Innovation Roadmap for Transmission Pipeline Transportation of Petroleum Products

Final Report
March 14, 2014

Prepared for Alberta Innovates – Energy and Environment Solutions and the Canadian Energy Pipeline Association

By Marc Godin
Portfire Associates

Acknowledgements

This report was prepared by a team under the leadership of PTAC Petroleum Technology Alliance Canada and the Pipeline Engineering Centre of the University of Calgary, and sponsored by Alberta Innovates – Energy and Environment Solutions and the Canadian Energy Pipeline Association. The lead author was Marc Godin with significant contributions from Dr. Ron Hugo, Dr. Frank Cheng, Dr. Harvey Yarranton, D. Horsley, Dr. A. Murray, Dr. M. Yoon, Dr. J. Oswell, R. Motriuk and A. Sinha. The author and contributors wish to express their appreciation for the invaluable assistance, insight and comments received during the course of this work from representatives of Alberta Innovates – Energy and Environment Solutions and the Canadian Energy Pipeline Association, particularly Dr. J. Zhou, Z. Saad, Dr. T. Zimmerman and V. Lightbown.

Executive Summary

Purpose and Scope

Transmission pipelines are generally viewed as the most reliable, energy efficient and cost-effective mode of transportation for large volumes of natural gas, oil, chemicals and fuels from producing areas to consumer markets. While pipelines are safe, incidents can happen and operating companies and stakeholders expect continuous improvement in reliability and integrity. In recent years, proposals for new major pipelines have faced scrutiny, primarily over issues related to system integrity and environmental impact. At the same time, the Canadian pipeline industry has moved to systematically improve collaboration and best practices, and has set an agenda of zero incidents.

Investments in research and innovation could contribute to the desired improvements. This project for an Innovation Roadmap for Transmission Pipeline Transportation of Petroleum Products was initiated to explore such improvements and its purpose is to inform industry, government and academia about research needs and technology investment opportunities in pipeline innovation to support continuous improvement in reliability, integrity and environmental impact, and to address concerns raised in recent years. The Roadmap`s unique contribution is to provide an overall and aggregated perspective with emphasis on Alberta and Canada. It notes research needs and technology opportunities that may not be fully addressed elsewhere, and identifies directions for international collaboration in areas where research is already active. Importantly, it delivers a blueprint for consideration by Canadian government organizations, pipeline operating companies, technology developers, learning institutions and the Canadian Energy Pipeline Association for leveraging their expertise, infrastructure capabilities and financial resources to jointly deliver technology solutions that would benefit the sector as a whole.

The domain of this Roadmap is limited to technology innovation; as a result, the scope excludes solutions that could arise from government policy and regulations, business strategy and management, and stakeholder consultations and public relations. It is calibrated to overall sector needs in a Canadian and Alberta context. It is not aimed at any specific company or pipeline project, and it fully recognizes that individual pipeline operators have a deep understanding of technology challenges and opportunities related to their business. It also does not enter the realm of government policy objectives and regulatory frameworks, and fully acknowledges that several government organizations have already studied technology gaps and possible futures. Finally, the report is aware of technology roadmap initiatives undertaken by industry associations in other countries and has accessed publicly available information about them in order to identify opportunities for collaboration and to avoid duplication.

The greenhouse gas (GHG) impact of products (such as oil sands derived products) transported inside pipelines is a public policy issue of great importance; however it is considered out of scope of this Roadmap because it is not directly relevant to pipeline technology. In addition, issues related to marine transportation of crude oil and liquefied natural gas, while directly related to some proposed pipeline projects, represent a different technology domain than pipelines and are not included in the scope of this Roadmap.

Roadmap Process

This Pipeline Innovation Roadmap is a conceptual document that captures a high level consensus among participants and that could form a foundation for a future strategic plan. It is composed of:

- Statement of strategic drivers that are leadership choices which provide the impetus to allocate resources and harness trends in order to respond to stakeholder needs or industry opportunities; the strategic drivers point in the direction of the desired future state;
- Assessment of the current state, including capabilities, knowledge gaps, research needs and prospective technology advances; and
- Paths and options to close gaps, build required capacity and realize opportunities to generate positive momentum from the current state to the desired future state.

Strategic Drivers

The strategic drivers were developed from a review (summarized below) of issues raised by stakeholders in the United States and Canada during recent public hearings and regulatory reviews. The strategic drivers established for this Roadmap project were the following:

- To minimize environmental footprint and social impact of the construction and operations of transmission pipelines; and
- To operate transmission pipelines at high and consistent levels of performance in terms of safety, reliability, efficiency and system integrity.

The strategic drivers are to be interpreted in the context of maintaining energy affordability for users and the public. The drivers provided the focus for the purpose of this report and could be further validated and refined in future work.

Issues Raised by Stakeholders

The recent hearings and regulatory reviews in the United States and Canada provided venues for governments, nongovernmental organizations and the public to voice comments and concerns about pipeline projects. A review of these proceedings is instructive as it highlights the key issues brought forward by stakeholders.

The U.S. debate appears heavily weighted to assessing the impact and appropriate response to the GHG emissions and the impact of potential spills of oil sands products (generally dilbit[1]) carried by pipelines rather than the direct impact of the pipelines. With respect to pipeline technology, the Keystone XL Final Environmental Impact Statement (FEIS) states that Keystone XL "*would have a degree of safety greater than any typically constructed domestic oil pipeline*

[1] Dilbit is the industry term for bitumen diluted with diluent.

system."[2] [3]Furthermore, the potential for increased transportation risks that could be associated with oil sands products was the object of a study that did *"not find any causes of pipeline failure … that would make diluted bitumen more likely than other crude oils to cause releases."*[4] However, critics pointed out that a dilbit spill is viewed by the Environmental Protection Agency (EPA) as potentially requiring different response actions and equipment than a conventional oil spill.

In Canada, proposed pipelines projects include the new Northern Gateway Pipeline by Enbridge, the Trans Mountain Pipeline Expansion Project by Kinder Morgan, the re-purposed Energy East Pipeline by TransCanada and the reversal of Enbridge's Line 9[5]. In December 2013, after 180 days of public hearings about the proposed Northern Gateway Pipeline Project, Joint Review Panel of the National Energy Board (NEB) recommended approval of the Project. The approval, if granted by the federal government, would be subject to 209 conditions.[6] In contrast to the U.S. regulatory review of Keystone XL, the NEB conditions do not address the GHG emissions of oil sands products. In general, the conditions specify detailed future reporting by Enbridge during all phases of the project regarding compliance to code and regulations.

In summary, the key issues related to pipeline technology raised by stakeholders in the United States and Canada were the following:

- The possibility of a pipeline failure with potential impact on safety, property damage and the environment; and
- The concern regarding whether a spill of oil sands products could be more difficult to clean up and could cause more environmental impact than a spill of conventional crude oil or a release of natural gas.

Of note, key issues raised in public debate did not, in general, emphasize subjects such as project need, costs, tariffs, project size, local and national economic impact, job creation, pipeline performance metrics, and the direct environmental impact of pipelines. In general, the core of the debate is about finding the appropriate balance between economic benefits and environmental impact, and the best means to proceed should the projects be approved.

Knowledge Network Mapping

The first task was to understand the current state of the pipeline technology knowledge system. Literature searches were conducted, resulting in a database that contained over 500 organizations

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[2] United States Department of State, Bureau of Oceans and International Environmental and Scientific Affairs (2011), Final Environmental Impact Statement for the Proposed Keystone XL Project
[3] Subsequently, in 2013 and 2014, the Draft and Final Supplemental Environmental Impact Statement reiterated the same conclusion.
[4] National Research Council of the National Academies (2013), TRB Special Report 311: Effects of Diluted Bitumen on Crude Oil Transmission Pipelines
[5] The reversal of Line 9 was approved by the National Energy Board on March 6, 2014.
[6] Joint Review Panel for the Enbridge Northern Gateway Project (2013), Connections, Report of the Joint Review Panel for the Enbridge Northern Gateway Project, Volumes 1 and 2. Volumes 1 and 2

and over 2,600 researchers and contributors in pipeline technology. Based on the survey, the countries with the highest number of active contributors to pipeline technology literature are, in descending order: the United States, Canada, China, Japan, the United Kingdom, Brazil and Germany. A considerable portion of work in pipeline R&D was found to be conducted by researchers and contributors affiliated with pipeline service companies, while government-affiliated researchers formed only a small portion of the pipeline innovation system. As such, a majority of pipeline research and innovation is driven by industry, be it through pipeline operators, pipeline service companies, or research institutes that garner an important fraction of their support from the pipeline industry.

It is also important to note that Alberta is home to the headquarters of major Canadian pipeline companies and their technical staff and facilities, Canadian pipe manufacturing, service and technology companies, and the principal Canadian office for many international pipeline operating and service companies. Some important provincial and federal government pipeline laboratories are also located in Alberta.

The survey identified a wide range in the level of effort between different technical subjects in pipeline technology. Integrity Management was by far the most active area. It is a broad category with a long standing interest that has grown over time to include a large number of research topics ranging from corrosion to in-line inspection. The second most active category was Design. Other research categories received proportionately less attention: Leak Detection, Spill Cleanup and Remediation, and Reclamation.

Gap Analysis

Knowledge gaps are the first barriers between the current status of technology and the desired future state and this task of the project sets the stage for the formulation of technology programs to fill identified gaps and harness opportunities. The identification of gaps/opportunities was done by project team members based on their experience and their knowledge of recent reviews of operating incidents. Approximately 50 gap worksheets were prepared, discussed and aggregated by the project team and the Steering Committee into 17 gaps/opportunities distributed as follows:

- Environment (Direct Impacts): 3 gaps/opportunities
- Design: 2 gaps/opportunities
- Materials: 1 gap/opportunity
- Construction: (Included in Environment)
- Operations and Maintenance: 2 gaps/opportunities
- Integrity Management:5 gaps/opportunities
- Leak Detection: 2 gaps/opportunities
- Spill Cleanup and Remediation: 1 gap/opportunity
- Reclamation: 1 gap/opportunity.

The gaps were placed into the Pipeline Innovation Research Opportunity Matrix according to (i) their impact on the strategic drivers and (ii) to the level of effort by existing research organizations based on the information assembled in the Knowledge Network Map. The Matrix was used to inform the development of the Roadmap and of the technology portfolios. As shown below, five high impact gaps/opportunities were identified: In-line Inspection, Defect Assessment, Risk-based Fitness for Service Defect Assessment, Secondary Leak Detection Systems and Cleanup and Remediation of Submerged Oil. There were six medium impact and six low impact gaps/opportunities.

Pipeline Innovation Research Opportunity Matrix

Impact/Value on Integrity, Reliability and the Environment	**High**	• In-line Inspection	• Defect Assessment • Risk-based Fitness for Service Defect Assessment • Secondary Leak Detection Systems	• Cleanup and Remediation of Submerged Oil
	Medium	• Fracture Propagation and Arrest • Internal Corrosion	• Strain-based Design and Materials • External Corrosion • Computational Pipeline Monitoring	• Geotechnical Hazard Risk Assessment
	Low	• Pipeline Repairs with Composite Materials		• Route Optimization • Noise Impact • Construction Right-of-Way • Hydrodynamics • Pipeline Abandonment
		Many	**Medium**	**Few**
		Existing Innovation Programs		

Technology Portfolios

This Roadmap is best described as a conceptual blueprint that captures a consensus among stakeholders about the motivation for improvement and about potential directions for achieving tangible results. This blueprint is a first step prepared for consideration by industry, government and academia, and may be a basis for improved dialogue and planning that could subsequently lead to a full strategic implementation plan with concomitant allocation of resources with the objective of making significant improvements in the integrity and environmental impact of transmission pipelines.

The initial task in developing the portfolios of potential technology solutions was the preparation of 16 technology solution worksheets from a process of analysing the 17 gaps/opportunities mentioned earlier, aggregating some and expanding others. On a preliminary basis, the worksheets captured the following: description, research objectives, benefits, probability of success, development costs, and time horizon. Prospective technologies were analyzed and summarized by subject matter experts. Greater emphasis was placed on high impact gaps/opportunities.

Technology solutions were then assessed with respect to value and to technology maturity. The concept of value builds from the concept of the impact of closing the gap or harnessing the opportunity, and adds to it the ease of market adoption (which is the cost and the potential for disruption to existing systems). Technology maturity describes how probable and how close the subject technology is to be translated to widespread industrial use. In general, investment in technology development would favor high-value projects in a mature technology space, in other words high reward/low risk technology investments. In practice, a technology development portfolio attempts to balance investment risk with potential returns in a continuum from incremental improvement (low risk but low value; typical of mature technologies) to game changing technologies (high risk but high reward; typical of early stage technologies).

Roadmap

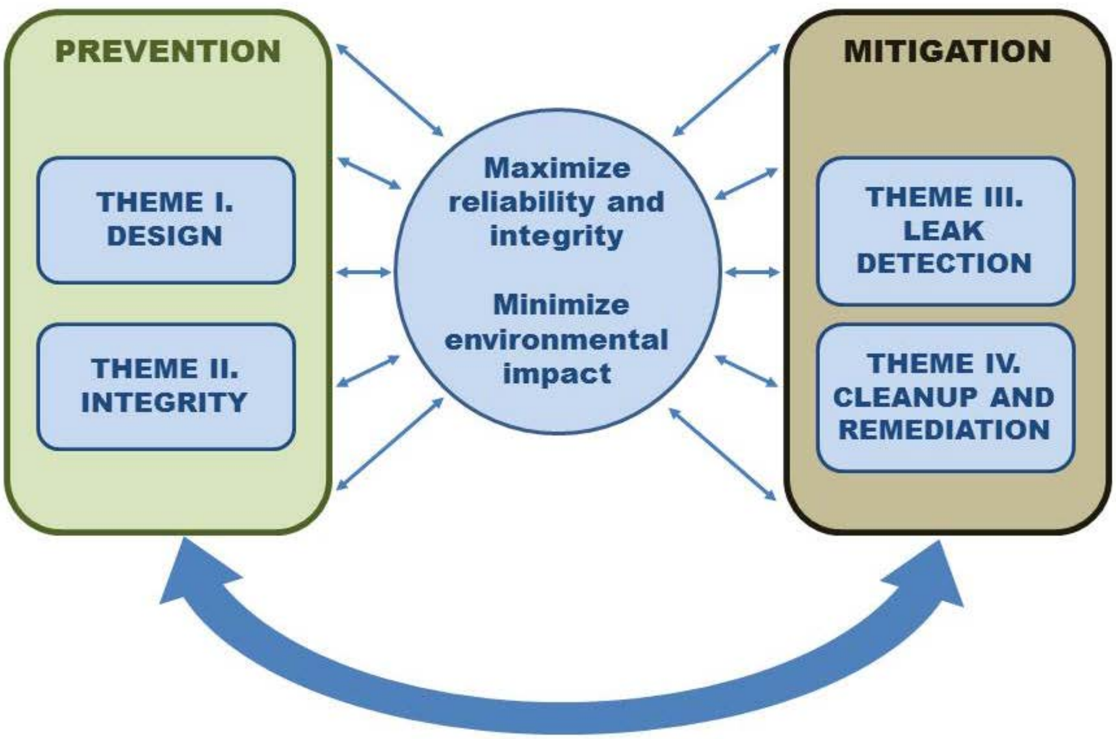
This Roadmap is a conceptual strategic framework that acts as a foundation and precursor to the future development of an implementation plan that would guide the allocation of resources to achieve strategic objectives. The review of issues raised by stakeholders and the gap analysis indicated that present priority needs and opportunities in pipeline technology are in the areas of integrity and of environmental impact. Other major areas such as cost reduction, economic impact, new commodities to be transported, frontier terrains and others were deemed of lower need or opportunity. Thus, the two roadmap strategic objectives are formulated as follows:

- To maximize reliability and integrity; and
- To minimize environmental impact.

The means to achieve these objectives can be classified temporally into prevention and mitigation. Prevention is what can be done before an incident in order to avoid it. Mitigation is what can be done after an incident to minimize or remediate its short and long-term impacts.

As illustrated in the Figure below, the two thrusts of the Roadmap are Prevention and Mitigation. Prevention fulfills the strategic objectives through design, construction and operation technologies that ensure high levels of reliability and integrity to prevent integrity and environmental incidents. Prevention is well aligned with the industry goal of zero incidents. Mitigation acknowledges that incidents can happen despite best technologies, practices and regulations; mitigation encompasses technologies to limit impact and restore the situation to its original condition.

Inside the two thrusts of Prevention and Mitigation, are the four themes of Design, Integrity, Leak Detection, and Cleanup and Remediation which aggregate technology solutions into convergent technology themes. The themes are subdivided into 13 technology focus areas. This structure offers a mission-oriented framework that is driven toward the strategic objectives and that covers all aspects of pipeline technology relevant to the objectives. Prospective technology solutions are then listed under the appropriate technology focus areas.



Overview of the Innovation Roadmap for Transmission Pipeline Transportation of Petroleum Products

Two portfolios of potential technology solutions were generated:

- Prevention technology portfolio: 15 potential technology solutions;
- Mitigation technology portfolio: 10 potential technology solutions.

The potential technology solutions were arranged by roadmap themes and technology focus areas with preliminary ratings assigned by the project team and the Steering Committee for value and for technology maturity, leading to a preliminary ranking:

- High interest: 7 potential technology solutions.
- Medium interest: 11 potential technology solutions.
- Low interest: 7 potential technology solutions.

Conclusion

The Roadmap was informed by a thorough review of needs, gaps and opportunities performed by a team of subject matter experts, in consultation with industry, government and academic stakeholders. The outcome is a conceptual blueprint for consideration by pipeline operators, service and technology companies, governments and regulators, and academic institutions that describes a strategic framework for innovation in pipeline technology. Action on this framework will lead to technology solutions that will respond to needs expressed by stakeholders and to opportunities identified by industry and researchers, in a way that leverages the resources of individual organizations for the benefit of the sector as a whole.

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1. Purpose

1.1. Motivation

Production of petroleum products is forecasted to increase significantly in western Canada in response to growing global energy demand and as a result of new technologies that have made economic the unconventional production of natural gas from shale deposits and of bitumen from oil sands resources. The construction of new pipelines or the re-purposing of existing ones will be required to allow increased petroleum production from western Canada to reach domestic and export markets in eastern Canada, the U.S. and Asia.

While pipelines have a strong safety and reliability record[7], incidents can happen and companies and stakeholders alike expect continuous improvement in reliability and integrity. Proposals for new pipeline projects have been under intense scrutiny, primarily over issues related to integrity and environmental impact. Promising technology advances offer opportunities to achieve the desired continuous improvement and ultimately the ability to achieve the industry goal of zero incidents. Investments in technology research and innovation could result in solutions applicable by industry and welcomed by stakeholders. This Roadmap project was initiated to explore such technology opportunities.

1.2. Scope

The intention of the Roadmap is to provide knowledge for industry, government and academia to address current and anticipated issues related to the pipeline transportation of petroleum products. The outcome will be to deepen the understanding of the potential of scientific research and technology development to provide required solutions, and to propose a blueprint for future technology investments.

Thus, the domain of this Roadmap is technology innovation. Therefore, the scope excludes solutions that could arise from government policy and regulations, business strategy and management, and stakeholder consultations and public relations. Issues related to the environmental impact of upstream oil sands production cannot be addressed through improvements in transportation technology and thus are not in scope. While the GHG impact of products transported inside pipelines is a public policy issue of great importance, it is not directly relevant to pipeline technology. In addition, issues related to the marine transportation of crude oil and liquefied natural gas, while associated with some proposed pipeline projects, represent a different technology domain than pipelines and are not included in the scope of this Roadmap.

1.3. Audience for this Report

This report was developed to inform industry, government and academia about research needs and technology investment opportunities in pipeline innovation to support continuous

[7] http://www.cepa.com/about-pipelines/maintaining-safe-pipelines/pipeline-integrity/cepa-member-pipeline-integrity-performance

improvement in reliability, integrity and environmental impact, and to address concerns raised by the public and regulators in recent years.

The primary value of this report is to aggregate and structure information about needs and opportunities. It is aimed at the overall sector in a Canadian and Alberta context. It is not aimed at any specific company or pipeline project, and it fully recognizes that individual pipeline operators do have a deep understanding of technology challenges and opportunities related to their business. It also does not enter the realm of government policy objectives and regulatory frameworks, and fully acknowledges that several government organizations have already studied technology gaps and possible futures. Finally, the report is aware of technology roadmap initiatives undertaken by industry associations in other countries and has accessed publicly available information on same in order to identify opportunities for collaboration and to avoid duplication.

As noted, the unique contribution of this report is to provide an overall and aggregated perspective with emphasis on Alberta and Canada. It notes research needs and technology opportunities that may not be fully addressed elsewhere, and identifies directions for international collaboration in areas where research is already active. Importantly, it delivers a blueprint for consideration by Canadian government organizations, pipeline operating companies, technology developers, learning institutions and the Canadian Energy Pipeline Association for leveraging their expertise, infrastructure capabilities and financial resources to jointly deliver technology solutions that would benefit the sector as a whole.

1.4.Roadmap and Strategic Drivers

This Roadmap is a blueprint that captures a high level consensus among participants and provides a foundation for a potential future strategic plan. It addresses the following:

- Statement of strategic drivers that are leadership choices which provide the impetus to allocate resources and harness trends in order to respond to stakeholder needs or industry opportunities; the strategic drivers point in the direction of the desired future state;
- Assessment of the current state, including capabilities, gaps, barriers, research needs, and prospective technology advances; and
- Paths and options to close gaps, build required capacity and realize opportunities to create positive momentum from the current state to the desired future state.

The strategic drivers were developed from a review of issues raised by stakeholders during recent public hearings and regulatory reviews. This review is summarized in Section 2 of this report. This review of documents by regulators and of public comment informed the selection of the strategic drivers which then guided the assessment of the current state and provided a prioritization framework for roadmap development.

The strategic drivers established for this Roadmap project were the following:

- To minimize environmental footprint and social impact of the construction and operations of transmission pipelines; and
- To operate transmission pipelines at high and consistent levels of performance in terms of safety, reliability, efficiency and system integrity.

The strategic drivers are to be interpreted in the context of maintaining energy affordability for users and the public. The drivers provided the focus for the purpose of this report and could be further validated and refined in future work.

2. Background

2.1. Pipeline Networks

Transmission pipelines are "energy highways" that have been considered for decades to be the most reliable, energy efficient and cost-effective method to transport large volumes of natural gas, oil, fuels and chemicals from producing areas to consumer markets. In Canada, more than 100,000 km of transmission pipelines[8] transport 97% of Canadian oil and gas production, including 3 million barrels of crude oil every day[9]. Pipelines benefit both producers and consumers of energy.

The pipeline sector directly, and indirectly through the petroleum industry, is a significant contributor to the economy. The Canadian pipeline sector has a total economic impact of over $51 billion per year.[10] The value of the pipeline sector extends beyond its domain as pipelines are critical enablers of the country's oil and gas industry, which accounted for 20% of Canada's economic growth in 2010 and 2011[11]. In 2011, most of the $82 billion in crude oil and natural gas exported from this country was by pipeline. Furthermore, the Canadian Energy Research Institute estimated that future growth in oil production could be valued at $1.3 trillion of GDP (in 2010 Canadian dollars) and $276 billion in taxes from 2011 to 2035[8].

Pipelines have performed their vital role for decades, receiving little public attention. In recent years, however, a number of broadly reported petroleum incidents and spills have thrust the pipeline industry into the spotlight of increased public and regulatory scrutiny. At the same time, global energy demand is increasing and Canada is responding by expanding production from natural gas, light tight oil and oil sands resources. As a result, major new pipelines have been proposed, particularly in western and northern regions of the country, as well as for exports to the United States and Asia. Some of these new pipelines have been described as a priority by the

[8] Canadian Energy Pipeline Association (2013) http://www.cepa.com/pipelines-101/types-of-pipelines, Accessed August 23, 2013
[9] Canadian Energy Pipeline Association (2013) http://www.cepa.com/library/factoids, Accessed August 23, 2013
[10] Canadian Energy Pipeline Association (2013) http://www.cepa.com/the-bottom-line-pipelines-and-canadas-gdp, Accessed August 23, 2013
[11] TD Economics (2012), Pipeline Expansion is a National Priority, online at http://www.td.com/document/PDF/economics/special/ca1212_pipeline.pdf , Accessed August 23, 2013

Federal Government and are a key element of present discussions regarding a national energy strategy. They are particularly vital for Alberta, a landlocked province.

2.2. Transportation of Bitumen Derived Products

Pipeline integrity has been an issue at the core of the well-publicized debates in the United States and in Canada about approval of the Keystone XL and Northern Gateway pipeline projects respectively. In particular, as these pipelines are intended to transport diluted and blended bitumen products (dilbit[12] and synbit[13]), questions have been raised about how these bitumen derived products may impact pipeline integrity and reliability, as well as risks to the public and the environment in comparison to conventional crude oil.

2.2.1. Review of Recent United States Regulatory Documents

In the United States, while most of the attention has focused on the Keystone XL Pipeline proposed by TransCanada Corporation, capacity additions also include a line reversal and twinning, and a number of expansions to existing systems.

Keystone XL Environmental Impact Statements

The Department of State prepared and issued in 2011 the Final Environmental Impact Statement (FEIS) for Keystone XL[14]. Subsequently, TransCanada updated its application and the Department of State issued in 2013 the Draft Supplemental Environmental Impact Statement (Draft SEIS)[15]. The updated Keystone XL application has two major differences from the original application: a new routing through Nebraska that avoids crossing the environmentally sensitive Sand Hills region and a termination point in southeast Nebraska rather than in Texas. The expansion of Keystone from Nebraska to Texas (the 700,000 barrels per day (bpd) southern leg) was removed from the original Keystone XL application because it does not cross an international border. The southern leg has since been approved under a separate process, was constructed and was started up in January 2014. Keystone XL in the updated application (the northern leg) would have a capacity to transport 830,000 bpd of oil from the U.S-Canada border in Montana to southeast Nebraska for onward delivery to Oklahoma and the Gulf Coast area using the now operational southern leg. Capacity allocation for the northern leg is planned to be 730,000 bpd of dilbit (and synbit) from Alberta and 100,000 bpd of light crude oil from the Bakken Shale Formation in North Dakota and Saskatchewan.

12 Dilbit is the industry term for bitumen diluted with diluent.
13 Synbit is the industry term for bitumen blended with synthetic crude oil.
14 United States Department of State, Bureau of Oceans and International Environmental and Scientific Affairs (2011), Final Environmental Impact Statement for the Proposed Keystone XL Project
15 United States Department of State, Bureau of Oceans and International Environmental and Scientific Affairs (2013), Draft Supplemental Environmental Impact Statement for the Keystone XL Project

In January 2014, the Department of State issued the Final Supplemental Environmental Impact Statement (Final SEIS[16]) which updated the environmental and market analyses of the FEIS and of the Draft SEIS, and confirmed their key findings.

The FEIS, Draft SEIS and Final SEIS addressed in great details the potential impact of the project on GHG emissions, in particular whether production and use of bitumen would cause more GHG emissions than the production and use of conventional oil. The FEIS and the Draft SEIS concluded that the GHG intensity of oil sands products is about 17% higher than for equivalent products from conventional oil[17]. However, the Impact Statements concluded that approving or denying approval for Keystone XL would not have an important impact on the amount of bitumen produced from the oil sands as alternative modes of transportation would be developed (rail and other pipelines) and other market destinations would be sought (e.g. Asia).

Pipeline technical issues, especially safety and the prevention of releases are also discussed in the Impact Statements. They note that TransCanada had accepted the 57 Special Conditions imposed by the Pipeline and Hazardous Materials Safety Administration (PHMSA), a federal agency within the U.S. Department of Transportation which is the primary federal regulatory agency responsible for ensuring the safety of U.S. energy pipelines. Acceptance of these 57 Special Conditions led the FEIS to conclude that "*incorporation of the Special Conditions would result in a Project that would have a degree of safety greater than any typically constructed domestic oil pipeline system under current regulations and a degree of safety along the entire length of the pipeline system that would be similar to that required in high consequence areas as defined in the regulations.*" The Draft SEIS and the Final SEIS reiterated this conclusion.

The 57 Special Conditions were for the most part already imposed on the existing Keystone Pipeline and are providing more details and limitations than existing U.S. regulations. They are arranged in four categories: materials, construction, operations and maintenance, and reporting and records retention. Detailed instructions are provided on such aspects as: steel properties, manufacturing standards, pipe seam quality, fracture control, puncture resistance, pipe coating, welding, SCADA system, cathodic protection, hydrotesting, corrosion surveys, direct assessment, damage prevention, and other tasks associated with designing, constructing and operating pipelines.

