Report to the State of Michigan

Evaluation of identified underwater technologies to enhance leak detection of the dual Line 5 pipelines

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Nomenclature and Abbreviations

AUV	Autonomous Underwater Vehicle
C-FER	C-FER Technologies
CPM	Computational Pipeline Monitoring
DAS	Distributed Acoustic Sensing
ELDER	External Leak Detection Experimental Research
FLD	Fluorescent Leak Detection
FOC	Fiber Optic Cable
HDPE	High Density Polyethylene
LD	Leak Detection
LDS	Leak Detection System
MA	Mackinaw Metering Station
MBS	Enbridge Material Balance System
NGL	Natural Gas Liquids
NO	North Straits Metering Site
OC	Fixed Optical Camera
OTDR	Optical Time Domain Reflectometry
PAHs	Polyaromatic Hydrocarbons
PHMSA	Pipeline and Hazardous Materials Safety Administration
PLC	Programmable Logic Controller
ppb	parts per billion
ppm	parts per million
PRCI	Pipeline Research Council International
ROV	Remotely Operated Vehicle
RP	Recommended Practice
SCADA	Supervisory Control and Data Acquisition
SwRI	Southwest Research Institute
UOC	Unusual Operating Condition
UV	Ultraviolet

Preface

Enbridge has prepared this Report to fulfill the requirements of Section D "Evaluation of Underwater Technologies to Enhance Leak Detection" of the "Agreement Between the State of Michigan and Enbridge Energy, Limited Partnership and Enbridge Energy Company, Inc." executed on November 27, 2017 (the Agreement).

Executive Summary

This Report reviews and assesses additional underwater leak detection technologies as required by the Agreement. This assessment focuses on the three underwater external technologies identified by the State of Michigan and agreed to by Enbridge: Fixed Optical Cameras (OC), Fluorescent Leak Detection (FLD) and Distributed Acoustic Sensing (DAS) cables. Fixed Optical Cameras was identified for assessment as part of the initial Agreement. DAS and FLD technologies were identified after the State's review of the *Report on Feasibility of Installing an Alternate Leak Detection System at the Straits of Mackinac* (Consent Decree Report).

This assessment uses a similar approach as that used in the Consent Decree Report. The approach uses a qualitative evaluation of the identified technologies based on a review of available information from eight general resources. These resources include: existing industry recommended practices, research organizations, literature review, pipeline operators, industry experts, Enbridge experience with the technologies, commercial technology providers and marine contractors.

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 (the Straits), (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. Prior to completing this assessment, Enbridge required that its external leak detection system provide continuous monitoring capability at the Straits.

A summary of the assessed relative effectiveness, practicability and cost of the evaluated technologies for underwater leak detection at the Straits is shown in the table below. Evaluation criteria and metrics are defined on pages 8-10 of this Report.

Enbridge is not aware of any implementation of these technologies for continuous operational underwater pipeline leak detection. This assessment concludes that none of the three technologies assessed are currently practicable for deployment at the Straits. However, as described in the Consent Decree Report, Enbridge has implemented the Hybrid Leak Detection System as an additional layer of leak detection for the Straits.

Technology	Leak Detection Effectiveness	Rupture Detection Effectiveness	Practicability of Deployment	Practicability of Long-term Operation & Maintenance	Net Present Cost	Current Assessment for the Straits
Fixed Optical Camera	Low	Low/Medium*	Impractical	Impractical	$$$$$	Not practical
Fluorescent Leak Detector	Low*	Not Applicable	Impractical*	Feasible	$$*	Does not provide continuous monitoring
DAS (FOC)	Medium*	Medium/High*	Difficult	Feasible	$$$$	Not operationally proven

* Subject to the assessment qualifications identified in this Report. The *Evaluation Criteria* section of this Report defines all evaluation criteria and metrics.

Scope and Approach

This Report reviews the three additional underwater leak detection (LD) technologies that were evaluated by Enbridge to address the requirements of the Agreement: Fixed Optical Cameras (OC), Fluorescent Leak Detection (FLD) and Distributed Acoustic Sensing (DAS) cables.

These three technologies are defined as “external” pipeline Leak Detection Systems (LDS). External LDS are technologies that are generally located externally to the pipeline and use sensors or images to detect a possible leak. They can provide an alternative method of leak detection to complement “internal” LDS methods such as Computational Pipeline Monitoring (CPM). Internal LDS use measurement-based calculations of the internal pipeline hydraulics or conditions to detect leaks. LDS can be either continuous (always on) or non-continuous. The current Enbridge Material Balance System (MBS) is an example of a continuous, internal LDS. A primary evaluation consideration in this assessment is that the external leak detection system should provide a continuous monitoring capability.

This evaluation uses a similar approach as that used in the Consent Decree Report. The approach uses a qualitative evaluation of the identified technologies based on a review of available information from the eight general sources identified below. Enbridge has no direct experience using these three external technologies for offshore, underwater leak detection. However, Enbridge does have experience using DAS cable-based LD technology for onshore pipeline leak detection through internal pilots, Joint Industry Partnership (JIP) laboratory-based research and through Pipeline Research Council International (PRCI) project participation. Enbridge also has experience in using camera imagery for facilities monitoring and experience with fluorescence technology for batch tracking and pipeline hydrostatic testing.

The eight sources of information used for this assessment were:

1. Industry recommended practices (RP).
2. Research organizations.
3. Literature review.
4. Pipeline operators.
5. Enbridge experience.
6. Industry experts.
7. Commercial technology providers.
8. Marine contractors.

Each of these sources was reviewed to provide informed guidance for the assessment of the three external leak detection technologies.

