Report on Feasibility of Installing an Alternative Leak Detection System at the Straits of Mackinac

United States v. Enbridge Energy et al Case 1:16 – cv-914

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1 Nomenclature and Abbreviations

ALD	Alternative Leak Detection
AOC	Abnormal Operating Condition
APD	Automated Pressure Deviation
AVB	Automated Volume Balance
CCO	Control Center Operations
CPM	Computational Pipeline Monitoring
CSM	Column Separation Management
ELDER	External Leak Detection Experimental Research
DAS	Distributed Acoustic Sensing
DTS	Distributed Temperature Sensing
FOC	Fiber Optic Cable
HCA	High Consequence Area
HDD	Horizontal Directional Drilling
HDPE	High Density Polyethylene
HSC	Hydrocarbon Sensing Cable
ILI	Inline Inspection
IR	Infra-Red
L	Liter
LD	Leak Detection
LDS	Leak Detection System
MA	Mackinaw Station
NGL	Natural Gas Liquids
NO	North Straits Site
OTDR	Optical Time Domain Reflectometry
PLC	Programmable Logic Controller
PVC	Polyvinyl Chloride
RDS	Rupture Detection System
ROV	Remote Operated Vehicle
SCADA	Supervisory Control and Data Acquisition
VST	Vapor Sensing Tube

2 Preface

This report addresses the requirements of the DOJ Consent Decree, paragraphs 81 to 83:

81. Within 180 Days of the Effective Date, Enbridge shall submit to EPA for review a report assessing the feasibility of installing an alternative leak detection system at the Straits of Mackinac. For the purposes of conducting this assessment, Enbridge shall evaluate the following leak detection technologies: fiber-optic cable (acoustic and temperature), vapor sensing tube, negative pressure wave, and hydrocarbon sensing cable. Such technologies would supplement Enbridge's existing MBS Leak Detection System, as well as the leak detection systems that Enbridge is required to implement under Paragraph 73 (Acoustic Leak Detection Tool) and Paragraph 102 (Rupture Detection System) of the Consent Decree.

82. With respect to each technology, the report required by Paragraph 81 shall evaluate (i) the potential effectiveness of the technology in detecting leaks and ruptures of different sizes, (ii) the practicability of deploying the technology in the Straits of Mackinac, (iii) the practicability of long-term operation and maintenance of the technology, and (iv) the net present cost of the technology, taking into account the initial capital cost to install the technology and the annual expense to operate and maintain the technology.

83. The report required pursuant to Paragraph 81 shall compare the relative performance of each of the evaluated technologies with respect to each of the factors enumerated in Paragraph 82 and any other factors that Enbridge may decide to add to its analysis. As a basis for comparison, Enbridge shall also evaluate the risks and benefits of each technology in the Straits of Mackinac versus the risks and benefits of continuing to rely solely upon the MBS Leak Detection System and those systems that Enbridge is required to implement under this Consent Decree.

3 Executive Summary

This report assessed the feasibility of installing alternative leak detection (ALD) systems at the Straits of Mackinac to supplement Enbridge's existing leak detection layers. The five ALD technologies specified in Paragraph 81 were subject of this assessment, including: fiber-optic cables (acoustic and temperature), vapor sensing tubes, a hybrid leak detection system that integrated negative pressure wave with flow measurements (which we refer to in this report as the "hybrid LDS"), and hydrocarbon sensing cables. These technologies were evaluated based on four criteria: (i) the potential effectiveness of the technology in detecting leaks and ruptures of different sizes, (ii) the practicability of deploying the technology in the Straits of Mackinac, (iii) the practicability of long-term operation and maintenance of the technology, and (iv) the net present cost of the technology, taking into account the initial capital cost to install the technology and the annual expense to operate and maintain the technology.

The hybrid LDS is being tested on pilot program basis on the Dual Pipelines in the Straits. The DAS, DTS, VST and HSC technologies were not specifically tested in underwater implementations. However, the feasibility assessments described in this report address underwater installation issues based on conclusions from our on-shore testing and evaluations. These include tests in water saturated environments and allow for the application of known underwater based conditions in evaluating the effectiveness and feasibility of these technologies at the Straits of Mackinac.

A summary of the assessed relative effectiveness, practicability and cost of the evaluated technologies for underwater leak detection at the Straits of Mackinac is shown in the table below. Definitions of the evaluation criteria are detailed in the following section. An overall recommendation regarding each technology is also given. The risks and benefits of adding these technologies to the current Enbridge LDS at the Straits identified that the hybrid LDS is currently the only technology that is feasible and known to be effective to detect leaks in underwater pipeline segments. The recommended technology for implementation as Alternate Leak Detection, from those assessed in this report, is the hybrid LDS which integrates pressure wave technology with statistical flow, volume balance measurement.

Based on the success of the pilot program testing, Enbridge is proceeding with the implementation of the hybrid LDS at the Straits. The DAS technology will be continue to be evaluated as the technology continues to mature. DTS, VST and HSC technologies are not suitable systems for application at the Straits and will not be further tested or pursued at this time.

Technology	Leak Detection Effectiveness	Rupture Detection Effectiveness	Practicability of Deployment	Practicability of Long Term Operation & Maintenance	Net Present Cost [1]	Recommendation for the Straits
DAS	Med	Med to High	Difficult	Feasible	$$$$	Requires further assessment
DTS	Low	Low	Difficult	Feasible	$$$$	No
VST	Low	Low	Difficult	Impractical	$$$$$	No
Hybrid LDS	High	High	Feasible	Easy	$	Yes
HSC	Low to Med	Med	Difficult	Difficult	$$$$$	No

4 Evaluation Criteria

This section discusses the evaluation criteria considered when assessing the technologies identified in Paragraph 81. The following four criteria were considered when assessing the feasibility of installing Alternative Leak Detection (ALD) technologies at the Straits of Mackinac:

(i) the potential effectiveness of the technology in detecting leaks and ruptures of different sizes;

(ii) the practicability of deploying the technology in the Straits of Mackinac;

(iii) the practicability of long-term operation and maintenance of the technology, and

(iv) the net present cost of the technology, taking into account the initial capital cost to install the technology and the annual expense to operate and maintain the technology.

Each criterion is explained below.

4.1 Potential effectiveness of the technology in detecting leaks and ruptures of different sizes

Enbridge primarily uses technical performance criteria to assess the effectiveness of a leak detection technology within its testing and assessment program. There are four performance criteria which are industry standards and these include: sensitivity, reliability, accuracy, and robustness. These criteria, which are defined in API 1130 (API RP 1130, Computational Pipeline Monitoring [CPM] for Liquids, 2012), are used primarily for CPM systems. Their use is being expanded for application across the various ALD systems being evaluated. These industry performance criteria are considered qualitative. At this time, there are generally no regulatory or industry performance targets for the ALD technologies described in this report. The application of these technical evaluation criteria can be made specific to the technology being assessed. The performance criteria are defined below, as per the API 1130 Recommended Practice:

[1] The significance of the dollar signs is discussed further below.

a) **Sensitivity –** Sensitivity is defined as the composite measure of the size of leak that a system is capable of detecting, and the time required for the system to issue an alarm in the event that a leak of that size should occur. Essentially it is a measure of how fast a leak of a particular size can be found. The relationship between leak size and the response time is dependent upon the nature of the leak detection system (LDS). Some systems manifest a strong correlation between leak size and response time, while with others, response time is largely independent of leak size (API 1130, Annex C). Metrics may include:

   - Sensitivity related to leak flow rate (The size of leak detected, as a percentage of nominal flow)
   - Sensitivity in response time or time taken to first alarm (The time taken by the system to detect the leak)

b) **Reliability –** Reliability is a measure of the ability of an LDS to render accurate decisions about the possible existence of a leak on a pipeline. It is directly related to the probability of detecting a leak, given that a leak does in fact exist, and the probability of incorrectly declaring a leak, given that no leak has occurred. A system which incorrectly declares leaks is considered to be less reliable; however, if the system has the capability to use additional information to disqualify, limit, or inhibit an alarm, a high rate of leak declarations may be considered less significant (API 1130, Annex C). Reliability is measured by the number of the false alarms (reporting a leak when there is no leak).

c) **Accuracy –** Accuracy is the ability to determine the location of the leak, its rate, and total leak volume.