The Final SEIS noted that TransCanada had also accepted 25 mitigation measures recommended in reports from Battelle and E^{x}ponent and 11 other additional mitigation measures to improve risk mitigation in Keystone XL's Facility Response Plan, Integrity Management Plan, Emergency Response Plan and Oil Spill Response Plan. The Final SEIS stated: "*An independent*

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[16] United States Department of State, Bureau of Oceans and International Environmental and Scientific Affairs (2014), Final Supplemental Environmental Impact Statement for the Keystone XL Project

[17] The Final SEIS confirmed the analysis, providing the information that the mix of oil sands crudes to be transported by Keystone XL would be 3 to 13% higher in GHG emissions than heavy crudes presently used in the U.S, and 8 to 19% higher when compared to light crudes.

analysis conducted by Battelle on the effect of applying the PHMSA Special Conditions indicates they could result in a sizable reduction in spill frequency."

Finally, the FEIS stated that dilbit and synthetic crude oil (SCO) derived from bitumen are similar in composition and quality to the crude oils currently transported by pipelines and processed in refineries in the U.S. The Draft SEIS offered a similar assessment, stating that "*the characteristics of WCSB SCO and dilbit are similar to those of conventional crude oils."* The Final SEIS also offered a similar assessment.

Environmental Protection Agency

In response to the FEIS, the U.S. Environmental Protection Agency (EPA) issued a letter providing comments[18]. With respect to pipeline technology issues, the EPA observed that the proposed leak detection limit is 1.5 to 2% of the pipeline flow rate and recommended to establish a network of sentinel or monitoring leak detection wells along the length of the pipeline, especially in sensitive or ecologically important areas. Furthermore, the Agency noted that a bitumen spill is likely to require different response actions and equipment than for conventional oil spills. The EPA cited the 2010 spill in Michigan, where oil sands crude sank to the bottom of the Kalamazoo River, making the oil difficult to locate and recover. After almost three years of recovery efforts, the EPA determined that dredging of bottom sediments will be required based on the EPA's determination that bitumen will not appreciably biodegrade. It should be noted that the EPA cleanup requirement far exceed past requirements from the Agency in similar situations.

National Academy of Sciences

Also informing the U.S. debate was a recent report from the National Research Council of the U.S. National Academy of Sciences[19] which was sponsored by PHMSA to study whether dilbit would cause an increased likelihood of releases compared to conventional crudes. The Committee that authored the report held meetings and public hearings, some of which received submissions from Alberta Innovates – Technology Futures (AITF) and Alberta Innovates – Energy and Environment Solutions indicating that the characteristics of dilbit are comparable to those of conventional crudes and that statistical data does not support the assertion that pipelines carrying dilbit are more prone to internal corrosion and pipeline failure than those carrying conventional crudes. The Committee's report was issued in June 2013 with the central finding that "*The committee does not find any causes of pipeline failure unique to the transportation of diluted bitumen. Furthermore, the committee does not find evidence of chemical or physical properties of diluted bitumen that are outside the range of other crude oils or any other aspect of its transportation by transmission pipeline that would make diluted bitumen more likely than other crude oils to cause releases*." The report also contained 3 specific findings as follows:

18 Environmental Protection Agency (2013), Letter to J. W. Fernandez and K-A Jones, Department of State from C. Giles

[19] National Research Council of the National Academies (2013), TRB Special Report 311: Effects of Diluted Bitumen on Crude Oil Transmission Pipelines

- "*Diluted bitumen does not have unique or extreme properties that make it more likely than other crude oils to cause internal damage to transmission pipelines from corrosion or erosion.*
- *Diluted bitumen does not have properties that make it more likely than other crude oils to cause damage to transmission pipelines from external corrosion and cracking or from mechanical forces.*
- *Pipeline operations and maintenance practices are the same for shipments of diluted bitumen as for shipments of other crude oils*."

While the Committee addressed the probability of a spill from pipelines carrying bitumen derived products, it did not study the question of the consequences of such a spill. Risk assessment is the combination of two factors: the probability of an incident happening and the consequences of the incident. Both factors can be acted upon to reduce risk. The fact that the Committee did not study the consequences of a dilbit spill was seen as a major deficiency by critics some of whom recommended that studies needed to be performed on the environmental consequences of dilbit spills[20]. It is possible that such studies may identify means to mitigate the impact of spills and thus reduce risk.

2.2.2. Review of Recent Canadian Regulatory Proceedings

In Canada, proposed pipelines projects include the new Northern Gateway Pipeline by Enbridge, the Trans Mountain Pipeline Expansion Project by Kinder Morgan, the re-purposed Energy East Pipeline by TransCanada and the reversal of Enbridge's Line 9[21].

In December 2013, the Joint Review Panel of the National Energy Board (NEB) recommended approval of the Enbridge Northern Gateway Project after 180 days of public hearings and a review of a detailed application by Northern Gateway. The Panel determined that potential benefits for Canada outweighed potential burdens and risks. The approval, if granted by the federal government, would be subject to 209 conditions set out by the Joint Review Panel.

The Northern Gateway Project is composed:

- One 36 inch diameter pipeline that would transport 525,000 barrels per day of oil sands derived products from Alberta to the Pacific coast at Kitimat, BC;
- One 20 inch diameter pipeline that would transport 193,000 barrels per day of condensate from Kitimat, BC to Alberta; condensate is used as the diluent for bitumen;
- One marine terminal at Kitimat BC where oil tankers would load diluted bitumen to export destinations.

Prominent during the hearings were concerns about marine and inland oil spills and the unresolved land rights and other rights of First Nations.

[20] New York Times (2013), Scientists find Canadian oil safe for pipelines, but critics say questions remain, available online at http://www.nytimes.com/2013/06/26/us/scientists-find-canadian-oil-safe-for-pipelines-but-critics-say-questions-remain.html?_r=0

[21] The reversal of Line 9 was approved by the National Energy Board on March 6, 2014.

In April 2013, the Board published 199 potential conditions for comment[22]. This list was expanded to 209 conditions in the recommendation for approval[23]. In contrast to the U.S. regulatory review of Keystone XL, the NEB conditions do not address the GHG emissions of oil sands products. In general, the conditions specify detailed future reporting by Enbridge during all phases of the project (pre-construction, construction and operations) regarding compliance to code and regulations. They require the future submission of detailed plans for the design, construction, and operations of the pipeline; environmental management plans for impacts on air, water and land; consultations with First Nations, land owners and relevant federal and provincial authorities; plans for emergency and cleanup response in the event of a spill; and plans specific to the Kitimat Terminal and marine operations.

The purpose of conditions is to mitigate potential risks and effects associated with the project so that the project would be designed, constructed, and operated in a safe manner that protects human health and the environment. This approach reflects the NEB's strategy to risk management by reducing the probability of incidents by requiring excellent project execution and quality control, and by mitigating the consequence of possible incidents by mandating pre-established response capabilities.

Of note, 3 conditions (no 169, 170 and 193) require the Northern Gateway Project to undertake and file annual and final reports about a research program into the behaviour and cleanup of heavy oil spills.

2.2.3. Key Issues in Public Debate

The above review of reports by regulators in the United States and Canada serves the purpose of proving context to the Roadmap. Other than concerns about the higher GHG intensity and the overall environmental impact of oil sands products, the key issues related to pipeline technology that were raised in public reports, hearings and comment can be summarized as follows:

- The possibility of a pipeline failure with potential impact on property damage and impact on the environment; and
- The concern regarding whether a spill of oil sands products could be more difficult to clean up and could cause more environmental impact than a spill of conventional crude oil or a release of natural gas.

Of note, key issues raised in public debate did not, in general, emphasize subjects such as project need, costs, tariffs, project size, local and national economic impact, job creation, pipeline performance metrics, and the direct environmental impact of pipelines other than the impact of an oil spill. In general, the core of the debate is about finding the appropriate balance between

[22] Joint Review Panel for the Enbridge Northern Gateway Project (2013), Collection of potential conditions – Northern Gateway Pipelines Inc. (Northern Gateway) – Enbridge Northern Gateway Project – Hearing Order OH-4-2011

[23] Joint Review Panel for the Enbridge Northern Gateway Project (2013), Connections, Report of the Joint Review Panel for the Enbridge Northern Gateway Project, Volumes 1 and 2. Volumes 1 and 2

economic benefits and environmental impact, and the best means to proceed should the projects be approved.

2.2.4. Legacy Pipeline Networks

While most of the attention of regulators and the public has been directed at proposed capacity additions through new builds, expansions and re-purposing, some observers are concerned that pipeline incidents are generally associated with legacy pipelines which could exhibit vulnerabilities due to their age. A recent study sponsored by the INGAA Foundation[24] reviewed 2059 pipeline ruptures or major leaks in natural gas pipelines reported to PHMSA over the 20 years between 1992 and 2011. Although the study was for natural gas service, the authors believe that the results are equally applicable to oil pipelines. The study found that for 85% of incidents a statistical relationship could not be of established with the age of the pipeline. Only 15% of incidents could be related in some way to age. In general, the authors concluded that the properties and performance of pipeline steels do not markedly change with time. In other words, pipe steel does not "wear out." The types of failures that were found to correlate in some way with age included external corrosion, manufacturing defects, component defects, girth and seam welds and stress corrosion cracking. In many cases, pipeline operators can take action to mitigate the effects of pipeline age.

However, a number of older pipelines were built using technologies that, while modern at the time, are no longer the best available. Examples include tape coating and Low Frequency Electric Resistance Welded (Low Frequency ERW) pipe. It may be the case that pipelines incorporating such technologies would warrant focused and tailored integrity and monitoring programs.

2.2.5. Gathering Lines

Some industry observers have raised issues related to gathering lines used in the petroleum industry. In Canada, while there are 100,000 km of transmission pipelines, more than 250,000 km of gathering lines are used, predominantly by oil and gas companies, to transport fluids from wells and production batteries to treatment plants and to connection points in the transmission pipeline network or to disposal sites. Gathering lines are generally of smaller diameters than transmission pipelines and transport a wide variety of process fluids that includes raw gas, sour gas, raw oil, produced water and mixtures thereof.

In general, gathering lines present greater integrity challenges than transmission pipelines due to the variety of products transported, many of which include water which is the primary cause for internal corrosion, as well as the fact that such smaller diameter pipelines offer fewer opportunities for in-line inspection tools and other monitoring technologies. However, the

[24] Kiefner, John F.-and Michael J. Rosenfeld (2012), The Role of Pipeline Age in Pipeline Safety, prepared for the INGAA Foundation, Report number 2012.04 , online at http://www.ingaa.org/Foundation/Foundation-Reports/PipelineAge.aspx

smaller diameters and the lower operating pressures of gathering lines also mean that the volume of possible spills is generally smaller.

3. Overview of Methodology

3.1.Roadmap Methodology

The value of this Roadmap is in capturing a high level consensus among participants as a first step toward a strategic plan. The outcome of the Roadmap is to describe the directions and potential paths that could be followed to deliver improvements from the current situation. Thus the Roadmap is composed of the following elements:

- Statement of strategic drivers that are leadership choices to respond to stakeholder needs or industry opportunities; the strategic drivers describe how the current state needs to change to reach the desired future state; they also represent criteria for the allocation of resources and the selection of technology and market trends that could be harnessed. The strategic drivers for this Roadmap were presented in Section 1.4 and are based on the issues described in Section 2.
- Assessment of the current state, including capabilities, knowledge gaps, opportunities, priority areas and prospective technology advances. In this report, this assessment is presented in two part:
    - Knowledge network mapping which, in Section 4, reports on worldwide capabilities and expertise in pipeline engineering as well as level of effort in the full range of pipeline technology research topics.
    - Gap analysis which lists in Section 5 technology gaps, barriers, research needs, and prospective research opportunities.
- The Roadmap, discussed in Section 6, which offers paths and options to close gaps and to realize opportunities in order to create positive momentum from the current state to the desired future state.

Thus, the Roadmap is inspired and motivated by the strategic drivers that directionally point toward the desired future state and presents for consideration possible path and options to navigate around or overcome gaps and barriers through continuous improvement or game changing technologies or a mix thereof.

3.2.Project Workflow

The project workflow was composed of 3 major tasks:

1. Knowledge network mapping;
2. Gap analysis; and
3. Innovation Roadmap for Transmission Pipeline Transportation of Petroleum Products.

Each task is summarized below and an overview of workflow integration is shown in Figure 1.

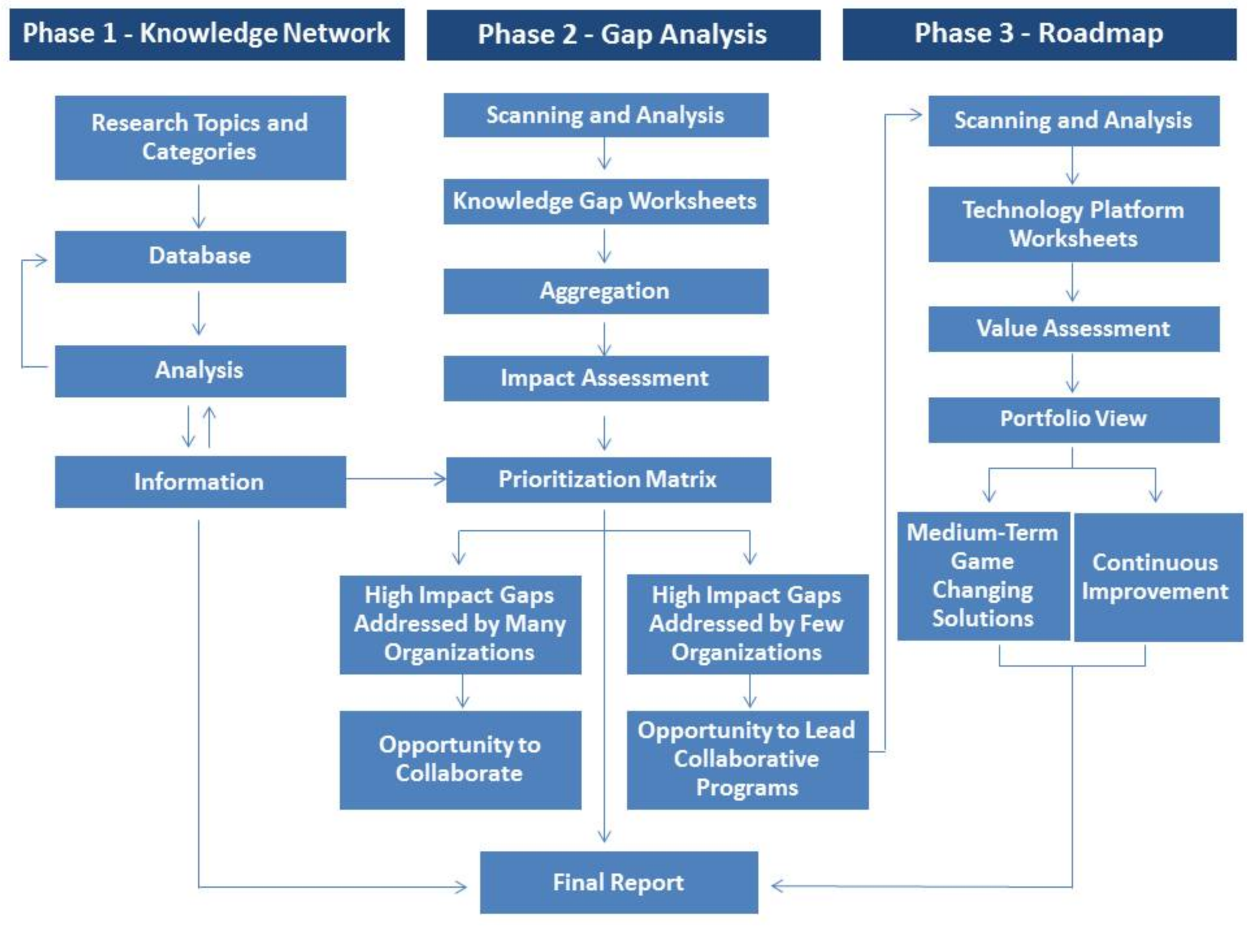

Figure 1. Pipeline Innovation Roadmap Workflow Overview

- Knowledge Network Mapping. Literature searches, complemented by internet searches and interviews, were conducted to identify individuals, institutions, research organizations and service providers, as well as key active programs in pipeline research globally, with emphasis on North America. The searches were based on public information but could not access information kept confidential by research organizations. The output of this task was to list and describe who is doing what and where the expertise is located.
- Gap Analysis. Technology gaps and barriers exist between the current situation and the desired future state based on the strategic drivers. Each aspect of pipeline technology was examined to identify and describe such gaps. The output of this task was to summarize gaps specific to improving the integrity and environmental impact of transportation of petroleum products by transmission pipelines, with some emphasis on bitumen derived

products. At the same time, opportunities presented by technology advances were also identified.

- Roadmap. Once gaps and research needs are identified, potential solutions, prospective areas for research and innovation programs can be formulated to present options and guide future technology investments by industry, government and academia. The output of this task was a Roadmap describing a portfolio of technology opportunities to bridge gaps, overcome barriers, realize opportunities and effect tangible movement toward the desired future state, thus fulfilling the strategic drivers.

Phase 1 was concerned with Knowledge Network Mapping, delivering a database and information analysis about energy pipeline research worldwide. This outcome is captured in Section 4 of this report. It also informed the Research Opportunity Matrix of Phase 2 (Section 5). Gaps, research needs and technology opportunities were configured according to their impact on the strategic drivers and the worldwide level of effort in the subject area in order to determine which gaps/opportunities presented leadership potential and which were best for collaboration with peer research organizations. Priority areas were subsequently explored further and developed into potential technology solutions which were analyzed and aggregated into the technology opportunities portfolios during Phase 3 (Section 6). Additional methodology details are provided later in this document in the relevant sections.

3.3.Project Organization and Key Events

The organizational structure of the project included the Steering Committee, PTAC Petroleum Technology Alliance Canada as the project manager, and the project team which facilitated work sessions and the final workshop, and which produced various work products such as worksheets, the Interim Report and the Final Report. Figure 2 illustrates the project organizational relationships.

The Steering Committee provided governance and strategic direction to the project. It was comprised of representatives from Alberta Innovates - Energy and Environment Solutions (AI-EES) and of the Canadian Energy Pipeline Association (CEPA). AI-EES is an agency of the Government of Alberta with a mission that includes ensuring that government policy decisions are informed by sound technical analysis, supporting and sharing the development of innovative clean energy technologies, and helping Alberta become a global leader in sustainable energy production. CEPA represents Canada’s transmission pipeline companies who transport 97% of Canada’s daily natural gas and onshore crude oil production from producing regions to markets throughout Canada and the United States.

PTAC provided project management and administrative services to the project and was the entity responsible for delivering it. PTAC is a 17 year old not for profit organization that was created to promote collaborative research and technology development for the Canadian hydrocarbon energy industry. PTAC’s network is comprised of approximately 200 member organizations, including oil and gas producers, who produce approximately 80% of Canadian conventional oil and gas, transporters, government bodies, research providers, venture capital firms, academic institutions, individuals, as well as service and supply companies. The project manager and lead report author was Marc Godin.

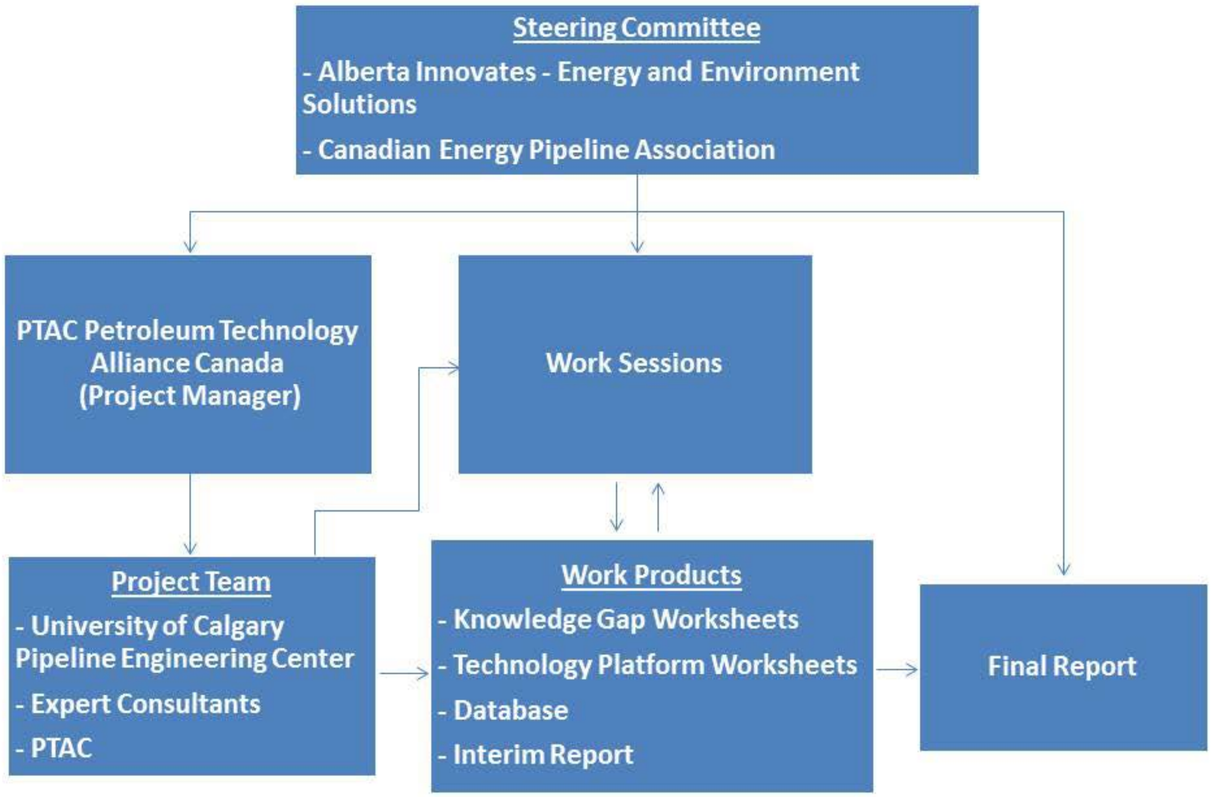

Figure 2. Pipeline Innovation Roadmap Workflow Relationships

The project team was tasked with producing the work products required for the execution and delivery of the project. It was composed of University of Calgary faculty (Drs. Ron Hugo, Frank Cheng and Harvey Yarranton) through the Pipeline Engineering Center (PEC), as well as industry professionals and subject matter experts (Dr. A. Murray, D. Horsley, Dr. M. Yoon, Dr. J. Oswell, R. Motriuk and A. Sinha). The PEC is the only pipeline engineering research and training centre in North America. The Center fosters and facilitates the generation, transfer and retention of knowledge of pipeline engineering. PEC researchers have complementary expertise in pipeline engineering and related fields and pursue innovation in pipeline science and engineering through projects with strong industrial participation.

The project involved a number of meetings, the most notable of which were three work sessions including the Steering Committee and the project team, and a final workshop. The work sessions were designed to review and integrate various individual assignments and obtain feedback from the Steering Committee regarding project contents and key messages. The final workshop presented key project findings and outcomes to a broad audience composed of invited partners and associates of AI-EES and CEPA.

The following sections of this document are dedicated to each of the project major tasks, describing methodological details, outputs and key messages:

- Knowledge Network Mapping (Section 4)
- Knowledge Gap Analysis (Section 5)
- Innovation Roadmap for Transmission Pipeline Transportation of Petroleum Products (Section 6).

4. Knowledge Network Mapping

The first task of the project was to develop a knowledge network map of pipeline transportation technology. This map acted as a foundation and resource for the next tasks of knowledge gap analysis and roadmap development.

4.1. Objective

The purpose of this task was to produce a knowledge network map of pipeline transportation technology for petroleum products. In other words, who is doing what; and where the expertise is located. The goal was to list individuals, institutions, research organizations, and service providers, as well as key active programs in pipeline research globally, with emphasis on North America.

4.2. Methodology

A systematic survey process was followed to map subject matter experts, to produce a database, with names, contact information, description, areas of expertise, capabilities and major activities. The process included the following steps which are illustrated in Figure 3:

- Preliminary listing based on the project team's collective experience;
- Identification of research topics starting from the structure of the International Pipeline Conference, and aggregating and complementing it with input from the project team;
- Preparation of a database to house the information;
- Systematic population of the database using literature searches of authors who published during the last 3 years in the research topics;
- Interviews of key individuals to fill any missing information and ensure completeness of the database;
- Validation of the Knowledge Network Map; and

- Update of the Knowledge Network Map based on feedback.

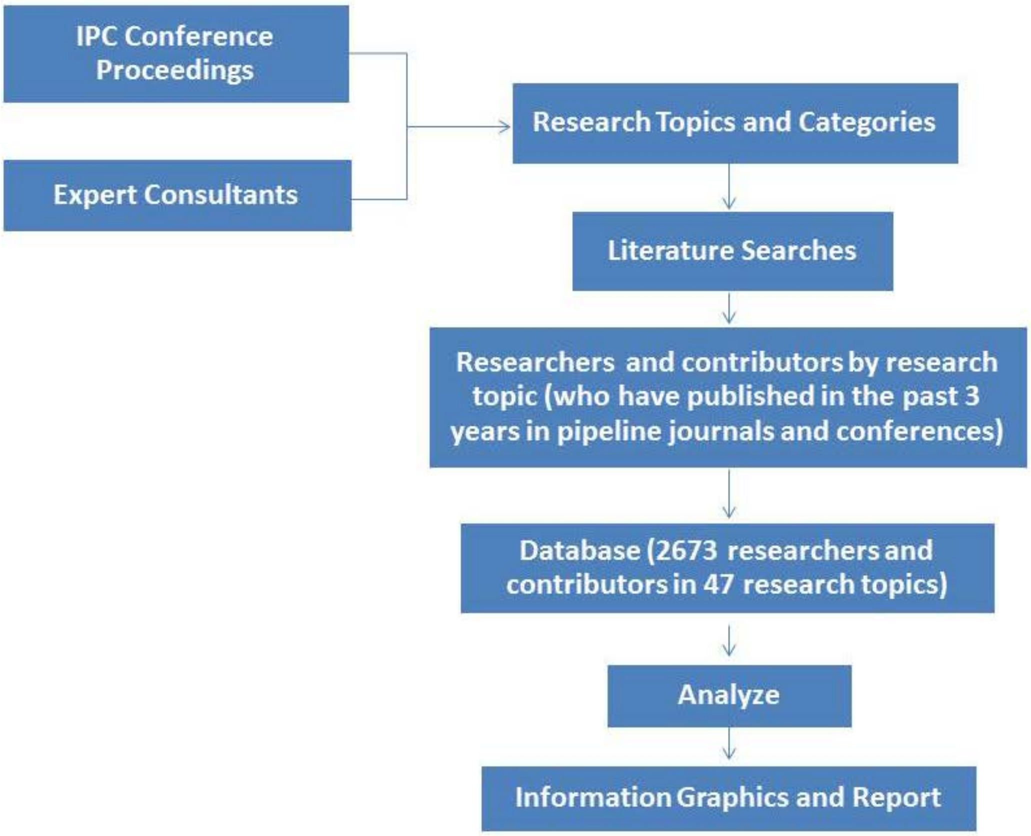

Figure 3. Knowledge Network Map Workflow

The literature searches were performed using the following information sources:

- Conferences:
    - International Pipeline Conferences
    - NACE conferences
    - International Offshore and Polar Engineering Conferences
    - Pipeline Technology Conference.
- Journals:
    - International Journal of Piping and Pressure Vessels
    - Journal of Pipeline Integrity
    - Corrosion
    - Pipeline & Gas Journal
    - World Pipelines

- Pipeline International
- Canadian Geotechnical Journal
- Journal of Geotechnical and Geoenvironmental Engineering
- Journal of Loss Prevention in the Process Industries.

Literature searches were supplemented by discussions with industry experts and representatives of organizations engaged in pipeline research and innovation, as well as internet searches.

4.3.Results

4.3.1. Overview

The survey data assembled through searches and consultations was analyzed quantitatively and qualitatively to extract information about key characteristics of pipeline research and innovation. The following sections present the results of this analysis in terms of the geographical distributions of researchers, highlights of key research centers and institutes, and the level of effort directed at different research topics.

4.3.2. Researchers in Pipeline Technology

As part of the knowledge network mapping task, an extensive list of researchers and contributors working in pipeline-related topics was produced.

The literature searches resulted in a database comprised of over 500 organizations with at least one identified sub-focus in pipeline-related innovation and over 2,600 researchers and contributors working in the field. The geographic distribution is displayed in Figure 4. As noted above, the literature searches emphasized North America and the results may understate participation in Europe and Asia.

