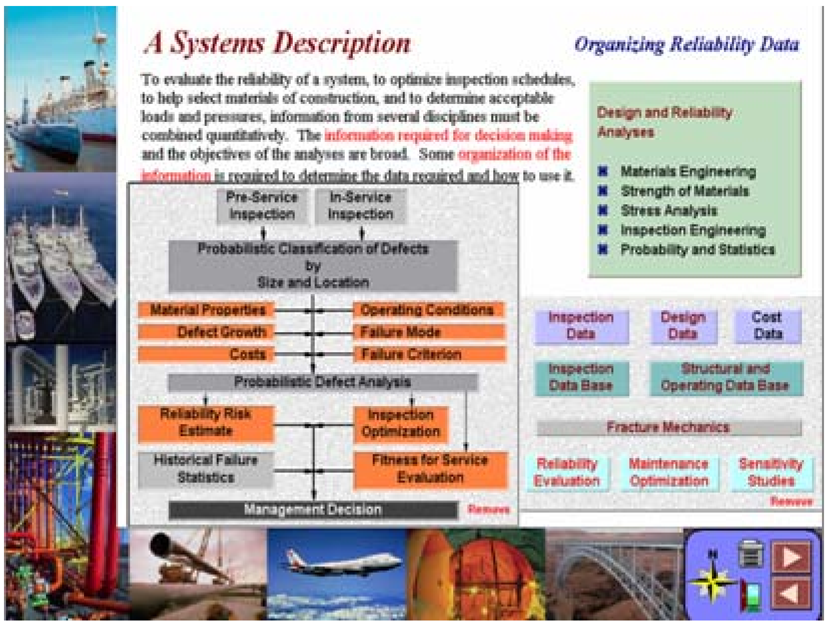



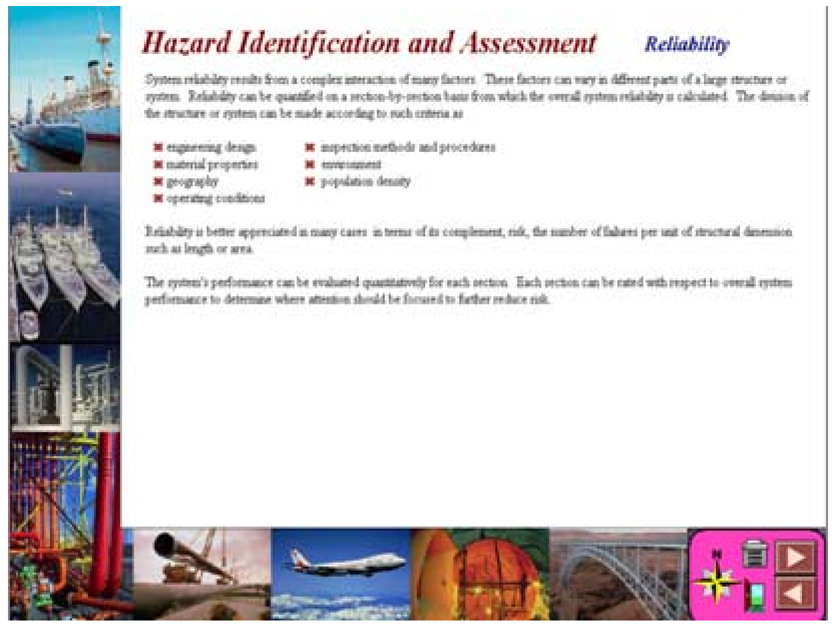

The third system component is a general multimedia data base to which reference can be made to assist in interpretation decisions and, since it is in multimedia form, can be integrated into application specific SIM-o-IP implementations. Its contents are shown on the next page. A complete User's Manual has been prepared for SIM-o-IP.

The materials and mechanics knowledge base is organized into a series of books. The main selection of information is shown below. Representative screens from several content areas are shown on the next two pages and the overall content is 219 video pages most of which are several layers deep.