Industry Recommended Practices

Leak detection on Line 5 is regulated by the Code of Federal Regulations, Title 49, Part 195 (*Transportation of Hazardous Liquids by Pipeline*, 10-1-09 Edition). The primary RP requirement identified is that any computational pipeline monitoring for leak detection should comply with specific aspects of API Recommended Practice 1130 (*Computational Pipeline Monitoring*) [API 1130]. This RP is focused on internal LD methods that use CPM. External LD methods are noted in API 1130 but are explicitly identified as beyond its scope. External leak detection technologies, such as the three being assessed here, are also identified in API RP 1175 (*Leak Detection Program Management*). However, there is currently no industry RP on applying or assessing external leak detection technologies. Also, there is no North American industry RP that Enbridge is aware of that explicitly addresses external leak detection for underwater pipelines.

The primary industry RP that Enbridge identified that addresses underwater leak detection is DNVGL-RP-F302. This RP was developed by Norwegian company DNV-GL, which has extensive experience with maritime energy industries. They have published numerous technical engineering RPs related to North Sea energy production. There are two versions of DNVGL-RP-F302, with different titles and different publication dates. The first version (*Selection and Use of Subsea Leak Detection Systems, 2010*) is a survey of available subsea LD technologies and extracted laboratory test results. This RP was replaced in 2016 by a new version as a result of a multi-industry JIP. This later version (*Offshore Leak Detection*) is more focused on the technology assessment process. Enbridge found value in both versions.

An additional industry RP published by DNV-GL is DNVGL-RP-F116 (*Integrity Management of Submarine Pipeline Systems, 2017*). *Appendix D* of that RP provides a short overview of LD technologies and methods and also identifies the use of submersibles, such as Remotely Operated Vehicles[1] (ROV) and Autonomous Underwater Vehicles[2] (AUV), for targeted LD tasks.

Research Organizations

Enbridge identified eight research organizations as possible resources to assist in its assessment of these technologies. These organizations were selected based on Enbridge's previous experience or by review of publically available information. These resources provided guidance either directly through discussions or indirectly through review of published documents.

Enbridge is an active member in the Pipeline Research Council International (PRCI, Washington, DC). PRCI is a primary vehicle for industry-sponsored research in LD technologies. PRCI research projects have specifically focused on the issues of applying DAS technology for onshore LD.

A major research provider for PRCI and other industry clients is the Southwest Research Institute (SwRI, Texas). SwRI has extensive involvement in DAS technology assessment work. It also has test facilities to test offshore acoustic technologies such as DAS or hydrophones.

The Offshore Technology Research Center (Texas) has a long history of providing services to industry, with a special reference to the Gulf of Mexico. It has participated in published reports on approaches and challenges for subsea LD.

A major resource that Enbridge has direct technology assessment experience with is C-FER Technologies (Canada). C-FER has been the lead testing facility for numerous internal, JIP, PHMSA, and PRCI leak detection assessment projects. C-FER conducted the recent, extensive ELDER[3] laboratory testing of DAS which is identified elsewhere in this Report. C-FER has also been active in testing of other external LD technologies, including oil-on-water monitoring systems.

A major European research facility for underwater technologies is SINTEF (Norway). SINTEF is a research institute that conducts specialized ocean and environmental engineering studies. SINTEF conducted the laboratory tests of some of the underwater LD technologies identified in DNV-RP-F302 (2010). These 2010 results included optical camera and acoustic (non-DAS) technologies. SINTEF also has a large marine testing lab that has been used to test underwater DAS cables.

1 Non-autonomous remotely operated underwater vehicle (ROV) controlled and powered from a tethered surface vessel with an operator.
2 An autonomous underwater vehicle (AUV) is a robot that travels underwater without attachment to a surface vessel.
3 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 DAS.

Another European-based resource is the current GRACE project (Integrated Oil Spill Response Actions and Environmental Effects). This Finland-based, 13-member joint research project has completed a task on fluorescence detection technologies that directly addresses FLD assessment.

Additional technical resources were provided by two industry organizations associated with fiber optic cable (FOC) technologies. SEAFOM (Fiber optical monitoring group, UK) provides industry insight and technical specifications for selected offshore down-hole monitoring. FOSA (Fiber Optic Sensing Association, Washington, DC) is a new industry organization that provides technical and potential application background on various FOC technologies, including DAS.

Literature Review

Enbridge reviewed existing published documents that are related to the three technologies identified in this Report. These documents included technical reports, journal articles, research organizations and government publications, published testing results, commercial technical information and reference materials. The selected materials from these reviews are referenced in the technology assessment sections in this Report.

Pipeline Operators

Enbridge contacted major pipeline operators to review their experience with these technologies for underwater leak detection. Two large, U.S.-based operators with extensive offshore experience provided valuable insights into their experiences with FLD and optical cameras. A number of operators had reviewed DAS technology. However, Enbridge is not aware of any operators with operational experience with DAS for underwater pipeline leak detection.

Enbridge Experience

Enbridge's evaluation of alternative monitoring technologies has been focused on land-based leak detection. This includes pilot projects and joint industry evaluations. For DAS systems, Enbridge has extensive involvement in laboratory and field evaluations. An example of laboratory experience is the comprehensive assessment of DAS using the ELDER test facility. In addition, Enbridge has two pilot installations of DAS technology along onshore pipeline segments.
For image-based systems represented by optical cameras, Enbridge has experience with facilities-based leak detection implementation. This experience is mainly focused on thermal imagery but does have an optical confirmation component. Enbridge has not tested FLD for underwater hydrocarbon leak detection. However, we have used dyes for visual leak detection during pipeline hydrostatic testing. In addition, Enbridge uses fluorometers on a regular basis to detect refined batches from other commodity types in order to avoid contamination.