As shown in Table 1, the countries with the highest number of active researchers and contributors identified in the survey are, in descending order: the United States, Canada, China, Japan, the United Kingdom, Brazil and Germany. Of these nations, the United States with 613 identified researchers, Canada with 429 and China with 418 identified researchers are clear industry leaders, with Japan, the United Kingdom, Brazil and Germany completing the list of countries with over 100 active researchers.

Figure 4. Geographic Distribution of the Pipeline Technology Researchers

Table 1. Countries with the Highest Number of Active Researchers	
Country	**Number of Researchers**
United States	613
Canada	429
China	418
Japan	153
United Kingdom	143
Brazil	136
Germany	107

It is also interesting to note that, as a critically important energy hub of the world, the Middle East also has an active research community working in the field of pipeline research, primarily based out of the petroleum and natural gas dependent economies of Kuwait, Iran, and Saudi Arabia. Their participation in international conferences may be hampered by political circumstances such as the sanctions imposed on Iran. Thus their representation in the database may be understated. The lack of identified researchers in the African continent and South Asia can potentially be attributed to the developing economies in those regions, where the pipeline infrastructure is currently nascent and very early in its development.

The database was also analyzed to determine the affiliation of researchers which was classified as affiliate of government, pipeline operator, pipeline service company, or research institute affiliated with a university or the private sector. The results are displayed in Figure 5.

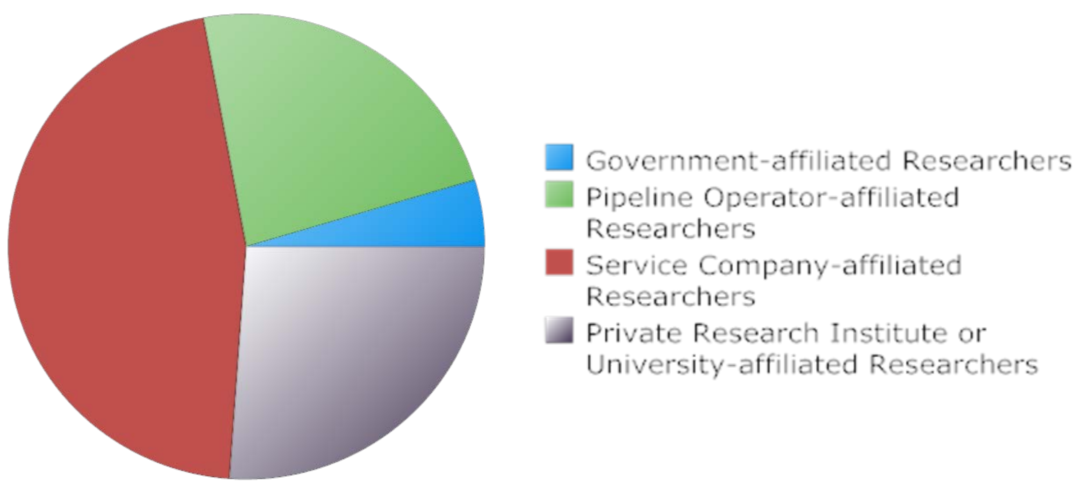

Figure 5. Affiliation of Researchers

It is evident from Figure 5 that a considerable portion of work in pipeline research and innovation is conducted by researchers and contributors affiliated with pipeline service companies, while government-affiliated researchers form only a small portion of the pipeline innovation system. The work conducted in many private research institutions and universities around the world is also primarily funded by the corporate sector. As such, it is evident that a strong majority of the research work in pipeline technology is driven by industry, be it through pipeline operators, pipeline service companies, or research institutes that garner a large fraction of their funding from the pipeline industry.

It is noted that research occurs in companies, universities and research institutes under confidentiality terms that may prevent publication of the results. Such proprietary work would not be published and would not be accounted for in this review. Furthermore, service companies and equipment suppliers may use journal and conference publications to disseminate information about new products and case studies of current technologies. Thus, it is possible that work done by universities, research institute and pipeline operators may be underrepresented in the literature, while work done by service companies may be overrepresented.

4.3.3. Research Organizations and Institutes

To add depth to the statistical analysis of the database, consultations with industry experts and representatives of pipeline research and innovation organization were undertaken to develop a non-exhaustive list of key organizations engaged in pipeline research and innovation. In addition, many sources of accessible and internet-based information were consulted.

The non-exhaustive list of information sources is presented in Table 2 where organizations are categorized as:

- Government institutions
- Industry trade organizations
- Codes and standards organizations
- Professional bodies
- Universities and research institutions
- Pipeline operating companies.

While not all of the listed organizations perform research and development, they are active in some aspect of the innovation process which, beyond the creation of knowledge and the development of new technologies extends to the dissemination and regulation of new technologies through conferences, standards and enhancements to regulatory frameworks.

Table 2. List of Organizations Active in Aspects of Pipeline Innovation

Organization	Focus of Activities
Government Institutions	
NRCan Office of Energy Research and Development (Canada)	• Oversight of programs on energy research and development
NRCan CanmetMATERIALS Testing Laboratory (Canada)	• Internal & external corrosion • Stress corrosion cracking • Coatings • Steel metallurgy • Fracture mechanics
NRCan Banff Pipeline Workshop Proceedings (Canada)	• Documented discussions on operational topics

National Energy Board (Canada)	• Regulator of national, territorial and export pipelines
Alberta Energy Regulator	• Regulator of Alberta intra-provincial pipelines
Alberta Innovates – Technology Futures	• Facilities and technical services for specialized testing and for leak detection, through its C-FER subsidiary
Pipeline and Hazardous Materials Safety Administration (PHMSA; United States)	• Federal regulator (Codes of Federal Regulations) • Construction quality issues • Damage prevention • Materials joining, remote sensing, risk, etc., through its Research and Special Projects Administration department which maintain a comprehensive research website.
NIST (National Institute of Science and Technology), Boulder, CO, United States	• Pipeline high strength material performance • Welding and joining processes
Health and Safety Executive (United Kingdom)	• Health and safety regulator • Incident statistics • Incident reports • Commissioning of research on pipeline integrity risk and reliability • Man/machine interfaces • Human factors
National Transportation Safety Board (United States)	• U.S. incident investigation reports
Transportation Safety Board (Canada)	• Canadian incident investigation reports
TNO (Netherlands Organisation for Applied Scientific Research)	• Pipeline standards
Industry Trade and R&D Funding Associations	
Canadian Energy Pipelines Association (CEPA)	• Represents Canada’s transmission pipeline companies • Pipeline statistics • Surface loading • Abandonment

Pipeline Research Council International (PRCI - a cooperative pooling of R&D funds and contracting)	• PRCI has developed relationships of varying degrees of formality with the many organizations and groups having complementary interests. These relationships include Tripartite work with Australian Pipeline Industry Association (APIA) and European Pipeline Research Group (EPRG) and Strategic Partnerships with Centro de Tecnologia em Dutos (CTDUT) and European Gas Research Group (GERG), as well as links with the following organizations: • PRCI also links with R&D organizations such as International Gas Union (IGU), NYSEARCH/Northeast Gas Association (NGA), C-FER, Det Norske Veritas (DNV), and Southwest Research Institute (SwRI).
Interstate Natural Gas Association of America	• Trade organization for the natural gas pipeline industry in North America • Efficient construction and safe, reliable operation
Australian Pipeline Industry Association (APIA)	• Australian incident reports • Standards development working papers • Competency assessments • Member of PRCI
United Kingdom Onshore Pipeline Operators' Association (UKOPA)	• UK pipeline operator incident reports
European Pipeline Research Group (EPRG)	• Mechanical damage models • High strength steel making and quality control • Material strength • Pipe mills and gas pipeline operators and European incident statistics • Tripartite PRCI partner
European Gas Research Group (GERG)	• European industry association focused on supporting R&D in natural gas energy infrastructure.
CONCAWE (Conservation of Clean Air	• European pipeline incident statistics

and Water in Europe)	
Centro de Tecnologia em Dutos (CTDUT)	• Located in Brazil, CTDUT is a technological center for developing pipelines and a partnership between Petrobras, Transpetro and Pontifícia Universidade Católica of Rio de Janeiro.
International Gas Union (IGU)	• International Association supporting the natural gas industry worldwide.
Codes and Standards Organizations	
Canadian Standards Association (CSA)	• Pipeline (Z662) and materials standards (Z245.xx) including coatings • Land Use Planning (Z663)
British Standards Institute	• Numerous design and materials standards
American Society of Mechanical Engineers (ASME)	• Pipeline codes and standards
NACE International (formerly National Association of Corrosion Engineers)	• Pipeline corrosion standards and recommended practices • NACE publication: Crude Oil Corrosivity Under Pipeline Operating Conditions • "How corrosive is heavy crude?" was addressed at the 2012 Northern Area Eastern Conference hosted by NACE International's Toronto Section in Toronto, Canada
American Petroleum Institute (API)	• Pipeline codes and standards (e.g. API 5L) • Tanks and storage vessels • Annual Conference proceedings
ABS (formerly American Bureau of Shipping)	• Offshore pipeline codes and standards
Det Norske Veritas (DNV)	• Submarine pipeline rules • Recommended practices for : o Pipeline remaining life assessment o Technology development etc.
Professional Bodies	
American Society of Mechanical Engineers (ASME)	• Conference proceedings e.g. OMAE Pipeline Symposium 82- 2012 • Technology transfer IPC 96- 2012

Institution of Gas Engineers and Managers (IGEM; United Kingdom)	• Technical standards
Universities and Research Institutions	
University of Calgary	• Stress corrosion cracking • Internal corrosion • External corrosion and coatings • Erosion-corrosion • Pipe soil interaction
Pipeline Engineering Center (University of Calgary)	• Pipeline integrity, maintenance, and management • New pipeline technologies • Project management
University of Alberta	• Metallurgy of steels • Pipe soil interaction • Stress corrosion cracking • Structural behaviour and buckling • Joining and welding • Geotechnical • Environmental and economic studies (Centre for Applied Business Research in Energy and Environment – CABREE)
C-FER Technologies	• Reliability-based design methodology • Quantitative risk assessment • Pipe-soil interaction analysis and strain-based design • Full-scale tests on the strain limits of high-strength line pipe • Finite element analysis of the structural capacity of line pipe • Assessment and evaluation of leak detection technologies
Alberta Innovates – Technology Futures	• Corrosion, stress corrosion cracking and corrosion fatigue • Industrial sensors • Advanced materials
University of Saskatchewan	• High-strength steel metallurgy • Stress corrosion cracking

	• Hydrology
University of Waterloo	• Defect modeling • Stress Corrosion Cracking
Queen's University	• Magnetic properties of pipeline steels (Barkhausen effect) • Telluric currents
University of Toronto	• Self-healing materials
Memorial University	• Research funding from levy on oil and gas production • Expertize in offshore pipelines and production systems • Centrifuge modeling of pipes/soil interactions
Centre for Cold Ocean Research (C-CORE)	• Offshore geotechnics, ice/seabed and soil/structure interactions • Reduced-scale physical modeling.
University of British Columbia	• The UBC Pipeline Integrity Institute has a long term technical capacity in research and training in pipe/soil interaction, materials and other areas.
McMaster University	• Soil-pipeline interaction • Computational geotechnical mechanics
McGill University	• Mathematical modeling • Frost heave effects
Ohio State University	• Internal corrosion
Colorado School of Mines	• Welding • Hydrogen cracking • Metallurgy
University of Newcastle	• Environmentally assisted cracking • Pipeline material science • Corrosion mechanisms including SCC
University of Ghent	• The Metal Structures Centre, in collaboration with the Belgian Welding Institute studies steel structures such as high pressure pipelines.
Pontifical University of Rio De Janeiro	• Hydrogen-induced cracking of pipeline steels • Defect assessment models • Biofilms and microbially influenced corrosion

Loughborough University	• Flammability and dispersion modeling
Cranfield University of Technology	• Welding and joining • Subsea pipeline technology • Fracture mechanics and stress corrosion cracking (SCC)
University of Wollongong /CRC	• Pipeline materials • Welding • Fracture
Edison Welding Institute	• Welding and joining • In service repair methods • Strain-based design
Southwest Research Institute	• Composite materials • Sensing technology • Remaining life assessment • Cathodic protection
Battelle Research Institute	• Fracture mechanics • Damage models • ILI tool development
NYSEARCH and the Northeast Gas Association (Collaborative natural gas RD&D; United States)	• Consortium research focused on leak detection and encroachment detection technologies for non-piggable lines (e.g. robotics, guided wave technology)
TWI (also known as The Welding Institute; Cambridge, UK)	• Welding and joining • Fracture mechanics/fatigue • Weld inspection • Guided wave technology
Pipeline Operating Companies and Technology Suppliers	
Pipeline operating companies, such as: TransCanada, Enbridge, Kinder Morgan, Alliance Pipeline, ATCO Pipelines, Gasunie, Petrobras and its research division Centro de Pesquisas Leopoldo Américo Miguez de Mello (known as Cenpes), PetroChina and its Research and Development unit (based in Langfang), and others.	• Discussion of operating practices via CEPA Operating and Technical Committee and other industry associations • Research and development activities and programs in integrity, leak detection, oil and gas dynamics and other areas.

A summary description of the major industry collaboration centers is provided below:

- The Pipeline Research Council International (PRCI) was founded in 1952 and is a globally recognized forum focused on the energy pipeline industry, based out of Virginia, U.S. The PRCI focuses on the development of research solutions to the operational, maintenance, and regulatory challenges facing its members and the energy pipeline industry as a whole through qualitative and quantitative analyses. PRCI is comprised of the world's leading pipeline companies as well as a number of technology developers, service providers and equipment manufacturing firms.

- The Gas Technology Institute (GTI) is an independent not-for-profit technology organization dedicated to research, development and training in the natural gas industry with emphasis in supply and energy efficient utilization. With 250 employees and $60 million in research and technical services annual revenues, GTI research initiatives address issues across the industry's value chain: supply, delivery, and end use.

- The American Petroleum Institute (API) is the trade association that represents all aspects of the U.S. oil and natural gas industry. API conducts or sponsors research ranging from economic analyses to toxicological testing. The Institute also maintains and publishes statistics, develops technical standards and offers technical training and certification.

- The Canadian Energy Pipeline Association (CEPA) represents Canada's transmission pipeline companies who transport 97% of Canada's daily natural gas and onshore crude oil production from producing regions to markets throughout Canada and the United States. CEPA committees focus on operating practices, statistics, surface loading, abandonment and other topics related to integrity and safety. The CEPA Foundation is dedicated to innovation and implementation of practices in respect of safety, quality, environmental stewardship, and social responsibility.

- The Australian Pipeline Industry Association (APIA) represents Australasia's pipeline operators and service and supply companies, and focuses on gas transmission, along with branches relating to the transport of oil, water, slurry and CO_2. Founded in 1998 and based out of Canberra, Australia, APIA's membership is comprised of constructors, owners, operators, advisers, engineering companies and suppliers of pipeline products and services, and the institution has strong and active relationships with leading research institutes in the region as well as with PRCI and EPRG.

- The European Pipeline Research Group (EPRG) is an association of European pipe manufacturers and pipeline operators based out of Duisburg, Germany. The group focuses on technical issues that relate to pipeline integrity, pipeline manufacture and design, as well as their operation and maintenance. The EPRG researches the various findings within the industry along with global guidelines on the same as published in journals or presented at conferences and facilitates their dispersion to the broader pipeline industry throughout Europe. EPRG comprises of members that focus primarily in Western Europe but also has partner companies based out of Greece, Finland, and Italy.

It should be noted that the European Union also funds pipeline research through several programs on a project by project basis.

Additionally, pipeline research and innovation is active in China. Key Chinese universities and industry organizations are:

- China University of Petroleum (Beijing)
- China University of Petroleum (East China)
- University of Science and Technology (Beijing)
- Institute of Metal Research, Chinese Academy of Sciences
- Southwest Petroleum University
- Dalian Technology University
- Petro-China Pipeline Research Center
- Sinopec Pipeline Research Center
- Petro-China Tubular Goods Research Institute
- China National Offshore Oil Corp (CNOOC) Research Institute.

It is also useful to mention that Alberta is home for the headquarters of major Canadian pipeline companies and their technical staff and facilities (e.g. TransCanada, NOVA Chemicals and Enbridge), and Canadian pipeline manufacturing, service and technology companies (e.g. Shaw Pipe, Stantec, CIMARRON Engineering (now part of Stantec), Pure Technologies and Nova Chemicals Testing Services), or the principal Canadian office for international pipeline operating (e.g. Kinder Morgan Canada) and service companies (e.g. ROSEN Canada). Furthermore, government laboratories with pipeline technology capabilities are located in Alberta: C-FER Technologies and Alberta Innovates – Technology Futures (Alberta Government) and CanmetMATERIALS and CanmetENERGY (Natural Resources Canada).

In addition, universities across the globe host institutes and research centres for pipeline research. The survey database was used to list university researchers and contributors by country of origin with the results shown in Table 3. The top 5 countries with the highest number of university-based researchers and contributors are China (165), Canada (116), United States (81), Australia (39) and Brazil (30).

Table 3. University Researchers by Country

Country	Number of Researchers	
North America		214
Canada	116	
Mexico	17	

United States	81	
South America		44
Brazil	30	
Chile	3	
Cuba	1	
Venezuela	10	
Europe, Turkey and Russia		85
Belgium	10	
Denmark	1	
France	4	
Germany	5	
Greece	7	
Italy	4	
Netherlands	3	
Norway	7	
Poland	1	
Russia	11	
Spain	5	
Turkey	2	
United Kingdom	25	
Middle East and Africa		29
Iran	18	
Israel	2	
Libya	2	
Saudi Arabia	5	
South Africa	2	
Asia		238
Australia	39	
China	165	
Japan	17	
Singapore	9	
South Korea	8	

4.3.4. Level of Effort by Research Topics

The knowledge network map was further analyzed to determine which areas of pipeline research were the most active. The overall results for the research interests of the 2,673 identified researchers are shown in Table 4 with a summary by research categories displayed in Figure 6. The research categories were derived and adapted from categories of topics used by the International Pipeline Conference, thereby reflecting how the industry approaches technology. As indicated earlier, the identified researchers are those who have published or presented papers in the noted journals or conferences in the last 3 years. The total number of entries in Table 4 is greater than the total number of researchers because many researchers are active in more than one research topic.

Table 4. Number of Active Researchers by Research Topics

Environment (Direct Impacts)	
Route Selection	36
Footprint Impact	2
Design	
Flow Assurance	14
Geotechnical and Civil Engineering	114
Geohazards, Weather-Related and Outside Force Threat Assessment	48
Design	229
Strain Demand	48
Tensile and Compressive Strain Capacities	111
Pipelining in Northern Environments	105
Materials	
Steel Metallurgy	228
Crack Propagation and Arrest	67
Materials for Strain-Based Design	61
Spiral Pipe Performance	4
Construction	
Construction	74
Pipe Production	76
Welding and Fitting	179
Operations and Maintenance	
SCADA, Automation and Instrumentation	9
Measurement and Metering	5
Pipeline Repair	53
Applied Modelling	12
Hydraulic Simulations and Real Time Advanced Functions	54

Integrity Management	
Internal Corrosion	268
External Corrosion	73
AC (Alternating Current) Corrosion	61
Coatings and corrosion under coating	131
Cathodic protection	122
Cracking and Stress Corrosion Cracking	227
Inspection, Monitoring and Testing	199
In-line inspection	131
Pipeline Pigging	40
Defect Assessment	115
Mechanical Damage	98
Structural Integrity	13
Facility Integrity	51
Facility Inspection Techniques	25
Failure Analysis	41
Failure Frequency and Consequences	6
Risk and Reliability Based Methodologies	92
Risk Assessment and Operational Reliability of Pipeline Systems	102
Risk and Reliability Application to Corrosion and Crack Management	17
Loss and prevention control	0
Process Safety	16
Leak Detection	
Leak Detection Tools	7
Leak Detection Models	11
Spill Cleanup and Remediation	
Oil Spills Remediation	50
Recovery techniques and equipment	5
Reclamation	
Pipeline Abandonment	0
Total	**3430**

Figure 6 shows the diversity in the level of effort across the different categories of pipeline research. It is evident that Integrity Management dominates, accounting for 53% of papers published or presented and representing at least one of the research interest of 68% of the researchers identified. It should be noted that Integrity Management is a broad category with a long standing interest that has grown over time to include a large number of research topics ranging from corrosion to in-line inspection.

Other categories that received a notable amount of attention were: Design, Materials, and Construction. The categories with the smallest publication record were: Environment, Maintenance, Leak Detection, Spill Cleanup and Remediation, and Reclamation. It should be noted that it could be possible that a number of researchers in Environment may publish in environmental sciences journals and conferences and may be under-represented in pipeline journals and events. Nevertheless, with an increased focus on pipeline integrity and environmental impact, a growing interest in the area of integrity management systems and environmental impact is foreseeable in the near future.

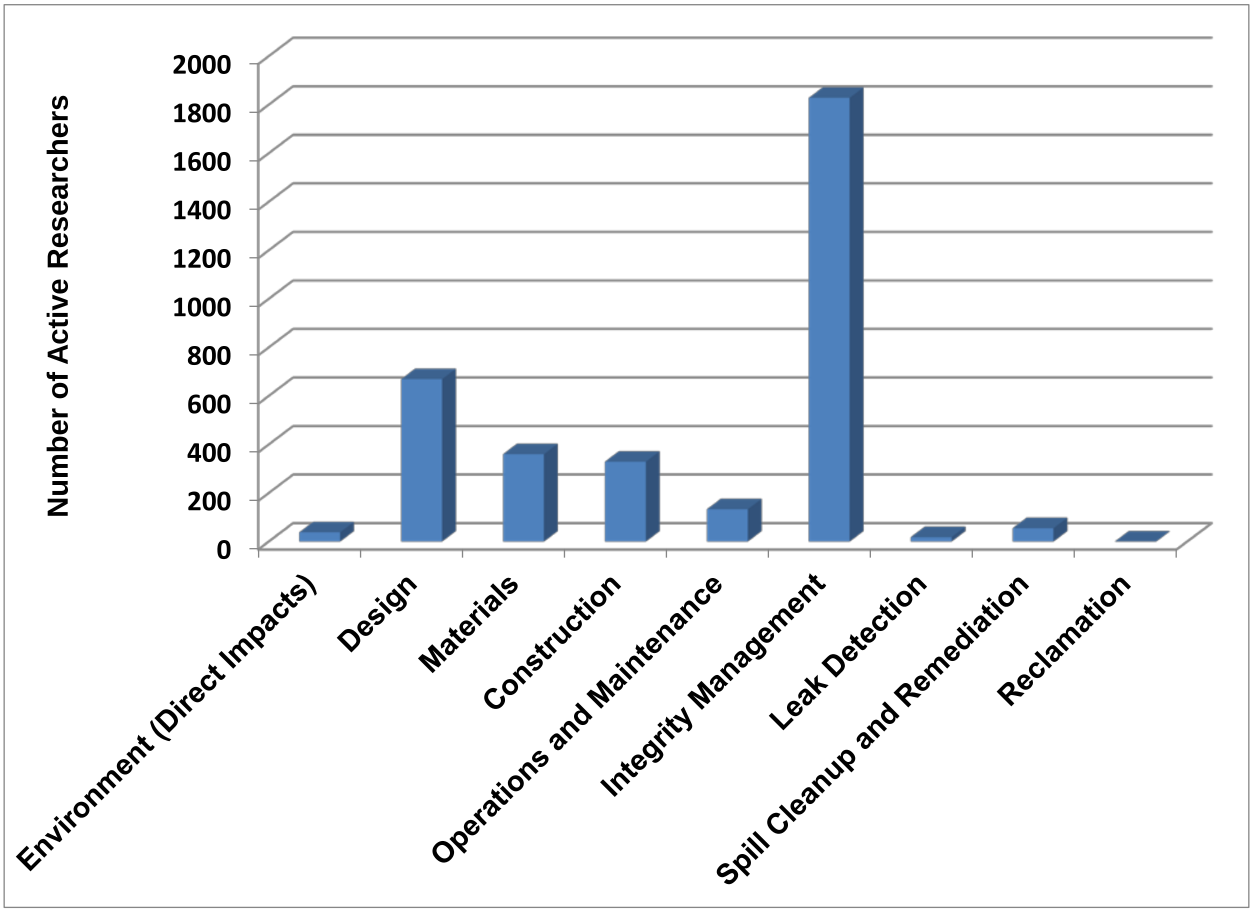

Figure 6. Overall Level of Effort Directed at Pipeline Research Topics

Given the high level of effort received by Integrity Management, further analysis was performed to drill down into specific research topics of interest. Figure 7 indicate the distribution of researchers active in specific research topics in Integrity Management. It can be observed that research topics related to corrosion and its prevention using coatings and cathodic protection received the largest share of researchers' interest. This is followed by topics related to inspection and assessment, whether in-line inspection, smart pigging, defect assessment or mechanical damage.

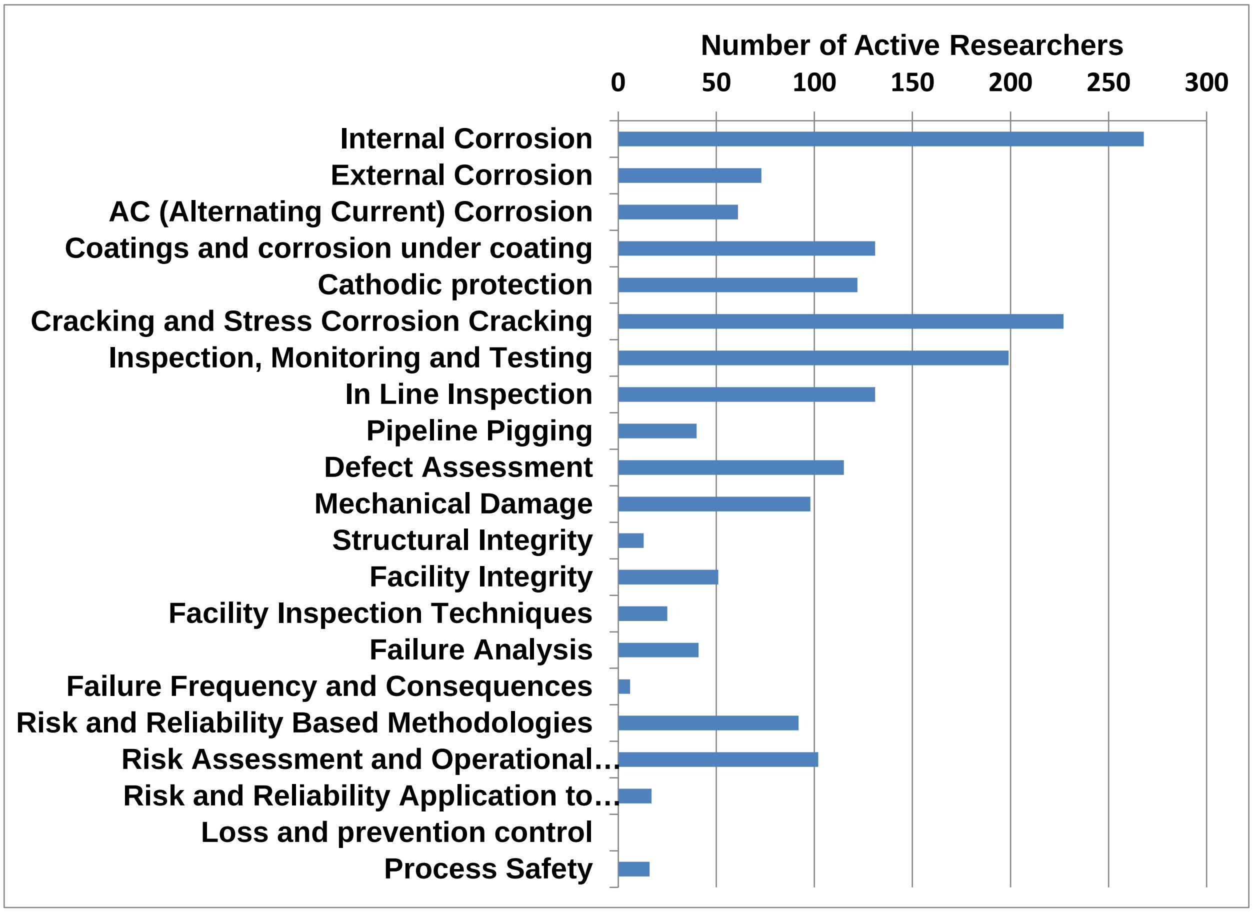

Figure 7. Level of Effort Directed at Integrity Management

Additional analysis was also performed in the other research categories. Figure 8 provides details in the Design category. It should be noted that the basics of pipeline design and engineering are well established. The specific area that received attention and that is also prioritized in the activities of PRCI and other organizations is Strain-based Design.

