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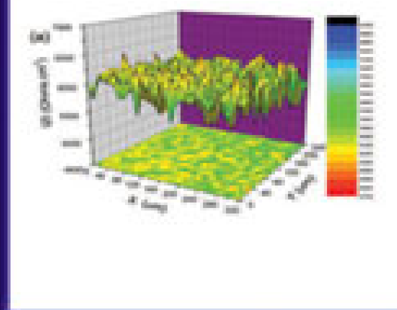
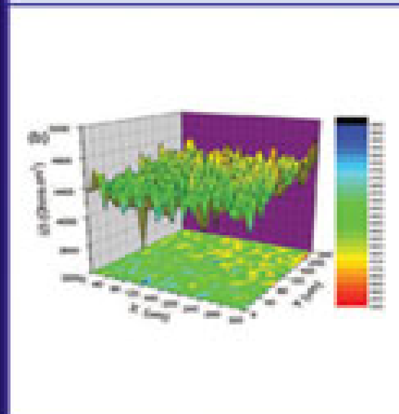
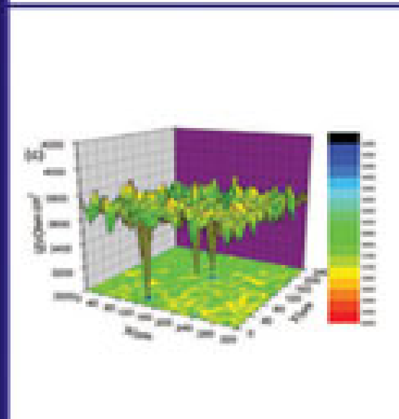
R. Winston Revie, Series Editor

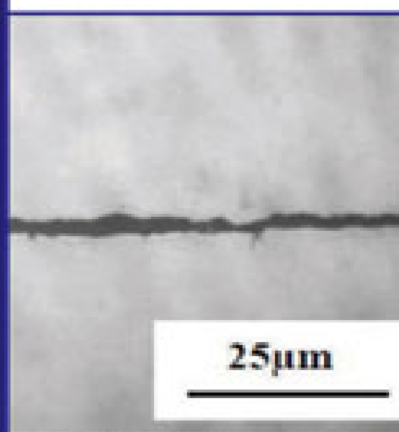
Stress Corrosion Cracking of Pipelines

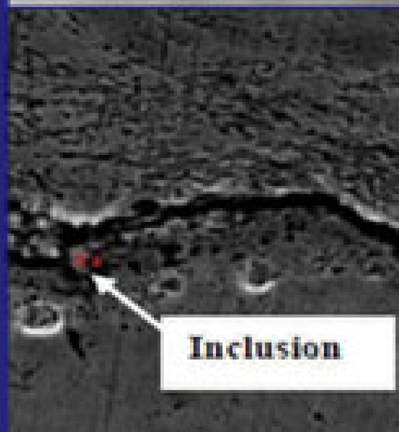
Y. FRANK CHENG











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Stress Corrosion Cracking of Pipelines

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To my wife, Jianshu (Jenny), and my son, Winston

Foreword

In this book, Dr. Cheng presents a lively discussion of stress corrosion cracking, sharing with readers his insights into this complex failure mode. He has written this book for all those who would like an understanding of stress corrosion cracking as it pertains to the reliability of the pipeline infrastructure on which society relies to meet energy needs.

Dr. Cheng skillfully explains and juxtaposes the most fundamental aspects of this type of corrosion with the realities of engineering experiences in the pipeline industry, including case histories. He outlines the situations that can develop over many years during the pipeline operational lifetime, leading to initiation and growth of stress corrosion cracks. In nine chapters, he leads the reader through the science of stress corrosion cracking, as it is currently understood at an atomistic level, into discussions of soil environments and engineering aspects of constructing and maintaining welded steel pipelines, with the complexities that weld zones entail.

