Technical Report

An Investigation into the Effect of Near Bottom Currents on the Structural Stability of Enbridge Line 5 in the Straits of Mackinac

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Abstract

The Straits of Mackinac is a four mile wide channel that connects Lakes Huron and Michigan. Resting on the bottom of the Straits is Enbridge Line 5, a twinned crude oil pipeline that was designed and constructed by Bechtel Corporation in 1953 for the Lakehead Pipeline Company. This was a unique engineering project at the time of construction and the designers attempted to account for the forces on unsupported sections of the pipe resulting from underwater currents. Recent research has shown the currents in the Straits of Mackinac to be stronger and more complex than originally contemplated by the designers of line 5. This paper reviews recent underwater current data for the Straits of Mackinac and draws conclusions about the implications of deficiencies in the original design basis for Line 5.

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Introduction

The need for liquid fuel to support the war effort in France in 1944 led to the development of undersea pipelines laid directly on the ocean floor in open water. Operation PLUTO[1] (Pipelines Under the Ocean) resulted in the development of technology to weld 20 foot sections of three inch steel pipe into 4000 foot strings and assemble many such strings into lines that spanned the depths and uncertain bottom terrain of the English Channel. By March, 1945, seventeen such pipelines had been laid capable of supplying a million gallons a day of liquid fuel for the continental war effort.

In 1953, The Lakehead Pipeline Company engaged Bechtel Corporation to design and build a crude oil pipeline to connect its terminal in Superior, Wisconsin with refineries in the Sarnia, Ontario area by taking a direct route across Michigan's Upper Peninsula, the Straits of Mackinac, Michigan's Lower Peninsula and across the St. Clair River. The land based segments of this pipeline were sized to be 30 inch diameter and were constructed similarly to the "Big Inch" pipelines laid across the United States in support of the war effort. The Straits of Mackinac underwater section of this pipeline, which is now known as Enbridge Energy Partners, Line 5, presented Bechtel Corporation with a unique engineering challenge since no such line of the required size had ever been constructed in deep open water. The very secret technology developed during Operation Pluto provided a basis for this effort but, because of the size of the line, Bechtel had to engineer this project as a first of its kind.

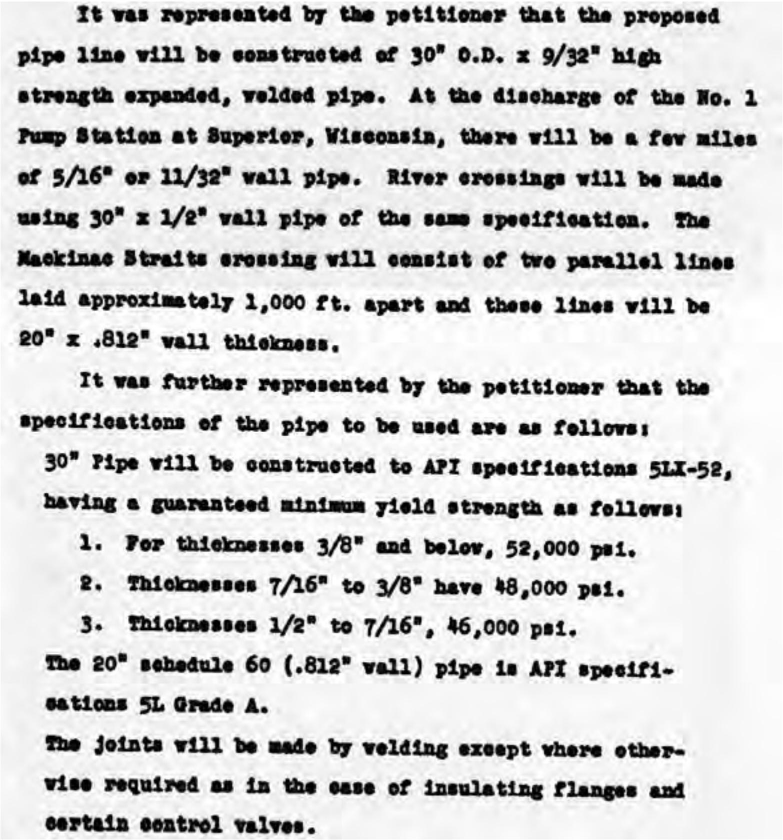
Laid in 1953, Enbridge Energy Partners Line 5, consists of two parallel 20 inch lines constructed of seamless X35 Grade, Schedule 60 pipe spanning the four mile crossing of the Straits of Mackinac. This design has stood the test of time with no significant failures to date. However, underwater currents much stronger than those specified in the original design basis have undermined the pipe in numerous locations resulting in unsupported spans. This necessitates a continual effort by Enbridge to detect and shore up excessive spans to prevent structural failure. Recent studies into the condition of these twin lines and ongoing research into the magnitude of the underwater currents in the Straits that affect these pipes have raised questions about the adequacy of the original design. This paper attempts to integrate recent information about the condition of Line 5 and the stresses imposed on it by gravity and currents to draw conclusions about the stability of the structure.

Design and Construction of Enbridge Line 5, Straits of Mackinac Section

Understanding the design and construction of Enbridge Line 5, Straits of Mackinac section required significant historical research. Following are excerpts from significant historical documents that facilitated developing an engineering understanding of this pioneering project.

Legal Documentation

The Lakehead Pipeline Company received permission to construct the pipeline that became known as Enbridge Line 5 in March 1953 from the Michigan Public Service Commission. MPSC Order D-3903-53.1[2] authorized construction of a pipeline from a point near Ironwood, Michigan, across the Straits of Mackinac and terminating on a point near the Canadian border on the St. Clair River. This document, which includes survey and technical information about the proposed pipeline, outlines the intent of the pipeline design and sets boundaries on some aspects of pipeline construction. The following language is taken from this document:



It was represented by the petitioner that the proposed pipe line will be constructed of 30" O.D. x 9/32" high strength expanded, welded pipe. At the discharge of the No. 1 Pump Station at Superior, Wisconsin, there will be a few miles of 5/16" or 11/32" wall pipe. River crossings will be made using 30" x 1/2" wall pipe of the same specification. The Mackinac Straits crossing will consist of two parallel lines laid approximately 1,000 ft. apart and these lines will be 20" x .812" wall thickness.