Per Table 2, Steel Metallurgy dominated the Materials category and Welding was by far the most active topic in Construction. Metallurgy research reported in pipeline journals and conferences would necessarily be limited to pipeline applications and it would be expected that additional metallurgy research is reported in journals and events of the steel industry. A similar comment is applicable to welding.

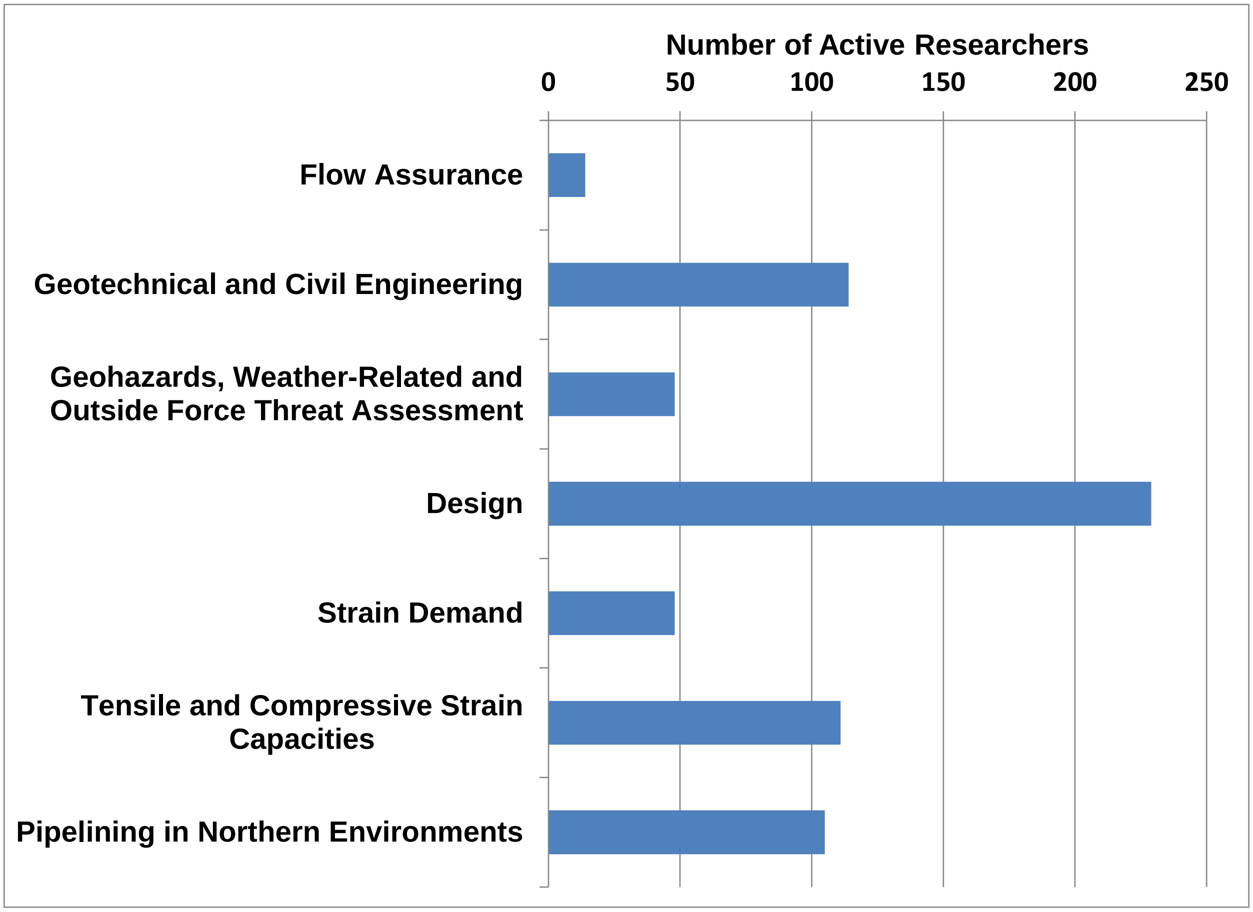

Figure 8. Level of Effort Directed at Design

The development of the knowledge network map also allows an analysis of the most prominent topics in the field of pipeline research and, just as importantly, the least active topics for the identified researchers. Figures 9 and 10 present the most and the least researched topics identified in the knowledge network map developed in this study. Not surprisingly, most of the research topics with the most interest are related to Integrity Management. The research topics which received the least amount of research attention, on the other hand, may indicate a knowledge gap that could need to be filled. With greater attention placed by stakeholders on integrity and environmental impact, such topics as Leak Detection, Footprint Impact and Reclamation may require more research investments in the future.

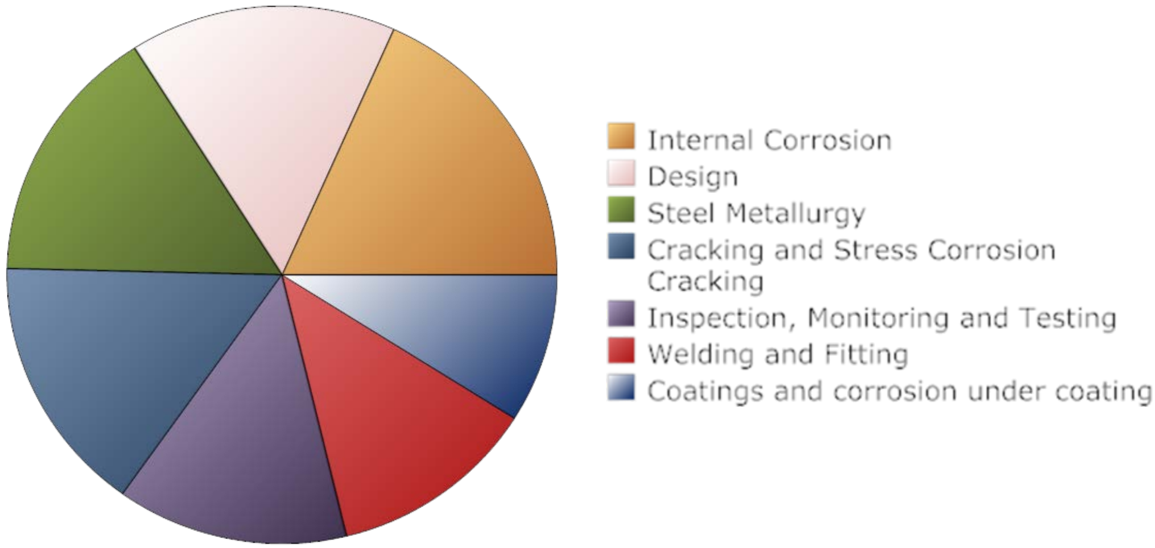

Figure 9. Most Active Research Topics

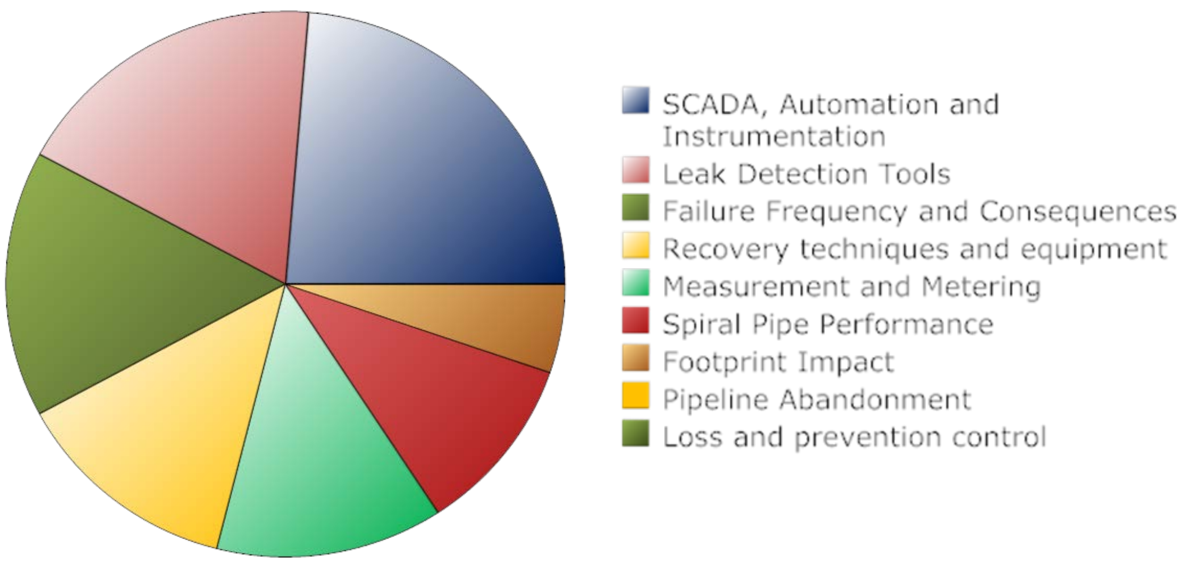

Figure 10. Least Active Research Topics

5. Gap Analysis

Gaps and barriers stand between the current state of technology and the desired future state. In addition, technology opportunities arise from advances in fundamental science and engineering, pipeline technology, and related fields. Identifying gaps and opportunities involves, for each major element of pipeline technology, comparing the current situation to what could be possible with future investment in research and development that would progress technology in the direction set by the strategic drivers. As indicated earlier in section 1.4, the strategic drivers are:

- To minimize environmental footprint and social impact of the construction and operations of transmission pipelines; and
- To operate transmission pipelines at high and consistent levels of performance in terms of safety, reliability, efficiency and system integrity.

The strategic drivers are to be interpreted in the context of maintaining energy affordability for users and the public.

5.1.Objective

This element of the roadmap project aims to identify gaps that would need to be filled and opportunities that could be realized in order to achieve significant progress in the direction set by the strategic drivers. The outcome is the identification and prioritization of gaps, research needs and technology opportunities in respect of system integrity and environmental impact of transmission pipeline and this outcome sets the stage for the formulation of potential technology programs.

It should be noted that this exercise was completed by the project team and the Steering Committee and has yet to be validated with a broad group of participants. However, it does serve as a useful starting point for planning and for exploring opportunities.

5.2.Methodology

The workflow included the review of the current status of technology and the identification of gaps and opportunities by subject matter experts, two work sessions involving the project team and the Steering Committee, and the aggregation of knowledge gap worksheets and work session deliberations into report sections that were further reviewed by a number of parties.

Specific process steps were as follows:

- Preliminary identification of key issues by project team members;
- Definition of the current state of knowledge for each of the key issues using literature searches and interviews of key individuals;
- Interaction with the Steering Committee to define the ideal future state against which the current state of knowledge will be compared in order to identify gaps and opportunities;
- Listing of preliminary gaps and opportunities using knowledge gap worksheets;
- Aggregation of gaps and opportunities into research opportunities;
- Interaction with the Steering Committee to formulate the prioritization framework;
- Prioritization of gaps and opportunities;

- Validation of the priority research needs and technology opportunities during the project workshop; and
- Update of the priority research needs and technology opportunities based on workshop feedback.

Approximately 50 knowledge gap worksheets were prepared by project team members based on their experience and expertise, as well as the knowledge by some members of recent reviews of operating incidents such as the Alberta Pipeline Safety Review[25] and the Marshall Incident Report[26]. The 50 gap worksheets were discussed and aggregated by the project team and the Steering Committee into 17 gaps/opportunities which are presented below. The gaps/opportunities were then prioritized according to positive impact on the strategic drivers and were also sorted with respect to the level of effort by existing research organizations based on the information assembled in the Knowledge Network Map.

5.3. Gap Analysis Results

This section describes the 17 gaps and opportunities and presents them according to the research categories used in the Knowledge Network Map, which are generally aligned with the pipeline life cycle, starting with Environment and ending with Reclamation, as follows:

- Environment (Direct Impacts);
- Design;
- Materials;
- Construction;
- Operations and Maintenance;
- Integrity Management;
- Leak Detection;
- Spill Cleanup and Remediation; and
- Reclamation.

Prioritization of the research needs and technology opportunities will be discussed in Section 5.4.

5.3.1. Environment (Direct Impacts)

5.3.1.1. Existing Situation

In general, transmission pipelines are composed of long linear segments of buried pipe in a designated right-of-way (ROW) and of relatively small and distributed surface facilities. The

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[25] Group 10 Engineering (2012), Alberta Pipeline Safety Review, prepared for the Energy Resources Conservation Board, available online at: http://www.energy.alberta.ca/Org/pdfs/PSRfinalReportNoApp.pdf

[26] National Transportation Safety Board (2012), Pipeline Accident Report, Enbridge Incorporated Hazardous Liquid Pipeline Rupture and Release, Marshall, Michigan, July 25, 2010, available online at: https://www.ntsb.gov/doclib/reports/2012/PAR1201.pdf

direct environmental impact of these features is generally not different from other industrial facilities. In fact, some analysts would argue that the direct environmental impact of pipelines is less than for typical industrial facilities because, for the most part, pipelines are buried and thus allow some concurrent land uses. Procedures, methods and indeed regulations exists and are applied to assess and manage impacts on land, ecosystem, water and air during pipeline construction and operations, including their presence in high consequence areas such as near population centres, water crossings and routings through environmentally sensitive areas.

It is also noted that pipelines consume energy for compression and pumping and that this energy is generated through the combustion of fossil fuels, generally natural gas and/or from electrical grid power. Opportunities exist for improved energy efficiency at compressor and pumping stations.

The environmental impact of potential for spills and releases of products transported by pipelines is a subject of concern highlighted by stakeholders. This subject is not addressed in this section but later in Section 5.3.8.

Three gaps were identified that could offer opportunities for improvement.

5.3.1.2. Gap/Opportunity Description – Route Optimization

A number of methods exist to enable the route selection process to be undertaken. Furthermore, social license to operate is becoming ever more important in routing pipelines. There is a need to address high consequence areas in a manner that would minimise the consequential effect of line leaks or ruptures. The ability to determine optimal valve spacings and burial depths, predict noise pollution, include fate and transport models (for the movement and alteration of chemical contaminants in the environment), and minimise quantities of water needed for hydrotesting would be valuable in the development of an optimal routing selection algorithm.

The current CSA Z663 Land Use Planning Standard could be upgraded to serve as a useful and effective planning tool and thus improve safety and help avoid costs associated with changing class locations.

Prospective Direction for Research and Innovation

The objective of research would be that all factors affecting route selection and their relationships with each other would be included in a single database and decision support system. New technologies that could be harnessed include: improved aerial images, immersive video to help determine topography and hydraulic profiles, and improved cut and fill algorithms to enable construction costs to be estimated.

A joint venture research program could be directed toward the development and proof testing of software providing an optimal approach to route selection. The joint venture would seek out a software developer as project lead and integrator, and use a modular approach to researching each topic. It would be a multi-disciplined research project embracing Geographical Information Systems (GIS), hydraulics, risk, construction, environmental and social impacts.

This initiative would then provide the necessary technical and environmental support to upgrade the CSA Z663 Standard and equivalent international standards.

Barriers

Stakeholder and landowner concerns about the potential for releases and spills have increased in recent years and, in general, are expressed only when a new pipeline project is proposed and is the subject of public hearings. Concerns about routing are moot for existing pipelines. Thus the subject of optimum routing selection receives attention occasionally, and even then, may not be seen as a high priority issue for existing pipelines.

Value

A software tool that could capture, analyze and optimize all aspects of pipeline routing would provide an assurance to the operator and to stakeholders that the necessary trade-offs made during route selection were the best ones. Its value would extend beyond the design and construction phase and ensure that operational impacts and the consequences of potential spills are mitigated to the extent possible. For example, by incorporating constraints such as seasonal fish habitat and migratory patterns, the impact of routing decisions on construction scheduling and hence costs could be sizable.

5.3.1.3. Gap/Opportunity Description – Noise Impact

Various approaches are available to deal with noise pollution during construction and operations, ground disturbance and reclamation. However, existing approaches provide non-uniform responses and have varying levels of success. In addition, the inclusion of a formal workflow to handle noise impacts in an integrated planning tool that would seek to minimise the environmental impact of a pipeline ROW would facilitate the acceptance of pipelines by impacted landowners.

Prospective Direction for Research and Innovation

The goal would be to seek technologies that would result in reductions in noise levels (attenuation) from compressor and pump station operations, directional drilling and blowing down of lines. Noise cancellation and attenuation techniques could be developed in a laboratory and scaled for field trials. Existing noise modeling software could be adapted for open country pipeline applications.

Barriers

Noise is generally a pipeline construction impact and a local impact near surface facilities such as gas pipeline compressor stations. Due to its temporary or local nature, it is often perceived as less of a concern than the risk of a major release or spill.

Value

Responding to landowner concerns and mitigating the direct impact of pipeline construction and operations would reduce overall environmental footprint and social impact. Most of the value would be during the construction phase and in operation for those residents near compressor and pump stations.

5.3.1.4. Gap/Opportunity Description – Construction Right-of-Way

The permanent pipeline ROW is the linear land feature, 18 to 36 meter wide, containing one or more pipelines. However, during construction a wider strip of land is required on a temporary basis to provide space for excavated soil, pipe welding activities and the movement of vehicles. The width of the temporary construction space will depend on the specifics of the construction project.

When new pipeline capacity is needed in a certain transportation corridor, adding pipelines to an existing ROW often results in less cost and less impact than routing a new pipeline on an entirely new ROW. However, the addition of pipelines to existing ROW could require construction in a narrower space due to the presence of the existing pipeline and related features.

It has been noted that pipeline construction techniques have lagged behind design improvements with little or no change recorded in the swaths of land required for temporary construction space. New construction techniques that would be cost effective in narrower space would lessen environmental and social impact, as well as facilitating construction work in congested areas when adding a pipeline in an existing ROW.

Prospective Direction for Research and Innovation

Improved ditching, laying methods would reduce ground disturbance and hence minimize reclamation effort. Work in collaboration with equipment manufacturers and pipeline operators could be undertaken to develop suitable techniques for handling inlaying pipe and generally working in narrower construction spaces safely and efficiently.

Barriers

The direct environmental impact of pipeline construction and operations is generally seen as less of a concern than the risk of a major release or spill and thus probably receives less attention.

Value

Construction techniques that create fewer disturbances would respond to landowner concerns and this would reduce the direct impact of pipeline construction. All of the value would be during the construction phase. This value is likely to increase over time as replacement of vintage pipelines and expansion in existing ROW become more common.

5.3.2. Design

5.3.2.1. Existing Situation

The design of a pipeline involves many well-established engineering tasks, the most important of which are design of the pipeline, hydraulics, materials, mechanical systems and geotechnical design. The basics are well known and have been taught and practiced for decades. Opportunities for significant improvements continue to exist, whether it is to respond to evolving expectations of pipeline companies and stakeholders, or to take advantages of scientific progress.

5.3.2.2. Gap/Opportunity Description – Geological Hazard Risk Assessment

Many aspects of pipeline integrity management are moving towards a fully quantified risk assessment, based on probability of occurrence and reliable return periods etc. Thus, a fully quantitative approach to risk management for geological hazards would be desirable. However, it is presently difficult to reliably apply probabilistic methods to some geohazards, such as soil creep, landslides and other mass wasting processes because of an inability to characterize soil behaviors with sufficient accuracy. In Canada, this gap is of particular importance to pipelines located in the mountainous regions of northeast B.C. Furthermore, the increasing prevalence of extreme weather such as heavier rainfall and snowfall causing flooding may create higher than anticipated applied loadings to pipelines in the future.

Prospective Direction for Research and Innovation

The goal would be to develop an approach to designing a fully quantitative risk assessment geohazard methodology. Once developed, it will be necessary to calibrate and test the methodology to real life pipeline routes.

Barrier

It is very difficult to quantitatively assess geohazards as the basic data is scarce and presently costly to generate.

As to the effects of weather, substantial work has been done to date by some operators in modeling the impact of rainfall.

Value

A systematic and quantitative workflow for assessing geohazard risk would greatly assist in route selection and pipeline design in geohazard areas, thereby reducing costs and reducing the probability of future incidents. Most of the value would be for areas with significant slopes such as the mountainous terrain in northeastern British Columbia. However the quantitative work flow would apply also to all routing and design situations.

5.3.2.3. Gap/Opportunity Description – Strain-based Design and Materials

This gap pertains to the strain-based approach to design and the requirement to validate current theoretical models for strain demand, tensile and compressive capacities.

Strain Demand

Significant strains may be applied to a pipeline due to various geological hazards that result in ground deformation, such as slope instability, seismic events, or permafrost effects. Each of these requires different methods for assessment, and all suffer from lack of sufficient information (local conditions, i.e. soil conditions and properties) at the design stage. However, even if soil deformation is known, there is still a need to determine the pipe displacement as a function of pipe/soil interaction, which is reliant again on numerous assumptions. Nevertheless, safe and reliable pipelines are possible by use of conservative assumptions and continuous monitoring during operations. For existing pipelines it is often difficult to determine the existing strain state unless baseline data was measured immediately after construction.

Tensile Capacity

The tensile capacity is an ultimate limit-state and therefore of primary importance. It is dependent on the behaviour of girth welds as these are the weak link; thus, the design objective is to ensure that their capacity is greater than that of the pipe material. A method for prediction of tensile capacity has recently been published by PRCI. ExxonMobil has also provided limited information on a proprietary assessment method. Furthermore, material testing guidelines are being developed by PRCI.

However, these models and methods need additional full scale testing and experimental validation to cover the full range of expected material grades and wall thickness. Furthermore, there is work remaining to incorporate strain-based design into Canadian and international standards.

Compressive Capacity

Compressive capacity is generally a serviceability limit-state that is highly dependent on geometry. Various methods have been developed and their range of application was recently defined in a report by C-FER for PRCI.

However, the effects of cold bending, joint misalignment, material anisotropy would require further work. This is also the case for the presence of fittings such as elbows, tees, valves etc. or other anomalies such as corrosion, or even repaired defects.

Strain-based Design

For both tensile and compressive capacities, a comprehensive consensus guideline does not exist and this limits regulatory acceptance. There is lack of confidence in existing methods and industry's ability to execute a project to the required level of assured integrity.

In February 2013, PHMSA published a draft of possible conditions that would apply to pipelines using strain-based design methodologies[27]. However this draft would need further work because the implementation of the various methodologies has not yet been fully documented and validated.

Materials for Strain-based Design

Requirements for good performance of materials in strain-based design are reasonably well known. For new pipelines it is possible to specify material properties and dimensional requirements to optimize tensile and compressive strain capacities, thus delivering safe and reliable pipelines. For existing pipelines, it is more difficult as various assumptions must be made, and thus uncertainty drives conservative (and costly) operational decisions.

Prospective Direction for Research and Innovation

Strain Demand

The first task would be to develop a framework to quantitatively estimate geohazards along the pipeline route (see 5.3.2.2 above). This would lead to improved means for predictions of soil movement and load application to pipelines.

The second task would be to develop methods to determine existing levels of stress/strain in operating pipelines.

Strain-based Design

The goal would be to develop methods to assess effects of material and geometric variation on tensile and compressive capacity. The major task would be to perform full scale tensile tests to extend the validation range of the existing models. This would lead to the development of comprehensive strain-based design guidelines that could be incorporated into standards (Canada, U.S. and other countries).

PRCI has proposed a 5 to 7 years research program to this effect that would cost $12 to 17 million. However, this program did not receive significant funds for its implementation. Most of the laboratory work proposed could be done by C-FER Technologies because it already possesses the required expertise and equipment.

Materials for Strain-based Design

The goal would be to develop methodologies to more precisely characterize the stress-strain behaviour of pipeline steels. The required tasks would be to evaluate technologies available from other industries, particularly for in-situ determination of mechanical properties. This could lead to improved means for in-situ property determination, possibly by tools run by in-line inspection (ILI).

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[27] Pipeline and Hazardous Materials Safety Administration (2013), Strain Based Design Possible Conditions Draft 1, online at http://www.arcticgas.gov/sites/default/files/documents/special-permit-possible-conditions-strain-based-design-example-0.pdf, accessed August 25, 2013

It is imperative that material properties be better known for new and existing grades of steel and for each unit of production. For example, each joint of pipe the material properties should be linked and available through industry databases. This would be particularly important when strain-based loading is anticipated. The effects of joint/joint material variation, including anisotropy, on strain demand and capacity also require further exploration.

Barrier

Strain Demand

Geohazards are difficult to assess quantitatively and this uncertainty is, in part, dealt with presently by applying safety factors to the design of pipelines in known geohazard areas.

However, collaborative research is currently underway that is examining ground movement hazards on existing pipelines. It considers strain demand, and both tensile and compressive capacities, with the aim of producing a guideline based on existing state-of-art methods (i.e. no new method is being developed).

Strain-based Design

The reason for the lack of support by PRCI is the large cost of the program for a limited range of applications. Strain-based design is mostly relevant to the design of pipelines crossing geohazardous areas, such as mountain ranges and permafrost regions (e.g. Northeast B.C. and Alaska).

CSA-Z662 has a working group to address strain-based design. No similar activity is presently underway for U.S. standards. Recent cutbacks in NRCan (CanmetMATERIALS) funding reduce their ability to act as a knowledgeable independent scientific authority supporting the development of improved standards.

Materials for Strain-based Design

The implementation of this program would require collaboration with the steel industry and groups engaged in the development of steel characterization methodologies.

There has also been some work done by PRCI investigating the assessment of material properties using neural networks with input from all known data, e.g. year of manufacture, grade, manufacturer, dimensions etc. While this work is helpful, it still leaves uncertainty which results in the use of large safety factors.

Value

Strain Demand

For new pipelines, the benefits would be to better estimate hazards along the pipeline route, and to organize these in a consistent manner using GIS.

Existing pipelines would benefit from better means to predict ground movement (slope instability, seismic hazards, permafrost).

For new and existing pipelines, improved means to estimate strain demand from geohazards would also lead to improved methods to determine pipe/soil interactions.

Strain-based Design

Methods for strain-based design that could be validated by experimental and field work would increase the confidence in pipeline design in geohazard areas. It would allow sound engineering decisions to be made in cases where ground movement is detected after pipeline construction.

Materials for Strain-based Design

For new pipelines, a standard method for specification of pipe material properties (definition of stress strain curve) would make it easier for designers and pipe suppliers to specify materials with high certainty.

For existing pipelines, as material properties are unlikely to be known with any degree of certainty, any means to either determine properties in-situ or to improve estimates of properties would be helpful. This is particularly important as the installed network of legacy pipelines continues to age and precise determination of their integrity is paramount to avoid integrity incidents.

5.3.3. Materials

5.3.3.1. Existing Situation

Several grades of steel are commercially available for pipeline service. In recent years, high strength steels have been developed that enable pipeline operators to realize significant economic benefits with increased operating pressures and reduced pipe wall thicknesses. Improvements are needed in the detailed characterization of steels and in the models for risk assessment and failure prediction.

5.3.3.2. Gap/Opportunity Description – Fracture Propagation and Arrest

This topic deals with two phenomena: decompression behaviour of gas mixtures under non-steady-state conditions, and the fracture resistance of the pipe material.

The present tool, the Battelle Two-Curve (BTC) method, provides a means to equate decompression and resistance by comparing the velocity of each. Decompression is well understood for hydrocarbon gas mixtures within the range expected for export from western Canada. It is less understood for CO_2 with impurities such as that expected for planned carbon capture and storage (CSS) projects, although work is presently underway that will likely resolve gaps.

The BTC method is generally believed to be adequate for design of pipe grades up to about GR448 or 483. However, there is worldwide concern regarding the effectiveness of this method to safely predict arrest for modern high strength steels. Fracture resistance is not well understood for modern high strength steels, as the BTC method relies on a correlation between Charpy energy and fracture velocity that is not valid for modern high strength steels; correction factors are used though these are not considered to be fully reliable. An additional problem exists in the failure of existing laboratory test methods used (e.g. Drop Weight Tear Test – DWTT) for material qualification, as often the tests are deemed to be invalid due the unique behaviour of these same steels. Work is presently underway by PRCI, EPRG, and APIA. A consortium of pipe producers, research institutes and pipeline companies is also being formed to address these issues.

An effective design tool to predict fracture propagation and arrest, applicable to the full range of material grades and manufacturing routes, is needed.

Prospective Direction for Research and Innovation

Research is underway, but may require full scale tests for validation. Each test would cost approximately $2 million.

Barriers

Topic suffers from lack of experienced people. High cost is also a deterrent, as perhaps a dozen full scale tests may be needed to fully validate the models against a range of materials and design conditions.

Value

High strength steels are used more frequently by industry and a clear understanding of their fracture behaviours would increase design safety. The importance and value of this gap is recognized by industry as evidenced by existing research efforts and consortium projects.