After reviewing the fundamental and engineering aspects, Dr. Cheng offers strategies for managing stress corrosion cracking by preventing, detecting, and monitoring to achieve the goal of zero failures—no failures—so that, indeed, *zero* means *zero*, and *no* means *no*, ensuring reliability of the pipeline, deliverability of the energy, protection of the environment, and safety of the public. Throughout the book, technologies for managing stress corrosion cracking are discussed as essential elements of maintaining pipeline integrity.

In summary, Dr. Cheng has provided an important service by writing this book, delivering a valuable source of knowledge and information on technologies for managing stress corrosion cracking and enhancing pipeline integrity. I commend this book to all those who have an interest in this exciting subject, this rapidly developing area of technology that is vital to all those who rely on energy for their standard of living and to fuel their ambitions and dreams for the future.

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Series Editor
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Preface

Pipelines sit at the nexus of national economies, of growing concerns for the natural environment, and of the global energy infrastructure. Environmental disasters such as the tragic explosion of the Deepwater Horizon drilling rig have diminished public tolerance for human activity that results in the release of hydrocarbons into the natural environment. After spending decades outside public focus, the pipeline industry now emerges at the center of a complex global debate that involves multiple interests.

First observed in pipelines in the United States during the 1960s and later reported in Canadian pipelines during the 1980s, stress corrosion cracking (SCC) has represented both a challenge to an industry that has grown increasingly concerned with the safe operation of pipelines as well as a source of scientific motivation for researchers trying to understand the detailed mechanisms behind this complex process. The main objective in writing this book is to provide a summative and, more important, up-to-date narrative of the current state of scientific understanding of and relevant engineering practice involving pipeline SCC. Moreover, preparation of this book is intended to pay tribute to the numerous researchers and engineers who have contributed to the body of knowledge in the field of pipeline SCC.

The nine chapters are designed to meet the needs of scientists, engineers, managers, technologists, students, and all of those requiring knowledge in this area. The book introduces pipelines, the development of the global pipeline industry, and the hazardous effects of SCC on the integrity of these systems. The second chapter explores the fundamentals of SCC in metals. Specifically, attention is given to (1) metal–environment combinations that give rise to SCC, (2) its metallurgical, mechanical, and environmental aspects, and (3) the various mechanisms that illustrate the initiation and propagation of stress corrosion cracks in metals. Moreover, the occurrence and characteristics of damage from hydrogen and corrosion fatigue are analyzed and compared to SCC. The role of microbiological activity in SCC processes is also discussed.

Chapters 3 through 6 describe SCC as a unique phenomenon and mechanism that can result in pipeline failure. Topics also cover a wide spectrum of environmental conditions that are relevant to pipeline operation, including nearly neutral pH, high-pH trapped electrolyte, and acidic soil environments. In addition, the primary characteristics of and contributing factors to pipeline SCC are summarized. This portrait of SCC includes both current theoretical and practical bodies of knowledge surrounding propagation kinetics, predictive methodologies, and of the crack initiation mechanism.

Chapter 7 focuses on corrosion and SCC that occurs at pipeline welds, with close connections to local steel metallurgy and electrochemical features. High-strength steel pipeline technology and the metallurgy of high-strength line pipe steels are discussed in Chapter 8. As advanced pipeline materials, high-strength steels distinguish themselves from conventional pipeline steels with unique metallurgical, mechanical, and microelectrochemical characteristics. All of these contribute to the occurrence of hydrogen damage, corrosion, and SCC. In particular, complex strains exerted on high-strength steel pipelines and the implications on corrosion of steels and the use of the mechanoelectrochemical effect theory for the prediction of defect propagation and evaluation on the remaining strength of steels are introduced. These discourses will serve as a reliable foundation for corrosion- and SCC-preventive strain-based design of pipelines.

Chapter 9 reviews current industrial practices in the management of pipeline SCC, including prevention, monitoring, and mitigation techniques. Moreover, it is shown how SCC management has been integrated with broader integrity management programs in use for modern pipeline systems.