Defects in Solids
Inherent Discontinuities
Inherent discontinuities are related to the melting and original solidification of the metal in the ingot. As the metal is poured, gas bubbles and slag are entrapped in the ingot. The ingot is then cropped, which removes most of the impurities gathered in the top; however, some entrapped discontinuities find their way into the finished product. Following is a list of the more common inherent discontinuities that may occur.
This group of discontinuities occurs during the initial melting and refining processes (ingots) and during solidification from the molten state (castings). Such discontinuities are present before rolling or forging is performed to produce intermediate shapes.
Inclusions
Porosity
Segregations
Pipe
Blowholes
Inclusions
There are nonmetallic impurities, such as slag, oxides, and sulphides, that are present in the original ingot. In the rolling of billets and bar stock, these materials are rolled out lengthwise to form long stringers, or lines, of nonmagnetic foreign materials. In bar stock and forgings they are called nonmetallic inclusions or nonmetallic stringers. Inclusions in bar stock are parallel to the longitudinal axis of the material and usually appear as fine lines. Often they are short and are likely to occur in groups. They seldom appear on the original bar surface, but are commonly found on machined surfaces.
In forgings, inclusions lie parallel to the grain flow lines. They are not, in general, objectionable except when they occur in critical areas, on highly stressed surfaces, or in unusual members.
Inherent Discontinuity - Inclusion

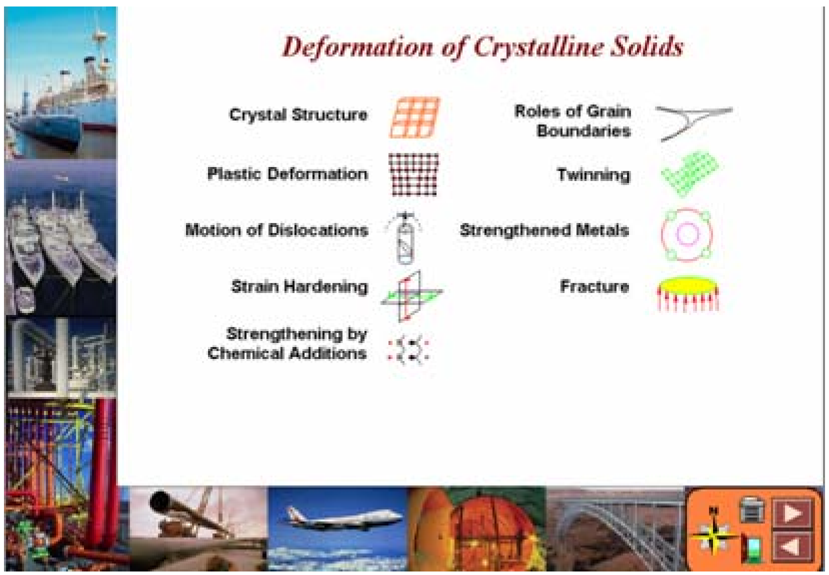

Why Metals Fail
Main Modes of Mechanical Failure
Materials fail for a variety of reasons. These include faulty design, faulty materials, faulty processing, and deterioration. Faulty design may include an inaccurate evaluation of loading conditions or of the environment in which the component functions.
Faulty Design
Faulty Materials
Faulty
Processing
Similarly, unforeseen conditions and errors would also constitute faulty design as would an inappropriate choice of materials. A faulty materials problem is encountered when material other than that specified is used and includes deviations from specifications and the presence of defects. Choice of raw materials and control over variation in the properties of raw materials can be important in eliminating material faults. Likewise, process control is important in eliminating faulty processing which leads to production of defects or variation in properties. In service, deterioration occurs by such means as wear, radiation damage, thermal cycling, and changes in metallurgical structure.
In load-bearing structures and components, mechanical failure induced by one of the reasons listed below can occur by several different modes.
Elastic
Large elastic deformation - jamming or seizing
Elastic instability - buckling
Plastic
Overall plastic deformation - yielding
Plastic instability - necking
Fracture
Fast crack propagation
Jamming or Seizing
Buckling
General Yielding
Plastic Instability
Fast/Brittle Fracture
Time Domain