   - Leak location detection – Estimates the location of a leak.
   - Total volume lost and leak rate estimation - Estimates the flow rate of a leak usually as a percentage of the nominal flow in the pipeline; as well as, gives an estimate of the volume of commodity lost during the leak.

d) **Robustness –** Robustness is defined as a measure of the LDS ability to continue to function and provide useful information in changing conditions of pipeline operation or in conditions where data is lost or suspect (API 1130, Annex C).

   - It can be a measure of the system's ability to function and provide useful information even under Abnormal Operating Conditions (AOC) which are defined as conditions identified by the operator that may indicate a malfunction of a component or deviation from normal operations.

     Examples of changing conditions may include: transient operations, column separation conditions, batch operations, instrumentation failure, communication failure, PLC failure, SCADA failure, presence of pipeline pigs and ancillary software processes failure.

For the purpose of this assessment, the effectiveness of each technology is evaluated based on a composite qualitative metric of High, Medium or Low. This composite metric represents the best estimate of the overall effectiveness based on the four identified API 1130 criteria. The two detection cases being assessed are ruptures and leaks as identified by paragraph 82. A rupture is defined as a structural loss of containment where the pipeline is no longer operable. A leak is defined as a loss of containment where the pipeline is still operable but a range of fluid loss occurs. The relative qualitative metric has the following definitions:

High: would indicate that this technology has a high likelihood of being effective for the defined detection cases.

Medium: would indicate that this technology may be effective for the defined detection cases.

Low: would indicate that this technology would not be expected to be effective for the defined detection cases.

4.2 Practicability of deploying the technology in the Straits of Mackinac

This criterion analyzes the ability of utilizing common construction practices that are readily available in industry to complete the installation of an ALD technology at the Straits safely. This includes ease of installation of sensors, as well as hardware and infrastructure requirements. In this report the deployment practicability is a qualitative metric and has the following definition:

Easy: The deployment can be completed with a minimum amount of construction effort and/or consistent with Enbridge's current asset and infrastructure.

Feasible: The deployment can be completed with some construction effort and/or with Enbridge's current asset and infrastructure modifications.

Difficult: The deployment can be completed with an extensive amount of construction effort (routine and non-routine) and/or with Enbridge's current asset and infrastructure modifications. New construction methods may need to be invented or borrowed from industries where contractors are not familiar with pipeline construction.

Impractical: The deployment is not feasible with current construction methods available in industry. New methods must be invented or borrowed from industries where contractors are not familiar with pipeline construction.

4.3 Practicability of long-term operation and maintenance of the technology

This criterion analyzes the long-term operation and maintenance required of the ALD technology if installed at the Straits of Mackinac. This includes the general durability of the sensors, their susceptibility to damage and on-going sensor maintenance to maintain functionality. This would also include an assessment of the practicality of integrating the ALD technology into pipeline operations. In this report, long-term operation and maintenance practicability is a composite qualitative metric and has the following definitions:

Easy: The technology is durable, can be easily integrated into operations and requires minimal maintenance to provide value for leak detection.

Feasible: The technology can provide value for leak detection, but only with considerable effort and ongoing maintenance.

Difficult: With a significant amount of effort, the technology may provide limited functionality and limited value for leak detection.

Impractical: The technology is not durable, and/or cannot be integrated into operations, and/or requires significant maintenance.

4.4 The net present cost of the technology

The net present cost is defined for this report as a composite cost metric that includes the capital installation cost and the annual operating/maintenance cost. It is a metric defined to provide a relative estimate of the overall financial impact of implementing the technology solution. For the purposes of this report, Enbridge has based its estimate of net present cost on a 20 year operating period. Enbridge does not have experience in installing cable-based ALD technologies for underwater conditions. The capital, operating and maintenance costs estimated for this report were derived mainly from on land project installation experience and were adjusted for a L5 in the Straits hypothetical installation and they are all conceptual estimates. These estimates are considered rough orders of magnitude because of the lack of documented pipeline industry experience with underwater installation.

In general, all of the technologies discussed here represent completely new methods or significant modifications to Enbridge's operation of Line 5 in the Straits. Deploying, operating and maintaining a new technology, often requires additional unforeseen costs and delays for items such as research and development, training contractors unfamiliar with pipeline operations, and repeating deployment or maintenance work to address issues with the technology, all of which would significantly increase costs.

Table 1 Cost metric definitions in US$

Net present cost	Capital installation cost (CAP)	20 year operating and maintenance costs (OM)
$: 1MM - 4MM	$ CAP: 1 – 2 MM	$ OM: 50k– 2 MM
$$: 4 MM – 8 MM	$$ CAP: 2MM - 4MM	$$ OM: 2MM – 4MM
$$$: 8MM - 16 MM	$$$ CAP: 4MM- 8MM	$$$ OM: 4 MM- 8MM
$$$$:16 MM-40 MM	$$$$ CAP:8 MM- 20MM	$$$$ OM: 8 MM – 20MM
$$$$$:> 40 MM	$$$$$ CAP> 20MM	$$$$$ OM: >20 MM

5 Evaluation of Alternative Leak Detection Systems for the Straits of Mackinac

Enbridge is not aware of ALD technologies being operationally implemented for underwater leak detection. Enbridge's assessment and evaluation of ALD technologies have been focused on land based leak detection. This includes pilot projects and the joint industry evaluations using the ELDER testing facility. These testing experiences provided understanding of various ALD system capabilities. ELDER did examine water saturated soil test cases that provides some limited insight into possible underwater performance capabilities. However, direct testing of underwater installations would be required for more comprehensive evaluation of ALD performance for underwater leak detection.

5.1 Fiber Optic Cable – Distributed Acoustic Sensing (DAS)

DAS technology uses the acoustic sensing response of fiber optic cables (FOC) to identify possible leaks based on their acoustic signature. The cable functions as a sensor and analyzes the sound profile in the time and frequency domains. This information is relayed to analysis software that determines if there is an acoustic signature that may be a leak. Some DAS systems also incorporate the sensing of a temperature differential that is associated with a leak. This technology may have an ancillary benefit of providing third party intrusion monitoring for security.

5.1.1 The potential effectiveness of the technology in detecting leaks and ruptures of different sizes

This technology was tested for land based applications and was not tested for underwater implementations. Given the lack of maturity and inconsistent performance of the land based testing, installing a FOC underwater was not deemed to be a reasonable next step at this time. The feasibility of the system needs to be confirmed first, and Enbridge was not able to achieve that confirmation. The results described here address underwater installation issues based on insights from our on-shore testing and evaluations. This technology is new and the pipeline industry has no experience using it, particularly in North America. Offering from multiple vendors were evaluated, with the effectiveness of the technology is highly dependent upon installation design and execution as well as the vendor maturity.

a) Sensitivity (related to leak flow rate, response time, time to first alarm)

Enbridge's evaluation in ELDER[2] showed that DAS technology (depending on the vendors as performance can vary significantly as between different vendors) was able to detect most of the simulated leaks created in various operating conditions and at various sensor placements in dry soil. The response time ranged from seconds to minutes for the simulated segments of up to 40 km in length. Successful detection of leak events in dry soil ranged from on average 0.9% to 95% among the different vendors. Such a wide range indicates a lack of maturity in the industry, even when testing in the conditions in which vendors advertise their capability.

The technology (depending on the vendors) was also able to detect most of the simulated leaks in a water saturated environment.

Enbridge has not evaluated the performance of DAS systems for underwater implementations through lab testing or pilots. However, Enbridge has assessed the feasibility of effectiveness and constructability of cable-based external LDS for monitoring the Line 5 dual pipelines at the Straits of Mackinac for anchor strike and leak detection. Through the evaluation, it was identified that "in principle" acoustic monitoring for offshore leaks and anchor strikes has the potential to be established with DAS technology. The level of sensitivity that can be achieved for the given subsea conditions in the Straits of Mackinac with fiber optic cables is still uncertain and requires more testing and evaluation.