Industry Experts

Enbridge has onshore experience with each of the three technologies being assessed but not on the application of these technologies for underwater leak detection. Consequently, Enbridge solicited independent, expert consultation on the current capabilities and operational status of these technologies for underwater leak detection.

Commercial Providers

Enbridge completed extensive market scans on external leak detection technologies as part of its continuing research assessment of leak detection methods. This included discussions and subsequent assessments of seven commercial DAS system providers. The primary focus for DAS was for onshore liquid hydrocarbon LD. For optical cameras, we reviewed multiple providers to assess possible underwater application. FLD is a mature technology and there are numerous commercial providers available. We reviewed the FLD capabilities and directly interviewed a major industry provider.

Marine Contractors

Enbridge scanned the marine industry for the general issues involved with underwater monitoring technology installations and operations. Enbridge had direct discussions with a marine contractor that has extensive underwater experience within the Great Lakes.

Evaluation Criteria

This section discusses the evaluation criteria considered when assessing the three technologies identified by the scope of the Agreement. The following four criteria were considered when assessing these external 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.

The Potential Effectiveness of the Technology in Detecting Leaks and Ruptures

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 considered industry standards for LDS and include: sensitivity, reliability, accuracy, and robustness. These criteria, which are identified in API 1130 (Annex C), are explicitly defined for CPM-style internal LDS. These standards provide a useful approach for comparing LDS, and Enbridge has extended these criteria to cover the external, sensor-based LDS being evaluated in this Report. Currently, there are no regulatory or industry performance standards or targets for the external LD technologies described in this Report. The following performance criteria are described below following API 1130:

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 for a leak of that size. 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 have 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 the minimum detectable leak (can be expressed as the size of smallest leak detected, as a percentage of nominal pipeline flow).

   – Speed of leak detection response (can be the time taken by the system to first alarm for a specific leak size).

b. **Reliability:** Reliability is a measure of the ability of an LDS to make 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 that incorrectly declares leaks is considered to be less reliable (API 1130, Annex C). Reliability is measured by the number of false alarms (reporting a leak when there is no leak).

c. **Accuracy:** Accuracy is a measurement of the validity of the LDS estimates of leak parameters such as the leak location, the leak flow rate and/or the total leak volume (API 1130, Annex C). Different LDS may provide different types of leak parameters. The accuracy of the LDS is assessed by comparing the LDS estimate of a particular parameter to the measured parameter, if available.

d. **Robustness:** Robustness is defined as a measure of the LDS capability 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 during an Unusual Operating Condition (UOC). UOCs are defined by Enbridge as unusual pipeline hydraulic conditions beyond the normal CPM-based LDS design capabilities or when the data or processes used by the LDS are compromised.
- Examples of UOC may include: unusual transient operations, two-phase flow or column separation, presence of pipeline pigs, instrumentation failure, communication failure, PLC failure, SCADA failure or ancillary software processes failure.
- Pipeline UOCs would not be expected to impact the external, sensor-based LDS evaluated in this Report. Robustness for sensor-based LDS would mainly reflect installed sensor durability and the integrity of its supporting power and communications.

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 for ruptures and for leaks. 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.

The 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 the 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 practical with current construction methods available in industry. New deployment methods must be developed.

The Practicability of Long-term Operation and Maintenance of the Technology

This criterion analyzes the long-term operation and maintenance required of the 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 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.

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. The capital, operating and maintenance costs estimated for this Report were derived mainly from on-land project installation experience and were adjusted for a Line 5 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 ($US)

Net Present Cost: Capital installation cost + 20 year operating and maintenance cost
$: 1 – 4 million
$$: 4 – 8 million
$$$: 8 – 16 million
$$$$: 16 – 40 million
$$$$$: > 40 million

Evaluation of Identified Leak Detection Systems for the Straits of Mackinac

The North American pipeline industry has very limited experience in testing or using these three external technologies for offshore, underwater leak detection. However, Enbridge does have experience using DAS cable-based LD technology for onshore pipeline leak detection through internal pilots, the ELDER JIP and through PRCI project participation. Enbridge also has experience in using camera imagery for facilities monitoring. Additionally, Enbridge has experience with fluorescence technology for batch tracking and pipeline hydrostatic testing.

Update: Hybrid LDS

As identified and described in the Consent Decree Report, Enbridge has implemented a commercial hybrid leak detection system (Hybrid LDS) that includes both negative pressure wave analysis and statistical flow measurements at the Straits of Mackinac. This LDS is provided by an experienced and well-established leak detection vendor. Enbridge has installed the statistical volume balance component from this vendor on other pipelines and is familiar with its performance. The pressure wave functionality uses high-resolution 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 functional. The reliability performance monitoring of the system has been completed and the Hybrid LDS is confirmed to be reliable. Operational implementation with full integration for leak monitoring and control room procedures was completed on June 18, 2018.

Fixed Optical Cameras (OC)

Leak detection with a fixed optical camera is based on utilizing color video camera imagery to monitor underwater assets for leaks. This technology provides local coverage and can potentially observe a leak if it is in the line-of-sight of the camera. The camera is a remote sensing device that monitors events without any direct contact. The success of the underwater detection, however, is strongly dependent on the environmental factors such as available light, visibility, the contrast in luminance or color between a hydrocarbon leak and the background, and conditions affecting clarity of the image such as water turbidity and biological growth.

As part of this review, thermal cameras were also considered for use in underwater leak detection. The suppliers responded noting they have no capability in underwater leak detection.

The focus of this review is on continuous real-time leak detection monitoring.