A Systems Description
Organizing Reliability Data
To evaluate the reliability of a system, to optimize inspection schedules, to help select materials of construction, and to determine acceptable loads and pressures, information from several disciplines must be combined quantitatively. The information required for decision making and the objectives of the analyses are broad. Some organization of the information is required to determine the data required and how to use it.
Pre-Service Inspection
In-Service Inspection
Probabilistic Classification of Defects by Size and Location
Material Properties
Defect Growth
Costs
Operating Conditions
Failure Mode
Failure Criterion
Probabilistic Defect Analysis
Reliability Risk Estimate
Inspection Optimization
Historical Failure Statistics
Fitness for Service Evaluation
Management Decision
Remove
Design and Reliability Analyses
Materials Engineering
Strength of Materials
Stress Analysis
Inspection Engineering
Probability and Statistics
Inspection Data
Design Data
Cost Data
Inspection Data Base
Structural and Operating Data Base
Fracture Mechanics
Reliability Evaluation
Maintenance Optimization
Sensitivity Studies
Remove

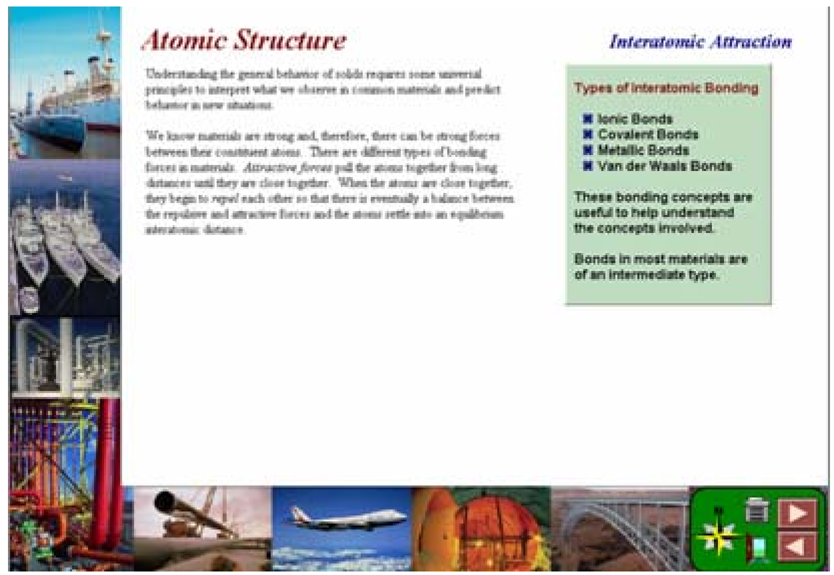

Hazard Identification and Assessment
Reliability
System reliability results from a complex interaction of many factors. These factors can vary in different parts of a large structure or system. Reliability can be quantified on a section-by-section basis from which the overall system reliability is calculated. The division of the structure or system can be made according to such criteria as
engineering design
material properties
geography
operating conditions
inspection methods and procedures
environment
population density
Reliability is better appreciated in many cases in terms of its complement, risk, the number of failures per unit of structural dimension such as length or area.
The system's performance can be evaluated quantitatively for each section. Each section can be rated with respect to overall system performance to determine where attention should be focused to further reduce risk.

Strength of Materials
Force and Deformation
Newton's 2nd Law
Newton's 3rd Law
Hooke's Law
Stress
Strain
Elasticity and Plasticity
What is Pressure?
Types of Loads
Fatigue
Force, Weight and Deformation
Structures are designed to resist forces and support loads. Although a force is one of the fundamental concepts of mechanics, a force does not lend itself to a simple or precise definition. At best a force may be defined as something that produces, or tends to produce, motion or a change in the motion of a body. One common type of force is the effect of gravity by which all objects are attracted downwards. This latter force is known as the weight of an object.