[2] ELDER (External Leak Detection Experimental Research) is a joint industry test facility that is used for evaluating the sensitivity of external leak detection systems including DTS, DAS, VST and HSC.

b) Reliability (Number of false alarms)

Reliability is assessed through piloting the DAS technology over an extended period of time. Enbridge has not piloted the technology underwater but Enbridge's on land pilot evaluations showed that after extensive tuning, the DAS system was relatively reliable with a limited number of false alarms per month.

However, DAS may be susceptible to false alarms for underwater applications. Water is a great transmitter of sound so any source of noise under or on a water surface such as underwater currents and ships might have a deteriorating effect on the performance of DAS systems in terms of reliability. There is a pump station (i.e. Mackinaw station) close by which might also have a degrading effect on the performance of DAS systems. To tune the system in noisy areas, the detection threshold may need to be adjusted which may result in degradation in sensitivity.

Additionally, there may be false alarms due to strain generated from the fast currents and ongoing redistribution of sediment near the pipeline. The reliability of the DAS technology needs to be further assessed.

c) Accuracy (Leak location detection, total volume lost, leak rate estimation)

Based on Enbridge's land-based pilot experience, A DAS system can locate a leak event within 10 meters. DAS systems are unable to estimate the leak volume or leak rate.

d) Robustness (function under AOC, instrument outage, fault tolerance)

DAS, as a sensor-based system, is expected to be functional under most pipeline AOCs. DAS cable integrity is expected to be robust when properly installed.

DAS performance is less prone to degradation due to placement of the FOC as it does not require contact with leaked product and thereby performance is not as dependent on FOC position. This provides some installation flexibility for the DAS FOC.

5.1.1.1 Overall effectiveness consideration for detecting leaks underwater

DAS technology "in principle" should be able to detect underwater leaks with a detection time of seconds to a few minutes. However, the performance of the system may be influenced by extraneous acoustic noises that need to be tuned out. Line 5 carries natural gas liquids (NGL) in addition oil products. The behavior of NGL leaks underwater and the performance of DAS in detecting NGL leaks has not been tested or fully understood.

Industry currently does not have a repeatable and reliable method to test or measure the sensitivity of this technology after installation underwater. DAS vendors are limited in the ability to define and track their sensitivity after installation. This inability to define or test sensitivity of an underwater installed DAS system makes evaluation of its effectiveness uncertain.

This technology has potential for installation at the Straits with the relative effectiveness estimated to be **Medium** compared to other identified technologies in this report. However, almost all of the DAS vendors in the market are new and not mature enough to handle the complex underwater leak monitoring of the Straits at this time. Final conclusions on the effectiveness of this technology need further evaluation and testing.

5.1.1.2 Overall effectiveness consideration for detecting ruptures underwater

DAS technology (depending on the specific vendor) is expected to detect an underwater rupture. The effectiveness of this technology is expected to be **Medium to High** compared to other identified technologies in this report for underwater rupture detection, but it is highly dependent upon installation design and execution as well as vendor maturity. As previously mentioned, the inability to define or test sensitivity of an underwater installed DAS system makes evaluation of its effectiveness uncertain. Final conclusions on the effectiveness of this technology need further evaluation and testing.

5.1.2 The practicability of deploying the technology in the Straits of Mackinac

To install this technology, a FOC needs to be installed next to the underwater pipeline at the Straits of Mackinac. DAS performance is less prone to degradation due to change in the release location or FOC position as it does not require contact with leaked product and therefore is not as dependent on FOC position. This provides some installation flexibility for the DAS FOC. For this installation method, the FOC may need to be installed in high density polyethylene (HDPE) conduit. The possible use of armored cable for direct underwater installation should be examined.

The Straits of Mackinac is 6.5 km in length. FOCs can be fabricated in lengths up to 8 kilometers, and spooled onto a single reel. This should make one continuous installation possible. HDPE conduit is typically fabricated in shorter lengths, but may be connected in the field using mature and reliable methods.

It is anticipated that other specialized methods are required to install the FOC underwater. This may include direct attachment of FOC to the pipeline, excavation of a shallow slot in the lake bed, or the addition of anchors or pegs to secure the cable in-place. Implementation requires contractors familiar with marine construction methods and underwater FOC installation.

Enbridge currently has no approved internal procedures or specifications to safely secure an underwater cable on or near an underwater pipeline segment. This would require time and expertise to be developed. Enbridge assigns the practicability of deployment to be **Difficult** for this technology.

5.1.3 The practicability of long-term operation and maintenance of the technology

5.1.3.1 Operation

The impact to operations is expected to be moderate. This is based on the fact that it is likely to consist of training of personnel for assessment and also maintenance of the equipment. Enbridge has small land based pilot projects with this technology but does not currently operate any DAS systems in a production role on the Enbridge system. Procedures will need to be developed to calibrate, assess, and maintain the system.

Fiber cable may be susceptible to false alarms when the cable moves and experiences strain caused by underwater conditions in the Straits. This may be mitigated with an appropriate design to limit cable movement.

The Straits are subject to currents and ongoing redistribution of sediment near the pipeline but these variations have potential to be tuned out without negatively affect the fiber optic sensing cable’s function.

5.1.3.2 Maintenance

The impact to maintenance is expected to be moderate, primarily due to the equipment requiring periodic integrity recertification using tests such as industry-standard Optical Time-Domain Reflectometry (OTDR) and visual underwater inspections of the cable using Remote Operated Vehicle (ROV). Underwater FOCs have a sufficiently long design life, which is in the order of 25 years, though many cables have been in-service for a longer period.

The practicability of this technology is identified as conceptually **Feasible** based on the general durability of the sensors, maintenance effort and the general ability to be integrated into operation. A more comprehensive feasibility assessment would be required before attempting installation.

5.1.4 The net present cost of the technology

The initial cost to install DAS technology at the Straits is expected to be high. An Enbridge conceptual estimate suggests the cost to be around $15MM. The install requires specialized materials, installation methods and external contractors with deep-water work experience. Enbridge currently has no experience installing this technology underwater, so the project team would require contingency funding to address possible schedule delays, construction problems, and other issues.

The annual operating expense of DAS is not expected to be a significant portion of the overall cost. However, the maintenance expense may be significant as the cable may require periodic inspections or repair, if damaged. Based on known costs of underwater work, the cost for repair could be significant at approximately $500k per location. To reduce cable inspection costs, it may be possible to use ROVs that are used for concurrent inspections of the dual pipelines. With a good installation, repairs are expected to be infrequent, approximately once every 10 years.

5.1.5 DAS evaluation summary

Table 2 DAS evaluation summary

Technology	Leak Detection Effectiveness	Rupture Detection Effectiveness	Practicability of Deployment	Practicability of Long Term Operation & Maintenance	Net Present Cost [3]	Recommendation for the Straits
DAS	Med	Med to High	Difficult	Feasible	$$$$	Requires further assessment

[3] The significance of the dollar signs is discussed further below.

5.2 Fiber Optic Cable – Distributed Temperature Sensing (DTS)

DTS technology uses the temperature sensing response of a fiber optic cable (FOC) to identify possible leaks based on changes in temperature compared to their environment. The fiber cable functions as a sensor and records the temperature profile over time. This information is relayed to software analytics that determine if there is a leak in the pipe.

5.2.1 The potential effectiveness of the technology in detecting leaks and ruptures of different sizes

This technology was tested for land based applications and was not tested in underwater implementations. However, the results described here address underwater installation issues based on Enbridge's on-shore testing and evaluations, which included testing in water saturated environments. While Enbridge tested the system on-shore, it is able to apply the feasibility assessment to underwater environments based on known physical properties of water and the abilities of the tested technology. The application of DTS technology for leak detection is new. The effectiveness of the technology is highly dependent upon installation design and execution as well as the vendor maturity.

a) Sensitivity (related to leak flow rate, response time, time to first alarm)

Enbridge's evaluations in ELDER showed that the technology was able to detect some of the simulated leaks created in various operating conditions and at various sensor placements in dry soil that ranged from, on average, 6% to 41% among the different participated vendors. The response time ranged from minutes up to a few hours for the simulated segments of up to 50 km in length. The technology was unable to detect most of the simulated leaks in a water-saturated environment.