The potential effectiveness of the technology in detecting leaks and ruptures

Enbridge has not tested fixed optical cameras for underwater leak detection. A review of offshore hydrocarbon leak detection indicates that this technology has only been assessed for North Sea installations. These review results are based on the two primary recommended practices (RPs) for offshore leak detection: *Selection and use of subsea leak detection systems*, DNV-RP-F302 (April 2010) and *Offshore leak detection*, DNVGL-RP-F302 (April 2016). These documents are the source of the information presented in this assessment. In addition, Enbridge discussed this topic with a marine contractor familiar with underwater surveys in the Straits of Mackinac.

These RPs reported that optical cameras have been used for underwater leak detection at three Statoil point locations in the North Sea: Heidrun Satelite, Kristin and Asgard fields. There is no information on the effectiveness of this technology at these locations. Enbridge is not aware of this technology being implemented on any pipelines in North America.

The approach used to assess the effectiveness of this technology will rely on the industry standard leak detection metrics identified by API-1130 (Annex C): sensitivity, reliability, accuracy and robustness. In this review the only reference coming from the underwater pipeline industry relevant to offshore leak detection comes from the SINTEF laboratory testing conducted as part of DNV-RP-F302. Enbridge notes that real-world performance differs widely from laboratory conditions, and so the effectiveness metrics can rarely be successfully applied or translated directly from laboratory results. In addition, the marine contractor's underwater experience at the Straits represents both insights into real-world conditions, and familiarity with the specific conditions at the Straits of Mackinac.

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

The SINTEF testing provided no information regarding the size of the simulated leaks. The testing did not provide any information on the system detection time.

The sensitivity was only reported in a context of environmental factors and the effective range. Results showed that for liquid hydrocarbon leak detection, the sensitivity was highly dependent on the water turbidity and available light in the area being monitored. The normal detection range was up to approximately three feet, and the cameras needed additional light for detection beyond that. With extra light, the detection range of a camera increased 10 to 13 feet. Another influential factor in detection identified the need for a background contrast between the object to be detected (liquid hydrocarbon) and the background environment. The testing represented an optimistic "best case" scenario, assuming the camera was directed toward the leak and that the released hydrocarbons remained in the direct line-of-sight of the camera.

Results also indicated that biological growth may have a degrading effect on sensitivity by covering the lens or line-of-sight.

Visibility underwater in the Straits is reported to be good when no other considerations are present[1], such as during daylight hours when sufficient ambient light is available and there is no ice on the surface. However, no visibility can be expected at night time and will be very limited near dawn and dusk. Moreover, any ice cover, weather, waves or currents can be expected to limit the available light and restrict visibility in various ways. Environmental conditions such as waves and currents may decrease visibility by stirring up biota and silt, thereby increasing water turbidity. The Straits are partially or fully covered by ice for significant periods of the year, during which underwater visibility is limited in the Straits, and especially so at the depth of Line 5. Weather brings significant cloudy conditions from October through April which also decreases visibility. Therefore, for almost half of the year, natural light is not expected to provide enough visibility for an optical camera to provide leak detection.

In conclusion, leak detection sensitivity is highly dependent on visibility which is expected to be limited for large periods of time due to insufficient natural light conditions. Any application of cameras would require a source of artificial illumination at each camera location to allow continuous real-time monitoring.

1 The information collected from a marine contractor and is based on their experience.

b. **Reliability (number of false alarms)**

The SINTEF testing did not provide any information on the system reliability. The three North Sea camera installations also did not address reliability issues. It is assumed that the detection is done by manual observation. There is no indication in any of the studies that there is an automated detection algorithm for this technology. If the system is incapable of automatic alarming, then number of false alarms would not be material for discussion.

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

The SINTEF testing indicates that the system can provide leak detection only in an area local to each camera. The leak must be both in the line-of-sight of a camera and observable. The system cannot estimate the leak volume or leak rate. The three North Sea camera installations also did not address accuracy issues.

d. **Robustness (function under UOC, instrument outage, fault tolerance)**

The SINTEF testing did not directly address robustness. The testing did identify functional limitations due to the environment such as light, water turbidity and biological growth. One of the three North Sea installations failed due to unspecified issues. Overall technology robustness remains uncertain. It is assumed that the technology would not be affected by pipeline operations. Robustness for OC technology would mainly reflect installed camera durability and the integrity of its supporting power and communications.

Overall effectiveness consideration for detecting leaks underwater

The use of optical camera technology is limited for underwater leak detection. It is a local single point detection system that would require many installations to cover a linear feature like a pipeline segment. Its effectiveness is highly dependent on the light, water turbidity, background contrast and biological growth. For continuous real-time monitoring it would require supplemental illumination at each location. There is no evidence from the limited installation base that shows that optical cameras are effective. Discussions with a major offshore operator indicated that this technology was not considered effective. Enbridge does not recommend this technology for the Straits of Mackinac application and ranks its effectiveness for underwater leak detection as **Low**.

Overall effectiveness consideration for detecting ruptures underwater

Optical camera encounters similar challenges for rupture detection as for leak detection but it would be expected to perform slightly better due to the larger visual signature of the rupture. Enbridge does not recommend this technology for the Straits of Mackinac application and ranks its effectiveness for underwater rupture detection as **Low/Medium**.

The practicability of deploying the technology in the Straits of Mackinac

There are two options for utilizing optical camera technology. One is by mounting the optical cameras on an ROV and inspecting the underwater pipeline segment for leaks on a periodic basis or when requested. This option does not provide a continuous real-time monitoring method which is the focus of this camera assessment.