5.3.4. Construction

5.3.4.1. Existing Situation

In the construction process, specified materials are assembled and installed according to the pipeline design. As noted in Section 5.3.1 about the Environment, improvements are sought to reduce the environmental impact of pipeline construction in areas such as construction space and noise impact. Recent reviews by regulators of pipeline projects have emphasized the importance of quality control and assurance during pipeline construction, in areas such as inspection of incoming materials, welding and system testing and acceptance.

No significant technology gaps requiring future R&D investments were identified in the area of Construction during the review conducted by the project team, other than the ones listed under Environment.

5.3.5. Operations and Maintenance

5.3.5.1. Existing Situation

Once the pipeline is commissioned and placed in service, routine operations commence and must be monitored and managed continuously. Maintenance is conducted on a periodic basis to maintain performance and repair system elements as needed. Integrity Management activities are treated as a separate category than operation and maintenance in this gap analysis workflow (see Section 5.3.6). Thus, the activities covered by operation and maintenance pertain to ongoing controls to ensure system performance, custody transfer and other normal operating activities.

5.3.5.2. Gap/Opportunity Description – Pipeline Repairs with Composite Materials

This is a broad topic, closely related to inspection and damage assessment. Repair methods vary with the type of damage and the type of expected loads. Once detected, damage must be assessed and the need for repair determined. Repair methods range from pipe replacement to application of methods to restore the pipe to a satisfactory state (may be short term up to permanent) by means of structural reinforcement. Structural reinforcement may be in the form of composite wrap, steel sleeves, or even direct-deposit weld overlay.

Composite materials are frequently used to repair damaged pipeline sections. However questions still exist about the permanency of such repairs when using composite materials as influenced by type of damage (corrosion, cracks, dents, adjacent welds, and combined effects), repair materials used, installation procedures, pressure effects, environmental effects, shielding of cathodic protection (CP), etc.

Prospective Direction for Research and Innovation

The proposed technology improvement program for repair sleeves would include the following:

1. Establishment of guidelines for inspection;
2. Preparation of a list of qualified repair methods, along with guidelines for proper installation and quality assurance; and
3. Incorporation into standards.

Some of the above research tasks are presently underway at PRCI under its composite materials roadmap.

Barriers

The PRCI roadmap covers the overall topic well. In other words, the low hanging fruits have been harvested and PRCI is working on several technical details and schedules are in place to address most of them. The gaps that remain are:

- Elevated temperatures
- Subsea repairs

- Repair of cracks such as caused by stress corrosion cracking (SCC)
- Detection of existing repairs by ILI
- Guidance documents on several topics.

PRCI already has a lot of momentum on the overall topic and should likely continue to lead the overall effort. The remaining individual gaps identified above might be addressed in collaboration with PRCI, as PRCI has a mechanism for collaboration with other organizations. The gap concerning the repair of cracks might be a worthwhile target, though success might be in the long term due to the inherent lack of pressure containment by composite materials.

Value

Improved methods for repairing pipelines would increase the confidence in the integrity of such repairs.

5.3.5.3. Gap/Opportunity Description –Hydrodynamics

Relationships between Hydrodynamics and Structures

One aspect of this gap pertains to the relationship between hydrodynamics and the structural responses of the piping, pipelines and facilities. The subject of pipeline dynamics has been studied extensively and adequate tools exist to perform analyses. Generally, when turbo-pump systems are analyzed from the fluid dynamics standpoint, only transient analysis is performed, with steady-state conditions used as a starting point. Invariably in pipeline system planning, steady-state modeling is used as this is much simpler to use and there are many repetitive routine calculations to be performed. This is despite the fact that steady-state processes, in certain conditions, could be much more dangerous than controllable transients.

A variety of sophisticated applications exist that allow predicting flow and acoustics in pipelines. Although the flow analysis is routinely performed at the design stage, it is not so for the acoustics analysis. In both cases, it is not uncommon that the results of analyses are misinterpreted and misunderstood. Also, an old belief that vibration and pulsation are of no importance in centrifugal pumps/compressors is prevalent in industry which occasionally leads to spills and pipeline failures, albeit within operators' facilities.

Speed of Sound in Dilbit

The second aspect of this gap pertains to the speed of sound in dilbit. The speed of sound is used to determine shock fronts during transient conditions in a pipeline; e.g. pulsations. Speed of sound is related to the compressibility of the fluid.

Compressibility data are available for some mixtures of bitumen and solvents at some temperatures and pressures. Correlations and equation of state models are available to estimate the compressibilities. However, gaps exist in the dataset. Data may not be available for multi-component diluents such as condensate over the conditions of interest. Excess volumes of mixing may not be accounted for correctly. Equations of state provide poor predictions for compressibility. Correlations have not been rigorously tested for these mixtures.

Prospective Direction for Research and Innovation

Relationships between Hydrodynamics and Structures

The goal would be to update thermodynamic properties related to the transient and steady state calculations and piping responses. Thermodynamic properties of the conveyed medium determine the pressure and fluid flow oscillations. Consequently, in either transient or steady state analysis the following thermodynamic properties are used:

1. Specific heat of the medium at constant pressure. It determines losses associated with molecular exchanges of pulsation energy.
2. Density of the medium (representing inertia). It affects magnitudes of resonant peaks.
3. Ratio of specific heats. Specific heat of the medium at constant pressure over that at constant volume affects pulsation energy losses.
4. Speed of sound or velocity of sound propagation within the medium. It affects resonant frequencies. (The speed of sound is very difficult to calculate/predict for diluted bitumen and multiphase flows.)
5. Thermal conductivity of the medium. It affects heat conduction losses of pulsation energy.
6. Viscosity of the medium. It affects viscous losses of pulsation energy due to relative motion between adjacent portions of the medium.

Speed of Sound in Dilbit

The required research program would acquire the needed data and could proceed according to the following tasks:

1. Conduct a literature review to identify gaps in the data.
2. Collect density data as required.
3. Identify and adapt correlation for dilbit density (and compressibility) as a function of temperature, pressure, and dilbit content and composition.
4. Fill in data gaps and develop appropriate model or correlations.

3 years should be sufficient to address this gap.

Barrier

The relationships between hydrodynamics and the response of structures in not well understood. Dilbit is a relatively new product and, while it has been extensively studied, it appears that a full set of reliable data about the speed of sound in dilbit has yet to be established.

Value

An improved understanding of the relationships between hydrodynamics and the response of structures based on updated thermodynamic properties would increase the integrity of design.

For transportation by pipeline, reliable information about the speed of sound is required to establish the accuracy of control systems and leak detection systems based on pressure variations and acoustics.

5.3.6. Integrity Management

5.3.6.1. Existing Situation

The purpose of Integrity Management is to ensure that the pipeline conditions remains sound and this is monitored through a number of inspection and measurement methods in order to determine needs for maintenance and intervention. Integrity Management generally supplements normal maintenance activities and encompasses the following tasks: inspection, monitoring, condition assessment, and risk mitigation actions.

5.3.6.2. Gap/Opportunity Description – Internal Corrosion

Crude oil and natural gas by themselves are not corrosive at pipeline operating conditions. However, internal corrosion potentially occurs when the pipe wall is wetted by water drops and/or solid particles over an extended time period. Due to their hydrophilic nature, sand particles tend to be encapsulated by a layer of water. Moreover, compared to water drops, wetted particles are more prone to settle on the pipe bottom due to their gravity. Thus, a corrosive environment may be generated under solid particle deposits. Under-deposit corrosion often manifests as localized pitting corrosion.

It is noted that transmission pipelines carry specification products that specify maximum amounts for water and solid particles. As a result, internal corrosion is not a priority matter in transmission pipelines. However gathering lines used in the upstream petroleum sector carry raw products that are generally not covered by detailed specifications for water and solid particles. In these situations, internal corrosion may become a challenge, if not mitigated by appropriate operating practices.

While considerable academic work has been performed to investigate internal corrosion, there are a number of issues that remain to be understood with respect to water and deposit accumulations in situations where oil is transported with high levels of water and sediments. Reliable models that are able to accurately predict the locations of water/sand accumulation based on crude oil type are lacking. There has been no model development to predict entrainment of solid particles in oil depending on flow rate. Moreover, the threshold flow rate to entrain water and solid particles as a function of crude properties, size and concentration of sands, pipe elevation and geometry and temperature is not well established. Furthermore, petroleum sludge is a complex substance containing a number of components with varied compositions, such as sands, clay, water, petroleum asphaltenes, salts, microorganisms, etc. To date, there has been little understanding of internal corrosion of pipelines under sludge deposits.

The following specific gaps exist:

1. Prediction of locations of wetted solid particle settlement on the pipe wall: NACE SP0208-2008 lists several models that could be used to predict the location of water accumulation. Currently, NACE Task Group 477 is working on the guidelines for selecting the most appropriate model for this purpose. To date, suitable models enabling prediction of the deposition of solids have not been available.
2. Mechanism and growth kinetics of under-deposit corrosion, especially pitting corrosion.
3. Modeling the effect of flow rate on sand settlement on pipe floor.
4. Microbial activity and its role in under-deposit corrosion.
5. Corrosivity of petroleum sludge.

Prospective Direction for Research and Innovation

The following tasks are proposed:

1. Experimental testing: Create testing environments simulating the actual conditions where corrosion potentially occurs in pipelines transporting oil with high levels of water and sediments, and utilize micro-probe techniques to characterize corrosion processes and parameters under deposit and petroleum sludge.
2. Numerical modeling: Develop models to simulate the effects of fluid mechanics parameters on pipeline corrosion, including the settlement of sand particles, pit growth kinetics under deposit, prediction of corrosion rate in sludge, etc.
3. Develop mechanistic models to understand the intrinsic science of pipeline corrosion. Develop models to enable quantitative prediction of corrosion kinetics under deposit and petroleum sludge.
4. Integrate the developed models with the internal corrosion management program for affected pipelines, including optimizing operating conditions to minimize and eliminate internal corrosion, and recommending timely pigging and inspection at appropriate locations.

Barriers

There has been some work investigating corrosion of pipeline steels conducted in autoclaves, which did not reproduce the actual conditions of pipelines. Thus, the testing is not representative of the reality. The results do not enable understanding of the fundamentals of corrosion processes and the parametric effects on the process, and thus, cannot contribute to development of models to predict corrosion. Actually, tests conducted in autoclaves focus on investigation of corrosivity of crude, which is undoubtedly low.

Value

Filling the gap will help industry to conduct timely pigging at appropriate locations, improving both maintenance efficiency and economic benefits. Moreover, filling the gap will further improve the present internal corrosion management program for enhanced operating safety.

5.3.6.3. Gap/Opportunity Description – External Corrosion

Reports of FBE Failures in Other Jurisdictions

One aspect of this gap pertains to circumstances when disbonding occurs in Fusion Bonded Epoxy (FBE) and multi-layered coatings and the effect of such disbondment on external corrosion of pipelines.

FBE coating is very well regarded by industry because of its strong adhesion to the steel substrate. A number of multi-layered coatings, such as 3LPE (3 layer polyethylene) and HPCC (high performance composite coatings), have also been developed to integrate the high adhesion of FBE, as a primer, with polyethylene (PE) as the top coat which provides a strong resistance to water permeation and mechanical damage.

However, there has been reported FBE failures (disbondment) and pitting corrosion under disbonded FBE in Colombia and in France. Since FBE is permeable to cathodic protection, it may be assumed that CP may contribute to disbondment of FBE, i.e., cathodic disbondment. Moreover, failure (disbondment) of multi-layered coatings has also been reported in France. However, the exact mechanisms regarding potential incidents of FBE disbondment and the role of CP in these incidents have remained unknown. While FBE disbondment has not been a problem in North America, it would be useful to investigate potential incidents abroad to ensure that any possible cause of failure is understood.

Effect of Alternating Current on Cathodic Protection

A second aspect of this gap pertains to cathodic protection. It is well accepted that the presence of alternating current (AC) causes interference and shifts the CP potential, thus affecting the effectiveness of corrosion protection from CP. There are some techniques available to measure in-situ AC voltage on pipelines. The commonly accepted method is to use a coated steel coupon (an artificial defect open at the center of the coating) that is buried with the pipeline and electrically connected with the monitoring facility.

The following specific gaps were identified:

1. Shift of CP potential under AC: The CP potential on pipelines could be shifted negatively or positively by AC, depending on the level of applied CP. However, the boundary value of applied CP is not known in terms of the shift direction. Moreover, the negative shift of the CP potential does not mean that the steel is more protected. It is actually misleading information because the pipeline is experiencing increased corrosion.
2. CP criteria for full protection of pipelines in the presence of AC: The presence of AC decreases the CP effectiveness for pipeline protection. Optimal CP design should be

based on the AC voltage/current density distribution, coating defects, soil properties, distance between pipeline and AC sources, etc. A computational software program needs to be developed for this purpose. Furthermore, the recorded voltage signals by the present AC monitoring techniques provide mixed signals containing both DC and AC components, and are not directly related to corrosion information. The present assembly for online AC corrosion measurements is not representative of a pipeline experiencing AC corrosion, including coating defect geometry (this is critical to determine local AC current density), coating status (lab coated coupon vs. years of services in field), inductive AC signals (flowing through a coupon vs. through a line pipe), etc.

Prospective Direction for Research and Innovation

Investigation of FBE Failures in Other Jurisdictions

If cases of FBE disbondment in Columbia and in France are determined to be valid, the tasks would be to investigate and analyze such cases and experimental testing of hypotheses. This would lead to a complete investigation to determine the possible reasons resulting in FBE disbondment - e.g. is it due to surface condition of steel pipes or other causes. The result would be an advanced understanding of the role of CP in disbondment of FBE and multi-layered coatings, which could lead to the development of improved coatings, improved inspection and maintenance procedures as well as improved pipeline integrity management.

Effect of Alternating Current on Cathodic Protection

The following research tasks are proposed:

1. Experimental testing for AC corrosion of pipelines under operating conditions.
2. Develop technique (equipment) for online monitoring of AC corrosion and CP performance.
3. Determine the effect of AC on CP potential and develop a model to optimize CP design in the presence of AC interference.
4. Design and develop an AC corrosion online measuring and assessing technique.
5. Installation of a novel AC corrosion monitoring technique in the field for the reliable evaluation of pipeline corrosion and CP performance.

Barriers

FBE is a coating with a strong adhesion to the steel substrate that has performed very well in North America. However, there have been reports internationally that FBE disbonds and that corrosion (pitting corrosion) occurs. The exact reason has remained unknown.

AC corrosion of pipelines and the relevant monitoring/assessment techniques have not been well studied (insufficient activity) in North America compared to European and Asian countries (this is inferred from the number of publications in this area). Even for the published work, there have been many missing essential elements. Moreover, the presently used online technique needs to be improved in order to provide more accurate information.

Value

Understanding incidents of FBE failures in other jurisdictions would enhance integrity of FBE-coated pipelines. Since today's pipelines depend heavily on FBE for integrity management, this may constitute a gap to be filled.

Improving resistance to AC corrosion will help pipeline operators address the effect of AC (from high voltage power transmission lines) on pipeline integrity.

5.3.6.4. Gap/Opportunity Description – Defect Assessment

The need is for new standards and codes for the accurate prediction of the failure pressure of pipelines with considerations of higher strength grade of steel, complex geometry of defects, internal pressure and soil strain.

By now, there have been several industrial models, such as ASME B31G, modified B31G and DNV-RP-F101, which enable the evaluation of the failure pressure of pipelines. The considerations include defect geometry (usually regular defect), internal pressure, and the steel grade (usually low grade of steel).

With the increasing use of high strength grades of steel (up to Grade 550 and Grade 690 steels) and complex defect geometry (corrosion and defects may interact), the predicted failure pressure by the available industry models will deviate from the actual value. This has been confirmed with a number of industry contractors working in this area. Moreover, an easy to use model that could predict defect growth under the synergistic effects of internal pressure, soil strain and corrosion reaction is not available.

However, while basic models are available, key uncertainties exist about methods to determine the shape and characteristics of defects. Generally, the defects are identified initially by ILI with considerable uncertainty regarding detailed characteristics. Thus, safety factors are applied to account for the uncertainty.

Prospective Direction for Research and Innovation

The following research tasks are proposed, some of which are already underway at PRCI:

1. Numerical modeling: integrate solid mechanics, materials properties and corrosion to develop a finite element-based model for this purpose.
2. Improve and strengthen existing models to enable prediction of failure pressure of pipelines at defects.
3. Improve and strengthen existing models to enable prediction of defect growth with time under synergism of internal pressure and local corrosion reaction.

4. Update or modify PRCI's guidelines, and industry standards and regulatory codes in failure pressure prediction and defect management.

Barriers

In the last 10 years, PRCI projects have addressed defect assessment through in-situ material property measurement methods. Two PRCI reports are available:

- "In-Situ Pipeline Property Characterization" (2003) provides a summary of the following methods
    - Field metallography and chemical analysis
    - Hardness testing to strength correlations
    - X-Ray diffraction analysis
    - Resonant Ultrasonic spectroscopy
    - Brakenhausen noise
    - Automated ball indenter
    - Small punch testing
- "In-situ measurement of pipeline mechanical properties using Stress-Strain Microprobe – validation of data for increased confidence and accuracy" (2007). However, the tool has not been accepted by industry for a number of valid reasons.

Nevertheless, the available standards generate failure pressure prediction and defect assessment outcomes that could benefit from improve accuracy. A critical element in improving the accuracy of models is enhancing the measurement accuracy of ILI techniques.

Value

New models must be developed to replace existing ones to enable reliable pipeline integrity management. Filling the gap will enhance pipeline integrity.

5.3.6.5. Gap/Opportunity Description – Risk-based Fitness for Service Defect Assessment

There is a need for defect assessment methods that are incorporated into a reliability and risk management framework. There currently exist several models for defect assessment, however these are deterministic based (e.g. RSTRENG, ASME B31G, and DNV-RP-F101). These models enable the evaluation of failure pressure on the basis of defect geometry, internal pressure and the material strength. One difficulty in using these equations is uncertainty associated with the input parameters, and then the choice of an appropriate level of conservatism or safety factor. Another difficulty is the incomplete consideration of the consequences of failure, with some models better than others (i.e., small diameter pipes may be treated the same as large diameter pipes; the pipe contents and the proximity to population or other sensitive areas may or may not be taken into account).

In order to accurately characterize uncertainty associated with these models, a reformulation of the models into a reliability and risk management framework is needed. In essence, this will be the next generation of tools for assessment of pipeline defects, and will provide a process to account for both uncertainties and risk in a consistent manner.

Prospective Direction for Research and Innovation

The following research tasks are proposed:

1. Reformulate defect assessment equations into a reliability format.
2. Incorporate a means to account for the consequences associated with a failure into the overall methodology (noting that Annex O in Z662 may provide some aspects in natural gas service).
3. Develop into a format suitable for inclusion in international standards.
4. Develop a protocol for establishing acceptance limits.

Barriers

Several initiatives are underway: a JIP being conducted by C-FER (Development of a limit states standard for pipelines) and work being conducted by the PRCI corrosion committee on assessing significance of defects and optimizing safety factors. Any development being considered should be coordinated with these efforts.

Value

A pipeline defect assessment method that incorporates reliability and risk management for both gas and liquids pipelines will ensure that the most appropriate decisions are made, i.e. innocuous flaws are not repaired and serious flaws are repaired, both in consideration of the likelihood and consequences of failure.

5.3.6.6. Gap/Opportunity Description - In-line Inspection

In-line Inspection is performed by inserting monitoring tools (often referred to as pigs or smart tools) inside the pipeline to take measurements of critical parameters such as pipeline geometry and length, pipe wall thickness, metal loss and pitting due to corrosion, gouging, weld and manufacturing features and other defects that may affect pipeline integrity. Generally, such inspection is preceded by cleaning of the pipeline with a standard cleaning pig or series of custom designed cleaning tools. In-line inspection tools are often designed as a single body tool with cups or as an articulated tool with many vessels that are connected to form a snake like device. Smart tools or pigs are inserted into what is known as a pig trap through which the pig gets launched into the flow of gas or liquid. Once it travels the entire segment of pipe it is then received in another trap device and removed from the pipeline. The tool uses the flow of gas or liquid to propel it as it travels inside the pipeline.

In-line inspection is one of the workhorse activities to ensure pipeline integrity. It is widely practiced and basic operations and instrumentation are well-established. The industry has identified the need to further develop both above ground and in-line technologies to inspect unpiggable pipelines (typically, due to conditions such as single access point, internal obstacles, insufficient flow, or changes in diameter). Research also continues to improve tool performance in an effort to replace or supplement the requirement for hydrotesting with accurate in-line inspection because, in certain situations, hydrotesting itself affects pipeline integrity, not to mention the environmental considerations when using vast amounts of water to carry out the hydrotest. Organizations such as PRCI and GTI have active programs to fill these gaps. The advent of new and improved electronics (miniaturization) as well as advancements in sensor design continues to provide the pipeline operator with greater insight into the conditions of their pipeline.

Further improvements made by vendors and operators continue to enhance the accuracy and performance of existing In-Line Inspection technologies. These existing technologies are briefly summarized below:

- Magnetic Flux Leakage (MFL). This technology is recognized as the industry standard for metallic pipe wall assessment. It is an electromagnetic method that is used to detect metal loss including features such as corrosion or pitting in metallic pipelines. The technology has been incorporated into tool designs that inspect for metal loss features oriented in either the longitudinal or circumferential direction. This non-destructive method can scan the full circumference and length of the pipeline as the in line inspection tool travels in the pipeline.
- Ultrasonic Inspection or Testing (UT). This technology is commonly used to inspect for metal loss and for weld or pipe body cracks. For metal loss, the sensors or probes mounted on the tool are oriented 90º to the pipe wall for measuring time of flight of the return signal; for cracks, the sensors or probes are oriented at an angle for detecting shear wavesback to the probe by a weld or pipe body crack. Ultrasonic is generally used in liquids pipeline because the tool must be in direct contact with the pipe wall by means of a liquid couplant.

  There are multiple forms of ultrasonic inspection. The two most common techniques are conventional ultrasonics which uses a focused transducer, and phase array ultrasonics which uses a virtual sensor design. The phased array sensor holds multiple sensors in a single array that can be programed or customized to inspect the pipe in various ways; metal loss and crack together or differing circumferential resolution to name a few. The phase array inspection however is expensive and limited by the fact that only one tool exist within the industry that can inspect diameters in the range of 24 to 42 inches.
- Electromagnetic Acoustic Transducer (EMAT) is also used for metal loss and crack detection, but generally in gas pipelines. The EMAT technology is similar to an ultrasonic technique in that it uses magnetics to introduce a sound wave (ultrasonic) into

the pipe as opposed to a transducer. It aims at providing a service equivalent to Ultrasonic Testing but without the requirement for a liquid couplant as the EMAT sensor rides directly on the pipe wall. The requirement for a liquid couplant limits the cost-effective use of ultrasonic tools for gas pipelines because filling the gas pipeline with a liquid for inspection or by batching the inspection tool in a liquid slug is generally impractical and may not be technically or economically feasible (e.g. interruptions in gas supply). EMAT has been used on more than 15,000 km of pipelines though it is still regarded as a relatively new technology that is continuously being improved.

Existing technologies still have opportunities for improvement. At the same time, service companies continuously introduce new technologies, some of which offer attractive potential.

Prospective Direction for Research and Innovation

Research programs are continuing to be targeted at improving the reliability and accuracy of all ILI technologies, including MFL, Ultrasonic and EMAT tools. As noted earlier, the advent of new electronic components and computer technologies continues to provide the inspection vendors with opportunities to enhance existing tools. Many of these tools are being redesigned or retrofitted to take advantage of miniaturization. What this means is inspection tools can carry more sensors, transfer data faster and in greater volume. Designs are also being developed to consider greater or tighter resolution needs. More information means an improved ability to detect, characterize and size features.

MFL is a widely used technology and improvement in its accuracy and precision could yield significant benefits. Once again developments in electronics have provided the inspection vendors with an ability to incorporate new MFL sensor designs. For example, vendors are incorporating not only more sensors onto the tools but sensors that are oriented differently. This allows the analyst to view and measure features in multiple dimensions. In the inspection world, the more views and characteristics of a feature that can be viewed or measured the better confidence in the classification and sizing

EMAT tools have been in use for some years now but still require improvements for reliable wall loss and crack detection. EMAT is still perceived as a recent technology and like other technologies will require tool capability and performance to evolve through experience. Measuring the tool performance with actual field results from pipe investigations continues to build a body of knowledge for the EMAT technology which will further develop confidence in its ability to detect, characterize and size pipe features not to mention its ability to complement the other inspection techniques.

The above paragraphs generally describe innovation in the areas of mechanical and electronic design however significant research and development efforts are also underway into how data collected by these tools is analyzed. Besides the obvious gain in computing power in recent years that provides an analyst with improved viewing capability and measurement tools, research and development is also being focused on using the meta data (data about the data) to help characterize a feature. This is done in conjunction with efforts to gain a better understanding of outliers through the correlation of field results. The improvement in analysis also includes learning being incorporated from pull testing and lab testing using Non Destructive Examination (NDE) of pipe samples (pipe with known features such as cracks) that are carried out by the operator or through various research organizations such as PRCI.

Below are a few examples of technologies that are being offered for In-line Inspection and that could be the object of further investigation. Although these techniques are not new, service providers are investigating new ways of using or incorporating them for pipe inspection.

- Acoustic Resonance Technology is an acoustic inspection technology based on the phenomenon of half-wave resonance, where the pipeline wall is excited by ultrasonic waves and exhibits longitudinal resonances at certain frequencies characteristic of the pipe's thickness. The resonant frequencies are used to calculate the target's thickness. It can be used without a liquid couplant.
- Guided Wave Ultrasonic Testing (GWUT) is based on using very low ultrasonic frequencies transmitted axially along the pipeline wall over long distances. It is viewed as a screening tool that can identify the location of defects or anomalies.

Barriers

Improvement of in-line inspection tools is a very active area globally by individual service companies and by collaborative research organizations such as PRCI and GTI. It is a complex area that requires the integration of detection technologies with ILI assemblies and the analysis and correlation of results over time.

Value

In-line inspection is at the core of Integrity Management because it aims to detect and anticipate problems before they occur through periodic inspection of the pipeline. Improving the accuracy and reliability of such measurements would provide significant benefits to pipeline integrity. System integrity is of particular significance for existing pipelines as it is necessary to continually assess their integrity as they age.

5.3.7. Leak Detection

Pipeline leaks are comparatively infrequent occurrences but they may have significant safety, operational, economic and environmental impacts. They can be initiated by a large variety of mechanisms. However, the majority of leaks are attributed to internal or external corrosion, to insufficient maintenance, to human intervention or to third party damage. In theory, a properly constructed, maintained and operated modern pipeline should not leak even as it ages over a number of decades. As noted earlier in Section 2.2.4, a 2012 study by the INGAA Foundation determined that 85% of pipeline ruptures or major leaks were not attributable to pipeline age. In the words of the authors, pipe steel does not "wear out."

However, incidents can happen and the ability to rapidly detect, locate and respond to a leak is invaluable given the potential risks to human safety, the impact on the environment and the costs of cleanup and remediation. Existing methods used to detect pipeline leaks include pump or compressor station flow monitoring, computerized analysis of flow parameters (generally flow rate, pressure and temperature), external distributed sensors placed along the pipeline, and ground patrols.

5.3.7.1. Existing Situation

According to the American Petroleum Institute (API), Leak Detection Systems (LDS) are divided into internally and externally based systems. Internally based systems utilize field instrumentation (for example flow, pressure or fluid temperature sensors) to monitor fluid hydraulics and to determine if a potential leak could be the cause of a deviation from expected conditions. Externally based systems are based on a number of technologies (for example infrared radiometers, thermal cameras, vapour sensors, acoustic microphones or fiber-optic cables) deployed along the pipeline ROW to detect changes that could be explained by a leak.

Computational Pipeline Monitoring

Computational pipeline monitoring (CPM) is the internal leak detection system that is the well-established workhorse system of the industry. The API has published several articles related to the performance of CPM in liquids pipelines. Some of the API publications are:

- API 1130 – Computational pipeline monitoring for liquids pipelines (which is incorporated into 49 CFR Part 195 by reference)
- API 1155 – Evaluation methodology for software based leak detection systems
- API 1149 – Pipeline variable uncertainties and their effects on leak detectability (an update is currently in preparation under a PRCI project)

In Canada, CSA Z662 Annex E is the portion of the standard that relates to leak detection systems.

CPM employs numerous monitored variables, a number of monitoring algorithms and computer modeling to identify process upsets or potential leak situations. The data from all sensors is compared against a baseline model to identify values that differ from the modeled case that could be explained by a potential leak.

CPM includes simplified methods of volume balance based on operator/controller monitoring of pressures and balancing of volume or mass flows. Simplified methods are generally applicable only to steady state conditions.