Enbridge has not evaluated the performance of DTS systems for underwater exposed pipeline implementations. DTS requires sufficient temperature difference between the FOC and the surrounding environment in order to alarm. This becomes even more challenging for underwater applications in which the temperature difference will disappear much more quickly and the released product and surrounding water will quickly come into thermal equilibrium. This technology also requires the leaked product to make contact with the cable (leak path dependent) and so placement of the fiber with respect to the pipeline becomes a very important factor in its effectiveness as an LDS. In this case, if the sensor is directly adjacent to the leak detection is possible; otherwise it is likely the leak will be missed.

b) Reliability (Number of false alarms)

Reliability is assessed through piloting the DTS technology over an extended period of time. Enbridge has not piloted the technology underwater but Enbridge's on land pilot evaluations showed that DTS false alarm count is highly dependent on the environmental conditions (e.g. rain, settling & strain, water table, etc.). Based on this, for possible underwater applications, DTS may be susceptible to false alarms due to normal temperature variations in the Straits. Additionally, there may be false alarms due to currents and scouring near the pipeline.

c) Accuracy (Leak location detection, total volume lost, leak rate estimation)

Based on Enbridge's land-based pilot experience, a DTS system can locate an event within a few tens of meters. However, there has been no Enbridge evaluation of DTS underwater. Also, a DTS system is unable to estimate the leak volume or leak rate. As noted in the reliability and sensitivity assessments, Enbridge expects that most leak alarms would be invalid and, consequently, leak location accuracy would not be material to the decision.

d) Robustness (function under AOC, instrument outage, fault tolerance)

DTS, as a sensor-based system, should be functional under all variations of pipeline AOCs. DTS cable integrity is expected to be robust when properly installed.

5.2.1.1 Overall effectiveness consideration for detecting leaks underwater

DTS requires sufficient temperature difference (usually more than 2oC) between the FOC and the surrounding released product in order to alarm. For underwater applications at the Straits, where the temperature difference will disappear much more quickly and the released product and surrounding water will quickly come into thermal equilibrium, the technology may not be sensitive to leaks. If the sensor is right beside the leak, and there is a sufficient temperature difference, there might be a chance of detection; otherwise the leak would be missed. The system is also prone to false alarms due to temperature variations and currents resulting in strain on the fiber. Enbridge does not recommend this technology for leak detection in the Straits and ranks its effectiveness for underwater leak detection as **Low**.

5.2.1.2 Overall effectiveness consideration for detecting ruptures underwater

DTS effectiveness is not expected to change drastically for ruptures. A huge volume of released product might slightly increase the chance of DTS cable to touch the leaked product but if the released product does not come in contact with the cable due to the location of the leak relative to the installed cable, the rupture would be missed. Enbridge does not recommend this technology for application in the Straits and ranks its effectiveness for underwater rupture detection as **Low**.

5.2.2 The practicability of deploying the technology in the Straits of Mackinac

To install this technology, a FOC needs to be installed next to the underwater pipeline at the Straits of Mackinac. DTS technology effectiveness is highly leak path-dependent since the FOC needs to sense sufficient temperature difference to detect leaks. For this, the sensor must be placed very close to the pipeline which makes the construction challenging and poses increased installation risks. For this installation method, the FOC may need to be installed in high density polyethylene (HDPE) conduit. The possible use of armored cable for direct underwater installation should be examined.

The Straits of Mackinac is 6.5 km in length. FOCs can be fabricated and in lengths up to 8 kilometers, spooled onto a single reel. This should make one continuous installation possible. HDPE conduit is typically fabricated in shorter lengths, but may be connected in the field using mature and reliable methods.

Other specialized methods are likely required to install the fiber underwater. This may include direct attachment of the fiber to the pipeline, excavation of a shallow slot in the lake bed, or the addition of anchors or pegs to secure the cable. Implementation requires contractors familiar with marine construction methods and underwater fiber optic installation.

Enbridge currently has no approved internal procedures or specifications to safely secure an underwater cable on or near an underwater pipeline segment. Actual installation methods would need to be developed by qualified marine contractors and would take time to develop. Retrofitting and working on existing pipe has inherent risk because of the risk of damage to the pipe or supporting structures. This risk, in addition to the absence of defined methods for install is why Enbridge evaluates the practicability of deployment to be **Difficult** for this technology.

5.2.3 The practicability of long-term operation and maintenance of the technology

This technology is identified as **Feasible** based on the general durability of the sensors and the general ability to be integrated into the pipeline operation. However, the very limited potential of this technology for underwater leak and rupture detection make operational and maintenance capabilities not material to the decision.

5.2.4 The net present cost of the technology

The initial cost to install DTS technology at the Straits is expected to be high. An Enbridge conceptual estimate suggested the cost to be around $15MM. The install requires specialized materials, methods and external contractors with deep-water work experience. Enbridge currently has no experience installing this technology underwater, so the project team would require large contingency funding to address possible schedule delays, construction problems, and other issues.

The annual operating expense for DTS is not expected to be a significant portion of the overall cost. However, maintenance expense may be significant as the cable may require periodic inspections or repair, if damaged. The cost for repairs could be significant at approximately $500k per location. To reduce cable inspection costs, it may be possible to use ROVs that are used for concurrent inspection of the dual pipelines. With good installation, repairs are expected to be infrequent, approximately once every 10 years.

5.2.5 DTS evaluation summary

Table 3 DTS evaluation summary

Technology	Leak Detection Effectiveness	Rupture Detection Effectiveness	Practicability of Deployment	Practicability of Long Term Operation & Maintenance	Net Present Cost [4]	Recommendation for the Straits
DTS	Low	Low	Difficult	Feasible	$$$$	No

[4] The significance of the dollar signs is discussed further below.

5.3 Vapor Sensing Tube (VST)

VST is an effective vapor analyzing system that obtains vapor samples from sensing tubes placed along the length of the pipeline. During a leak, hydrocarbon vapors permeate through the soil and diffuse into the tube causing a high vapor concentration in the tube. Once or twice per day the contents of the tube are purged and a gas analyzer will detect the vapor location. VST technology can be used for on-shore pipelines but its application for underwater pipelines is uncertain.

5.3.1 The potential effectiveness of the technology in detecting leaks and ruptures of different sizes

This technology was tested for land based applications and was not tested for underwater implementations because conducting such testing was not feasible and the mechanisms of this technology do not suggest that it would be useful to undertake underwater testing. The results described here address underwater installation issues based on insights from Enbridge's on-shore testing and evaluations. Enbridge is not aware of this technology being implemented in an underwater application in North America.

a) Sensitivity (related to leak flow rate, response time, time to first alarm)

The technology was able to detect every simulated leak in ELDER that was specifically designed to evaluate the technology, within hours, up to a full day for both dry and water saturated soil conditions. However, the mechanism of detection was different for dry and wet soil. In dry soil, the hydrocarbon vapors permeate through the soil and diffuse into the VST tube. The results of water saturated soil showed that vapor permeation in water is extremely slow and VST cannot detect liquid leaks through detecting vapor diffusion into the tube. But if the liquid hydrocarbon comes into direct contact with the VST tube, the leak would be detected.

As noted, Enbridge has not evaluated the performance of VST systems for underwater implementations. However, diffusion of vapors in water is an extremely slow process which makes the effectiveness of this technology very limited.

b) Reliability (Number of false alarms)

Frequency of false alarms would require further investigation through an evaluation install. However, as noted in the sensitivity assessment, Enbridge expects that VST system not to be effective for underwater leak detection and, consequently, reliability would not be material to the decision.

c) Accuracy (Leak location detection, total volume lost, leak rate estimation)

The system cannot estimate the leak volume or leak rate. Leak location would require further investigation through an evaluation install. However, as noted in the sensitivity assessment, Enbridge expects that VST system is not effective for underwater leak detection and, consequently, leak location accuracy would not be material to the decision.

d) Robustness (function under AOC, instrument outage, fault tolerance)

VST, as a sensor-based system, may not be robust for underwater applications. The varying pressures underwater may lead to the intermittent or failure of the sensing tube.