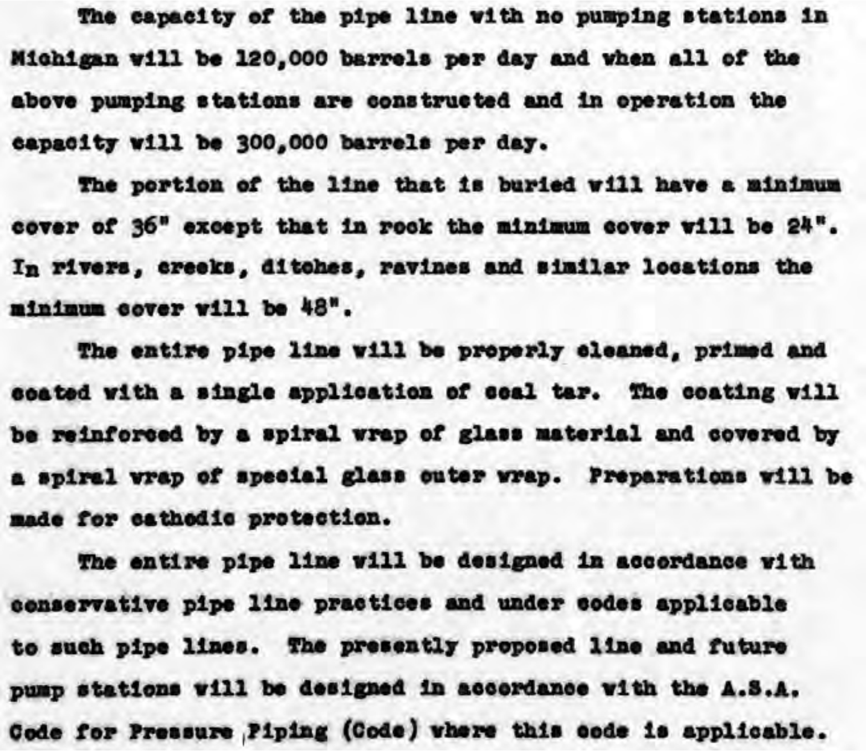
It was further represented by the petitioner that the specifications of the pipe to be used are as follows:

30" Pipe will be constructed to API specifications 5LX-52, having a guaranteed minimum yield strength as follows:

1. For thicknesses 3/8" and below, 52,000 psi.
2. Thicknesses 7/16" to 3/8" have 48,000 psi.
3. Thicknesses 1/2" to 7/16", 46,000 psi.

The 20" schedule 60 (.812" wall) pipe is API specifications 5L Grade A.

The joints will be made by welding except where otherwise required as in the case of insulating flanges and certain control valves.



The capacity of the pipe line with no pumping stations in Michigan will be 120,000 barrels per day and when all of the above pumping stations are constructed and in operation the capacity will be 300,000 barrels per day.

The portion of the line that is buried will have a minimum cover of 36" except that in rock the minimum cover will be 24". In rivers, creeks, ditches, ravines and similar locations the minimum cover will be 48".

The entire pipe line will be properly cleaned, primed and coated with a single application of coal tar. The coating will be reinforced by a spiral wrap of glass material and covered by a spiral wrap of special glass outer wrap. Preparations will be made for cathodic protection.

The entire pipe line will be designed in accordance with conservative pipe line practices and under codes applicable to such pipe lines. The presently proposed line and future pump stations will be designed in accordance with the A.S.A. Code for Pressure Piping (Code) where this code is applicable.

Crossing the Straits of Mackinac also required the Lakehead Pipeline Company to get an easement from the State of Michigan to cross bottomlands held in public trust. This easement[3] incorporated many conditions intended to assure the structural stability of the pipeline under the Straits. The following language is taken directly from this document.

(1) All pipe line laid in waters up to fifty (50) feet in depth shall be laid in a ditch with not less than fifteen (15) feet of cover. The cover shall taper off to zero (0) feet at an approximate depth of sixty-five (65) feet. Should it be discovered that the bottom material is hard rock, the ditch may be of a lesser depth, but still deep enough to protect the pipe lines against ice and anchor damage.
(2) Minimum testing specifications of the twenty inch (20") OD pipelines shall not be less than the following:

Shop Test	1,700 pounds per square inch gauge
Assembly Test	1,500 pounds per square inch gauge
Installation Test	1,200 pounds per square inch gauge
Operating Pressure	600 pounds per square inch gauge

(3) All welded joints shall be tested by X-Ray.
(4) The minimum curvature of any section of pipe shall be no less than two thousand and fifty (2,050) foot radius.
(5) Automatic gas-operated shut-off valves shall be installed and maintained on the north end of each line.
(6) Automatic check valves shall be installed and maintained on the south end of each line.
(7) The empty pipe shall have a negative buoyancy of thirty (30) or more pounds per lineal foot
(8) Cathodic protection shall be installed to prevent deterioration of the pipe
(9) All pipe shall be protected by asphalt primer coat, by inner wrap and outer wrap composed of glass fiber fabric material and one inch by four inch (1" x 4") slats prior to installation.
(10) The maximum span or length of pipe unsupported shall not exceed seventy-five (75) feet.
(11) The pipe weight shall be not less than one hundred sixty (160) pounds per lineal foot
(12) The maximum carbon content of the steel from which the pipe is manufactured shall not be in excess of 0.247 percent
(13) In locations where fill is used, the top of the fill shall be no less than fifty (50) feet wide
(14) In respect to other specifications, the line shall be constructed in conformance with the detailed plans and specifications heretofore filed by Grantee with Lands Division, Department of Conservation of the State of Michigan.

Presumably, additional easements and permits were required to cross other federally regulated navigable waters held in trust by the State of Michigan. These documents have not been discovered.