The uniqueness of this book does not lie in the fact that it is the first book especially contributing to pipeline SCC, but that it contains the latest research results and data relating to pipeline SCC. To assist the reader in understanding the scientific aspects associated with the phenomena of pipeline SCC, a number of theoretical models and concepts have been developed. Moreover, these conceptual and modeling results are supported by and based on advanced microscopic electrochemical measurements. In turn, effective integration of electrochemical, microelectrochemical, materials science, and surface analysis techniques helps to advance a fundamental understanding of the engineering phenomenon. Furthermore, the scientific concepts and models explored in the ensuing discussions provide reliable and accurate methodology for industry to predict, monitor, and manage pipeline SCC.

I am very pleased to express my deepest gratitude to Dr. Winston Revie, who wrote the Foreword for the book. In the past seven years, I have had the good fortune of frequent interactions with Winston on a wide variety of issues in the area of pipeline engineering. His guidance, encouragement, and mentorship have been and remain invaluable to me in the formation and evolution of my professional career.

I wish to thank Dr. Ron Hugo for his devoted support of my academic career at the University of Calgary. The role that he plays in the development of the Pipeline Engineering Centre at the university and in the local community cannot be overemphasized. These efforts have contributed to creating an ideal working environment for my research in pipelines.

I acknowledge the numerous fruitful discussions I have had with Drs. Bill Shaw, Jingli Luo, Fraser King, and many other colleagues and friends. I am also indebted to the dedicated and unfailing assistance provided by the numerous students and postdoctoral fellows that I have had the pleasure to supervise in my research group.

I thank Mr. Michael Leventhal of John Wiley & Sons for his patience and understanding of the lengthy time period required to prepare this book. Indeed, there have been frequent unexpected events interrupting the overall process. Michael's support was crucial to completing the project.

Research grants from the Canada Research Chairs Program, Natural Science and Engineering Research Council of Canada (NSERC), Canada Foundation for Innovation (CFI), Pipeline Engineering Center of the Schulich School of Engineering, University of Calgary, and a number of industrial organizations have created the favorable conditions that helped support an active research environment that has enabled the writing of this book. I am grateful and indebted to the assistance provided by these programs, agencies, and organizations.

Finally, I thank my wife and my son, who, in many ways, have provided encouragement and have supported the creation of this book.

Y. FRANK CHENG

Calgary, Alberta, Canada

List of Abbreviations and Symbols

AD	anodic dissolution
AF	acicular ferrite
API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
BCC	body-centered cubic
bcf	billion cubic feet
BF	bainitic ferrite
CCT	continuous cooling transformation
CE	counter electrode
CEPA	Canadian Energy Pipeline Association
CF	corrosion fatigue
CGR	crack growth rate
CP	cathodic protection
CO_2	carbon dioxide
CSA	Canadian Standards Association
CSL	coincidence site lattice
DNV	Det Norske Veritas
DOS	degree of sensitization
DOT	Department of Transportation
DSAW	double submerged arc welding
EAC	environmentally assisted cracking
EAT	equivalent aging time
EBW	electron beam welding
ECDA	external corrosion direct assessment
EDX	energy-dispersive x-ray
EMAT	electromagnetic acoustic transducer
ERW	electric resistance welding
ESCM	electrochemical state conversion model
FBE	fusion-bonded epoxy
FCC	face-centered cubic

FEA	finite element analysis
FIB	focused ion beam
GBF	grain boundary ferrite
GPS	global positioning system
H_2S	hydrogen sulfide
HAGB	high-angle grain boundary
HAZ	heat-affected zones
HE	hydrogen embrittlement
HIB	hydrogen-induced blistering
HIC	hydrogen-induced cracking
HPCC	high-performance composite coating
HSSCC	hydrogen sulfide stress corrosion cracking
ICDA	internal corrosion direct assessment
IDQ	inter-ruptured direct quenching
IEA	International Energy Agency
IEAW	indirect electric arc welding
IGSCC	intergranular SCC
ILI	in-line inspection
IMP	integrity management program
IOB	iron-oxidizing bacteria
IRB	iron-reducing bacteria
ISO	International Standards Organization
LAGB	low-angle grain boundary
LAP	local additional potential
LEIS	localized electrochemical impedance spectroscopy
LPB	low-plasticity burnishing
MAG	metal active gas
MAOP	maximum allowable operating pressure
MFL	magnetic flux leakage
MIC	microbially influenced corrosion
MIG	metal inert gas
MnS	magnesium sulfide
M/A	martensite/austenite
MOC	management of change
MOP	maximum operating pressure
MPI	magnetic particle inspection