5.3.1.1 Overall effectiveness consideration for detecting leaks underwater

VST technology is not identified as a viable underwater leak detection technology. VST effectiveness, underwater, will be degraded drastically due to the fact that vapors diffuse in water much slower than in a dry soil unless the VST tube comes into direct contact with liquid hydrocarbon release. The level of sensitivity that can be achieved for a given subsea condition is still a question which needs more testing and evaluation. Enbridge does not recommend this technology for the Straits of Mackinac application and estimates its effectiveness for underwater leak detection as **Low**.

5.3.1.2 Overall effectiveness consideration for detecting ruptures underwater

VST lack of effectiveness is not expected to change for ruptures. A large volume of released product might slightly increase the probability of the VST tube touching the leak and detecting the rupture through the direct contact; otherwise the rupture would be missed. Enbridge does not recommend this technology for the Straits application and ranks its effectiveness for underwater rupture detection as **Low**.

5.3.2 The practicability of deploying the technology in the Straits of Mackinac

To install this technology, a hollow tube filled with air would need to be installed within a slotted conduit next to the underwater pipeline, in close proximity to the pipeline. The Straits of Mackinac is 6.5 km in length. The custom tubes are typically fabricated in shorter lengths, significantly less than a kilometer, which may make it difficult to install longer lengths using a continuous construction method. Slotted conduits made from HDPE or rigid Polyvinyl Chloride (PVC) are typically fabricated in shorter lengths, but may be connected in the field using mature and reliable methods.

It is unclear what the impacts of underwater pressure would be on the VST installation. It is likely that other specialized methods are required to install the tube underwater. This may include direct attachment to the pipeline, excavation of a shallow slot in the lake bed, or the addition of anchors or pegs to secure the tube. Installation is to be completed by qualified marine contractors familiar with marine construction methods and underwater tube installation.

Enbridge currently has no approved internal procedures or specifications to safely secure an underwater tube on or near an underwater pipeline segment nor to commission such a system. As noted above, retrofitting and working on existing pipe has inherent risk because damage to the pipe or supporting structures is possible. The development of the necessary procedures would require time and expertise. Enbridge assigns the practicability of deployment to be **Difficult** for this technology.

5.3.3 The practicability of long-term operation and maintenance of the technology

5.3.3.1 Operation:

It is expected that there would be a moderate impact to operations. This would likely require training of personnel for assessment and maintenance of the equipment. Enbridge has no pilot projects or experience deploying this technology. Procedures to calibrate, assess, and maintain the system would need to be developed.

The Straits is subject to currents and ongoing redistribution of sediment near the pipeline. Also, it is not clear if the varying underwater pressures may lead to failure of the sensing tube, e.g. the tubing collapses under pressure. Underwater operations remain uncertain at this time.

5.3.3.2 Maintenance

The impact to maintenance is expected to be significant, primarily due to the fragility of the sensing tube itself, and the rigid conduit proposed by vendors to house the tube. It's likely that this technology will require frequent integrity recertification by visual underwater inspections of the conduit and the sensing tube using ROVs and other testing methods to be determined, such as pressure certification.

Enbridge is not aware of any underwater VST that have been installed for an extended period. There is a significant potential for a failure which requires complete replacement of the system within 25 years or less.

The practicability of this technology is identified as **Impractical** based on the general durability of the sensors, maintenance effort and the general ability to be integrated into operation.

5.3.4 The net present cost of the technology

The initial cost to install VST technology at the Straits is expected to be **High**. An Enbridge conceptual estimate suggests the cost to be around $20MM. The install requires specialized materials, methods and contractors with deep-water work experience. Enbridge currently has no experience installing this technology underwater, so the project team would require a large funding for contingency to address possible schedule delays, construction problems, and other issues.

The annual operating costs for VST system are not expected to be a significant portion of the overall cost. However, maintenance expense may be significant as the tube may require periodic inspections and repair, if damaged. The cost of repair could be significant at approximately $500k per location. Inspections of this sensing method by ROV may be achieved at the same period as inspections of the pipeline. We anticipate repairs will be frequent about 3 times per year of operation (i.e. $3MM/year).

5.3.5 VST evaluation summary

Table 4 VST evaluation summary

Technology	Leak Detection Effectiveness	Rupture Detection Effectiveness	Practicability of Deployment	Practicability of Long Term Operation & Maintenance	Net Present Cost [5]	Recommendation for the Straits
VST	Low	Low	Difficult	Impractical	$$$$$	No

[5] The significance of the dollar signs is discussed further below.

5.4 Negative Pressure Wave

Enbridge has implemented a commercial hybrid system that includes both negative pressure wave analysis and statistical flow measurements at the Straits of Mackinac. This system is provided by an experienced and well established vendor. Enbridge has installed the statistical volume balance component from this vendor on other pipelines and is familiar with its performance. The pressure wave component has been assessed previously in a Pipeline Research Council International study (PRCI Field Testing of Negative–Wave Leak Detection Systems, Catalog No.PR-015-123713-R01) and it was used as guidance. The pressure wave functionality uses pressure transmitters to detect the transient pressure waves associated with the onset of a pipeline leak. The flow measurement component utilizes statistical volume balance methods to identify a possible leak. The combination of both methods provides benefits over the use of either of the technologies individually. The hybrid system allows for reduced uncertainty combined with enhanced performance, as the strengths of each method are leveraged with the ability to validate leak signatures for increased confidence.

Currently the system is installed and fully functional, however alarms are not being sent to the Control Center. The reliability of the system is being actively monitored before full operational implementation. This selected hybrid LDS is assessed in this report.

5.4.1 The potential effectiveness of the technology in detecting leaks and ruptures of different sizes

a) Sensitivity (related to leak flow rate, response time, time to first alarm)

Enbridge has piloted a hybrid LDS at the Straits of Mackinac as a possible complementary LDS to enhance existing leak detection capabilities. The expected benefit of including the pressure wave component in the hybrid system is to shorten the detection time. The sensitivity (i.e. leak size and detection time) identified by the vendor is tabulated below:

Table 5 Hybrid LDS sensitivity performance (identified by the vendor)

Leak Size (%)	Leak Size (m^3/h)	Detection Time (min)
1.5	54	25
3	108	20
5	180	15
10	360	10
20	720	8
30	1080	4
40	1440	2

b) Reliability (Number of false alarms)

Enbridge performs reliability assessments for LDS that are expected to be put into operation. The latest reliability test, conducted for 70 days, showed that the hybrid LDS had zero false alarms.

c) Accuracy (Leak location detection, total volume lost, leak rate estimation)

Both flow measurement and pressure wave components of the hybrid LDS estimate leak location. Although not tested at the Straits, pressure wave is expected to estimate the location of the leak more accurately compared to the flow measurement component. The flow measurement component can estimate the total volume lost and leak rate while pressure wave does not.

d) Robustness (function under AOC, instrument outage, fault tolerance)

This LDS is generally optimized for steady-state operations. The pressure wave component is less successful at detecting leaks when the pipeline is transient (during startup and shutdown conditions). Transient events have the potential to introduce additional background noise that makes the detection of leaks more difficult with this system. Pigs also have a degrading effect to the negative pressure wave component of the system that will increase the leak detection time. While in the line, the Pig can physically interfere with the expansion wave introduced from the pressure oscillations created when a leak occurs. Instrumentation outages of flow and pressure transmitters would also degrade the performance of the hybrid LDS.

5.4.1.1 Overall effectiveness consideration for detecting leaks underwater

The hybrid LDS is expected to be effective for leak detection of the size of 1.5% of the mainline flow rate and higher. The system showed zero false alarms in Enbridge latest reliability tests. Enbridge ranks the effectiveness for underwater leak detection as **High**.

5.4.1.2 Overall effectiveness consideration for detecting ruptures underwater

The hybrid LDS is expected to be very effective for rupture detection. Enbridge ranks the effectiveness for underwater rupture detection as **High**.