Technical Documentation

In 2012 the National Wildlife Federation released a documentary report entitled "Sunken Hazard"[4] which argued the Straits of Mackinac crossing of Enbridge Line 5 was unacceptably hazardous to Michigan's economy and ecology. This argument found a ready audience because of Enbridge's negligent operation of their Line 6b which ruptured in 2010 causing the one of the largest onshore oil spills in US history. In 2014, an executive order from Michigan's governor formed a task force to examine the safety of the Line 5 Straits of Mackinac crossing. This task force required Enbridge to produce documentation concerning the construction, operation and inspection of the pipeline so that it could make recommendations concerning its safety. After a negotiation, Enbridge surrendered a great deal of historical documentation. After two years of deliberation, the Task Force did not reach any conclusions but rather recommended further study of the extensive documentation from Enbridge. The summary report of the task force and an index to the archived documentation can be found on the State of Michigan's web site.[5,6]. In 2015, Governor Snyder issued another executive order forming the Michigan Pipeline Safety Advisory Board which was intended to follow up on the work of the Michigan Petroleum Pipeline Task Force. This board is expected to reach conclusions in 2017.

The documents that best illuminates original design basis of Line 5 are two letter reports[7] by the famed structural engineer Mario G. Salvadori of Columbia University issued on January 19,

1953. These reports are a critical analysis of all the design calculations done by the engineers at Bechtel. A careful review of this report is what led to this critique of the design basis for Line 5. In the following sections of this report, it will be shown that the design basis for stresses due to gravity and current loading are not consistent with recent information. The implications of this inconsistency are considered to be sufficiently significant that further analysis of Line 5 as it exists today is warranted to ensure acceptable structural stability.

Many historical documents that address the engineering and construction challenges faced by Bechtel, Inc. and Merritt, Chapman and Scott, the firm responsible for constructing the Straits crossing of Line 5 were also released by the Michigan Petroleum Pipeline Task Force. These documents include as constructed drawings, progress reports, dredging logs, photographs and other material. This material is incomplete but, by taking this fragmentary evidence as a whole, it is possible to understand the challenges faced in this pioneering construction project. Particularly challenging, was the dredging and filling necessary to construct the well graded lake bottom “bed” for the pipe so that the pipe could be placed without stressing the pipe material beyond its yield strength or leaving unsupported spans.

Overview of Current Measurements in the Straits of Mackinac

Successful design of a marine structure requires knowledge of the forces it must resist to maintain structural stability. The primary forces affecting an underwater pipeline are due to gravity, internal pressure and currents. The design calculations that assure a structure can resist the stresses due to gravity and internal pressure are relatively straightforward since the magnitude of these forces are known. The design calculations necessary to assure that a structure is sufficiently strong to withstand the drag forces that result from underwater currents require knowledge of the velocity of these currents and their variability.

The Straits of Mackinac is a four mile wide channel connecting lakes Huron and Michigan. This channel has sufficient flow capacity to ensure that very little hydraulic gradient exists between the northern ends of Lake Huron and Lake Michigan. Hydrologists consider the lake Huron/Michigan system to be a single basin with the great majority of inflow coming from Lake Superior via the St. Mary’s River and the great majority of outflow leaving via the St Clair River. Inflows to this basin from other rivers and streams are a small fraction of total inflow and outflow via the Chicago Drainage Canal is a small fraction of total outflow. A thorough review of the literature describing currents in the Straits of Mackinac can be found in Anderson and Schwab’s seminal paper entitled: “Predicting the oscillating bi-directional exchange flow in the Straits of Mackinac.”[8] In addition to this literature review, this paper also presents a contemporary numerical model describing flow through the Straits and the data used to calibrate it. This paper makes it clear that currents in the Straits are much more complicated than simple bulk flows and that the Lake Huron/Lake Michigan basin functions as a Helmholtz resonator. Surface level disturbances due to weather forcing induce storm surges, seiches and meteotsunamis[9] which result in waves that reflect and refract through the entire system. These waves cause strong and unpredictable currents as water levels equilibrate. These currents often take the form of a bi-directional oscillating current in the Straits with the development of opposing stratified flows when the Straits is stratified with a strong thermocline.

The first reported study of currents in Lake Michigan was conducted by Judson[10] in 1909 but it was not until 1975 that Saylor and Schloss[11] acquired sufficient data to elucidate the complexity of current flows in the Straits of Mackinac. This complexity was not known to the designers of the pipeline across the Straits in 1953. It is clear from the Salvadori report that Bechtel made lake bottom current measurements to determine what effect currents would have on both the pipe laying operation and the structural stability of the finished pipeline. Based on these measurements, the design basis for maximum underwater current strength was set at 1.96 knots (~2.25 mph, ~1 m/s). No documentation has been discovered about the details of these measurements or how the design basis for maximum current velocity was set.

The advent of Acoustic Doppler Current Profiler (ADCP) technology in the 1970's made it possible to make current measurements across the depth of a channel over extended periods of time. The first reported use of this technology in the Straits of Mackinac was in the previously referenced work of Saylor and Schloss. Since that study, four other studies have been conducted and the raw data from these studies forms the basis for this work. These data sets will be discussed in the following four sections of this report. Table 1 is a compilation of some identifying attributes of these four sets of Straits current measurements. A Google Earth© graphic showing the mooring locations of the buoys used to make these measurements along with the twin Straits sections of Enbridge Line 5 is shown as Figure 1.