mpy	mils per year
NACE	national Association of Corrosion Engineers
NDT	nondestructive testing
NEB	National Energy Board
NRTC	NOVA Research and Technology Center
OPS	Office of Pipeline Safety
PE	polyethylene
PECPMS	pipeline environment and CP monitoring system
PIM	pipeline integrity management
PRCI	Pipeline Research Council International
PSB	persistent slip band
PWHT	postweld heat treatment
RE	reference electrode
ROW	right-of-way
RP	rolling plane
RRA	reduction-in-area
SAW	submerged arc welding
SBD	strain-based design
SCC	stress corrosion cracking
SCCDA	stress corrosion cracking direct assessment
SCE	saturated calomel electrode
SEM	scanning electron microscopy
SF	safety factor
SHE	standard hydrogen electrode
SKP	scanning Kelvin probe
SMYS	specified minimum yield strength
SOB	sulfide-oxidizing bacteria
SPH	smooth particle hydrodynamics
SRB	sulfate-reduced bacteria
SSC	sulfide stress cracking
SSCC	sulfide stress corrosion cracking
SSRT	slow strain rate tensile
SVET	scanning vibrating electrode technique
TFI	transverse field inspection
TGSCC	transgranular SCC
TM	thermomechanical

TMCP	Thermomechanical controlled processing
UT	ultrasonic tool
UTCD	ultrasonic crack detection
VSR	vibratory stress relief
YPE	yielding point elongation
a	crack length
A_1	areas of a crack tip
A_2	area of the region ahead of the crack
b_{a}	anodic Tafel slope
b_{c}	cathodic Tafel slope
C	capacitance of space-charge layer of passive film
C_{app}	hydrogen apparent solubility
d	initial depth of grain
da/dN	fatigue crack propagation rate per cycle
D_{eff}	hydrogen diffusivity
D_l	lattice diffusion coefficient of hydrogen
e	elongation
E	Young's modulus
E°	standard electrode potential
E_a	anodic potential
E_{app}	applied potential
E_{corr}	corrosion potential
E_{corr1}	corrosion potential at a crack tip
E_{corr2}	corrosion potential at a region adjacent to a crack tip
E_g	galvanic potential
E_0	electrode potential at an intact site
E_{pi}	potential at a local active site
E_{pit}	pitting potential
f	frequency
F	Faraday constant
G	formation free energy of individual species
H_{ave}	average depth of source dislocation
I_g	galvanic current

i_1	anodic current density at a crack tip
i_2	cathodic current density at the adjacent region from a crack tip
i^0	exchange current density
i_a	anodic current density
i_a^*	anodic current density immediately after the film rupture
i_{corr}	corrosion current density
i_{corr1}	corrosion current density at a crack tip
i_{corr2}	corrosion current density at the adjacent region from a crack tip
i_D	current density at defect
i_p	passive current density
i_{pit}	pitting current density
i_N	current density at a nondefect area (i.e., intact area)
i_{total}	total current density measured
J_H	hydrogen flux
$J_H L_H$	hydrogen permeation rate
k	constant
k_B	Boltzmann constant
k_H	effect of hydrogen on the anodic dissolution rate of steel
k_σ	effect of stress on anodic dissolution in the absence of hydrogen
$k_{H\sigma}$	synergistic effect of hydrogen and stress on the anodic dissolution at a crack tip
K_{ISCC}	minimum threshold stress intensity for SCC
K_{max}	maximum of stress intensity factor
L	initial size and depth of grain
L_H	thickness of the specimen for hydrogen permeation test
M	atomic weight
n	number of electrons exchanged in the electrode reaction
n_0	number of dislocations on the steel surface
n_d	number of dislocations in a dislocation pile-up
N	number of stress cycles to failure
N_0	initial density of dislocations prior to plastic deformation
N_{max}	maximum dislocation density
N_T	hydrogen trapping density
r	distance from the local charged point on the steel surface to the