CPM also includes a number of sophisticated computer modeling methods based on physics principles of conservation of mass, energy and momentum. Monitored inputs include operating parameters for temperature, pressure, volume and mass flow, and density, and include equipment inputs such as pump start/stop and valve open/close signals. Operational transients such as pump starts, line fills, valve closures, etc., may be modeled as well, using methods such as the Real-Time Transient Model so that the leak detection system can continue to work during operational changes that occur in the normal day-to-day operation of a pipeline system. Finally new CPM methods such as the pressure wave or negative rarefaction wave technology are being evaluated by operators and PRCI and may require further development.

Improvements in CPM performance could be achieved by:

- Cataloguing fluid properties including time and shear rate effects;
- Improving modeling under transient conditions of startup, shut down and slack flow; and
- Inclusion of property changes when using drag reducing agents.

Examples of providers of CPM solutions (generally integrated with SCADA and based on API documents) are Atmos International, GL Noble Denton, Colt Engineering (now Worley Parsons), CriticalControl Solutions, EFA Technologies, Energy Solutions International, Enviropipe, and Telvent. These solutions may use some of the following techniques, some of which are described in API documents: volume balance, statistical analysis of imbalance, Real-Time Transient Model, Pressure Point Analysis (detects signature of the expansion wave associated with a leak), etc.

Small leaks fall below the threshold of CPM leak detection systems. In general, due to limitations in pipeline hydraulics, accuracy of the detectors, and alarm thresholds, CPM would not detect small leaks. Large leaks are more easily detected by CPM, but must be detected quickly. Rate-of-change and computational pipeline monitoring are typically employed to detect large leaks. Volume or mass balance systems can be employed to detect small leaks, but the present reality is that many small leaks cannot be detected by CPM methods.

The detection limit of CPM is in fact a range that depends on the specific method used, the quality and amount of instrumentation, the experience and skill of the pipeline operator and the selected trade-off between reliability and sensitivity. For example, the leak detection limit of the systems proposed for the Keystone XL Pipeline is considered to be 1.5 to 2% of the pipeline flow rate. This assessment may be conservative and may not be typical of the performance achieved by skilled operators. It is well recognized that a leak detection system is a combination of technology and human factors and that well designed workflows and high levels of training will significantly improve sensitivity and the accuracy of analysis and response actions.

A key parameter in the operations of CPM systems is the selection of the balance between sensitivity and reliability. Sensitivity is a combination of the minimum size of the leak to be detected and of amount of time required to detect the leak. Reliability is related to the number of false alarms. CPM systems tend to generate false alarms (low reliability) when the system is not tuned properly, including an improper selection of the balance between sensitivity and reliability. A system is considered to be reliable if it consistently detects actual leaks without generating incorrect declarations (false positives or false negatives). Often false alarms are a trade off with sensitivity; there is always a conflict between the desire for greater sensitivity and the requirement to minimize false alarms.

Secondary Leak Detection Systems

In general, the industry considers CPM to be the primary leak detection system due to the fact that it is a proven and well established system. Various technologies and strategies have been proposed to complement CPM and to act as a secondary system, primarily for detecting leaks smaller than the optimum CPM sensitivity setting. These technologies tend to be external to the pipeline and include fiber optic cables, airborne surveillance, vapor sensing tubes, wireless sensor networks, and others. Internal sensing technologies have also been proposed; an example among others is a system of acoustic sensors enclosed in an aluminum ball that rolls inside the pipeline propelled by fluid flow or that could be included in ILI tools. Whether external of internal, some technologies offer continuous monitoring, while others are based on periodic survey and/or on data download and analysis post-acquisition.

However, most of these novel technologies remain unproven in field applications; they are often expensive and may require further technology development before they become deployed extensively.

5.3.7.2. Gap/Opportunity Description – Computational Pipeline Monitoring

Most liquid pipeline companies operate CPM technologies as specified in API 1130. However, as discussed above, these technologies tend to generate false alarms (low reliability) when extending their sensitivity limit. Current practices regarding the interpretation of CPM data mostly depend on proper procedures and the experience and training of pipeline operation staff. Data analyses are sometimes not reliable and may take excessive time to diagnose.

Prospective Direction for Research and Innovation

The objectives of a Leak Detection Decision Support System (LD DSS) are to improve reliability, in terms of reducing the number of false alarms, and to improve sensitivity in terms of leak size and speed of detection. Computing power has improved significantly in recent years such that it is possible to contemplate the development of sophisticated systems that would be built by codifying best practice procedures and expert staff knowledge and automating them into automated decision-making rules that would dramatically reduce the time required for data analysis and diagnosis. “Big data”, machine learning and artificial intelligence technologies could be harnessed.

The elements of a program could be as follows:

1. Recruit a few operating companies that are willing to provide their leak detection operating data and share their operating expertise with experience in leak detection.
2. Analyze the operating data using various expert or artificial intelligence systems to conduct a feasibility study.

3. If feasible, develop an LD DSS and implementation/operating guideline.

The initial objectives would be to conduct a technical feasibility, and develop and implement a working LD DSS on several pipelines. Long-term objectives would be to gather operating data and enhance its effectiveness and capability.

Barriers

The development of a LD DSS is likely to be a major undertaking that would require aggregation of operating data from many operators. Furthermore, there is no certainty that the endeavor will be successful as some of required data may not be available to the extent and quality required. For an expert system to be developed, a larger number of incidents would need to be analyzed. There may not be sufficient rich data sets available covering the range of possible operating conditions.

Furthermore, in principle, the case can be made that efforts and resources would be better spent on leak prevention rather than detection. Investments in Integrity Management reduce the probability of leaks and their associated costs and impacts. However, incidents can happen despite state of the art integrity tools and systems. Therefore, investing in leak detection and mitigation research is crucial to minimize impact to the environment.

Value

The value of being able to quickly and reliably know when a large or small leak occurs is very high. It would significantly reduce the consequences and cost of releases by limiting the volume of the release to the volume in the pipe up to the nearest valve and by triggering immediate containment and mitigation response.

5.3.7.3. Gap/Opportunity Description - Secondary Leak Detection Systems

There are several secondary leak detection systems that are the object of development by technology providers and evaluation by operators. These include fiber optic cables, vapour sensing tubes, acoustic detectors, wireless sensor networks, and airborne surveillance. However, their reliability, sensitivity, accuracy and robustness in operating pipelines are not fully proven in all operating conditions.

Fiber Optics

A number of field implementations of fiber optic cables have taken place worldwide. For example, BP commissioned Schlumberger to install a fiber optics system based on distributed acoustic sensors (DAS) on the BTC Georgia pipeline. In combination with helicopter patrols, the purpose was intrusion detection system to prevent illegal hot taps. A short trial section was installed several years ago, and then another 75 km installed between two pump stations with the highest threat of illegal taps. The fibre was laid in hand-dug trenches, by 150 labourers over a period of 120 days. The system was apparently successful, as previously there were as many as 25 illegal taps per year, and there have been none in the two years after system installation.

Schlumberger and Omnisense are examples of established suppliers of fiber optic cables for pipeline applications.

While DAS fiber optic systems have been shown to perform well for intrusion detection, the application of fiber optics for leak detection is still under development. DAS systems have been proposed to detect the noise from a leak and/or the vibration caused by the event (e.g. wall rupture) that preceded the leak. However, most of the technology development appears to be aimed at fiber optic cables with distributed temperature sensors (DTS) which are used to detect the change in soil temperature caused by the escaping fluid. Variables such as placement of the cable and the difference in temperature of the soil and the fluid in the pipeline require careful consideration. Some researchers have also suggested specialty fiber optic cables with a hydrocarbon sensing coating but such technology is at an early stage of development.

The fiber optic system would also be capable of sensing land movement geohazards, monitoring operational activities such as pig tracking and high speed data transmission.

Vapour Sensing Tubes

Vapour sensing tubes are hydrocarbon permeable tubes laid near the pipeline along the entire length of the section of interest. The tubes are permeable to hydrocarbon vapours such that vapours from leaked fluid would permeate inside the tube. An inert gas is constantly transported inside the tube and carries the hydrocarbon vapours to a detector located at the pipeline pumping or compressor station. Location of the leak is determined by adding tracer compounds to the inert gas.

Wireless Sensor Networks

Wireless Sensor Networks (WSN)) take advantage of advances in electronics such as Microelectromechanical Systems (MEMS) which can combine a sensor with a wireless transmitter on a small electronic chip. The sensor can be selected to measure properties of interest such as temperature, pressure strain and presence of hydrocarbons. Their wireless capability enables them to communicate to remote nodes which in turn communicate with the central controller using telecommunication systems. WSN offers the possibility of vast increases in pipeline parameters that can be monitored and analyzed without the risk and cost of wired networks. However, buried pipelines present special challenges due to the fact that wireless signals have a limited range in the subsurface.

Airborne Surveys

Generally, pipeline operators will conduct airborne surveys for intrusion and encroachment detection. Technology developers have proposed attaching chemical sensors to airborne and fixed wing aircrafts used in these surveys in order to also detect the presence of hydrocarbon associated with leaks. Some systems have been evaluated and have shown to be able to detect small leaks using infrared and multispectral detectors.

Prospective Direction for Research and Innovation

There is a need to assess secondary leak detection systems and the program could follow the steps outlined below:

1. Information search for commercially developed and implemented leak detection systems to clearly understand the status of such techniques.
2. Determine if further improvement is required to be used as an effective leak detection system.
3. Recruit potential major pipeline operators as partners to participate in joint assessment of the technology.
4. If successful, develop an operating and implementation guideline.

Technology developments in secondary leak detection techniques have been promising, particularly for detecting small leaks, and it would be worthwhile to investigate their leak detection capability. However, technology evaluations have and continue to be performed by collaborative organizations such as PRCI and by individual pipeline companies; any new program will need to be mindful of not duplication existing work.

Barriers

The main barriers appear to be:

1. That some of the proposed technologies such as fiber optic cables would be not practical or very high cost for legacy pipelines because they need to be installed close to the pipe to detect leakage; and
2. The difficulty to validate with field experience the systems based on temperature or acoustic changes.

As mentioned in Section 5.3.7.2 above regarding CPM, the value of leak detection is limited to mitigating the impact of leaks by enabling a more timely response to the event. By contrast, investments in Integrity Management pay off by reducing the probability of leaks and their associated costs and impacts. However, while prevention is better than mitigation, incidents can happen despite state of the art integrity tools/programs. Therefore, investing in leak detection and mitigation research is crucial so that a pipeline company can detect a leak quickly thus minimizing impact to the environment.

Value

The value of being able to quickly and reliably know when a large or small leak occurs is very high. It would significantly reduce the consequences and cost of releases by limiting the volume of the release to the volume in the pipe up to the nearest valve and by triggering immediate containment and mitigation response.

5.3.8. Spill Cleanup and Remediation of Submerged Oil

Oil spills are infrequent events that can be very serious if not dealt with quickly and effectively. Major oil spills that are still etched in the public's consciousness are however not related to pipelines: Deepwater Horizon and Exxon Valdez. In addition, spills caused by marine tankers also receive prime media attention when they occur. Pipeline related oil spills have also attracted public attention in recent years.

5.3.8.1. Existing Situation

Well-established technologies exist to contain, clean up and remediate oil spills. These generally involve floating booms, skimmers and earthmoving equipment. Waste from cleanup operations is generally sent to landfills with the appropriate classification or to managed bioremediation sites. In addition, equipment is available on standby to facilitate the emergency response to these unplanned events. For example, the Western Canada Marine Response Corp and Western Canada Spill Services are industry cooperatives that hold such equipment in western Canada.

There is much literature on the dispersion of conventional crude oils with and without chemical additives. However, the bulk of the literature focuses on marine spills. Remediation methods for offshore spills include containment and skimming, sorbents, burning, fertilizers, and dispersants. There are few studies on oil spills in rivers and potential remediation techniques. The effects and benefits of dispersants in river spills appear to be little investigated. An additional option for river spills is dredging.

5.3.8.2. Gap/Opportunity Description – Cleanup and Remediation of Submerged Oil

A U.S. National Academy of Sciences report issued in June 2013 concluded that transportation of dilbit by pipeline is not more likely to result in a release than conventional crude oil[28]. Because it was not within the assigned terms of reference, the question about the consequences of a dilbit spill vs. a spill of conventional oil was not addressed in the report. Critics of the report have pointed out that this omission is a weakness. Perceived concerns that may require scientific validation generally center on two potential differences between dilbit and conventional crude oil that could worsen the impact of a spill:

- The heavy fraction of dilbit could be denser than fresh water and, over time, it has been suggested that the heavy fraction could sink more quickly when it is spilled in a water body such as a lake or a river. This could increase the impact of a spill as it is no longer contained on the surface of the water and existing technologies such as booms and skimmers may not be sufficient to clean up the spill. The EPA cites the recent spill in Marshall Michigan as evidence that the impact of a dilbit spill could be greater than what is normally anticipated from conventional crude oil.

[28] National Research Council of the National Academies (2013), TRB Special Report 311: Effects of Diluted Bitumen on Crude Oil Transmission Pipelines

- The heavy fraction of any crude oil is considered to be non-biodegradable. It is generally assumed that crude oil that would escape cleanup operations would biodegrade over time from a natural remediation process. However, heavy oil and dilbit contain a large amount of non-biodegradable heavy components and there is a concern that such heavy components that may escape cleanup operations could have a long-term environmental impact.

The fate of spilled crude oil on water is governed by a complex set of mechanisms. Initially, the oil spreads on the surface through advection and spreading mechanisms. Advection is the movement of the oil from drag by the water current and wind. Spreading is the expansion of the crude oil film from turbulent diffusion and surface forces. Over time, some of the crude oil and water may become emulsified and allowing the oil to settle through the water column. Some of the oil droplets may settle to the bottom of the river especially if they adhere to particulates. The settled oil may form sludge with the river bed sediment. Some of the oil from the surface film or emulsion will also deposit on the river banks and some will be carried downstream. The properties of the crude oil will change over hours and days as the lighter components evaporate or dissolve and over months and years as the oil is photochemically reacted and biodegraded.

The same mechanisms apply to dilbit. The main difference is that dilbit is a bimodal mixture of a relatively light diluent and a very heavy crude oil. When dilbit is spilled on water it will initially float. It may form a film and/or emulsion depending on its chemistry how much shear it encounters. As the diluent evaporates, the density of the spilled and weathered dilbit increases, and it may eventually reach the point where natural convection allows it to sink. However, recent laboratory and meta-scale tests indicate diluent evaporation is a gradual process and a significant portion of diluent will remain in the weathered dilbit even after 10 days. (Yarranton, 2013, private communication).

A recently published report by the Canadian Federal Government[29] presented laboratory and wave tank experiment results from spilling and weathering diluted bitumen on salt water. It was found that like conventional crude oil, diluted bitumen floated on saltwater (free of sediment), even after evaporation and exposure to light and mixing with water. When fine sediments were suspended in the saltwater, high-energy wave action mixed the sediments with the diluted bitumen, causing the mixture to sink or be dispersed as floating tarballs. Testing of a commercial chemical dispersant was found to have quite limited effectiveness in dispersing dilbit. In summary, the study found similarities and differences in the behavior of dilbit vs. conventional oil when spilled on salt water.

[29] Environment Canada, Fisheries and Oceans Canada and Natural Resources Canada (2013, Properties, Composition and Marine Spill Behaviour, Fate and Transport of Two Diluted Bitumen Products from the Canadian Oil Sands, available online at: http://www.ec.gc.ca/scitech/F5C2D374-AC34-4429-BB1A-93FD61E2D3F3/1633_Dilbit_Technical_Report_e_v2_FINAL-s.pdf

Prospective Direction for Research and Innovation

The elements of a research program aimed at better understanding dilbit cleanup and remediation could be as follows:

1. Dispersion tests of dilbit in water over time, effect of solvent evaporation, effect of dispersants.
2. Assess effectiveness and consequences of dredging.
3. Long term fate of the heavy fraction deposited at river bottom or onshore (e.g. biodegradation and burial).
4. Understand dispersion fundamentals for dilbit particularly the effect of diluent evaporation and the low potential for biodegradation.
5. Identification of most effective dispersion control and remediation methods for spills in rivers.

Barriers

The bulk properties of dilbit are within the range of properties of the crude oils transported by pipeline systems and it was generally assumed that cleanup procedures would be similar. However, new cleanup methods may be beneficial to more quickly mitigate and reduce the cost of dilbit spills. Scaling up of novel cleanup methods found to be effective at lab-scale would be an opportunity.

Value

Ensuring that effective and proven methods exist and are available to clean up and remediate potential dilbit spills would respond to a critical stakeholder concern.

5.3.9. Reclamation

5.3.9.1. Existing Situation

There have been several studies performed on this topic and a few isolated case studies. However none have really taken and in depth and systematic approach to dealing with abandoned pipe or the costs likely to be associated with such measures.

5.3.9.2. Gap/Opportunity Description – Pipeline Abandonment

Landowners have expressed concerns about abandoning pipelines in place, postulating that overtime:

1. They would collapse and result in major subsidence; and
2. In a corroded state they would act as undesirable conduits for water.

No research exists that would either disprove or validate such beliefs if pipe were to be left in place. Nor has work been done to quantify the pros and cons of pipe removal over the full range of sizes required. Further CSAZ662 provides only general guidelines as to the level of cleanliness required for abandoned pipe.

Research is needed into:

1. Safe, practical means of abandoning pipe in place including establishing levels of cleanliness and prevention of collapse;
2. The full effects (environmental and financial) of substantial removal of pipe.

Prospective Direction for Research and Innovation

A research and innovation program to address landowner concerns about abandoned pipelines could include the following:

1. Small scale lab plus field testing on real pipe of reversed CP polarity to accelerate corrosion followed by surface loadings.
2. Construct in parallel continuum models of soils with buried cylinders in various stages of structural decay subject to surface loads.
3. Examine costs and means of deployment of low density concrete/polyurethane foam to fill buried pipe so as to prevent structural collapse and water migration. Test water tightness in lab models.
4. Determine if low cost passive protection can be introduced to pipe surfaces to prevent long term degradation.
5. New pipe will eventually become abandoned pipe; so determine if a passive film substrate can be placed on pipe surfaces prior to coating or as part of it, to halt corrosion degradation. In short, develop an "Intelligent Skin" for new pipe surfaces.

Barriers

Pipeline abandonment has been the subject of studies in the past decades. However, experimental results and validation are missing, in part because it is difficult to replicate the process of long term degradation in a controlled laboratory setting. Of note, CEPA has recently undertaken a research program in pipeline abandonment in collaboration with landowners groups and the National Energy Board.

Value

Developing experimental data to determine the expected state of abandoned pipelines over time would assist in determining if they would eventually present a hazard to the public and landowners or would result in unfavourable environmental impact. This would also allow the establishment of procedures and methods to safely abandon pipelines in a reliable manner.

5.4. Analysis and Prioritization of the Gaps and Opportunities

5.4.1. Prioritization Methodology

The purpose of the Roadmap is to provide a blueprint for future investments in research and innovation for the development of technology solutions that would address stakeholders concerns. Subsequently, the Roadmap may lead to an action plan to implement a portfolio of technology opportunities. The gap analysis is an exercise in scanning the landscape for needs and opportunities to capture the significant issues. It is a necessary precondition and foundation for the Roadmap. After the gaps and opportunities have been identified, they need to be sorted and arranged in a manner that would contribute to the prioritization of future research and innovation investments.

The gap prioritization workflow is based on the information available at this stage and described in Figure 11:

- Each gap/opportunity is reviewed for its potential impact on fulfilling the strategic drivers;
- Each gap/opportunity is also reviewed for the level of effort of active research programs worldwide which are aimed at addressing it;
- Gaps/opportunities are placed in a matrix capturing the impact of the gap on the vertical axis and the extent to which it may already be addressed on the horizontal axis.

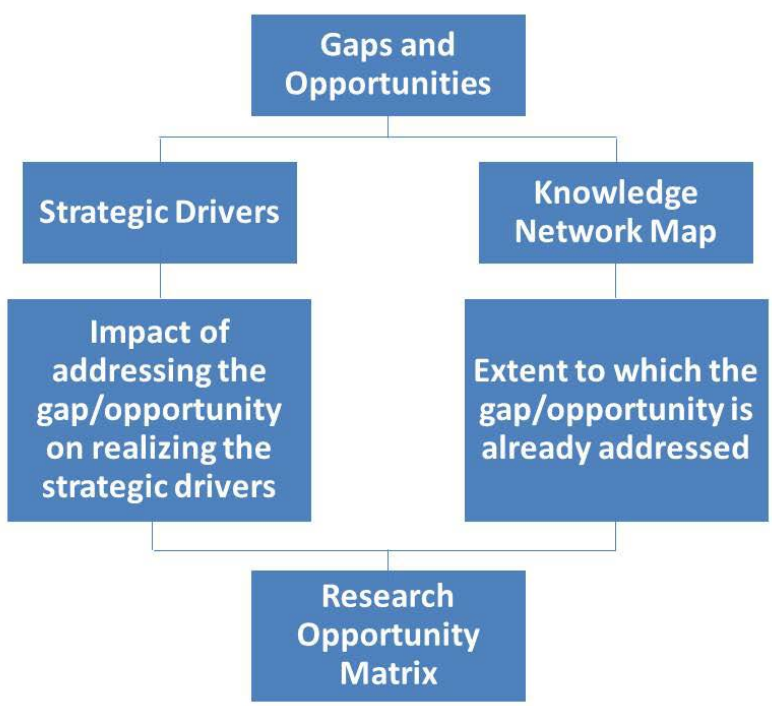

Figure 11. Prioritization Workflow

The Research Opportunity Matrix is shown in Figure 12. The vertical axis gauges the impact on the strategic drivers, in other words the impact on improving integrity and reducing environmental impact. The scale rates such impact as low, medium or high, as follows:

- Low impact. Closing the gap or realizing the opportunity will have a positive impact on some elements of at least one of the two strategic drivers.
- Medium impact. Closing the gap or realizing the opportunity will have a significant impact on the strategic drivers; prior research may have already partially closed the gap or harnessed the opportunity, thus reducing the impact of new research.
- High impact. Closing the gap or realizing the opportunity would result in a profound impact on the strategic drivers. There may be existing research programs but much work remains to be done to close the gap or realize the opportunity.

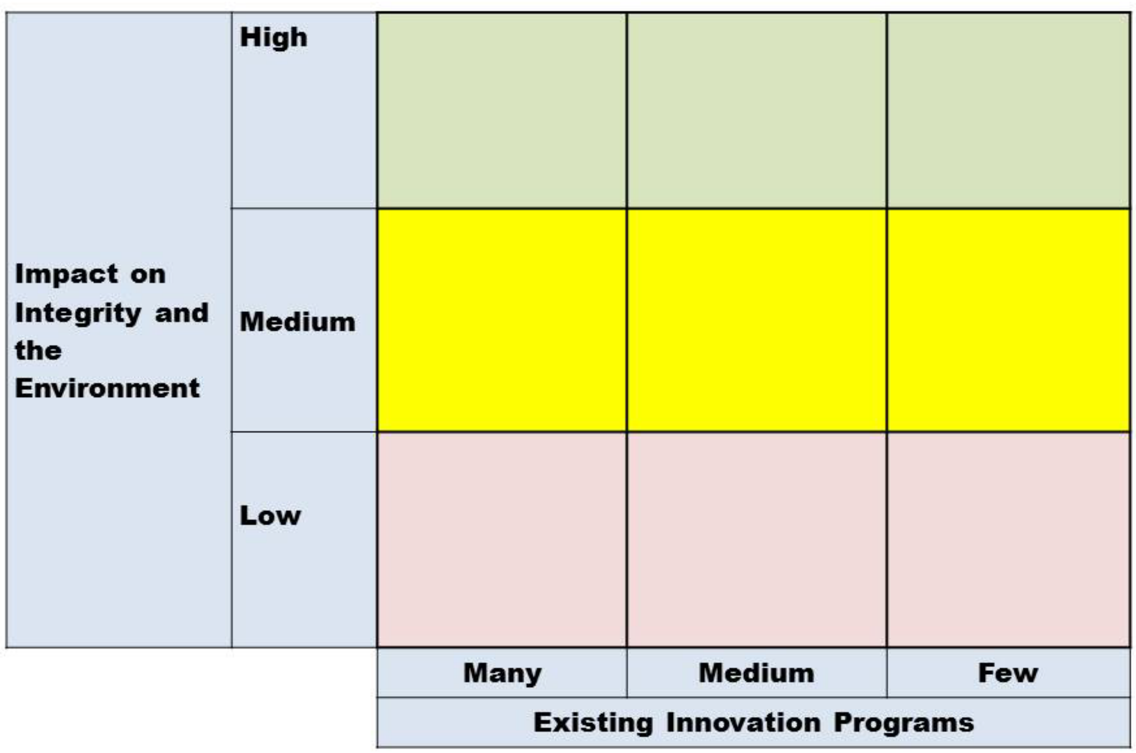

Figure 12. Research Opportunity Matrix

The horizontal axis is informed by the Knowledge Network Mapping and gauges the worldwide level of effort in the subject area. The existence of research programs will inform the priority for allocating new resources to the topic but, most importantly, the method by which such investment could be made whether it is leadership for a new research initiative from Canada and Alberta or participation and collaboration in existing programs nationally or internationally.

It is important to note that the prioritization of the gaps is only one of the factors that would lead to future investment decisions. At the roadmap development stage that will come after this gap analysis, factors such as value (which combines impact and costs) and technology maturity (which encompasses probability of success, time horizon, cost of research and other factors) will need to be considered. Thus, prioritization of gaps/opportunities is only a first screening mechanism and other filters will subsequently be applied.

5.4.2. Overview of Gaps and Opportunities

The 17 gaps and opportunities discussed earlier in this section are listed below in the order they were presented.

Environment (Direct Impacts)

1. Route Optimization
2. Noise Impact
3. Construction Right-of-Way

Design

4. Geological Hazard Risk Assessment
5. Strain-based Design and Materials

Materials

6. Fracture Propagation and Arrest

Construction

- Gaps/opportunities were captured under Environment

Operations and Maintenance

7. Pipeline Repairs with Composite Materials
8. Hydrodynamics

Integrity Management

9. Internal Corrosion
10. External Corrosion
11. Defect Assessment
12. Risk-based Fitness for Service Defect Assessment
13. In-line Inspection

Leak Detection

14. Computational Pipeline Monitoring

15. Secondary Leak Detection Systems

Cleanup and Remediation

16. Cleanup and Remediation of Submerged Oil

Reclamation

17. Pipeline Abandonment

5.4.3. Pipeline Innovation Research Opportunity Matrix

Figure 13 distributes the gaps and opportunities according to their respective impact and level of current activity. The interpretation of the Pipeline Innovation Research Opportunity Matrix is as follows:

- Gaps/opportunities with high impact but addressed by few research organizations represent an opportunity or a need for future investment in new research initiatives that could be led from Alberta and Canada.
- High impact gaps/opportunities that are the object of a high level of effort represent opportunities for collaboration and partnerships with the research programs already addressing the gap or opportunity.
- Medium and low impact gaps/opportunities are of lower overall priority but some aspects may be of higher interest to specific participants in the innovation system.

The rationale for the placement of each gap/opportunity in Pipeline Innovation Research Opportunity Matrix is provided below:

Green Shaded Area (5 high impact gaps/opportunities)

- In-line Inspection. ILI is fundamental to Integrity Management and is prescribed in regulations. Many opportunities for improvement exist which are pursued by several service companies worldwide and PRCI is setting up a test loop for this purpose.
- Defect Assessment. This gap has been the object of much industry research and development because it is critical to integrity. PRCI undertook relevant projects in the last decade. Opportunities still exist to advance the state of knowledge and to improve and strengthen existing models. The most effective avenue appears to be through collaboration with initiatives that are already underway.
- Risk-based Fitness for Service Defect Assessment. While defect assessment models exist and are generally well understood, the insertion of these models in a risk-based framework is necessary to allow industry to make optimum decisions.

Figure 13. Pipeline Innovation Research Opportunity Matrix

Impact/Value on Integrity, Reliability and the Environment		Many	Medium	Few
	High	• In-line Inspection	• Defect Assessment • Risk-based Fitness for Service Defect Assessment • Secondary Leak Detection Systems	• Cleanup and Remediation of Submerged Oil
	Medium	• Fracture Propagation and Arrest • Internal Corrosion	• Strain-based Design and Materials • External Corrosion • Computational Pipeline Monitoring	• Geotechnical Hazard Risk Assessment
	Low	• Pipeline Repairs with Composite Materials		• Route Optimization • Noise Impact • Construction Right-of-Way • Hydrodynamics • Pipeline Abandonment
		Existing Innovation Programs		

- Secondary Leak Detection Systems. While the potential of new technologies is recognized, technology development efforts appear uneven. The fiber optics opportunity has yet to be fully understood and deployed in leak detection service. Other prospective technologies such as remote sensing and acoustic devices are also being investigated by some pipeline operators. Most innovative technologies originate from service companies but the industry would benefit from leveraging resources into concerted and coordinated efforts to evaluate promising candidates.
- Cleanup and Remediation of Submerged Oil. A critical concern of stakeholders is the potential consequences of a heavy oil or dilbit spill in inland or marine waters. There are few published scientific papers in this area. Furthermore, new methods could be developed to mitigate the potential environmental impact and to reduce cleanup costs. Few, if any, research groups are presently addressing this gap.