Table 1. Compilation of Straits Current Measurement Data

Author and Buoy Identification	Date	Mooring Latitude	Mooring Longitude	Water Depth, (ft)	Nearest Distance to Pipeline, (ft)
Saylor and Miller[12], LM 01	1991	45°48'55.44"N	84°44'56.40"W	115'	2500' West
Saylor and Miller[12], LM 02	1991	45°49'19.20"N	84°45'07.80"W	215'	1100' West
Meadows[13], NOAA 45175	2015	45°49'30.94"N	84°46'19.81"W	~100'	1100' East
Anderson[14], wh 3748_2014_1S	2014	45°48'56.80"N	84°49'17.04"W	242'	9700' East

Current profilers typically average velocity readings over a ten minute to one hour time span at 1 meter depth intervals and record this data as well as other data such as water temperature, air temperature, barometric pressure, wave height, etc. The buoys associated with the ADCPs are deployed in the spring and recovered before ice forms. Current velocity vectors are binned according to water depth and the data ensemble is recovered with the buoy or transmitted. These data sets are quite large and when the LM 02 data ensemble was put into an EXCEL spreadsheet it had dimensions of 11 columns by 197,000 rows. Since the object of this study was to investigate near bottom currents, only the current velocity data in the bin nearest the lake bottom was analyzed. Further details of the data analysis from the four sets of data referenced in Table 1 make up the next four sections of this report.

The objective of extensively analyzing the available current data from the Straits is to determine the probability density function for current velocitiy near the bottom of the Straits. This probability density function can then be used to determine if and how often currents exceed the design basis of 2.25 mph that was set in 1953 without knowledge of the complexity of flows in the Straits. To this end, the entire set of current measurements from the selected buoy and the lowest depth bin will be fitted with an extreme value distribution. Several of the multipliciticy of extreme value distributions have been used to fit this data and the Weibull distribution function has been selected as represenative of current data. Other extreme value distributions such as the Frechet, Log Normal, or Beta distribution can also be made to fit current data but, for the purposes of this work, the Weibull distribution provides as good a fit as any.

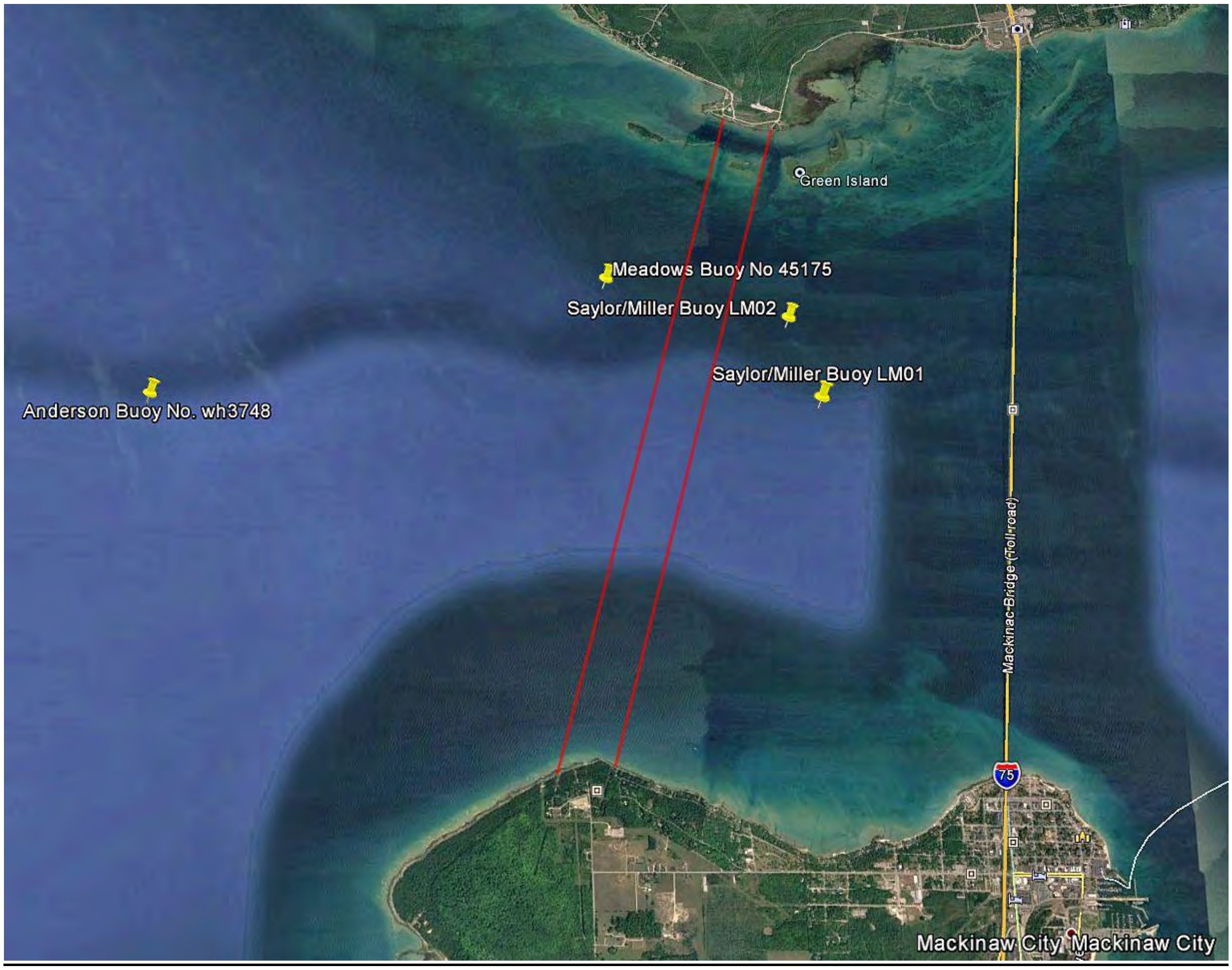


Figure 1. Google Earth© Graphic Showing Locations of Current Measurement Buoys and the Twin Exposed Sections of Enbridge Line 5

Saylor and Miller Buoy LM 01 and LM 02 Data, 1991

In 1991, Saylor and Miller deployed two buoys with ADCP capabilities at the locations shown in Table 1 and Figure 1. LM 01 was deployed near the middle of the Straits on the southern side of the ancient river bed that forms a small “canyon” in the Straits bottom. LM 02 was deployed in much deeper water near the center of the canyon. Figure 2, taken from Saylor and Miller’s publication, shows a cross sectional view of the Straits with the ADCP location superimposed. The differing ordinate and abscissa scales used in this plot have led many to think that there is a steep “canyon” in the Straits but with the Straits having a maximum depth of ~230 feet and a width of four miles, this canyon is only about 120 feet deep and a half mile wide. In fact, this canyon is more of a gentle grade albeit one with grade discontinuities and rocky soil that presented many challenges for the preparation of the “bed” where the pipeline was intended to rest.