solution layer

r_0	atomic radius
R	ideal gas constant
$R^0_{ct,\sigma}$	charge-transfer resistances of steel without hydrogen charging
$R^H_{ct,\sigma}$	charge-transfer resistances of steel with hydrogen charging
q_i	charge of electrons
Q_F	electric charge passed between two successive film-rupture events
S	stress
t	time
t_L	time lag
t_0	start time that passive film ruptures
T	temperature
U	ultimate tensile stress
V_H	average volume of hydrogen in steel
V_m	molar volume of steel substrate
W	thickness of grain
W_m	molar weight
x	amount of hydrogen atoms permeating into the steel
y	amount of hydrogen atoms permeating stressed steel
Y/T	yielding strength/tensile strength ratio
z	repassivation exponent

$[H^+]$	concentration of hydrogen ions in solution
$[H^+_{CP}]$	concentrations of hydrogen ions in solution in the presence of CP
$[H^0_{ads}]$	subsurface concentration of hydrogen adsorbed in uncharged steel
$[H_{ads}]$	subsurface concentration of adsorbed hydrogen in charged steel
ΔE	LAP at defect
ΔG	change in free energy
ΔK	stress intensity factor
ΔK_{th}	threshold of stress intensity factor
ΔN	density of new dislocations during plastic deformation
ΔP	excess pressure
ΔS	entropy change
ΔU	change of internal energy

$\Delta\mu$	difference of chemical potentials of the steel in the presence and absence of hydrogen charging
$\Delta\varphi_e^0$	change of electrochemical corrosion potential of steel during elastic deformation
$\Delta\varphi_p^0$	change of electrochemical corrosion potential of steel during plastic deformation
$\Delta\varphi_T^0$	shift of total corrosion potential during tensile testing
$\Delta\tau$	hardening intensity
α	charge-transfer coefficient (cathodic)
β	charge-transfer coefficient (anodic)
β_c	cathodic Tafel slope
σ	stress
$\sigma_{0.2}$	applied stress level resulting in a 0.2% of total deformation and often used as an approximation of the proof stress of steels
σ_h	hoop stress
σ_V	volume stress
σ_{ys}	yield strength
ε	strain
ε_F	rupture ductility of passive film
ε_r	dielectric constant of water
ε_p	plastic strain
$\dot{\varepsilon}$	strain rate
$\dot{\varepsilon}_{\mathrm{ct}}$	strain rate at a crack tip
ρ	density
V_{th}	minimum mobility velocity of dislocations
φ	electrode potential
φ^{θ}	standard equilibrium electrode potential
μ	chemical potential
i_p^{∞}	steady-state hydrogen permeation current density
I_{ψ}	ratio of reduction-in-area obtained in solution to that in air
ν	orientation-dependent factor

1

Introduction

Statistically, pipelines provide the safest and most economical form of transportation of crude oil, natural gas, and other petrochemical commodities compared to truck, rail cars, and tankers [Cheng, 2010]. There are about 2 million kilometers of transmission pipelines worldwide. These include natural gas, oil, condensates, petroleum gas, and other refined petroleum products, as well as carbon dioxide (CO_2) and hydrogen. The pipelines could be very large in diameter (e.g., a Russian pipeline system has a diameter of up to 1422 mm) and can be over several thousand kilometers in length [Hopkins, 2007]. Most pipelines are buried or under the sea, but some operate aboveground.