The second option is a fixed camera underwater installation next to the pipeline. Fixed installation needs cameras that can withstand the pressures in deeper water. For nights and when the natural light is limited, an auxiliary source of light is needed at each camera location. This auxiliary source of light is not expected to be as good as ambient light for detection. Cameras also need a source of power and a method for communications. This could be done by installing power cables and an optical fiber to transmit the camera signals. This may be possible by a custom cable that includes both power and signal.

The Straits crossing is about 4.5 miles in length and there is approximately 23,000 feet of exposed underwater pipe (12,000 feet on one leg and 11,000 feet on the second leg). Assuming 13 feet as the visibility limit of a camera with extra light, approximately 1,800 cameras would be needed to cover the exposed segments.

In addition, there are risks and challenges installing cameras underwater with proper infrastructure close to a pipeline with appropriate power and communications. Enbridge has no approved internal procedures to do so. The complexity of installation and the very large quantity of cameras required for coverage makes this approach **Impractical**.

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

Operation

Based on DNV-RP-F302 and industry discussions, the optical cameras do not appear to generate leak alarms automatically. A fixed installation would be expected to require continuous monitoring for leak detection by trained operators. The very large camera count would require a very significant number of operators to monitor the systems continuously.

Maintenance

DNV-RP-F302 collected available camera suppliers' technical data. Based on that, the system designed life is expected to be 25 years. The RP suggested that the system needs to be inspected and the lens cleaned every two years. This would require a very large amount of experienced diver time and may take several months to complete the task. The integrity of the power and communication cable should also be inspected regularly.

Enbridge identified the practicability of this technology as **Impractical** based on the general operation and maintenance effort.

The net present cost of the technology

The initial cost to install optical camera technology at the Straits is expected to be very high. The cost of the cameras (sensor only) is around $4 million. Added to this are the costs of installing cables for power, camera images and a source of extra light for each camera location. An Enbridge conceptual estimate suggests $20 million for extra light and cable installation. Installation would require specialized materials, methods and contractors with underwater work experience. Due to lack of experience installing this technology underwater at this time, 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 camera system would be significant considering the team who needs to monitor the large number of cameras. A conceptual estimate suggests $54 million per year for 24/7 monitoring assuming one operator monitors four cameras at a time.

Maintenance expense would also be high due to the number of cameras needs to be inspected by divers. The maintenance cost is estimated to be about $2 million every two years.

Fixed optical camera evaluation summary

The results of this assessment are summarized in *Table 2*. The assessment showed that this technology has low effectiveness, very high cost and impractical monitoring requirements. Enbridge is currently not aware that this technology has been applied for operational leak detection for underwater pipelines. This technology is not practical for the Straits and is not currently recommended.

Table 2: Fixed Optical Camera evaluation summary

Technology	Leak Detection Effectiveness	Rupture Detection Effectiveness	Practicability of Deployment	Practicability of Long-term Operation & Maintenance	Net Present Cost	Current Assessment for the Straits
Fixed Optical Camera	Low	Low/Medium*	Impractical	Impractical	$$$$$	Not practical**

* Depends on size of rupture, location and environmental conditions such as time of day.

**Not practical due to low effectiveness, very high cost and impractical monitoring requirement.

Fluorescent Leak Detection (FLD)

Fluorescence forms the basis of a widely used leak detection approach that is primarily focused on hydrostatic testing for new subsea installations and oil leak detection on an inspection basis. Fluorescence is an optical phenomenon in which a compound within a medium absorbs light from a light source at one wavelength and emits it at a longer wavelength. When fluorescent compounds are excited, some of the energy is absorbed through the excitation of electrons to higher energy states. Once the light source is removed, the excited electrons fall back to their ground state, giving off light which can be picked up by a detector. Typically, the absorbed light is in the ultraviolet (UV) range and the emitted light is in the visible range.

To use the fluorescent method, the medium to be detected must naturally fluoresce or fluorescent tracers (i.e. dyes) must be added in very low concentrations (in the order of 20 ppm) into the fluid being detected. Gases do not fluoresce but crude oil has a significant natural fluorescence. It typically absorbs light between 300 to 400nm, and emits light in the 450 to 650nm range[2]. FLD relies on the fact that certain compounds in oils absorb UV light and emit light in the visible range. Those compounds are called Polyaromatic Hydrocarbons (PAHs) and are comprised of fused rings containing strong unsaturated bonds. Due to the structural arrangement, they tend to fluoresce quite distinctly. Despite a difference in molecular structure, alkanes (saturated hydrocarbons) will also fluoresce when exposed to a focused light source, but they do so at a lower wavelength outside the visible light spectrum (UV-A bandwidth; 320-400 nm). This makes them less viable indicators of leaked oil[3].

Many hydraulic fluids have fluorescent tracers added as a standard. Commonly used fluorescent tracer dyes include Fluorescein, Roemex RX-9022, Rhodamine, Castrol SFP dye, etc. Tracer dyes used for FLD should be chosen to be compliant with environmental standards. The detectors can potentially differentiate between hydraulic fluid and oil leaks due to the signature differences within the fluorescence spectrum but the sensors should be tuned to the specific product that needs to be detected.

The fluorescent detectors can be diver held or could be mounted on ROVs or AUVs for underwater inspection or monitoring. This leak detection method is non-continuous. Enbridge is not aware of any permanent installation of these sensors for continuous monitoring. For some systems, leak fluorescence is identified by visual monitoring. For other systems, a sensor monitors fluorescence and alarms on leak recognition above an operator specified threshold.

For effective application of this technology, the pipeline operator would have to identify the hydrocarbon fluids to the commercial providers so that the appropriate detection wavelengths are used.