Failure Prevention
Role of Inspection
Inspection of large structures are costly operations that produce large volumes of valuable data. These data are used to determine corrective actions at the site of the anomaly indication at the time of inspection. This can include repair or removal of the defective component.
Load-Bearing Structures
&
Pressurized Systems
Oil and Gas Pipelines
Nuclear Plants
Railway Systems
Oil and LNG Tankers
LNG Liquefaction Plants
Offshore Drilling Rigs
Chemical Plants
Petrochemical Plants
Aerospace Structures

Deformation of Crystalline Solids
Crystal Structure
Roles of Grain Boundaries
Plastic Deformation
Twinning
Motion of Dislocations
Strengthened Metals
Strain Hardening
Fracture
Strengthening by Chemical Additions

Atomic Structure
Interatomic Attraction
Understanding the general behavior of solids requires some universal principles to interpret what we observe in common materials and predict behavior in new situations.
We know materials are strong and, therefore, there can be strong forces between their constituent atoms. There are different types of bonding forces in materials. Attractive forces pull the atoms together from long distances until they are close together. When the atoms are close together, they begin to repel each other so that there is eventually a balance between the repulsive and attractive forces and the atoms settle into an equilibrium interatomic distance.
Types of Interatomic Bonding
Ionic Bonds
Covalent Bonds
Metallic Bonds
Van der Waals Bonds
These bonding concepts are useful to help understand the concepts involved.
Bonds in most materials are of an intermediate type.

### 5.3 Chemical and Microbiological Sensors

Microbiologically influence corrosion (MIC) may be a cause for more than 30% of the total pipeline failures. The current practices for MIC, both culture-based methods (Broth Bottles, Agar Deeps and Melt Agar Tubes) or direct methods (Adenosine Triphosphate Assay and Epifluorescence Microscopy by staining with specific antibody) are time consuming, and/or required sophisticated instruments. Additionally these techniques have limited in situ applications. In order for the pipeline companies to get maximum benefit from on-line continuous monitoring MIC, it is necessary to develop a biosensor for MIC and integrate it with other corrosion sensors. Since both the strain and MIC sensors can use fiber-optic sensors, some effort was applied in this project to using investigating fibre-optical sensors to detect microbiologically-induced corrosion (FOMIC) with a longer term view of integrating both into a system. Project effort concentrated on the technology of producing the FOMIC sensors.

## 6 SUMMARY OF KEY RESEARCH RESULTS

Progress was made in the areas of sensor design, instrumentation, communications and knowledge management and the system operation demonstration from data acquisition through interpretation. The project technology provides a sound basis for system development and application within the pipeline and process industries as well as in other structural integrity monitoring applications. From sensor to knowledge system, the system is modular, thereby providing significant flexibility for the configuring the system for a wide range of applications.

The project partners feel that a major advance in the technology of strain measurement using fiber-optic sensors was made during the project and that this advance has made it possible to move from the project directly into the marketplace with a number of basic system configurations and to have a number of new configurations available within a year of project completion.

## 7 PROJECT BENEFITS

The unique benefits of the products, systems and services developed by the performing participants are directed to a clientele of owners and operators of load-bearing structures and pressurized fluid containment systems that are part of the civil and industrial infrastructure. By monitoring strain, the optical strain measurement and interpretation technology offers an extremely cost-effective approach to collecting real-time data on the fitness for service of critical structural systems. The product benefits are made possible using emerging fiber-optics technologies from the communications industry that permit both sensing and communications in a single system component – the optical fiber. Combined with intelligent agent software design and standardization of knowledge representation it is feasible to integrate sensing with data interpretation, fault diagnosis and overall knowledge-based system management.

The economic viability of certain oil and gas fields may depend on the economics of pipeline construction, maintenance, and repair. Similarly, the existing pipeline network must continue to deliver oil and gas, although many Canadian pipelines have passed their amortized design life. Technology is required to economically assess and maintain pipelines for many years to come The ISPIR approach is more cost-effective than periodic inspection and provides real-time detection of fault conditions. This provides the owner/operators with an earlier appraisal of potential fault conditions and the ability to act on a timely basis to prevent costly failures and optimize the deployment of maintenance resources. These result in lower costs of maintenance and failure and the attendant corporate benefits of higher system safety and reliability as well as reducing the costs associated with false calls.

In addition to client benefits, the benefits to Canadian society include reduction of the large number of current pipeline failures and the costs to communities impacted by the failures including less oil spillage on Canadian farms and sensitive frontier areas, and less natural gas emitted to the environment. With the ISPIR technology there will be a reduced need for cathodic protection sacrificial anode ground beds and heavy metals, zinc, magnesium, and aluminum pollution will be reduced. In general the oil and gas industry will benefit from productivity gains by delivering oil and gas more efficiently.