5.4.2 The practicability of deploying the technology in the Straits of Mackinac

To deploy this technology, specifically for the pressure wave component, special high fidelity pressure transmitters need to be installed on the pipeline. The hybrid LDS also uses the existing flowmeters for the flow measurement component. This technology can be retrofitted on an existing pipeline relatively easily and is suitable for high consequence areas (HCAs) and water crossings. The technology is effective for segment lengths (distance between pressure transmitter locations) of less than 50 km.

Enbridge has installed this hybrid system at the Straits of Mackinac. The practicability of deployment is **Feasible** for this technology.

5.4.3 The practicability of long-term operation and maintenance of the technology

5.4.3.1 Operation

The impact to operations is expected to be low/moderate, likely to consist of training of personnel for alarm assessment and also maintenance of the equipment. Procedures to calibrate, assess, and maintain the system will need to be developed.

5.4.3.2 Maintenance

The impact to maintenance is expected to be low. The active sensors are solid state pressure transmitters installed onto the pipeline. They require a small amount of yearly maintenance to ensure calibration.

The maintenance of the signal processing hardware and software will be contracted to the system vendor.

The practicability of the long term operation and maintenance of this technology is identified as **Easy** based on the general durability of the sensors, maintenance effort and the general ability to be integrated into operation.

5.4.4 The net present cost of the technology

The hybrid LDS installation cost was $1.1 MM for the Straits of Mackinac. This included installation of the vendor product, high fidelity PTs and internal installation costs. The yearly cost to maintain this system is $15-20k for the vendor and $33k for internal labor.

5.4.5 Hybrid LDS evaluation summary

Table 6 Hybrid LDS evaluation summary

Technology	Leak Detection Effectiveness	Rupture Detection Effectiveness	Practicability of Deployment	Practicability of Long Term Operation & Maintenance	Net Present Cost [6]	Recommendation for the Straits
Hybrid LDS	High	High	Feasible	Easy	$	Yes

5.5 Hydrocarbon Sensing Cable (HSC)

In Hydrocarbon Sensing Cable (HSC) systems, a cable with electrical properties that change when they come in contact with liquid hydrocarbon is placed in the trench with an underground pipeline. When the cable properties change, electrical signals are sent to software through the cable and leak location is then determined.

[6] The significance of the dollar signs is discussed further below.

5.5.1 The potential effectiveness of the technology in detecting leaks and ruptures of different sizes

This technology was tested for land based applications and was not tested for underwater implementations because conducting such testing was not feasible and the land-based testing results did not suggest that it would be useful to undertake underwater testing. The results described below address underwater installation issues based on insights from Enbridge's on-shore testing and evaluations. Enbridge is not aware of this technology being implemented in an underwater application in North America.

a) Sensitivity (related to leak flow rate, response time, time to first alarm)

Enbridge's evaluations in ELDER indicate that in dry soil, the technology was able to detect some of the simulated leaks, especially for leaks which were close to the HSC sensor. The detection success of the technology is highly dependent on the leak path, and choice of sensor placement is crucial to its effectiveness. The detection response time was within 1.5 to 12 hours for the simulated segments of up to one kilometer in length. Successful detection of leak events ranged from on average 24% to 44% among the different vendors. For a water saturated environment, the technology was mostly unsuccessful, with only a few vendors detecting a subset of the leaks. The results of this test suggested that strategic placement of cable is an important factor for successful detection. Since oil is lighter than water, and direct contact with the liquid hydrocarbon is needed, the sensing cable should be placed on top of the pipe to increase the chances of successful detection.

Enbridge has not evaluated the performance of HSC systems for underwater implementations. HSC technology requires the leaked product to make contact with the cable (leak path dependent) and so placement of the cable with respect to the pipeline becomes a very important factor in its effectiveness. In this case, if the sensor is right beside the leak there might be a chance of detection, otherwise the leak will probably be missed.

b) Reliability (Number of false alarms)

Reliability needs to be assessed through piloting HSC over an extended period of time. Enbridge has not piloted the technology underwater. However, Enbridge's land-based installs have shown that there may be reliability issues and the system may be prone to false alarms in conditions with a high water table and the presence of trace residual hydrocarbons.

c) Accuracy (Leak location detection, total volume lost, leak rate estimation)

The system cannot estimate the leak volume or leak rate. Leak location would require further investigation through a pilot evaluation of the technology.

d) Robustness (function under AOC, instrument outage, fault tolerance)

HSC, as a sensor-based system, should be functional under all variations of pipeline AOCs underwater. HSC cable integrity is expected to be robust when properly installed.

5.5.1.1 Overall effectiveness consideration for detecting leaks underwater

This technology needs direct contact with liquid hydrocarbons. Therefore, the HSC cable must be placed at a location where released product is likely to collect upon leaking. This makes it even more challenging for underwater applications in which currents and water movement may change the leak path and avoid contact with the HSC cable. The level of sensitivity that can be achieved for a given subsea condition is an open question. Line 5 carries NGL in addition to oil products. The behavior of NGL leaks underwater and the performance of HSC in detecting an NGL leak are not fully understood. We rank the effectiveness of this technology for underwater leak detection as **Low to Medium**.

5.5.1.2 Overall effectiveness consideration for detecting ruptures underwater

HSC is expected to be slightly more effective for rupture detection. A large volume of released product may increase the probability of the HSC cable touching the leak, but if the leaked product does not come in contact with the cable due to the location of the leak relative to the installed cable, the rupture would be missed. Enbridge ranks the effectiveness for underwater rupture detection as **Medium.**

5.5.2 The practicability of deploying the technology in the Straits of Mackinac

To install this technology at the Straits of Mackinac, a custom cable within a slotted conduit would need to be installed next to the underwater pipeline in a relatively close proximity so as to enable sensing. The Straits of Mackinac crossing is 6.5 km in length. The custom cables are typically fabricated in shorter lengths, significantly less than a kilometer, which may make it difficult to install longer lengths using a continuous construction method. Slotted conduit made from HDPE or rigid PVC are typically fabricated in shorter lengths, but may be connected in the field using mature and reliable methods.

Enbridge anticipates unique installation methods will be required to secure the cable underwater which may require direct attachment of a slotted conduit to the pipeline, excavation of a shallow slot in the lake bed, or the addition of anchors or pegs to secure the tube in-place. Regardless of the specific method, the install requires a contractor familiar with marine construction methods including safe excavation and deep-water dives, and contractors familiar with underwater installation testing and termination of the sensing cable.

Enbridge currently has no approved internal procedure or specification to safely secure an underwater cable on or near an underwater pipeline segment nor to commission such as system. Any installation procedure that might be successful would require time and expertise to develop. Enbridge evaluates the practicability of deployment to be **Difficult** for this technology.

5.5.3 The practicability of long-term operation and maintenance of the technology

5.5.3.1 Operation:

The impact to operations is expected to be moderate, likely to consist of training of personnel for assessment and also maintenance of the equipment. Enbridge has no pilot projects or experience deploying this technology. Enbridge would need to develop procedures to calibrate, assess, and maintain the system.

The Straits is subject to currents and ongoing redistribution of sediment near the pipeline, but these pressure or temperature variations do not negatively affect the hydrocarbon sensing cables' ability to function when installed properly.

5.5.3.2 Maintenance

The impact to maintenance is expected to be significant, primarily due to the fragility of the conduit proposed by the vendor to house the cable. It's likely that this technology will require frequent integrity recertification using visual underwater inspections of the conduit and the sensing tube using ROVs and other testing methods to be determined. This concern may be mitigated with an appropriate design prior to install.

HSC will trigger an alarm if sensing a hydrocarbon from any source, including a hydrocarbon from foreign sources, lubrication and sealing fluids containing wax or lubrication during install of pipe or anchors. Any hydrocarbon sensed on this cable will require a diver to repair the affected segment, either by cleaning or replacing the segment.

The practicability of this technology is identified as **Difficult** based on the general durability of the sensors, maintenance effort and the general ability to be integrated into operation.

5.5.4 The net present cost of the technology

The initial cost to install HSC technology at the Straits is expected to be **High**. An internal conceptual estimate suggests the cost to be around $18MM. The install requires specialized materials, methods and contractors with deep-water work experience. Enbridge currently has no experience installing this technology underwater, so the project team would require a large contingency funding to address possible schedule delays, construction problems, and other issues.