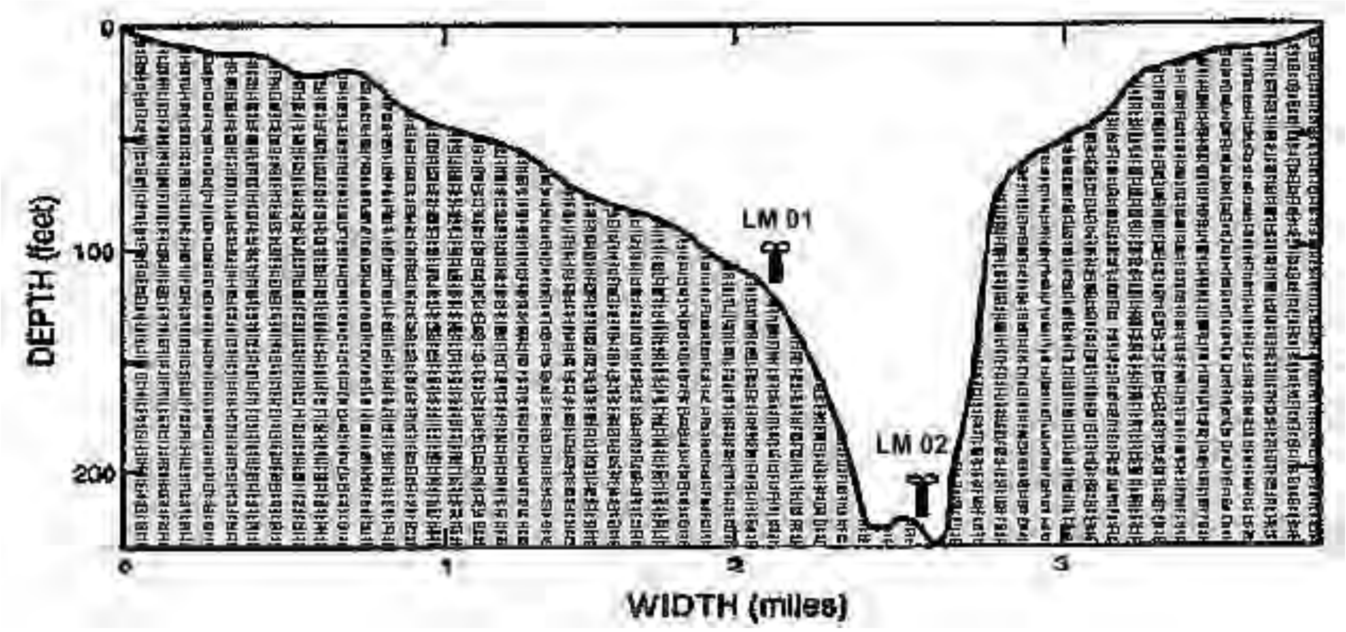


Figure 2. Cross Section of the Straits of Mackinac Showing Buoy Placement, (North to Right)

The raw data from Buoy LM 01 was placed into an EXCEL® spreadsheet and sorted twice. The first sort was by the depth bin number with bin 1 containing all the current velocity data from closest to the bottom of the Straits. All the bin 1 data was then pasted into another spreadsheet and sorted according to velocity. This data file was edited to remove a very small number of questionable data sets where it appeared that the ADCP was not reporting correctly. Most of the excised data was at the high end of the velocity distribution so, if this editing biased the results of this study, it is biased towards lower values. The ranked data set for bin 1 contains 3312 individual current velocity measurements and it is plotted as a cumulative probability density function in Figure 3 along with the fitted Weibull distribution.

Extreme values for current velocity and their associated probabilities cannot be reliably estimated from Figure 3 because, even though it appears that the Weibull distribution fits the overall data very well, the fit is not particularly good for the upper tail. To get a better estimate of the probabilities associated with extreme values for current velocity, the upper 1% of the cumulative probability distribution was refitted with a Weibull distribution to give a robust interpolation of the actual data. The upper 1% of the current data acquired by Buoy LM 01, Bin 1 along with the fitted interpolation equation is shown in Figure 4. Table 2 contains the Weibull fit parameters obtained by using the solver function in EXCEL®.

Table 2. Weibull Fit Parameters for Current Velocity Data Set LM 01, Bin 1

Fit Name	Weibull Offset Parameter, (mph)	Weibull Normalization Parameter, (mph)	Weibull Shape Parameter
LM 01, Bin 1, All Data	0.0144	0.3670	1.1005
LM 01, Bin 1, Upper 1%	1.1807	0.0010	0.2676

The fit parameters for the upper 1% of the LM 01, Bin 1 data can be used to estimate the cumulative probability that the current velocity is greater than a specified value. This increment of probability is called the “tail risk” as it is the total amount of risk that an event with