Yellow Shaded Area (6 medium priority gaps/opportunities)

- Fracture Propagation and Arrest. The full understanding of the fracture behavior (particularly running ductile fractures) of high strength steels is critical as these grades of steel are used more frequently. It is an active area of research worldwide that involves international collaboration.
- Internal Corrosion. As crude oil and natural gas are not inherently corrosive to steel, much of the attention by industry and regulators is on technologies to prevent external corrosion. Nevertheless, gathering lines is a pipeline application where internal corrosion may take place due to the presence of water with the hydrocarbon fluids. Researchers worldwide continue to improve the understanding of basic mechanisms and inform industry practices.
- Strain-based Design and Materials. This gap has received significant attention in recent years but not enough progress has been made to enable cost-effective implementation in regulations. While PRCI has a roadmap and a proposed technology program, opportunities exist for external collaboration and the laboratory infrastructure for such collaboration is available in Alberta.
- External Corrosion. FBE is the workhorse coating technology for protecting modern pipelines from external corrosion and it has an excellent performance record in North America. Questions about potential failures in other jurisdictions could be investigated collaboratively due to the broad use and importance of the technology. The impact of AC on CP is known and recognized by regulators and industry. Test and monitoring methods exist. The need to continuously improve current methods is addressed by consortium projects, for example under PRCI.
- Computational Pipeline Monitoring. CPM is the industry's established technology for leak detection. However, it is not likely suitable for detecting small leaks due to

limitations of instruments and modeling complexity. Furthermore, several service companies are very active in this area. The opportunity to apply artificial intelligence and "big data" techniques could be very valuable, if technically feasible.

- Geological Hazard Risk Assessment. Quantitative assessment of geohazards is necessary to fully enable the promise of strain-based design and optimum route selection. Anticipated cost reduction in satellite data may open opportunities for more widespread use of interferometric synthetic aperture radar (InSAR) technologies.

Red Shaded Areas (6 low priority gaps/opportunities)

- Pipeline Repairs with Composite Materials. This gap was identified by industry and PRCI has implemented a number of projects to address it. Most of these projects are near completion.
- Route Optimization. Optimum and transparent route selection could have an impact on social acceptance and on mitigating potential incidents. The opportunity exists to develop a comprehensive decision support system to better inform and explain route selection decisions. The impact would be limited to future new pipeline proposals.
- Noise Impact. In general, the impact of noise is smaller than other identified gaps.
- Construction Right-of-Way. In general, the impact takes place during the construction phase which is smaller in scope than the operational phase.
- Hydrodynamics. Poor understanding, analysis and design of facilities and structures can lead to premature failure caused by hydrodynamic factors. These situations appear not to be frequent and not to attract the attention of many researchers. Filling the knowledge gap about the speed of sound in dilbit appears to be an enhancement to support the transportation of Alberta bitumen derived products.
- Pipeline Abandonment. This gap has been a recurring topic of studies in recent years but research activity is now taking place under the leadership of CEPA, in collaboration with the NEB.

6. Innovation Roadmap for Transmission Pipeline Transportation of Petroleum Products

6.1. Objective

The third and final element of project workflow is to propose a Roadmap for investments in research, technology development and innovation that would be aimed at filling gaps and harnessing opportunities. The Roadmap is best described as a conceptual blueprint that captures a consensus among stakeholders about the motivation for improvement and potential directions for achieving them. This blueprint is prepared for consideration by industry, government and academia, and may be a basis for improved dialogue and planning that could subsequently lead to a full strategic implementation plan with concomitant allocation of resources with the objective to make significant improvements in the integrity and environmental impact of transmission pipelines.

6.2.Methodology

The Roadmap articulates a strategic framework for potential technology solutions aimed at addressing gaps and realizing opportunities.

Gaps and opportunities were placed in a research opportunity matrix in Section 5 to understand relative priority for allocation of resources and the creation of value. An example of a gap/opportunity is improved leak detection. This gap/opportunity received a high impact rating. In this Section 6, potential technology solutions are evaluated based on their prospect and value at closing the gap or harnessing the opportunity. Examples of potential technology solutions to improved leak detection include fiber optics, remote sensing, acoustic sensors, etc. Each of these solutions may present a different profile for value and probability of success, which may lead to different decisions as to the allocation of resources by different stakeholders.

Workflow details are shown in Figure 14. Prospective technologies were analyzed and summarized by subject matter experts in the areas identified by the gap analysis. Greater emphasis was placed on high impact gaps/opportunities. The results of this initial analysis were captured in technology solution worksheets which were discussed, updated and aggregated in a work session and during the final workshop.

The specific workflow steps were as follows:

- For each gap or opportunity, the current state of knowledge was identified through literature searches and discussions with key researchers;
- 16 technology solution worksheets were prepared. (A technology solution includes a number of discreet solutions that are vendor specific or technical variations on a technology platform.);
- Interaction with the Steering Committee;
- Aggregation and prioritization of the 15 final technology solutions into 2 portfolios;
- Validation of the Roadmap during the workshop; and
- Update of the Roadmap based on workshop feedback.

Technology Solutions. A technology solution represents the aggregation of individual technologies aimed at the same outcome as an area of technology development requiring a convergent set of skills and capabilities. For example, secondary leak detection is an opportunity aimed at the gap of improved leak detection. Secondary leak detection is further developed into a number of technology solution such as fiber optics, remote sensing, acoustic devices and other solutions, each being a unit of technology development requiring similar skills and capabilities and presenting similar profiles as to cost and risk of development. In a technology solution, such as fiber optics, there would be a number of embodiments of the technology pursued by different technology developers.

Once identified and defined, each technology solution was assessed with respect to value and to technology maturity.

Value. The concept of value embedded in a prospective technology builds from the impact of closing the gap or harnessing the opportunity, and adds to it costs and the potential for disruption to existing systems of implementing the solution. For example, one could consider two potential solutions to the gap of improved leak detection and assume that both could be successfully developed and made to deliver the same level of improvement in leak detection. A fiber optics solution will result in significant capital costs and the added complexity of ROW placement from laying hundreds of kilometers of fiber optic cables. By contrast, an artificial intelligence solution that could significantly improve CPM would incur far lower costs and be compatible with existing practices and regulations. Thus, an artificial intelligence solution would offer greater value, assuming a similar impact. It is acknowledged that artificial intelligence has a lower probability of success and this aspect is discussed below.

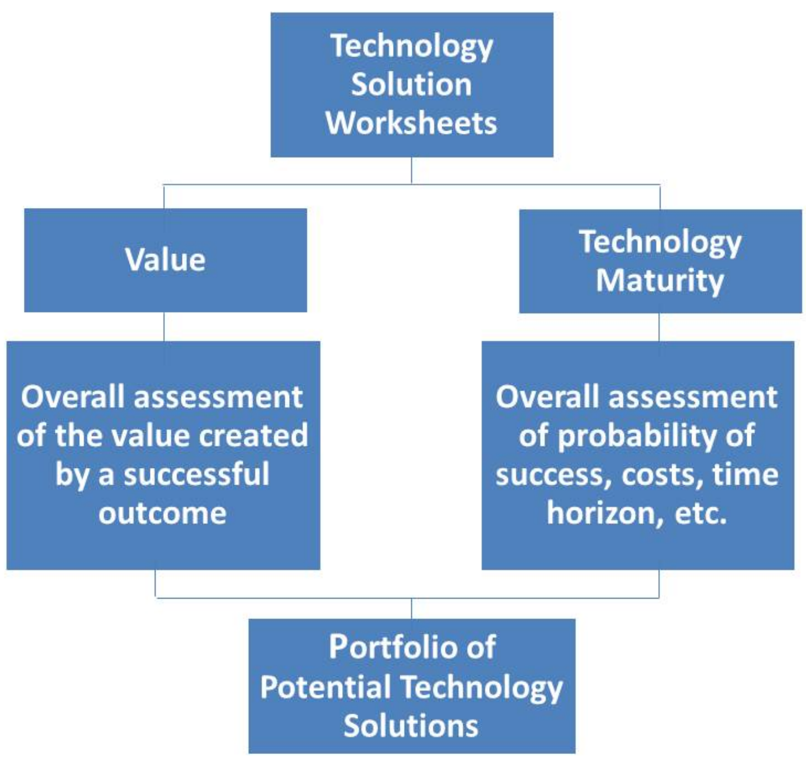

Figure 14. Pipeline Innovation Roadmap Workflow

Technology Maturity. Technology maturity describes how probable and how imminent a technology solution is to translation to widespread industrial use. It encompasses variables such as:

- Probability of technical success;
- Ease of market uptake;
- Cost of research and development;
- Time horizon for complete development and commercialization.

For example, a low maturity technology would exhibit one or more of the following characteristics:

- Technically challenging (Could need one or more inventions.)
- Market disruptive (The sector would need to acquire new skills or capabilities, change procedures or regulations, invest in new infrastructure, etc.)
- High technology development expenditures;
- Long technology development timelines.

A mature technology would exhibit converse characteristics to the attributes listed above.

Portfolio Approach. In general, investment in technology development would favor high-value projects in a mature technology space, in other words high reward/low risk technology investments. In practice, a technology development portfolio attempts to balance investment risk with potential returns in a continuum from incremental improvement (low risk but low value; typical of mature technologies) to game changing technologies (high risk but high reward; typical of low maturity technologies).

6.3.Roadmap Overview

The Roadmap is a conceptual strategic framework that acts as a foundation and precursor to the future development of a strategic implementation plan that would guide the allocation of resources to achieve strategic objectives.

In earlier sections of this report, it was made clear that the present needs and opportunities in pipeline technology are in the areas of integrity and environmental impact. Other major areas such as cost reduction, economic impact, new commodities to be transported, frontier terrains and others were deemed of lower need or opportunity. Thus, the two Roadmap strategic objectives are formulated as follows:

- To maximize reliability and integrity; and
- To minimize environmental impact.

The means to achieve these objectives can be classified temporally and logically into prevention and mitigation. Prevention is what can be done before an incident in order to avoid it or to reduce its scope. Mitigation is what can be done after an incident to minimize or remediate its short and long-term consequences.

A visual representation of the Pipeline Innovation Roadmap is provided in Figure 15. Details are presented in Table 5.

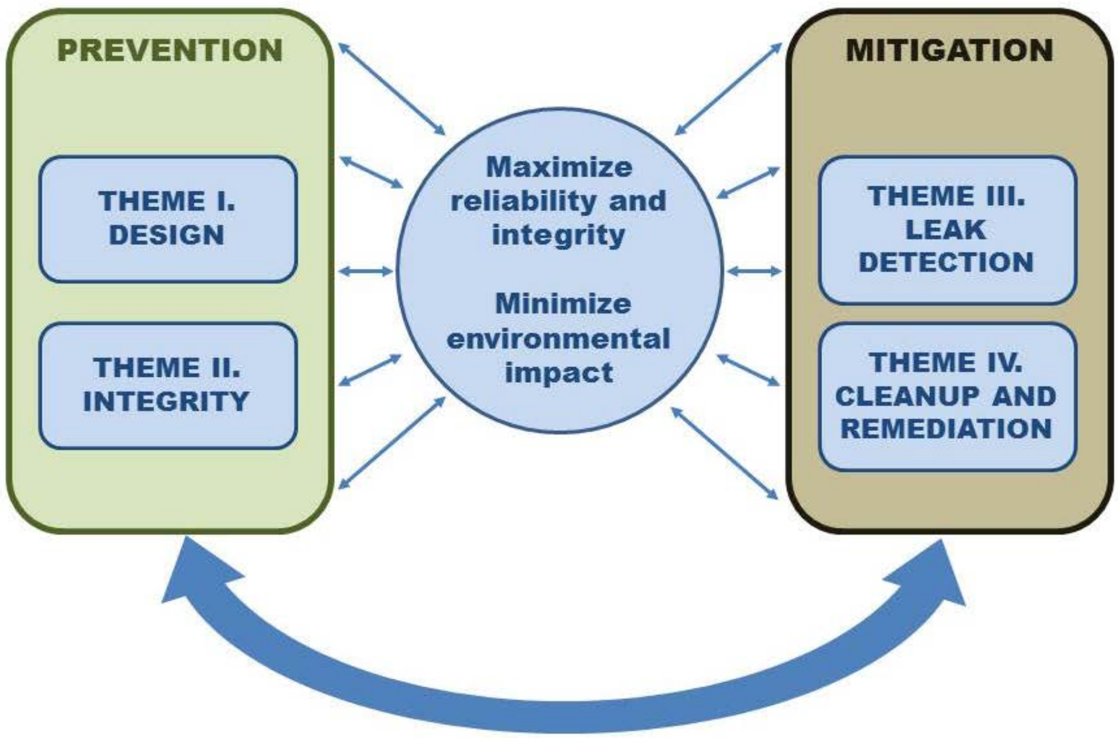

Figure 15. Overview of the Pipeline Innovation Roadmap

The two major thrusts of the Roadmap are Prevention and Mitigation. Prevention fulfills the strategic objectives through design, construction and operations technologies that ensure high levels of reliability and integrity to prevent safety, integrity and environmental incidents. Mitigation acknowledges that incidents can happen despite best technologies, practices and regulations. Mitigation encompasses technologies to limit consequences and restore the situation to its original condition.

Inside the two thrusts of Prevention and Mitigation, are the four themes of Design, Integrity, Leak Detection, and Cleanup and Remediation which aggregate technology solutions into convergent technology themes. Each of the themes is further subdivided into technology focus areas as detailed in Table 5. This structure offers a mission-oriented framework that is driven toward the strategic objectives and that covers all aspects of pipeline technology relevant to the objectives. Prospective technology solutions are then classified under the appropriate technology focus areas.

Table 5. Pipeline Innovation Roadmap Themes and Technology Focus Areas	
Prevention	Theme I. Design, Materials and Construction Technology Focus 1.1 - Strain-based Design and Materials Technology Focus 1.2 - Hydrodynamics Technology Focus 1.3 - Fracture Propagation and Arrest Technology Focus 1.4 - Direct Environmental Impacts
	Theme II. Integrity Management, Operations and Maintenance Technology Focus 2.1 - In-line Inspection Technology Focus 2.2 - Defect Assessment Technology Focus 2.3 - Internal Corrosion Technology Focus 2.4 - External Corrosion Technology Focus 2.5 - Pipeline Repairs
Mitigation	Theme III. Leak Detection Technology Focus 3.1 - Computational Pipeline Monitoring Technology Focus 3.2 - Secondary Leak Detection Systems
	Theme IV. Cleanup, Remediation and Reclamation Technology Focus 4.1 - Cleanup and Remediation of Submerged Oil Technology Focus 4.2 - Pipeline Abandonment

6.4. Technology Portfolios

The initial task in developing the portfolios of potential technology solutions was the preparation of 16 technology solution worksheets. The worksheets were informed by the gap/opportunity analysis, and, on a preliminary basis, captured: description, research objectives, benefits, probability of success, development costs, and time horizon.

Through further analysis, including general assessments of value and technology maturity, two portfolios of potential technology solutions were generated:

- Prevention technology portfolio: 15 potential technology solutions;
- Mitigation technology portfolio: 10 potential technology solutions.

The portfolios are summarized in Tables 6 and 7. Details of potential technology solutions and justification for value and technology maturity ratings are provided in Section 6.5.

In Tables 6 and 7, the potential technology solutions are arranged by roadmap themes and technology focus areas with preliminary ratings for value and for technology maturity shown. The portfolios are color-coded to facilitate resource allocation decisions as follows:

- High interest (green): Potential technology solutions with high-value combined with medium or high technology maturity; and with medium value and high technology maturity.
- Medium interest (yellow): Potential technology solutions with high-value and low technology maturity; with medium value and technology maturity; and with low value and high technology maturity.
- Low interest (red): Potential technology solutions with medium value and low technology maturity; and with low value and low or medium technology maturity.

The color coding is graphically illustrated in Figure 16.

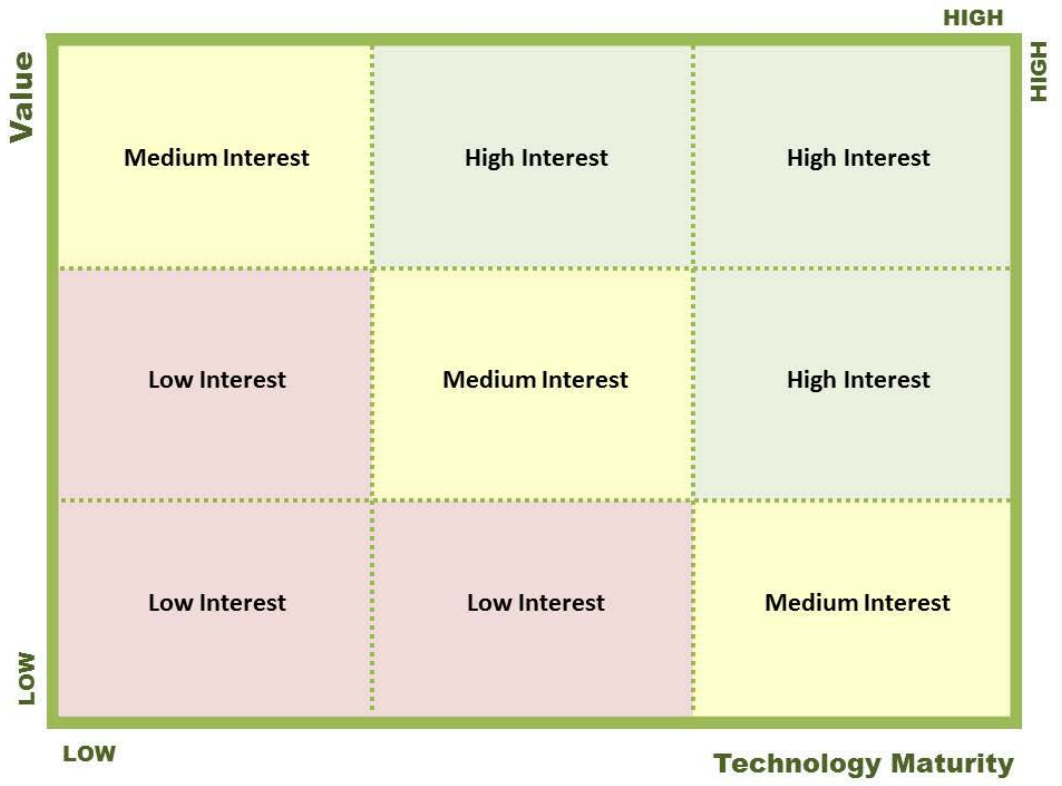

Figure 16. Portfolio View

Table 6. Overview of the Prevention Technology Portfolio

Theme	Technology Focus	Potential Technology Solution	Value	Technology Maturity
I. Design, Materials and Construction	1.1 - Strain-based Design and Materials	1.1.1 - InSAR Technology for Geological Hazard Risk Assessment	Medium	Medium
		1.1.2 - Validation of Tensile and Compressive Capacity Models	Medium	High
	1.2 - Hydrodynamics	1.2.1 - Speed of Sound in Dilbit and Synbit Compositions	Low	High
		1.2.2 - Friction and Drag Reducers	Medium	Medium
	1.3 - Fracture Propagation and Arrest	1.3.1 - Running Ductile Fracture Models for High Strength Steels	Medium	Medium
	1.4 - Direct Environmental Impacts	1.4.1 - Route Selection Decision Support System	Low	Medium
II. Integrity Management, Operations and Maintenance	2.1 - In-line Inspection	2.1.1 - New ILI Tools Evaluation and Validation	High	Low/Medium/ High
	2.2 - Defect Assessment	2.2.1 - Defect Assessment Models for High Strength Steel	High	Medium
		2.2.2 - Risk-based Fitness for Service Defect Assessment	Medium	High
	2.3 - Internal Corrosion	2.3.1 - Internal Corrosion under Deposits	Medium	Medium
		2.3.2 - Superhydrophobic Treatments of Steel	Medium	Low
	2.4 - External Corrosion	2.4.1 - Investigation of FBE Issues	Low	High

		2.4.2 - Self-healing Coatings	Medium	Low
		2.4.3 - Intelligent Coatings	Medium	Low
	2.5 - Pipeline Repairs	2.5.1 - Composite Materials Repair Methods Validation	Low	High

Table 7. Overview of the Mitigation Technology Portfolio

Theme	Technology Focus	Potential Technology Solution	Value	Technology Maturity
III. Leak Detection	3.1 - Computational Pipeline Monitoring	3.1.1 - CPM Decision Support System	High	Low
	3.2 - Secondary Leak Detection Systems	3.2.1 - Fiber Optics Leak Detection	Medium	Medium
		3.2.2 - Remote Sensing Leak Detection	High	Medium
		3.2.3 - Vapour Sensing Tubes for Leak Detection	Medium	Low
		3.2.4 - In-line Acoustic Sensors for Leak Detection	High	Medium
		3.2.5 - Distributed Wireless Sensor Networks for Leak Detection	Medium	Low
IV. Cleanup, Remediation and Reclamation	4.1 - Cleanup and Remediation of Submerged Oil	4.1.1 - Fate and Impact of Heavy Oil in the Environment	Medium	High
		4.1.2 - Behaviour of Submerged Oil in Inland Water Bodies and Coastal Waters	Medium	Medium
		4.1.3 - New Cleanup Methods for Submerged Oil in Inland Water Bodies and Coastal Waters	High	Low
	4.2 - Pipeline Abandonment	4.2.1 - Abandoned Pipelines Models	Low	Medium

6.5. Description of Potential Technology Solutions

6.5.1. Theme I. Design, Materials and Construction

Theme I covers all aspects prior to pipeline operations including design, materials selection and construction. In general, this encompasses a number of mature science and engineering disciplines that are widely practiced.

Technology Focus 1.1 - Strain-based Design and Materials

1.1.1 - InSAR Technology for Geological Hazard Risk Assessment

Value *Medium*

The development of interferometric synthetic aperture radar or InSAR would have a number of applications in design and integrity monitoring, but the application most often cited is the crossing of mountainous terrains. It would incrementally improve design and monitoring.

Technology Maturity *Medium*

InSAR technology is well developed and understood. The new paradigm expected to take place in the next 5-10 years is a very large increase in the amount of monitoring data and a significant reduction of its cost. In concert with improved data availability, automated data analysis and new workflows will need to be developed to enable practical use by pipeline operators.

Description

When designing pipelines crossing terrains susceptible to ground movement, the rate and extent of such movements must be measured or estimated. One technology to gather such data is InSAR. It is a technique that uses radar from a moving source such as satellites or aircrafts to generate precise elevation maps of the Earth’s surface. The technology claims to measure centimeter or even millimeter scale changes in elevation over time periods. However, the application of InSAR for routine monitoring of ground displacement has proven to be expensive as it requires the acquisition and comparison of satellite data at frequent intervals.

In the next 5 years, multiple satellite missions (particularly the RADARSAT Constellation from Canada and Europe’s Sentinel missions) will be launched with free and open (or low cost) data policies which will drastically reduce the cost of data access. This greater availability of frequent and quality satellite data will likely enable the use of InSAR to (i) better characterize terrain vulnerable to ground movement and (ii) routinely monitor such terrains traversed by critical infrastructure such as pipelines.

1.1.2 - Validation of Tensile and Compressive Capacity Models

Value *Medium*

Costly laboratory work is required to validate tensile and compressive capacity models for strain-based design in order for the models to be used with confidence by industry and codified in regulations without onerous safety factors. The completion of this work will result in lower cost and more reliable design in areas where strain-based design is applied.

Technology Maturity *High*

The tensile and compressive capacity models are well understood and a validation program was proposed by PRCI. This program is progressing slowly and the contribution of additional resources would accelerate it.

Description

Models and guidelines exist to estimate tensile and compressive capacities in the strain-based design of pipelines. However, the scarce experimental validation of these models limits their use and requires the application of conservative safety factors. This research program would undertake the necessary laboratory tests to calibrate and validate the models. Most of the equipment required is available at C-FER in Alberta.

Technology Focus 1.2 – Hydrodynamics

1.2.1 - Measurements of the Speed of Sound in Dilbit and Synbit Compositions

Value *Low*

Speed of sound datasets exist for heavy oil and some compositions including diluent. Completing the datasets for all compositions and operating conditions would incrementally improve the measurement methods that rely on acoustics.

Technology Maturity *High*

Measurement methods for the speed of sound and the application of the information are well understood.

Description

Data about the speed of sound in dilbit mixtures is important for precise use of technologies such as CPM that are, in part, based on acoustics. Basic information exists but there are gaps in the datasets. The project would compile a complete dataset for a number of dilbit and synbit mixtures under a range of conditions.

1.2.2 - Friction and Drag Reducers

Value *Medium*

The use of friction and drag reducing chemicals in heavy oil transportation would incrementally increase the pipeline capacity without major capital expenditures or environmental impact.

Technology Maturity *Medium*

Friction and drag reducers were developed some years ago by suppliers of lubricants. Improving their performance and reducing their cost in heavy oil applications could be an attractive research target.

Description

In liquids pipelines, pump stations apply pressure to move liquids over long distances. Pumping action is required, in part, to overcome drag and friction. Drag reducers are chemical additives that can reduce drag and improve the turbulent flow of liquids transported in pipelines. The desired outcomes are increased flow rate and throughput, increased pumping efficiency and reduced operating pressure. Key parameters in the selection of friction reducing chemicals include the ability to perform at low concentrations (preferably parts per million) and compatibility with other additives such as corrosion inhibitors.

Typically, drag reducers are high molecular weight, synthetic polymers that are compatible with the oil carried in the pipeline. They act by improving the transition between laminar flow at the pipeline wall and turbulent flow in the centre of the pipeline. They perform their role by reducing the amount of turbulent energy wasted in this transition zone.

Chemical producers have developed friction and drag reducers and are presently extending the use of such chemicals to heavy oil applications. Increased activity in technology development could result in a more efficient use of existing pipeline capacity.

Technology Focus 1.3 - Fracture Propagation and Arrest

1.3.1 - Running Ductile Fracture Models for High Strength Steels

Value *Medium*

Running ductile fracture models are well understood in gas pipelines using conventional steels. With high strength steels, the existing models are less precise and generous safety factors are applied to ensure safety of operations. The value of this research lies in a better understanding of the behavior of high strength steels and in cost reduction from a more accurate design.

Technology Maturity *Medium*

Consortium research is underway to precisely characterize the fracture behavior of high strength steels and the properties that affect performance. Such research is costly and relies on the support of many stakeholders for it to happen in a timely fashion.

Description

There is a need for a greater understanding about the issue of running ductile fractures in high strength steel. Running ductile fractures occur when the fracture propagates faster than the acoustic wave of the depressurizing gas (If the fracture propagates slower, the depressurization wave overtakes it and the fracture will be arrested due to the lower pressure.). A complex equation of state is required to calculate the acoustic velocity of depressurization.

Pipeline steels are required to exhibit sufficient resistance to fracture propagation so that running ductile fracture does not occur. Models exist to predict fracture velocity, which is also influenced by pressure. Correlations have been established between steel properties such as Charpy toughness and resistance to running ductile fracture without having to perform full-scale destructive tests. These models and correlations are acceptable for conventional steel grades such as Grade 290, Grade 414 and for some grades of Grade 483. However adjustment factors are required for grades of high strength steels such as Grade 550 and Grade 690 and the adjustment factors are not optimal. In high strength steels, Charpy toughness may not correlate with the ability to arrest running ductile fracture. There is a need for new steel characterization tests that would predict resistance to running ductile fracture without the need of performing running ductile fracture test at full scale on a routine basis.

An international project is underway to address this issue. The high cost of performing full scale tests and of characterizing steel with advanced microscopic techniques required a consortium approach. Members of the project include PRCI, a Russian National Institute, Gazprom and the China National Petroleum Corporation. It is led by Companhia Brasileira de Metalurgia e Mineração (CBMM) which is a leading producer of niobium, an alloying element which is expected to improve the running ductile fracture resistance of steel. The project also involves collaboration with the University of Ghent in Belgium and the University of Wollongong in Australia. The consortium has conducted a number of full scales test to date. The outcome will be a correlation between (i) mechanical properties and the ability of the steel to dissipate the fracture energy through plastic deformation over a broad area, and (ii) the effect of metallurgical factors such as texture, orientation of the crystal planes within the grains, and the interaction between chemical composition and rolling processes on the resulting mechanical properties and the resistance to running ductile fracture.