During the course of the project, university collaboration was called upon for specific tasks. This included the University of Alberta for data acquisition on their unique full-scale pipe testing facility. The University of Ottawa was used to provide initial testing of the Brillouin technology and the University of New Brunswick for further development of the Brillouin system. TISEC and Fox-Tek signed an understanding on marketing the technology and will explore in the near future how to build on this.

TISEC has hired two new engineers to work on the latter part of the project and to further work on the project. In addition to the specific projects referred to in this report, TISEC anticipates a number of spin-off products including SIM-o-IP as a generic system for remote structural integrity monitoring, data interpretation and diagnosis. The project has placed a new layer of intelligent systems technology on the company that will influence product development and deployment across the product line. Although difficult to quantify, the project will result in increased employment and growth at TISEC.

In general, the project technology will improve the safety of the public in cases where the technology is used to monitor structures such as pipelines that come into close proximity to the public and reduce operating costs to pipelines and similar system operators by providing more timely and accurate data upon which to base maintenance decisions.

# 8 CONTINUATION OF RESEARCH

It is expected that the research work will continue using contract demonstrations for first adopters and opinion leaders. A recent contract with Saudi Aramco is one such example that is a favorable indication of the feasibility of this approach. TISEC intends to develop its SIM-o-IP further under its own funding.

# 9 PROJECT DELIVERABLES

The material summarized in this Final Report is described in detail in the following deliverables.

## *9.1 Quarterly Reports*

Nine quarterly progress reports were delivered as was a Mid-Term Report and this Final Report. In addition, a Business Case report was provided. All the work reported on in the quarterly reports has been incorporated into the five deliverables reports that are appended to this Final Report.

## *9.2 Deliverables*

| | |
|---|---|
| Under Task 1: | System Specification Document |
| Under Task 2: | A Report on Demonstration and Field Data Acquisition |
| Under Task 3: | A Report on Sensor System and Performance Development |
| Under Task 4: | A Report on Interpretation, Fault Identification and Diagnosis |
| Under Task 5 | A Business Case Analysis |
| | A System Reference and Operations Manual |
| | A Workshop on ISPIR |
| | A Final Report |
| | Software Files |

## 9.3 Publications and Presentations

1. **"Application of Brillouin Fiber Optic Sensors to Monitor Pipeline Integrity",** R.C.Tennyson, W.D Morison, B.Colpitts, A.Brown, Proceedings of IPC 2004, Oct 2004, Calgary, Alberta, Canada
2. **"Fiber Optic Structural Health Monitoring System",** R.C.Tennyson, W.D.Morison Proceedings of 2nd International Workshop on Structural Health Monitoring of Innovative Civil Engineering Structures, Sept. 2004, Winnipeg, Manitoba, Canada
3. **"Application of Fiber Optic Sensors to Monitor Pipeline Corrosion",** R.C.Tennyson, W.D. Morison, W.Revie, Proceedings of NACE Corrosion 2004, New Orleans, Paper # 04739, USA
4. **"Application of Fiber Optic Sensors to Monitor Pipeline Corrosion",** R.C.Tennyson, W.D.Morison, W.Lin, W.Revie, A.Doiron, Proceedings of NACE Northern Area Eastern Conference, Corrosion Control for Enhanced Reliability and Safety, Sept.2003, Ottawa, Ontario, Canada
5. **"Application of Fiber Optic Sensors to Monitor Pipeline Corrosion",** R.C.Tennyson, W.D.Morison, T.Cherpillod, W.Revie, Proceedings of International Conference on Structural Faults and Repair – 2003, July 2003,Commonwealth Institute, London, UK, Engineering Technics Press Pub, Edinburgh, UK
6. **"Intelligent Pipelines Using Fiber Optic Sensors",** R.C.Tennyson, W.D.Morison, G.Manuelpillai, Proceedings SPIE Smart Sensor Technology and Measurement Systems, Smart Structures and Materials Conference, March 2003, San Diego, USA