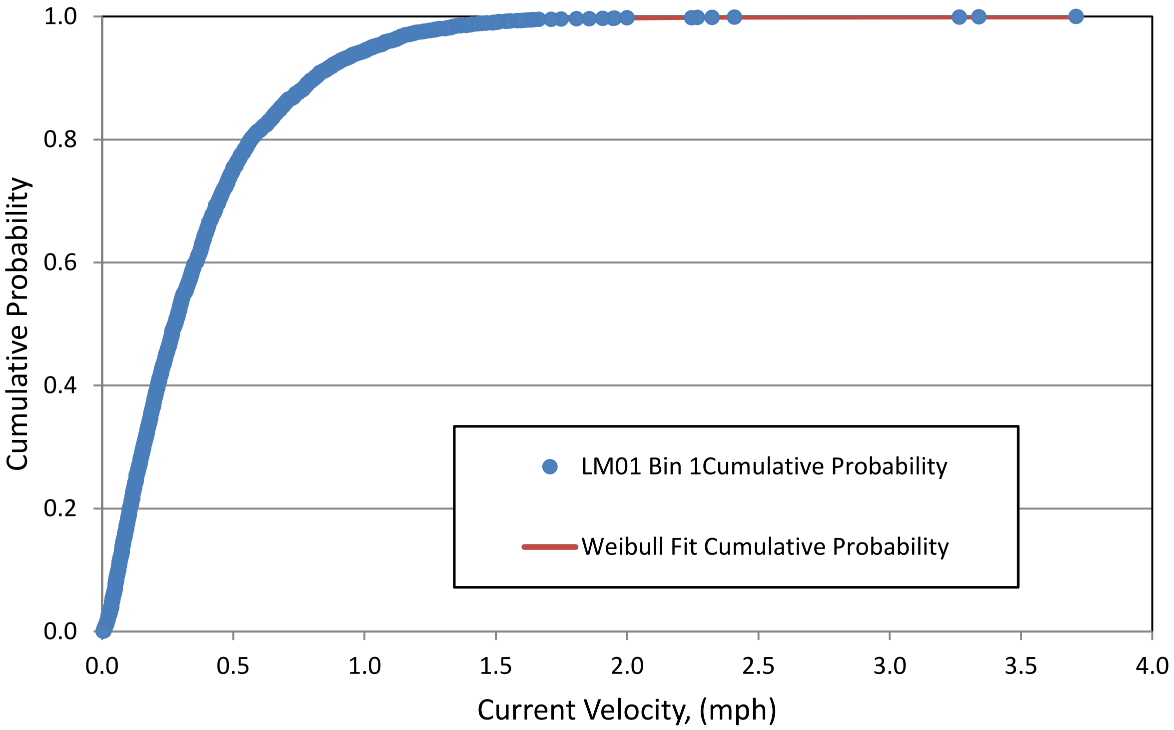


Figure 3. Data and Weibull Fit for the Cumulative Probability Density Function for Buoy LM 01, Bin 1

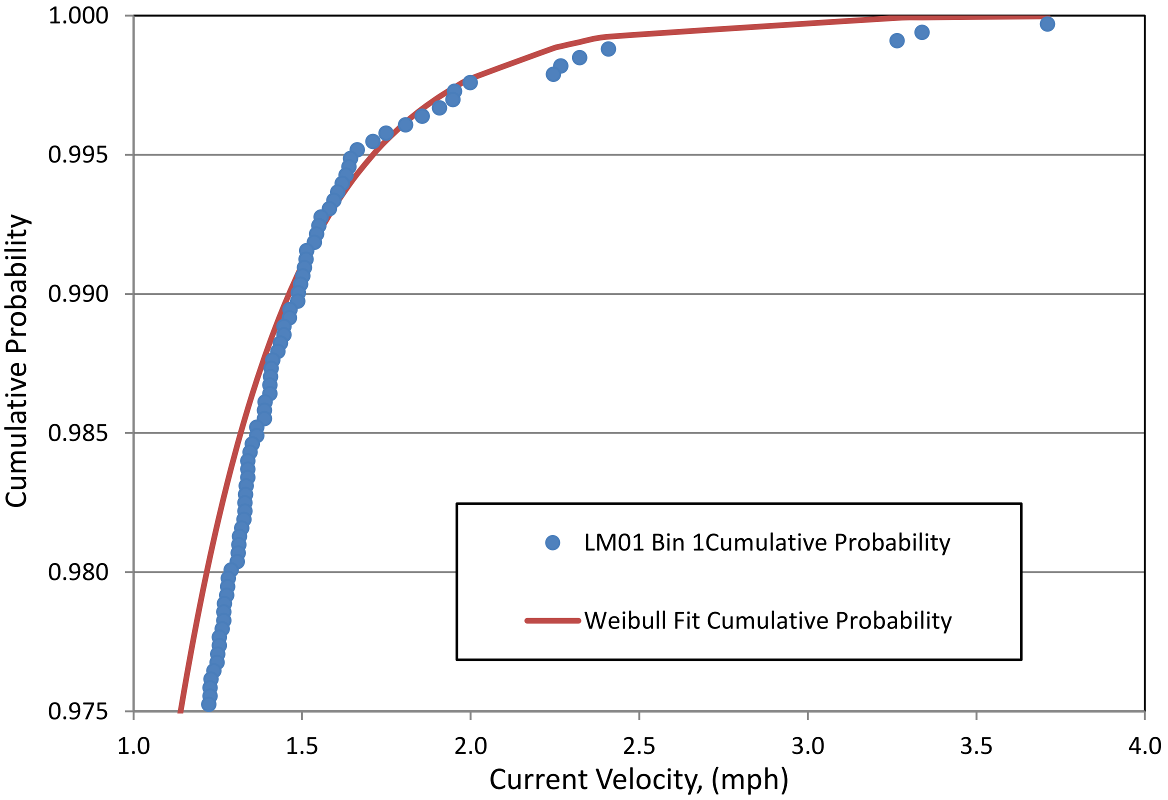


Figure 4. Data and Weibull Fit for the Cumulative Probability Density Function for Buoy LM 01, Bin 1, Upper 1% of Data

a greater than specified current value will happen. If this tail risk is multiplied by the amount of time in a year, the result is an estimate of how long the current velocity can be expected to be greater than the specified value. Table 3 contains the result of this calculation resulting in an estimate that the current velocity measured at Buoy Lm 01, Bin 1 is estimated to be greater than the original design basis for maximum current velocity for 818 minutes each year. Multiplying this estimate by the time since the line was constructed results in an expectation that currents at this location have been above the design basis for a total of 873 hours since construction.