Liquids and gases have been transported by pipelines for thousands of years. Ancient Chinese and Egyptians used pipes to transport water, hydrocarbons, and even natural gases [Hopkins, 2007]. Most of the current pipeline industry was developed to transport oil, bringing considerable profits to energy producers and pipeline operators, and development is driven by expanding energy demands. Tens of thousands of kilometers of new pipelines are constructed every year. Pipelines have become one of the most environmentally friendly and safest means of oil and natural gas transportation and contribute to strong national economies. As a consequence, they have been integrated into the components of national security in most countries.

More than 90% of pipelines are made of steel, primarily carbon steel, with aluminum, fiberglass, composite, polyethylene, and other types making up the remaining 10% [Alberta Energy and Utilities Board, 2007]. Requirements for higher capacities and operating pressure and additional economic benefits have led to a demand for higher-strength pipeline materials, especially high-strength steels, as well as new techniques for welding, construction, inspection, and pipeline integrity and maintenance programs.

1.1 PIPELINES AS “ENERGY HIGHWAYS”

Human beings need energy to survive. For today and tomorrow, fossil fuels, including oil and gas, are the predominant forms of energy consumed worldwide. In fact, “even if the use of renewable energies doubles or triples over the next 25 years, the world is likely to still depend on fossil fuels for at least 50 percent of its energy needs” [Chevron, 2012]. The International Energy Agency estimated in 2010 that the world oil supply rises by 85 million barrels per day and forecast that the global demand would average nearly 88 million barrels per day in 2011 [Whipple, 2010], which demonstrates a clear relationship between oil consumption and a country's economic situation.

Oil and gas are usually found in very remote regions that are different from the locations where they are processed and consumed. Pipelines provide the necessary transportation function for this form of energy. Pipelines are regarded as “energy highways” of the global oil and gas industry, and their impact on the energy industry and the general economy therefore cannot be underestimated. In North America, a total length of over 800,000 kms of transmission pipeline network transports 97% of Canadian crude oil and natural gas from the producing regions to markets throughout Canada and the United States. Statistics show [Canadian Energy Pipeline Association, 2007] that Canadian pipelines transport approximately 2.65 million barrels of crude oil and equivalent and 17.1 billion cubic feet (bcf) of natural gas daily. Moreover, virtually all oil and gas exports—worth $60 billion in 2009—are carried by pipelines [Canadian Energy Pipeline Association, 2012]. With an asset value of approximately $20 billion, the Canadian pipelines are anticipated to double in size by 2015 to meet the oil and gas production increases that are forecast. Among the world's nations, the United States and Canada have the largest networks of energy pipelines for both oil and natural gas.

Oil pipeline networks are classified into crude oil lines and refined product lines, and the crude oil lines are subdivided into gathering lines and trunk lines. Gathering lines are small pipelines, from 2 to 8 in. in diameter, and are used where crude oil is found deep within the Earth where it is impractical to use larger diameters [Alberta Energy and Utilities Board, 2007]. It is estimated that there are between 48,000 and 64,000 kms of small gathering lines in the United States. These small lines gather oil from many wells, both onshore and offshore, and connect to larger trunk lines ranging from 8 to 24 in. in diameter. Trunk lines include a few very large lines, such as the TransAlaska Pipeline System, which is 48 in. in diameter [Alberta Energy and Utilities Board, 2007]. There are approximately 89,000 km of crude oil trunk lines in the United States.

Gas gathering lines connect individual gas wells to field gas-treating and processing facilities or to branches of larger gathering systems. Most gas wells flow naturally with sufficient pressure to supply the energy needed to force the gas through the gathering line to the processing plant. Like crude oil trunk lines, gas transmission systems can cover large geographical areas and be several hundreds or thousands of miles long. One of the largest natural gas supplies is in western Siberia. A large-diameter pipeline system moves gas from that area, including a pipeline almost 4600 km long, to export gas to Western Europe [Hopkins, 2007]. These trunk lines, which have diameters ranging from 40 to 55 in., constitute an impressive pipeline network. Compared to crude oil pipelines, gas transmission lines operate at relative high pressures.