The potential effectiveness of the technology in detecting leaks and ruptures

Enbridge has not tested FLD for underwater oil leak detection. However, Enbridge has used dyes for visual leak detection during pipeline hydrostatic testing. In addition, Enbridge uses fluorometers on a regular basis to differentiate between refined product batch types in order to avoid contamination.

The approach used to assess the effectiveness of this technology will rely on the industry standard leak detection metrics identified by API-1130 (Annex C): sensitivity, reliability, accuracy and robustness.

This assessment also uses the previously mentioned resources including RPs, research organizations, literature review, industry experts, pipeline operators, commercial suppliers and marine contractors.

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2 *In-situ oil detection sensor-technology overview and experiment design*, D1.1, WP1: Oil spill detection, monitoring, fate and distribution, GRACE grant no 679266, Ares (2016) 6207149 – 31/10/2016.

3 *Detection of Oil in Water Column: Sensor Design*, Acquisition Directorate, Research and Development Center, United States Coast Guard, February 2013, Report No. CG-D-05-13.

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

The FLD detectors are reported to be quite sensitive to crude oil. Detection sensitivity as low as ppm[4] or, ppb[5,6] in ideal conditions, have been reported. DNV-RP-F302 and FLD commercial providers identified that this technology can provide coverage of up to 10 to 16 feet when mounted on ROVs or AUVs. Environmental factors such as turbidity, high water flow and reflection of light from the seabed or marine life may degrade detection[7]. Distance from the leak source can also reduce detection.

Water turbidity can interrupt the signal by strongly scattering the emitted light. Currents can rapidly dilute the leak and decrease the chance of detection, particularly for very small leaks. The two pipeline segments of Line 5 at the Straits are mostly not buried and are accessible for ROV monitoring. However, the Straits are partially or fully covered by ice for significant periods of the year. During these periods, there will be limited opportunities for normal ROV operations. High water flow and currents can occur in the Straits which could decrease the sensitivity of FLD for leak detection.

Another important consideration is that FLD is not expected to be effective for natural gas liquids (NGL), which represent a significant portion of Line 5 shipments. NGL includes ethane, propane, butane, isobutene and pentane, which are all alkanes and do not fluoresce in the visible range.

b. **Reliability (number of false alarms)**

There is limited reporting on FLD reliability. FLD may be affected by potential sources of false alarms in the marine environment. This could include false response to chlorophyll from algae and seaweed which are fluorophors[8], compounds that naturally fluoresce. Bright sunlight may also saturate the sensor and cause difficulty with detection. The seabed (e.g. white sand) and some marine life may also reflect the light in the same wavelengths used for leak detection. Reliability may be improved by the operator conducting multiple scans of the target area to confirm repeatability.

Reliability of an FLD system would have to be determined in the Straits.

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

Small leak location estimation using FLD is expected to be fairly accurate with operator review and analysis. If the leak size is significant, there is a chance that the leak travels along the pipe at some distance from the original leak source.

FLD cannot determine the leak rate and amount because it focuses on total hydrocarbon concentration. FLD can provide a gross estimate of the underwater leak concentration. It does this by comparing the intensity of fluorescence signal to the calibrated signal. In order to get an accurate estimate of the absolute concentration of the leak, the following conditions are required; otherwise the accuracy of the leak concentration estimation will be low:

- "The sensor needs to be calibrated with the same substance that is known to have spilled. Calibration of the fluorometer is generally carried out using specific oil, thus, the concentration results obtained in the field are relative to the specific oil and the procedure used to calibrate the instrument. This is required because different compounds and oil products respond differently to the excitation light. Since spilled oil is a mixture of compounds, the relative contribution of each is critical to determining the response.

4 *Hydrocarbon sensors for oil spills prevention and response*, Workshop proceedings, Alliance for coastal Technologies, No. ACT-08-01, Ref. No. [UMCES]CBL 08-095, Seward, Alaska, April 8-10, 2008.

5 *Fluorescence techniques for the determination of polycyclic aromatic hydrocarbons in marine environment: an overview*, J.J. Santana Rodríguez* and C. Padrón Sanz, Analusis , Volume 28, Number 8, October 2000, Luminescence spectroscopy: applications and recent trends, pages 710-717.

6 *In-situ oil detection sensor-technology overview and experiment design* D1.1, WP1: oil spill detection, monitoring, fate and distribution. GRACE grant no 679266, Ref. Ares(2016)6207149 – 31/10/2016.

7 *Sunken oil detection and recovery operational guide*, API Technical Report 1154-2, First Edition, February 2016.

8 *Heavy Oil Detection (prototypes)—Final Report*, Acquisition Directorate, Research and Development Center, June 2009, Report No. CG-D-08-09.

- Effects of weathering and biodegradation can be ignored. This is required because the oil that is oxidized, degraded, or otherwise modified from its original state will not respond the same to the excitation wavelength.
- Effects of other substances can be removed. This is required because other (natural) substances also fluoresce at the same excitation/emission bands."[9]

FLD accuracy is expected to be limited to leak location and would not provide information on leak rate and amount.

d. **Robustness (function under UOC, instrument outage, fault tolerance)**

FLD is a non-continuous LDS and is expected to be functional under most pipeline UOCs. However, because it is an inspection-based approach, the normal aspects for LDS robustness do not apply.

Overall effectiveness consideration for detecting leaks underwater

FLD technology is an established technique for measuring oil concentrations in water. It is primarily used in the offshore oil industry for targeted inspections of underwater facilities such as manifolds including connectors, flanges, seals and valves. As an example, FLD was used to determine oil concentration in the water column during the Deepwater Horizon spill in 2010[10,11]. FLD has been used for leak monitoring during hydrostatic testing for facilities and short pipe segments. Enbridge is not aware of any routine scheduled use of FLD for significant underwater pipeline segments.