Table 3. Estimated Tail Risk for Current Velocity Exceedances for Buoy Data Set LM 01, Bin 1

speed (mph)	Weibull Cumulative Probability	Tail Risk	Minutes per Year
0	0.0000%	100.0000%	525600
1	0.0000%	100.0000%	525600
2	99.7572%	0.2428%	1276
3	99.9421%	0.0579%	305
4	99.9771%	0.0229%	121
5	99.9887%	0.0113%	59
2.25	99.8444%	0.1556%	818

The LM 01, Bin 1 data set was also examined to determine the direction of current flow. The upper 25% of current velocity data was used to calculate the differential probability density of current direction. This data was sorted into bins of 10^o width resulting in the differential probability distribution for current direction shown in Figure 5.

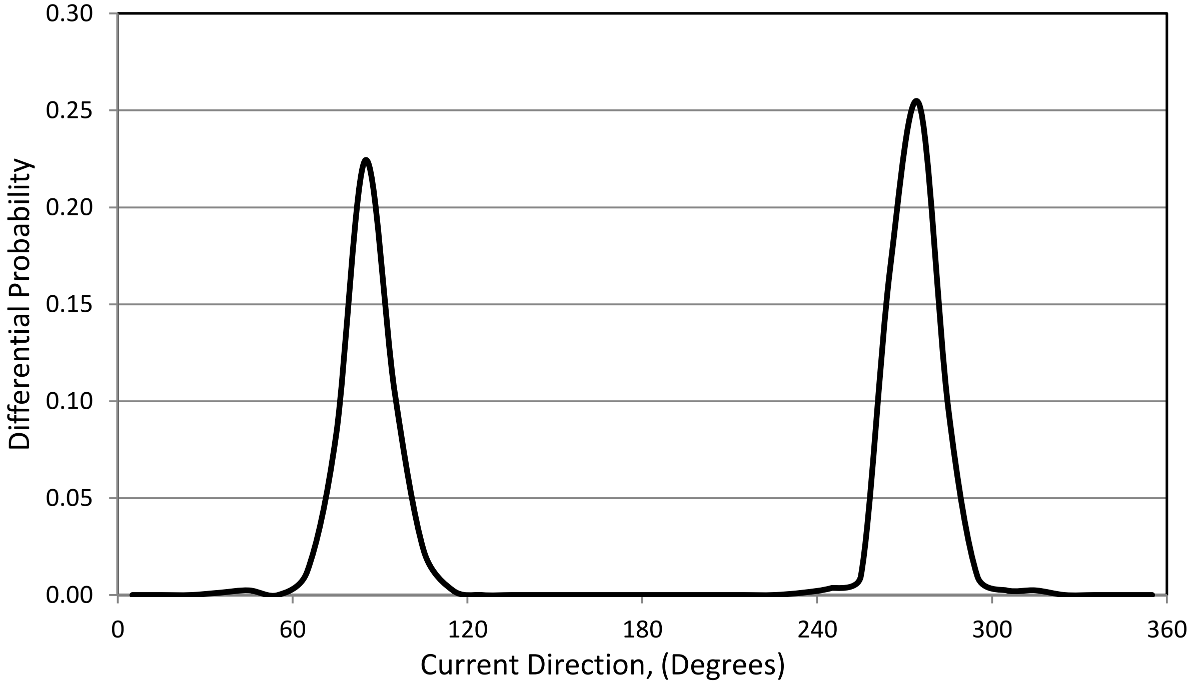


Figure 5. Differential Probability of Current Direction for Upper Quartile of Current Velocities for Buoy Data Set LM 01, Bin 1. *(Current Direction is the direction towards which the flow moves*)

The upper 25% of the current velocity data was used to construct Figure 5 so as to focus on the direction of strongest current flow. This flow is primarily perpendicular to the pipeline although this is not always true.

The Buoy LM 02, bin 1 data set is appears relevant because it is the closest physically to Line 5 in deep water, however, as will be discussed later, the LM 01, bin 1 data is more important to the subject of this paper. The same calculations that were used for the LM 01, Bin 1 data set were to characterize the LM 02 data set of 3313 data points. Figures 6, 7 and 8 show these results and Table 4 contains the Weibull fit parameters.