The annual operating costs for HSC system are not expected to be a significant portion of the overall cost. However, maintenance expense may be significant as the HSC cable may require periodic inspections or repair if damaged. The cost of repair could be significant at approximately $500k per location. Inspections of this sensing method by ROV may be achieved at the same period as inspections of the pipeline. We anticipate repairs will be required approximately 3 times per year of operation (i.e. $3MM/year).

5.5.5 HSC evaluation summary

Table 7 HSC evaluation summary

Technology	Leak Detection Effectiveness	Rupture Detection Effectiveness	Practicability of Deployment	Practicability of Long Term Operation & Maintenance	Net Present Cost [7]	Recommendation for the Straits
HSC	Low to Med	Med	Difficult	Difficult	$$$$$	No

[7] The significance of the dollar signs is discussed further below.

6 Enbridge's Current Leak Detection Methods and Systems at the Straits of Mackinac

Enbridge uses multiple layered leak detection methods for liquids pipeline leak detection for the Straits of Mackinac. These methods are designed to provide comprehensive and overlapping leak detection capabilities. These methods include the following:

- **Computational Pipeline Monitoring (CPM)**. This is computer-based monitoring using continuous measurements of pipeline conditions.
- **Visual surveillance and third party reports**. These are from Enbridge line patrols and by third-party reports of oil or oil odors.
- **Controller monitoring**. This is the continuous monitoring of pipeline conditions by the Pipeline Controller.
- **Sensor-based leak detection.** These methods include external sensors for direct leak detection and specialized pipeline integrity inline inspection tools (quarterly acoustic Smartball tool runs).

The primary method for continuous mainline leak detection monitoring is CPM-based Leak Detection Systems. A more detailed description of the current CPM-based and sensor-based leak detection as implemented at the Straits of Mackinac is summarized below.

6.1 CPM-based

6.1.1 MBS and embedded layers

The Material Balance System (MBS) is the primary leak detection system for Line 5. MBS is a Real Time Transient Model (RTTM) which uses enhanced statistical methods for leak identification. The purpose of the Line 5 MBS is to provide a sensitive and reliable continuous method of leak detection. Embedded within the current Line 5 MBS are additional layers to enhance and extend the leak detection capabilities. These include the following:

- **Automated Volume Balance (AVB):** A CPM method which determines a time-averaged volume imbalance using injection and delivery flow meters. If the imbalance exceeds a pre-set threshold, it will generate an alarm. The purpose of AVB is to provide an extended 24 leak detection window. AVB is not designed for shut-in operations (when the pipeline is shutdown).

- **Automated Pressure Deviation (APD):** A CPM supplementary leak detection embedded layer during the period when pipeline is shut-in and not flowing. APD is intended to provide additional pressure-based leak detection solution by exploring the situations where the rate of change in measured pressure with respect to time does not match with the thermal cooling process in the pipeline while it is shut-in.

- **Rupture Detection System (RDS):** A CPM-based pattern recognition method to provide rapid and reliable rupture detection in addition to normal MBS monitoring. The system can detect leaks that follow a defined rupture profile.

6.1.2 Complementary CPM

As discussed above, Enbridge has installed a commercial hybrid LDS which integrates negative pressure wave technology with statistical volume balance methods at the Straits of Mackinac. The assessment of this technology is in the final stages and Enbridge is developing emergency response procedures and appropriate training so as to facilitate integration of this technology into daily operational monitoring.

6.2 Sensor-based leak detection

The two following sensor-based systems are currently being used to supplement the installed CPM-based systems and enhance leak detection at the Straits of Mackinac.

- **Smartball ILI:** Enbridge is assessing the integrity of the two 20 inch legs of Line 5 at the Straits of Mackinac by running an acoustic In-Line Inspection (ILI) leak detection tool called Smartball. It will be used on a quarterly basis for the duration of the Consent Decree to examine the pipeline for pinhole leaks. No leaks have been detected to date.

- **Cameras at North Straits:** An Infra-Red (IR) based camera system is installed at the North Straits facility to enhance leak detection at this unstaffed facility which is located upstream of the Straits of Mackinac. This technology senses above ground facility spray and pooled oil leaks. This is done primarily by detecting temperature changes resulting from a leak. Along with the temperature variance, the camera analytics also detect image changes that may be the result of a leak. When the analytics detect a leak, an alarm will be generated.

7 Technology Performance Comparison against the Identified Factors

The table below summarizes the relative performance of the evaluated technologies with respect to each of the identified factors enumerated in previous section. At this time, the recommended technology for implementation as an Alternate Leak Detection from those assessed in this report, is the Hybrid LDS that integrates pressure wave technology with flow measurements. DAS Technology also shows some promise, but will require further investigation. The final recommendation on DAS technology effectiveness is dependent on the results of Enbridge's ongoing technology assessments and is not available at this time.

Table 8 Relative Technology Performance Comparison for the Straits Application

Technology	Leak Detection Effectiveness	Rupture Detection Effectiveness	Practicability of Deployment	Practicability of Long Term Operation & Maintenance	Capital Installation Cost[8] (CAP)	Annual Operating and Maintenance Cost (OM)	Net Present Cost (NPC)	Recommendation for the Straits
DAS	Med	Med to High	Difficult	Feasible	$$$$CAP	$$$OM	$$$$	Requires further assessment
DTS	Low	Low	Difficult	Feasible	$$$$CAP	$$$OM	$$$$	No
VST	Low	Low	Difficult	Impractical	$$$$$CAP	$$$$$OM	$$$$$	No
Hybrid LDS	High	High	Feasible	Easy	$CAP	$OM	$	Yes
HSC	Med	Med	Difficult	Difficult	$$$$CAP	$$$$$OM	$$$$$	No

[8] The separate cost metric values are defined in the evaluation criteria section.

8 Risks and Benefits of Adding Alternative Leak Detection Systems versus Current Leak Detection Systems at the Straits

In this section, Enbridge has evaluated the risks and benefits of each ALD technology discussed above versus the risks and benefits of continuing to rely solely upon the MBS Leak Detection System and those systems that Enbridge is required to implement under the Consent Decree. Enbridge defines risk as the probability of occurrence multiplied by the severity of the consequences. An LDS cannot reduce the likelihood of having a leak, but can reduce the severity of the consequences by early alarming and subsequent early initiation of effective mitigation measures to limit the total volume loss. Based on this, the risks and benefits identified in Table 9 are mainly based on sensitivity enhancement that the addition of an ALD technology may offer as compared to Enbridge's existing MBS Leak Detection System, which incorporates the leak detection requirements under the Consent Decree.

As indicated in the Table below, Enbridge has identified the primary risks and benefits provided by the existing MBS Leak Detection System on the Enbridge system. The table also identifies the benefits that may result from implementing the existing MBS Leak Detection System together with each ALD technology. As demonstrated by the table below, Enbridge has concluded as a result of this assessment that the existing MBS Leak Detection System is effective, and that the ALD technologies only add, if at all, marginal benefits to the existing system. This is due to the fact that the risks posed by the ALD technologies – i.e., feasibility of implementation and ineffectiveness in conditions in and around the Straits – outweigh any marginal sensitivity enhancement to Enbridge's existing MBS Leak Detection System. The only ALD technology that is shown to have any benefit over and beyond the existing MBS Leak Detection System is the hybrid pressure/flow system, which Enbridge found does enhance sensitivity with minimal implementation risk. Assessed benefits of the other tested ALD technologies are outweighed by the risks associated with installation, and/or lack of effectiveness. Accordingly, Enbridge concluded that the ALD technologies, other than the hybrid pressure/flow system, would not provide incremental value over reliance on the existing release detection methods, including MBS.