Oil and gas pipeline systems are remarkable for their efficiency and low cost. Compared to other conventional means of transportation, such as rail and trucks, pipelines provide a very cheap way to transport oil. For example, for every 1000 barrel-miles of transportation of petroleum, the cost by pipeline is between 4 and 12 cents, whereas those by rail and truck are 12 to 60 cents and 52 to 75 cents, respectively [Kennedy, 1993]. Oil and gas pipelines are also energy-efficient, consuming about 0.4% of the energy content of the crude oil or gas transported per 1000 km [Marcus, 2009].

1.2 PIPELINE SAFETY AND INTEGRITY MANAGEMENT

Pipeline integrity is maintained by coating and cathodic protection (CP) as well as by comprehensive pipeline safety maintenance programs generally called *pipeline integrity management* (PIM) programs. A PIM is a process to develop, implement, measure, and manage the integrity of a pipeline through assessment, mitigation, and prevention of risks to ensure safe, environmentally responsible, and reliable service [Nelson, 2002]. Integrity management of pipeline systems is essential to the safe and efficient transport of oil and natural gas on the basis of safety assessment and lifetime prediction. Attempts to define pipeline performance, structural strength, and lifetime spawn a number of specialized fields, including corrosion, materials science, fracture mechanics, nondestructive evaluation, electrochemistry, environmental science, and mathematical modeling on both microscopic and macroscopic scales.

The goal of a PIM program is to ensure that the risk is "as low as is reasonably practicable" [Nelson, 2002]. An integrity management program (IMP) is usually valid for two or three years and is then updated to include new or modified processes, developed during implementation of the PIM, through multiple time-driven integrity plans. A PIM program supports monitoring, inspection, and maintenance programs to reduce greatly the risk of failures that could cause disastrous consequences to human life, the environment, and business operations.

1.3 PIPELINE STRESS CORROSION CRACKING

A number of factors contribute to pipeline failures. Although corrosion is identified as the most common cause of oil and gas transmission pipeline failure [U.S. Department of Transportation, 2005], stress corrosion cracking has been identified as leading to a number of pipeline leaking and/or rupture events, with catastrophic consequences [National Energy Board, 1996].

Stress corrosion cracking (SCC) is a term used to describe service failure in engineering materials that occurs by slow, environmentally induced crack propagation. The crack propagation observed is the result of the combined and synergistic interactions of mechanical stress and corrosion reactions [Jones, 1992]. For a certain material, SCC occurrence depends on both an aggressive environment and a stress, especially a tensile stress. During the operation of pipelines in the field, line pipe steels are exposed to electrolytes trapped under disbonded coating, where solution chemistry or electrochemistry is developed to support pipeline SCC [Fu and Cheng, 2010]. The stress is due primarily to the internal operating pressure or pressure fluctuation of natural gas or liquid petroleum [Zheng et al., 1997]. Moreover, soil movement–induced longitudinal stress and strain contribute to the initiation and propagation of stress corrosion cracks in pipelines [Canadian Energy Pipeline Association, 1998]. A wide variety of factors experienced by pipelines during their operation have been demonstrated to affect and contribute to SCC at somewhat different levels, such as the steel metallurgy (chemical composition, grade, microstructure, heat treatment, alloying elements, impurities, and welding), environmental parameters (soil chemistry, conductivity, seasonal dry–wet cycle, temperature, humidity, CO_2 and gas conditions, and microorganisms), coatings, and CP (type, properties, failure mode, coating compatibility with CP, and CP potential/current), stressing condition (pressure, pressure fluctuation, residual stress, longitudinal stress, local stress–strain concentration), and corrosion reaction (corrosion pits, geometry of pits, hydrogen evolution, passivity and passive film formation, active dissolution, and mass transport) [Parkins, 2000].

Pipeline SCC incidents throughout North America and the world, including in Australia, Russia, Iran, Saudi Arabic, Brazil, and Argentina, have highlighted threats to pipelines from this problem. In Canada, two major ruptures and fires on the TransCanada Pipeline System in 1995, together with further evidence of the more widespread nature of SCC, led to the initiation of a national inquiry. This was the first comprehensive inquiry in the world on pipeline SCC and has