The system is based on optical methods, and while robust, there are typical optical limitations similar to optical camera technologies. These limitations include water clarity (turbidity), high water flow and environment factors that can reduce sensitivity and reliability. Also FLD is not expected to be effective for NGL, which does not fluoresce in the visible range.

The technology is currently used by divers or submersibles and is a non-continuous leak detection method. It would require frequent use for a good coverage but would still be limited by the duration of the inspection period. It would also be significantly restricted by seasonal constraints at the Straits.

Because it is a non-continuous method and is subject to environmental and seasonal limitations, it would be effective only for periodic or on demand inspection. FLD could provide effective leak detection on a limited inspection basis. However, for overall continuous monitoring, Enbridge ranks its effectiveness for underwater LD as **Low**.

Overall effectiveness consideration for detecting ruptures underwater

FLD is a non-continuous method and there is a very small chance that a rupture would occur during an FLD inspection. This technology would not be a viable method for rupture detection. Enbridge ranks this technology as **Not Applicable** for the Straits.

The practicability of deploying the technology in the Straits of Mackinac

The FLD sensors can be deployed by mounting on ROVs or AUVs and used to monitor underwater pipeline segments as an inspection tool. The technology can be used day and night. The advantages of FLD sensors are ease of operation, light weight, low power consumption, low detection limits and maturity of deployment. Application would require Enbridge to engage marine contractors with underwater experience in using this technology.

Industry generally uses this technology on ROVs and Enbridge is not aware of any fixed underwater installation of these sensors for continuous monitoring. A continuous FLD implementation would require a fixed sensor placement along the pipe as close as every 10 to 16 feet. A fixed FLD installation would be subject to similar extensive deployment requirements as those identified for fixed optical cameras.

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9 *Ready for Oil Spill*, Project White Paper. UReady4OS, Version 1.1, March 2016. A project co-funded by EU DG-ECHO.
10 *Detection of Oil in Water Column: Sensor Design*, Acquisition Directorate, Research and Development Center, United States Coast Guard, February 2013, Report No. CG-D-05-13.
11 *Methods of oil detection in response to the Deepwater Horizon oil spill*, Helen K. White, Robyn N. Conmy, Ian R. MacDonald, and Christopher M. Reddy, Oceanography 29(3):76–87.

Applying this technology would not be practical for significant periods of the year due to seasonal constraints (i.e. ice cover and bad weather days).

FLD deployment on an inspection basis would be feasible for selected periods of the year and under appropriate environmental conditions. However, for overall continuous monitoring, Enbridge ranks the practicability of deployment of this technology as **Impractical**.

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

Operation

This technology would be used on an inspection basis and the long term requirement identified in this assessment would not apply.

Operation would require the use of a marine contractor with experience with this technology. A marine contractor has advised that each of the two segments of Line 5 should be surveyed at the 2 and 10 o'clock position. The marine contractor estimated that the effort for scanning both segments would be about a week. ROVs can be deployed anytime of the day subject to marine conditions.

Maintenance

This technology would be used on an inspection basis and the normal maintenance requirement identified in this assessment would not apply. The only expected maintenance would be the calibration of the FLD for the targeted oil type.

Enbridge identified the practicability of operation and maintenance of this technology as **Feasible** based on the general operation and maintenance effort.

The net present cost of the technology

The net present cost is a function of deployment frequency. A marine contractor with Great Lakes experience has estimated an inspection at the Straits using ROVs to cost under $100,000 for both segments.

Fluorescent leak detection evaluation summary

The results of this assessment are summarized in *Table 3*. The main limitation with this technology is that it is non-continuous. The assessment showed that this technology could be sensitive for crude oil detection but probably not effective for NGL leaks. This technology is not applicable for rupture detection because it is non-continuous. Deployment and operation should be feasible but the technology does not provide significant additional value to the current methods which includes periodic inspection for possible very small leaks by SmartBall[12]. Enbridge is currently not aware that FLD has been applied for operational leak detection for underwater pipelines. FLD is not recommended for the Straits because it is not operationally continuous and it is not an improvement to the current monitoring methods.

Table 3: FLD evaluation summary

Technology	Leak Detection Effectiveness	Rupture Detection Effectiveness	Practicability of Deployment	Practicability of Long-term Operation & Maintenance	Net Present Cost	Current Assessment for the Straits
Fluorescent LD	Low*	Not Applicable	Impractical**	Feasible	$$***	Does not provide continuous monitoring

* Non-continuous and not effective for NGL.

** Non-continuous and impacted by environmental conditions and seasonal limitations.

*** Net present cost is a function of deployment frequency.

12 SmartBall is an acoustic in-line inspection leak detection tool that is used on a periodic basis.

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.

The potential effectiveness of the technology in detecting leaks and ruptures

Enbridge has tested this technology for land-based applications, but it was not tested for underwater implementations. Given the lack of vendor maturity and inconsistent performance of the land-based testing, installing a FOC underwater is not currently recommended as a next step. The results discussed in this section address underwater installation issues based on insights from Enbridge's onshore testing. This technology is relatively new for liquid hydrocarbon leak detection and the pipeline industry has limited experience using DAS. The operational value of DAS technology depends on installation quality and effective tuning for leak signature recognition.

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

Enbridge's evaluation in ELDER showed that DAS technology (for some vendors) was able to detect most of the simulated leaks created in various operating conditions and at various sensor placements in dry soil. However, the performance was quite variable among the evaluated vendors. The response time ranged from seconds to minutes for the simulated segments of up to 25 miles in length. Successful detection of leak events in dry soil ranged from on average 0.9 percent to 95 percent 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 vendor) was also able to detect most of the simulated leaks in a water saturated soil 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 leak detection. Through the evaluation, it was identified that "in principle" acoustic monitoring for offshore leaks 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 remains uncertain.