Technology Focus 1.4 – Direct Environmental Impacts

1.4.1 - Route Selection Decision Support System

Value *Low*

Route selection decisions are presently made through a number of separate analytical processes, compliance with regulations and public hearings. A computer-based decision support system would streamline the separate workflows and improve communications with stakeholders. It may or may not lead to different route selection decisions.

Technology Maturity *Medium*

Computer technology to develop decision support systems is well understood. Significant work would however be required to aggregate disparate sources of information and develop a computer tool that would satisfy the needs of a wide range of stakeholders.

Description

The purpose is to build an optimum and transparent route selection decision support system. The system would have a dashboard providing access to all the information databases required to make routing decisions, as well as calculation engines to estimate the impact of scenarios and decisions on capital and operating costs, risk, environmental footprint and social impact.

6.5.2. Theme II. Integrity Management, Operations and Maintenance

Once a pipeline is constructed and commissioned, operations and routine maintenance take place according to established procedures and practices. Ensuring continued system integrity is a significant component of operations that involves the use of a number of leading-edge technologies.

Technology Focus 2.1 - In-line Inspection

2.1.1 - New ILI Tools Evaluation and Validation

Value *High*

The periodic inspection of active pipelines by ILI anticipates potential integrity issues and prevents incidents from occurring by allowing corrective measures to be implemented in a timely fashion. ILI is the critical process for maintaining pipeline integrity.

Technology Maturity *Low, Medium or High, depending on technology specifics*

ILI encompasses a wide range of technologies and innovation projects and thus covers the spectrum of technology maturity:

- Low technology maturity: development of new technologies for integrity inspection beyond those that are presently in industrial practice.
- Medium technology maturity: Significant improvements to tools by incorporating major advances in microelectronics, MEMS and computer technologies.
- High technology maturity: ongoing improvements to analysis methods for defect validation.

Description

ILI refers to the use of costly and sophisticated tools to non-destructively inspect the pipeline wall from the inside for geometry and for the presence of defects, cracks and wall loss that could over time become structural weaknesses leading to leaks or ruptures. ILI is widely practiced at different levels of technical sophistication by different operators and service companies.

The principal technologies in industrial practice are Magnetic Flux Leakage, Ultrasonic Testing, and Electromagnetic Acoustic Transducer. Newer technologies proposed for the purpose of integrity inspection include Acoustic Resonance Technology and Guided Wave Ultrasonic Testing.

While the scientific principles behind each technology are well understood, research directions for improving performance include:

- Development and demonstration of new tools. Significant advances in microelectronics, MEMS and computer technologies now allow the miniaturization of sensors and the addition of more sensors on a single tool, thereby increasing the volume of data and the reliability of the information derived from the data. Service companies lead these developments and PRCI is setting up a test loop to assist tool development.

- Validation of defects. ILI tools detect features identified from the analysis of data. Whether these features are in fact defects of varying severity is determined through ongoing validation from digs of suspect pipe joints performed by operators.

Technology Focus 2.2 - Defect Assessment

2.2.1 - Defect Assessment Models for High Strength Steel

Value *High*

Potential defects or features are identified by ILI runs and by quality control inspection for mechanical damage during installation or after third-party hits. Models exist to predict whether potential defects will in time become significant structural weaknesses and the predictions from these models are used to determine corrective actions. It is clear that improving the accuracy of such models is critical to improving integrity.

Technology Maturity *Medium*

Validated models exist for relatively simple defects and failure modes. Improvements are required to understand the combined impact of different failure processes operating synergistically.

Description

Existing models predict failure pressure of defects based on size, geometry and other characteristics. However, these models were developed for conventional grades of steel. The use of high strength grades of steel (up to Grade 550 and Grade 690 steels) is increasing. There is uncertainty about the accuracy of defect assessment models when applied to high strength steels. Furthermore, there are opportunities to improve and strengthen existing models to allow them to handle complex defect geometries and the combination of failure processes such as the combined effect of mechanical stress and corrosion.

The purpose of future research would be (i) to strengthen defect failure models when applied to high strength steel, and (ii) to improve the models by enabling them to predict defect growth under complex geometries and under the synergistic effects of internal pressure and corrosion.

2.2.2 - Risk-based Fitness for Service Defect Assessment

Value *Medium*

A risk-based fitness for service framework would incrementally improve the selection of measures to repair pipe exhibiting defects of varying severity.

Technology Maturity *High*

Risk assessment and management is a well understood discipline and such frameworks are applied in industrial practice. The application of a risk framework to defect assessment, while a significant task, does not appear to involve major technology risks.

Description

The outcome of defect assessment methods need to be incorporated into a reliability and risk management framework in order to determine the appropriate corrective measure. Current defect assessment models (e.g. RSTRENG, ASME B31G, and DNV-RP-F101) enable the evaluation of failure pressure on the basis of defect geometry, internal pressure and the material strength. Subsequently, two challenges still need to be addressed to determine the appropriate corrective measure:

- The uncertainties associated with input parameters require the choice of an appropriate level of conservatism or safety factor.
- Existing models or practices lack consideration of the consequences of failure (i.e., small diameter pipes are treated the same as large diameter, regardless of pipe contents, and the proximity to population or other sensitive areas).

In order to accurately characterize uncertainty associated with these models and to factor in the consequences of failure, a reformulation of the models into a reliability and risk management framework is needed. Technology development is needed to produce the next generation of tools for assessment of pipeline defects, which will provide a process to explicitly determine risk by accounting for uncertainties and consequences in a consistent manner.

Technology Focus 2.3 - Internal Corrosion

2.3.1 - Internal Corrosion under Deposits

Value *Medium*

Internal corrosion remains a key threat, principally to gathering lines used in upstream petroleum production. However, periodic cleaning and inspection practices mitigate this threat.

Technology Maturity *Medium*

Extensive research has taken place to understand the basic mechanisms of internal corrosion. Understanding how deposits accumulate in gathering lines and how corrosion takes place under such deposits could lead to improve methods to prevent internal corrosion incidents.

Description

Corrosion is not caused by the presence of natural gas or crude oil, but by the presence of water as a contaminant. The issue of internal corrosion is more germane to gathering lines which are used in upstream petroleum operation to transport produced fluids to treatment facilities. Such fluids contain varying amounts of water and sediments which can accumulate as wet deposits at some pipeline locations creating a favorable environment for corrosion. Under-deposit corrosion often manifests as localized pitting corrosion.

While research is active to investigate and understand this phenomenon, there are significant issues that remain to be understood and addressed. New research could lead to more reliable models to accurately predict the locations of water/sand accumulation and the resulting corrosion processes.

2.3.2 - Superhydrophobic Treatments of Steel

Value *Medium*

Proof of concept exists for the treatment of steel surfaces so that they effectively repel water thereby minimizing opportunities for corrosion to take place. The value of such treatment would be to reduce opportunities for internal corrosion.

Technology Maturity *Low*

Significant research and development remains to be done to convert the proof of concept into a cost-effective industrial solution.

Description

Early work has been done in superhydrophobic surfaces that dramatically repel water, thereby limiting the opportunity for corrosion to take place. For example, pipe manufacturer Tenaris has reported on superhydrophobic self-cleaning steel surfaces for corrosion prevention and flow assurance, based on nanotechnology.

Technology Focus 2.4 - External Corrosion

2.4.1 - Investigation of FBE Issues

Value *Low*

FBE has an excellent performance record in North America and is the workhorse technology to prevent external corrosion. Investigation of failures in other jurisdictions would be a precautionary measure.

Technology Maturity *High*

FBE failures are generally due to poor quality materials and/or poor application methods and the identification of these situations is well understood.

Description

FBE has performed very well as a coating to protect pipe from external corrosion. However failures have been reported in Columbia and in France. Monitoring and understanding such failures could inform and improve existing practices.

2.4.2 - Self-healing Coatings

Value *Medium*

When using quality materials and applied to clean surfaces, FBE has an outstanding performance record. The development of self-healing coatings to replace FBE could incrementally improve performance.

Technology Maturity *Low*

Self-healing coatings are in limited commercial use and a major development project would be required to develop a material that would match or exceed the performance of FBE in industrial practice.

Description

Coatings with self-healing capability are materials featuring unique chemical bonds among hydrocarbon molecules and atoms that provide a response to damage that functionally restores coating performance. However, this type of coating has not been explored for use in pipelines in combination with other requirements including resistance to permeation, CP compatibility, impact resistance, etc.

2.4.3 - Intelligent Coatings

Value *Medium*

Intelligent coatings provide information on their performance and status thereby allowing the early detection of issues and the implementation of corrective measures in a timely fashion. Incorporating MEMS sensors into FBE coatings would incrementally improve their overall performance.

Technology Maturity *Low*

Significant challenges remain with respect to the provision of power and network communication capabilities to microelectronic sensors applied to buried pipelines and significant long-term development research efforts would be required.

Description

Advancements in microelectronics have led to significant improvements in sensor technology, significantly reducing the cost and size of sensors. It is possible to envision microelectronic devices small enough to be incorporated into coatings and which would provide information on the performance of the coating or on the emergence of problems such as disbondment and corrosion.

Technology Focus 2.5 - Pipeline Repairs

2.5.1 - Composite Materials Repair Methods Validation

Value *Low*

PRCI has an active research program to answer questions by industry and regulators about the permanency of pipeline repair methods using composite materials. The value of additional research would be to incrementally extend the scope of PRCI's program.

Technology Maturity *High*

Repair methods using composite materials are in industrial practice and are generally well understood.

Description

Sleeves made of composite materials are frequently used to repair damaged pipeline sections. The permanency of such repairs are influenced by type of damage (corrosion, cracks, dents, adjacent welds, combined effects), repair materials used, installation procedures, pressure effects, environmental effects, shielding of cathodic protection (CP), and other factors.

PRCI presently has an active research program to answer questions related to the use of composite materials. It encompasses matters such as guidelines for proper installation, quality assurance and inspection, and incorporation into standards. Through collaboration, the scope of PRCI's program could be extended to cover subjects such as elevated temperatures, repair of cracks, and detection of existing repairs by ILI.

6.5.3. Theme III. Leak Detection

Leak detection does not reduce the probability of leaks occurring. It is an after-the-fact set of technologies that allow mitigation measures to be quickly deployed in order to reduce impact. Leak detection should be treated as a system composed of technology, effective procedures and trained personnel. A leak detection system is an engineered solution that needs to be customized for every pipeline. A technology best for one pipeline may not be optimum for another one.

Leak detection technologies are generally divided into two groups:

- Internal systems based on computer analysis of acquired data from field instrumentation and sensors that monitor pipeline integrity and flow parameters such as pressure, temperature, viscosity, density, volumetric flow rate, mass flow rate etc. These data are inputs into sophisticated computer models that infer a leak to explain situations when actual pipeline conditions differ from expected conditions.
- External systems that detect physical parameters associated with a leak such as noise, vibration, temperature change, presence of hydrocarbons, etc.

However, it may be helpful to divide leak detection systems into primary and secondary systems. CPM is the well-established leak detection technology employed by the vast majority of pipelines and can be considered the primary leak detection system. Secondary systems are technologies not intended to replace CPM but to complement it in a way that would vastly improve overall performance.

Improvements to CPM are still possible and a number of vendors are pursuing incremental improvements. An example is an artificial intelligence decision support system, which could offer high-value because it would leverage existing infrastructure and industry practices.

Secondary systems are technologies that would enhance and complement CPM to achieve an overall higher level of performance in reliability, sensitivity, accuracy and robustness. A non-comprehensive overview of available technologies is presented in Table 8.

Table 8. Overview of Secondary Leak Detection Systems

	Continuous Monitoring	Periodic Monitoring
Internal Deployment		• Acoustic sensors traveling inside the pipeline propelled by fluid movement as dedicated devices (e.g. SmartBall from Pure Technologies) or as part of ILI tools.
External Deployment	• Distributed sensors using fiber optics: o Temperature anomalies caused by the leaking fluid o Vibration/acoustic waves from the leak o Hydrocarbon detection • Vapor Sensing Tubes • Wireless Sensor Networks: o Temperature o Vibration/acoustics o Hydrocarbon detection • Standoff cameras and instruments (for surface facilities): o Optical image analytics (e.g. Intelliview) o Near Infrared laser and detection instrument (Boreal Laser)	• Visual surveys: o Airborne o Foot patrols • Hydrocarbon detection in conjunction with airborne surveys (e.g. air sampling analysis by Boreal Laser; sunlight reflection analysis by Synodon)

Technology Focus 3.1 - Computational Pipeline Monitoring

3.1.1 - CPM Decision Support System

Value *High*

CPM is the established leak detection system of the industry. Vastly improving its performance by the application of artificial intelligence techniques could be an approach that would require relatively low capital and operating costs and be compatible with existing industry practices.

Technology Maturity *Low*

Artificial intelligence, while understood at the theoretical level, has yet to see widespread deployment in industrial practice.

Description

CPM is the well-established leak detection system of the industry. CPM employs numerous monitored variables, algorithms and computer modeling to identify process upsets or potential leak situations. The data from all sensors is compared against a baseline model to identify values that differ from the modeled case that could be explained by a potential leak.

In general, due to limitations in pipeline hydraulics, accuracy of the detectors, and alarm thresholds, CPM would not detect small leaks. The detection limit of CPM depends on the specific method used, the quality and amount of instrumentation, the procedures, experience and skill of the pipeline operator and the selected trade-off between reliability and sensitivity.

A key parameter in the operations of CPM systems is the selected balance between sensitivity and reliability. Sensitivity is a combination of the minimum size of the leak to be detected and of amount of time required to detect the leak. Reliability is related to the number of false alarms. There is always a conflict between the desire for greater sensitivity and the requirement to minimize false alarms.

The reliability of CPM could be improved by the development of a decision support system based on artificial intelligence technology. The primary objective would be to reduce the number of false alarms, and the secondary objective is to improve the sensitivity to smaller leaks.

Artificial intelligence technology would extract more reliable information from the steady stream of data from instruments and sensors by analyzing for signature patterns and increasing the sophistication of decision rules. The development of a DSS is likely to be a major undertaking that would require aggregation of operating data from many operators.

Technology Focus 3.2 - Secondary Leak Detection Systems

3.2.1 - Fiber Optics for External Leak Detection

Value *Medium*

Improving leak detection methodologies would have a high impact. However, the deployment of sensitive fiber optic cables along the full length of long-distance pipelines could prove to be expensive both from the initial capital outlay and on-going maintenance costs.

Technology Maturity *Medium*

Field trials and commercial implementation of fiber optics have taken place for intrusion detection applications. Leak detection is proving however to be more challenging and further technology development is required.

Description

Fiber optic cables offer the possibility to conduct measurements over long distances.

There has been successful deployment of fiber optics in pipeline situations. For example, BP uses this technology successfully for intrusion detection. This application addresses the need for damage prevention. Damage by unauthorized third parties is a significant risk to the pipeline industry. A fiber optic cable buried near the pipeline will detect activity in the vicinity and send an alarm to the control center, allowing prompt investigation.

Papers have been published about applying fiber optics to leak detection and trials have taken place, notably in Italy. PRCI has performed laboratory studies and, in Canada, Enbridge, TransCanada and C-FER are collaborating in an emerging joint evaluation program. While the basic technology is known and proven for intrusion detection, practical reliable methodology to detect leaks using fiber optic cables appears to remain challenging.

3.2.2 - Remote Sensing Leak Detection

Value *High*

Remote sensing involves the use of various optical and/or multispectral detectors to identify the presence of leaks along the pipeline ROW. This technology is compatible with existing airborne patrols of ROW for encroachment and intrusion detection.

Technology Maturity *Medium*

Proof of concept trials have been successfully completed by some technology developers but full validation and deployment remain to be done.

Description

Technologies are emerging to detect leaks from remote sensing platforms. In general, these involve detection equipment attached to helicopter or fixed wing aircrafts patrolling pipeline ROW. Examples of Alberta based companies developing such technologies are Boreal Laser (laser optic methane detector), Synodon (spectral image analysis for ethane) and Intelliview (automated image analysis from standoff cameras for gas and liquid leaks from surface facilities).

3.2.3 - Vapour Sensing Tubes for Leak Detection

Value *Medium*

This technology involves laying hydrocarbon vapor sensing tubes along the length of interest in the pipeline ROW which could imply significant capital and operating costs.

Technology Maturity *Low*

Vapor sensing tubes require the active operation of a number of pumps and chemical detectors. They have yet to be extensively deployed in transmission pipeline applications.

Description

When an oil leak takes place, volatile compounds from the oil form vapors that permeate the soil surrounding the leak area. A vapor sensing tube is a tube made of hydrocarbon permeable material that will accept hydrocarbon vapors from leaked oil by diffusion through the tube wall and convey such vapors to a detector. This method thus involves the installation of a secondary conduit along the pipeline length of interest.

Generally, air is pumped through the tube and this air flow conveys hydrocarbon vapors to the detection point. Tracer compounds added to the air flow are used to determine the location of the hydrocarbon leak. The amount of hydrocarbon vapors detected at the detection point correlates with the size of the leak.

Due to the fact that the vapor sensing to must be installed along the length of the pipeline, this technology is usually intended for short lines carrying hazardous substances.

3.2.4 - In-line Acoustic Sensors for Leak Detection

Value *High*

This technology involves the insertion into the pipeline of acoustic sensors on a periodic basis on their own or in combination with ILI runs. It would be compatible with existing industry practices and incur lower costs than systems that require infrastructure deployment along the full pipeline ROW. However, it is not a continuous monitoring system.

Technology Maturity *Medium*

Proofs of concept and demonstration trials have been successfully concluded.

Description

In-line inspection is used for pipeline integrity management. However, other in-line techniques could be used for leak detection. For example, Alberta based Pure Technologies has developed acoustic sensors to detect the noise made by a leak; the sensors are contained in a ball that rolls inside the pipeline and is moved by the flowing fluid.

3.2.5 - Distributed Wireless Sensor Networks for Leak Detection

Value *Medium*

An infrastructure of networked sensors and communication devices could be deployed along the full length of the pipeline to enhance monitoring and detection capabilities, potentially requiring significant capital and maintenance costs.

Technology Maturity *Low*

Reliable and robust sensors for the detection of hydrocarbons appear to require further developments. In addition, the deployment of communication systems and power supply issues appear challenging and require significant additional technology development.

Description

Significant developments in the area of microelectronics during the last 10 years have resulted in the miniaturization of sensors. In particular, two classes of sensors are of interest:

- MEMS are microelectronic devices that can measure and communicate physical properties such as temperature, pressure, elevation, orientation and many others. In particular, they are ubiquitous in today's smartphones.
- Lab-on-a-chip which can perform chemical analyses and integrate with other microelectronic devices such as wireless transmitters.

The availability of the above microelectronic devices have led to the concept of distributed wireless sensor networks whereby pipelines could be instrumented with microelectronic sensors communicating wirelessly to nodes and gateways which would in turn transmit the information to network systems such as SCADA, satellite networks or next generation wireless networks such as Long Term Evolution (LTE).

However, long-distance buried pipelines present challenging situations for the deployment of wireless sensor networks. Firstly, radio frequencies only travel short distances underground as they suffer significant attenuation in soil. Other propagation technologies have been proposed such as magnetic induction; however significant technology development appears to be required. Secondly, microsensors and wireless transmitters require power albeit in small amounts. In long-distance pipelines crossing remote areas, batteries or energy harvesting devices lasting multi-years, even decades would be required for cost-effective operations. Thirdly, while MEMS devices to monitor physical attributes such as temperature, pressure and strain appear mature, robust and reliable lab-on-a-chip devices appear to require significant additional research.

6.5.4. Theme IV. Cleanup, Remediation and Reclamation

Heavy oil and dilbit spills have been recognized as an important issue that warrants further research and investigation. Research has been done with regards to the effects of crude oil spills on the environment. However, the focus of past work has mostly been marine spills of conventional oil. Heavy oil differs from conventional crude oil in the amount of the heavy molecular weight fraction. This characteristic may create temporal and size differences between the consequences of a light crude oil spill versus a heavy oil spill.

Technology Focus 4.1 - Cleanup and Remediation of Submerged Oil

4.1.1 - Fate and Impact of Heavy Oil in the Environment

Value *Medium*

The long-term impact of heavy oil that could potentially remain in the environment after spill cleanup represents an issue raised by stakeholders and investigating it would respond to stakeholder concerns.

Technology Maturity *High*

The impact of oil spills in the environment has been studied for decades. However, the object of past studies has primarily been conventional crude oil in marine spill situations.

Description

In the event of a dilbit or heavy oil spill, it is possible that some of the spilled material will remain in the environment despite thorough cleanup activities. Heavy oil contains a high amount of the heavy fraction that may resist natural biodegradation. Thus heavy oil may have an incrementally greater impact than light crude oil.

The long-term impact of remaining heavy oil fractions on fauna and flora may need to be better understood. Of particular interest are the potential effects of spills in inland water bodies or in coastal areas. Studies of the Athabasca River where bitumen deposits outcrop and are naturally scoured by the river could prove instructive. Research may also be needed to characterize impact on groundwater sources.

Information about the fate and impact of heavy oil fractions left in the environment would be helpful in determining the extent of cleanup required and other mitigation measures after active cleanup.

4.1.2 - Behaviour of Submerged Oil in Inland Water Bodies and Coastal Waters

Value *Medium*

The possibility that heavy oil fractions would become submerged if spilled in water bodies has been raised as a concern by stakeholders. Submerged oil could increase the impact of the spill and add to the cost of remediation. Factual information about the behavior and extent of the heavy oil fraction that may become submerged would inform industry and stakeholders and assist the use of cleanup methods.

Technology Maturity *Medium*

Past studies have been done in a laboratory context and for marine spills of heavy oil.

Description

The behavior of heavy oil fractions into exposed bodies of water (inland or marine) also calls for a deeper understanding. The potential of submerged oil greatly increases the complexity and cost of cleanup operations. Research has been conducted in Spain and Venezuela on this topic. While the former focused primarily on a heavy oil spill off the coast of Spain, the latter has focused on lab-scale modeling of Venezuelan diluted bitumen in the event of a marine oil spill.

From a Canadian perspective, research could be focused on heavy oil and dilbit. All crude oils contain a heavy fraction that, if disassociated from the bulk material, could become submerged. However, this heavy fraction is present in a higher concentration in heavy oil and dilbit. The purpose of this work would be to fully understand the factors that govern the behaviour of the heavy oil fraction when spilled on inland water and in coastal waters.

Research could be conducted on the disassociation in water of the heavy fraction. Lab-scale modeling could determine the temporal and spatial profile of dilbit and heavy oil decomposition in water. There is an expectation that, initially, spilled dilbit or heavy oil will float on the surface of the water. Over time however, disassociation would take place and the heavy fraction may enter the water column and eventually settle on the bottom under the water body. Time may be a critical factor as there may be a window when spilled dilbit or heavy oil may be cleaned up on the water surface using the same equipment as for conventional oil spills. Under the effect of time, sunlight, waves, wind and water current, the decomposed heavy fraction may start to sink and cleanup methods may need to be extended to include filtration and dredging.

The effects of parameters that differ between marine environments and inland water bodies, like salinity and mineral composition, waves, tides and currents, and other parameters could also be investigated and correlated with respect to disassociation behavior.

Thus, the analysis and simulation of dilbit and heavy oil decomposition in water bodies is important for the optimization spill cleanup and remediation processes.

4.1.3 - New Cleanup Methods for Submerged Oil in Inland Water Bodies and Coastal Waters

Value *High*

While studies of environmental impact and behavior of submerged heavy oil provide factual scientific information, the development and deployment of improved cleanup and remediation methods may be required to in fact repair environmental damage and return the environment to its original condition, thus creating the value sought by stakeholders. Heavy oil is produced and transported in a number of regions around the world, and furthering advanced methods would be of value to all concerned.

Technology Maturity *Low*

Concepts exist for the use of dispersants, surfactants and other approaches that could mitigate the impact of heavy oil spills in water. However demonstration and commercial deployment may prove to be challenging.

Description

Conventional cleanup methods used in the industry have been developed to tackle spills of conventional oil, and thereby are grounded in the fundamental assumption that the leaked substance will have a lower density than any water body affected by the leak. As such, these contemporary methods are primarily centered on the water surface, whether containment devices or skimmers.

In the event of a dilbit or heavy oil spill in a water body, proven methods that can be used to clean up the release must be deployed as soon as possible, particularly because the water currents in both inland and ocean environments can greatly increase the rate of dispersion of the leaked hydrocarbons. Booms and skimmers can also be used to collect the spilled oil from the surface of the water. However, depending on local circumstances, these methods may not capture all of the spilled oil volume.

As the heavier components comprising the heavy oil may over time enter the water column and settle towards the bottom of the water table, the overall water volume that must be covered to clean up the spill becomes considerably larger. Other mechanical systems like vacuum and pumping systems aboard small ships can remove pools of aggregated oil and could be highly effective as a first stage of heavy oil spill response, before the mixture decomposes and begins settling on the bottom which may make dredging a necessity.

Once more accurate models are developed to simulate the behavior of heavy oil in water bodies, novel methods could be designed. For instance, chemical compounds such as dispersants to further accelerate and catalyze the breakup of heavy oil into smaller, more biodegradable compounds could be deployed. The important consideration here is to select the optimum dispersants to ensure that the remaining oil droplets can be decomposed by natural bioremediation techniques such as bacteria. Underwater dispersants can also be developed further, although leading up to the Deepwater Horizon incident they were still only experimental in nature and lack field data.

Similarly, surfactants could be developed to increase the interaction of the hydrocarbon-based components and the surrounding water molecules to promote surface chemistry and create more chemically stable structures as hydrates that are benign to the local environment or more prone to be collected during the cleanup procedures.

Flotation devices can also be employed in clean-up operations and possibly coated with an oleophilic coating to increase the retention of heavy oil components. Along with oleophilic materials that increase oil retention, the use of particular sorbent materials that absorb the spilled oil is also an interesting strategy that has gained attention since the Deepwater Horizon accident in the Gulf of Mexico. Sorbents can be classified as natural organic, the natural inorganic, and synthetic sorbents. Examples of natural sorbents include peat moss, straw, sawdust, feathers and even ground corncobs, while natural inorganic sorbents currently include materials like clay, perlite, glass wool, sand or volcanic ash all can soak up 4 to 20 times their weight in oil. Synthetic sorbents are similar to plastics and can absorb liquids into their solid structures that cause the material to swell. According to the EPA, most commercial synthetic sorbents can absorb up to 70 times their weight in oil. These could be tailored further towards application in heavy oil spill cleanups.

From a chemistry perspective, the development and application of gelling agents to clean up heavy oil spills also warrant further investigation. A gelling agent is a chemical used to convert spilled oil into a solid phase, thereby making it easier to collect. Using the motion of the sea, the gelling agent turns the oil into a rubbery substance that can be easily removed from water with nets, suction devices or skimmers. Commercial gelling agents require three times as much gelling agent as the volume of oil to be recovered. Efforts into making this volume ratio more favorable and economically feasible could be an important field of study.

Technology Focus 4.2 - Pipeline Abandonment

4.2.1 - Abandoned Pipelines Models

Value *Low*

Concerns have been expressed about the impact of abandoned pipelines over the long-term.

Technology Maturity *Medium*

The fate of abandoned pipelines can be reasonably predicted based on current understanding of corrosion and soil geomechanics.

Description

Pipeline abandonment refers to the permanent removal from service of a pipeline. Depending on a number of factors, sections of pipeline may be abandoned in place or removed. Stakeholders, in particular landowners in agricultural communities, have expressed concerns about the long-term impact of abandoning pipelines in place. Improves scientific understanding is required to address the potential for major subsidence and/or for creating undesirable conduits for water. Another concern is a possibility that abandoned pipe segments could surface over time from the frost heave effect and create hazard for ground engaging farm machinery.

Research to develop improved models that would more reliably predict the fate of abandoned pipelines would be needed to address these concerns. Efforts led by CEPA and the NEB are currently underway.

7. Conclusion

The Roadmap was built on the foundation of a thorough review of needs, gaps and opportunities, informed by recent regulatory documents in Canada and in the United States, and by the knowledge and expertise of a team of subject matter experts, in consultation with industry, government and academic stakeholders. Research and development in pipeline technology was found to be active worldwide with Canada and Alberta prominent contributors.

The Roadmap is a mission-oriented framework to maximize reliability and integrity and to minimize environmental impact for consideration by pipeline operators, service and technology companies, governments and regulators, and academic institutions. It proposes portfolios of opportunities for innovation in pipeline technology. Action on this framework will lead to technology solutions that will respond to needs expressed by stakeholders and to opportunities identified by industry and researchers, in a way that leverages the resources of individual organizations for the benefit of the sector as a whole.