Table 9: Risks & Benefits of the addition of ALD systems to the current leak detection layers on Enbridge Line 5 at the Straits of Mackinac

Leak Detection Monitoring System(s)	Risks	Benefits
Current Enbridge LDS which includes: • MBS • APD • RDS • AVB (24 hour window) • Smartball ILI	• Smartball is a very sensitive tool to detect pinhole leaks but it is a non-continuous method. • RDS can only detect leaks that followed the defined rupture profiles. • MBS has limited ability to detect leaks below 2% on a continuous basis. • Leak location estimation is limited to an MBS segment. • APD requires correct valve closures during shut-in operations.	• RDS is highly reliable for rupture detection and triggers an immediate and automatic pipeline shutdown. • Leaks larger than 2% of the line rate can be detected reliably by MBS. • Smartball can detect pinhole leaks on quarterly basis (non-continuous) • Implementation of MBS allows for the addition of more leak detection layers such as AVB & APD. In addition, MBS provides operator decision support tools such as Column Separation Management, Batch Tracking and a graphical representation of the pipeline hydraulic profile.
Current Enbridge LDS + DAS	• DAS is difficult and complex to retrofit onto an existing underwater pipeline. • Almost all of the vendors in the market are new and not experienced enough to deal with a complex operational installation (retrofit) of this nature. • DAS may be influenced by background acoustic noises such as ships, underwater currents, etc. that need to be tuned out. Increased or erratic background noise can affect sensitivity. • May require a prolonged tuning period once system is installed to reduce false alarms.	• DAS has the potential to enhance sensitivity in small leak detection as underwater leak sounds are potentially detectable, however further investigation is required. • DAS may be able to detect anchor strikes; however, further investigation is required.
Current Enbridge LDS + DTS	• DTS is not suitable for underwater exposed pipelines. • DTS is difficult and complex to retrofit on to an existing underwater pipeline.	• Installation of this technology will not add leak detection benefits.

Leak Detection Monitoring System(s)	Risks	Benefits
Current Enbridge LDS + VST	• VST is not suitable for underwater installations. • VST is very difficult and complex to retrofit on to existing underwater pipelines.	• Installation of this technology will not add leak detection benefits.
Current Enbridge LDS + Hybrid LDS	• Hybrid LDS has comparable leak size sensitivity to CPM. Small pinhole size leaks below 1.5% can go undetected by the CPM. • If the acoustic signal of the leak onset is not recognized by the wave component of the system, the leak will not be detected by the Hybrid LDS. • Transient conditions and presence of pigs on the line may degrade the performance of the hybrid LDS.	• Hybrid LDS can be retrofitted to pipelines (requires hot tapping and installations of high fidelity pressure transmitters) and can cover underwater pipeline using existing on-shore infrastructure • Hybrid LDS could identify leak locations and can complement existing CPM systems for more accurate leak location estimation.
Current Enbridge's LDS + HSC	• HSC needs direct contact with liquid hydrocarbon so it is leak-path dependent. It may miss a leak, even a rupture, if the released product does not come in direct contact with the cable. This makes it unreliable for underwater applications. • HSC is very difficult and complex to retrofit on existing underwater pipelines.	• HSC has the potential to enhance leak detection sensitivity but requires direct contact with the leak.

9 Next Steps for Evaluations

Enbridge is assessing various technologies to enhance leak detection and threat monitoring on Line 5 across the Straits of Mackinac. In addition to leak detection, pipeline strike detection is identified as an additional way to improve preventive monitoring at the Straits. This waterway is actively being used by maritime transportation and commercial fishing. One of the risks identified are anchors dragged by vessels that may strike the underwater Line 5 pipeline segment. Enbridge is continuing to evaluate technologies which have potential for leak and strike detection. These evaluations are described below:

9.1 The CPM-based hybrid system

Enbridge is in the final stages of assessment for this hybrid LDS. The latest 70 day reliability test results showed zero false alarms. Enbridge is currently completing the development of Leak Detection alarm assessment and response procedures. The developed procedures will be assessed against previous false alarms generated by the system to ensure reliability and completeness.

9.2 DAS Technology

Enbridge evaluation results of DAS showed that this technology has some potential in detecting small underwater pipeline leaks. This technology also shows potential in detecting anchor strikes against the pipeline at the bottom of the Straits. Enbridge has started an evaluation process to evaluate DAS technology for leak and anchor strike detection. The installation of FOC at the Straits, even for evaluation purposes, is a challenging task. Before committing to install a fiber on the pipeline, in August 2017, three underwater hydrophones were connected close to the underwater pipe to measure background acoustic noise. The purpose of this was to evaluate if the background acoustic signals, captured by the hydrophones, would interfere with the DAS technology's ability to identify the acoustic signal from a leak or anchor strike. DAS technology uses similar acoustic sensing logic as hydrophones. Some audible noise scenarios were simulated for hydrophone capture. These simulations consisted of fixed frequencies noise generation by an underwater speaker and multiple water leak spray tests using a pressure washer. The hydrophones were retrieved after one month of data capture. A third party was hired to review and analyze the hydrophone data and to assess if DAS would be a potential solution for strike and leak detection. The third party report is in progress and is expected to be complete by February 2018.

9.3 A commercial hydrophone-based strike detection technology

In parallel to DAS technology assessment, Enbridge is also evaluating the ability of a commercial hydrophone-based system to reliably detect an underwater anchor strike. Earlier in 2016, after as extensive market scan, Enbridge has selected a hydrophone-based product for underwater pipeline strike detection. This product detects abnormal conditions on the pipe by analyzing the acoustic data captured from inside of the pipe using stationary hydrophones that are installed on the pipe at onshore locations. The vendor's initial assessment for Enbridge indicated that the effectiveness of this technology is highly dependent on background noise inside the pipe. Two installation sites are required to identify pipe strikes on the underwater segment at the Straits of Mackinac. In February 2017, Enbridge installed the vendor's hydrophones temporarily on Line 5 at North Straits site (NO) and Mackinaw station (MA) to record the internal pipeline background noise. The vendor analyzed the captured background data. Their analysis indicated that the background noise is low enough at NO for detection but was a concern at MA because of excessive pump noise. The vendor suggested that this problem might be resolved by improving their algorithm using a longer monitoring period. Enbridge is currently planning to install the vendor hydrophones at NO and MA stations for a three month period to further assess the capability of this vendor in detecting a possible line strike through acoustic data captured inside the pipe. The installation will commence in 2017 and will be followed by an analysis of the acoustic data in 2018. Analysis results will determine next steps.

10 Enbridge's Plans to Enhance Monitoring at the Straits

Enbridge is planning to implement the following additional monitoring methods:

The hybrid LDS: Enbridge is planning to put this system into production and is completing all the required documentation and training to implement this technology into operation. Current timing is to complete implementation with the enabling of alarms from this system in production by Q3 2018. Implementation is dependent upon successful completion of the current pilot and demonstration of system reliability.

Thermal camera system at NO: A new generation of the leak detection cameras has been released by the vendor. Enbridge assessment showed this new version has improved sensitivity and reliability. Enbridge is planning to replace the current thermal cameras at NO with this new generation of thermal cameras to enhance leak detection performance at this facility by Q1 2018.

A commercial automatic identification system: In 2017, Enbridge identified a vendor that can provide a system to alert any vessels and ships near Line 5 not to drop their anchors. The system provides a wireless notification to vessels passing within a predefined zone. Additionally, the system will also notify remotely Enbridge of a stationary vessel within the zone for a predetermined amount of time. The system has been procured and will be installed at the Straits in 2018.

Enbridge will continue to evaluate DAS technology and the hydrophone solution to improve leak and anchor strike detection on Line 5 at the Straits.

11 Conclusions

This report assesses the feasibility and effectiveness of installing an ALD system on Enbridge Line 5 at the Straits of Mackinac. This assessment suggests that DTS, HSC and VST are not suitable systems for an underwater implementation. The hybrid LDS that includes both pressure wave analysis and statistical volume balance measurements is recognized to be the most suitable option for detecting leaks and ruptures based on the four identified assessment factors. Enbridge is planning to put this system into production at the Straits of Mackinac and is completing the required documentation and training to implement this technology into operation. DAS and Hydrophone technologies are also identified to have potential for detecting leaks and anchor strikes, “in principle”. The effectiveness of DAS technology is highly dependent upon installation design and execution as well as the vendor maturity. Almost all of the DAS vendors in the market are relatively new and have not been implemented widely in the industry and are just being adopted. Enbridge is in the process of further evaluating this technology.