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.

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 approximately 30 feet. DAS systems are unable to estimate the leak volume or leak rate.

d. **Robustness (function under UOC, instrument outage, fault tolerance)**

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

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 NGL in addition to 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.

DAS "in-principle" effectiveness in detecting leaks estimated to be **Medium**. 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.

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 /High** 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. Enbridge does not recommend this technology for the Straits at this time.

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 Line 5 Straits crossing is approximately 4.5 miles in length. FOCs can be fabricated in lengths up to five miles, 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.

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

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 land-based pilot projects with this technology but does not currently operate any DAS systems in a production role on Enbridge system. Procedures would 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 affecting the fiber optic sensing cable's function.

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 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.

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 $15 million. The install requires specialized materials, installation methods and external contractors with deep-water work experience. Due to lack of experience installing this technology underwater at this time, 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 $500,000 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.

DAS evaluation summary

The results of this assessment are summarized in *Table 4*. The main limitations with this technology are that this technology is not mature and deployment would be difficult. In principle, the technology may provide leak and rupture detection capabilities but is not operationally proven for underwater pipeline leak detection. Enbridge is not aware that this technology has been applied on any offshore pipelines. Enbridge is not currently recommending DAS for the Straits.

Table 4: DAS evaluation summary

Technology	Leak Detection Effectiveness	Rupture Detection Effectiveness	Practicability of Deployment	Practicability of Long-term Operation & Maintenance	Net Present Cost	Current Assessment for the Straits
DAS	Medium*	Medium/High*	Difficult	Feasible	$$$$	Not operationally proven

* Not a mature technology; has not been proven effective in underwater applications. Enbridge will continue to monitor the maturity of this technology.

DAS update

In August 2017, Enbridge connected three underwater hydrophones close to the underwater Line 5 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. DAS technology uses similar acoustic sensing logic as hydrophones. Some audible noise scenarios were simulated for hydrophone capture. A third party was hired to review and analyze the hydrophone data and to assess the background noise and its potential impact on DAS. This review concluded that the background noise did not indicate any major restrictions to apply DAS technology. Selected commercial DAS providers are being engaged to assess their system capabilities to filter background noise for leak signature recognition and define the tuning process for reliable automatic leak detection.

Summary and Conclusions

This Report reviews the three additional underwater leak detection technologies that were evaluated by Enbridge to address the requirements of the Agreement: Fixed Optical Cameras (OC), Fluorescent Leak Detection (FLD) and Distributed Acoustic Sensing (DAS) cables.

This evaluation uses a similar approach as that used in the Consent Decree Report. The approach uses a qualitative evaluation of the identified technologies based on a review of available background information from the eight general resources. These resources included: existing recommended practices, research organizations, a literature review, pipeline operators, industry experts, Enbridge experience with the technologies, commercial technology providers and marine contractors.

A primary evaluation consideration is that the external leak detection system should provide a continuous monitoring capability at the Straits.

In *Table 5*, the challenges and benefits of these three assessed external LD technologies are summarized. These results show that there are significant challenges and no significant benefits for continuous leak detection in the Straits.

Table 5: Challenges and benefits of the assessed external LD technologies

External Leak Detection System	Challenges	Possible Benefits
Fixed Optical Cameras (OC)	• OC is impractical to install and operate on an underwater pipeline. • OC is limited by environmental factors. • OC has no proven industry operational value.	• Installation of this technology will not add leak detection benefits.
Fluorescent Leak Detection (FLD)	• FLD is a non-continuous method that is limited to scheduled inspections. • FLD is limited by seasonal and environmental factors. • FLD would not be effective for NGL.	• FLD can be sensitive to small leaks depending on environmental conditions. • FLD does not add incremental value to current operational SmartBall use.
Distributed Acoustic Sensing (DAS)	• DAS is difficult and complex to retrofit onto an existing underwater pipeline. • Vendors are new and have very limited experience with a complex underwater installation. • DAS may be influenced by background acoustic noises which would require significant tuning for reliable operation.	• DAS is a potential effective technology for continuous leak detection based on testing and is actively being investigated. • DAS is not a proven operational technology for underwater leak detection.

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.

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 6*. An overall recommendation regarding each technology is also given.

Enbridge is not aware that any of these technologies have been applied for continuous operational underwater pipeline leak detection. This assessment concluded that none of the three technologies assessed are currently recommended for deployment at the Straits.

This evaluation is based on the current status of these identified technologies. Enbridge is committed to ongoing research of new leak detection methods. Enbridge will continue to monitor the progress of emerging technologies as they mature.

Table 6: Overall technology evaluation

Technology	Leak Detection Effectiveness	Rupture Detection Effectiveness	Practicability of Deployment	Practicability of Long-term Operation & Maintenance	Net Present Cost	Current Assessment for the Straits
Fixed Optical Camera	Low	Low/Medium*	Impractical	Impractical	$$$$$	Not practical
Fluorescent Leak Detector	Low*	Not Applicable	Impractical*	Feasible	$$*	Does not provide continuous monitoring
DAS (FOC)	Medium*	Medium/High*	Difficult	Feasible	$$$$	Not operationally proven

* Subject to the assessment qualifications identified in this Report.

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Life Takes Energy™

200, 425 – 1st Street S. W.
Calgary, Alberta, Canada T2P 3L8

Telephone: 403-231-3900
Facsimile: 403-231-3920
Toll free: 800-481-2804

enbridge.com