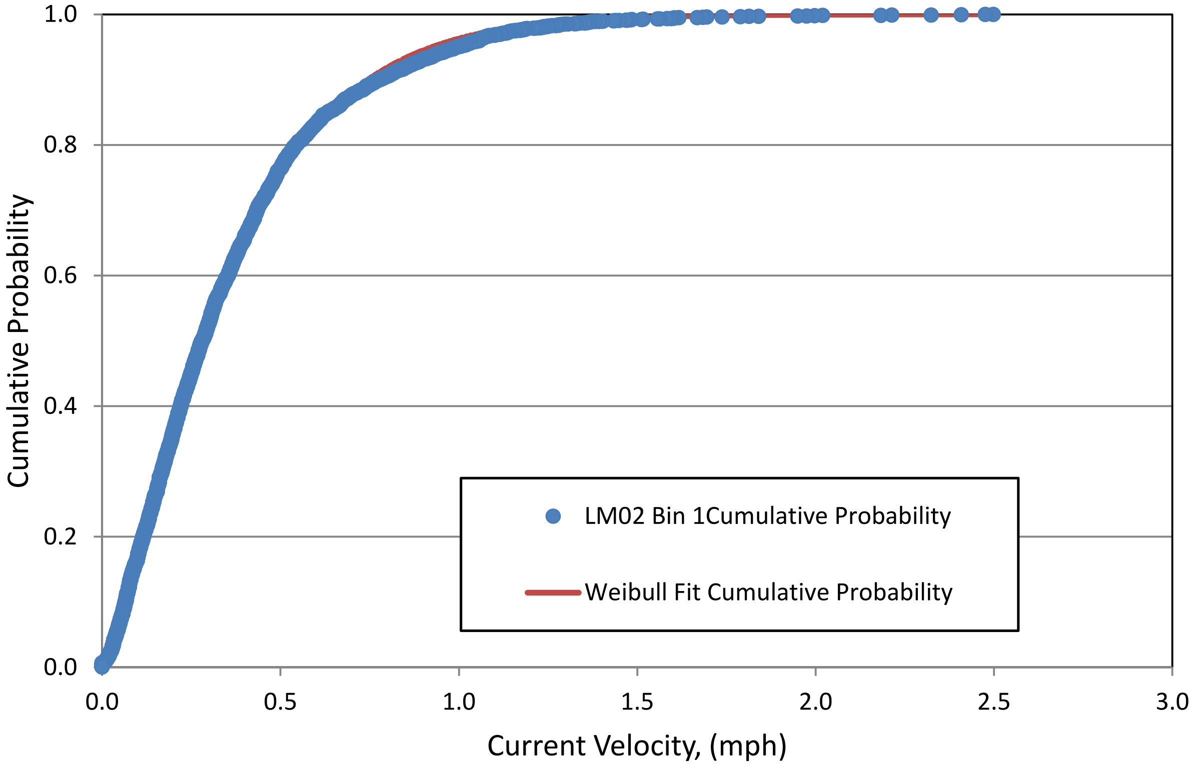


Figure 6. Data and Weibull Fit for the Cumulative Probability Density Function for Buoy LM 02, Bin 1

Table 4. Weibull Fit Parameters for Current Velocity Data Set LM 02, Bin 1

Fit Name	Weibull Offset Parameter, (mph)	Weibull Normalization Parameter, (mph)	Weibull Shape Parameter
LM 02, Bin 1, All Data	0.0086	0.3689	1.2067
LM 02, Bin 1, Upper 1%	0.0090	0.2507	0.8827

Table 5 shows the current velocity measured at Buoy LM 02, Bin 1 is estimated to be greater than the original design basis for maximum current velocity for 522 minutes each year or 557 hours since construction. This value is less than the value for LM 01, Bin 1 because the measurement was made in deeper water near the center of the ancient riverbed. The differential probability density for current direction in this location is shown in Figure 8. The current direction is rotated to the north by approximately 15-20 degrees compared to the data from LM 01, Bin 1. This difference is probably due to the influence of the ancient river channel on the overall Straits flow field but, since Line 5 is oriented at about 15^{o} true, this means that the flow tends to be nearly perpendicular to the pipe.

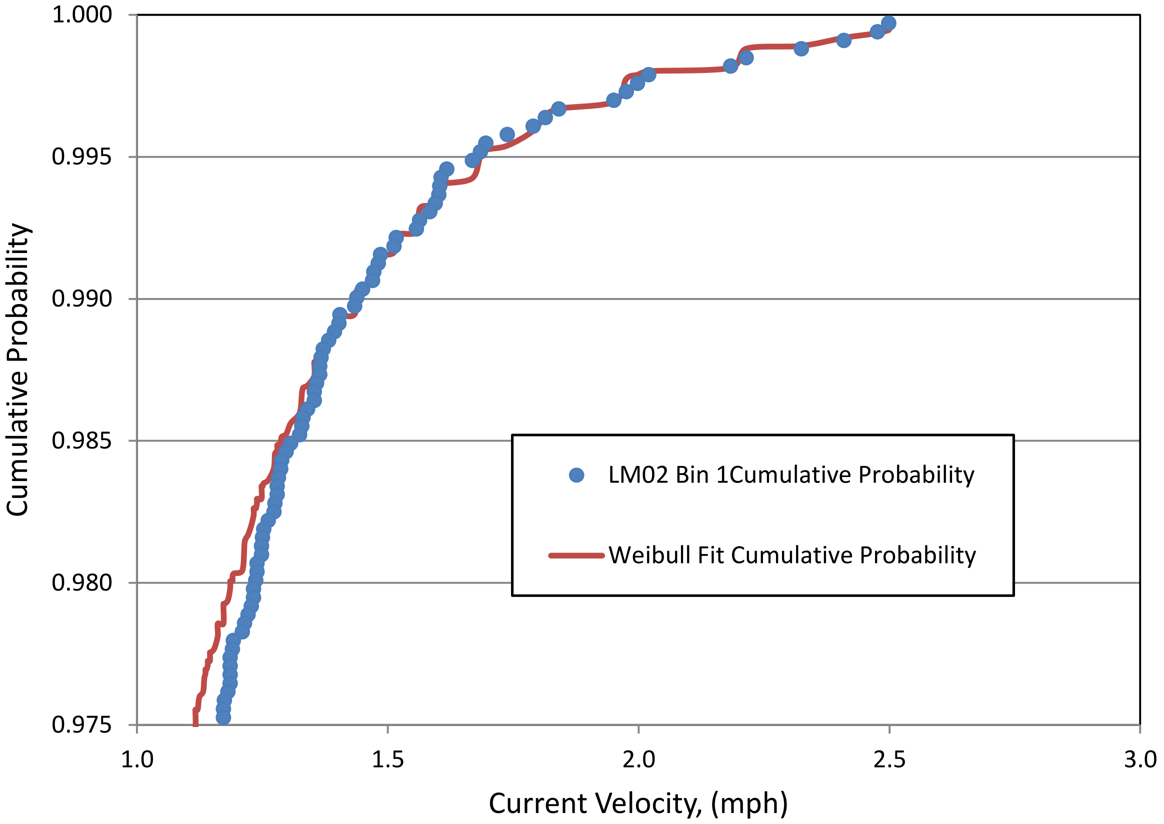


Figure 7. Data and Weibull Fit for the Cumulative Probability Density Function for Buoy LM 02, Bin 1, Upper 1% of Data

Table 5. Estimated Risk for Current Velocity Exceedances for Buoy Data Set LM 02, Bin 1

Current Velocity (mph)	Weibull Cumulative Probability	Tail Risk	Minutes per Year
0	0.0000%	100.0000%	525600
1	96.5422%	3.4578%	18174
2	99.8028%	0.1972%	1037
3	99.9866%	0.0134%	70
4	99.9990%	0.0010%	5
2.25	99.9006%	0.0994%	522

None of the above considerations serve address how the flow around Line 5 can vary in a short period of time. Figure 9 displays current velocity and direction during the ten hours before and after a peak current event. The current goes from a negligible velocity to a peak velocity of 2.0 mph towards the west in about 2.5 hours then drops to a negligible velocity and reaches a peak velocity of 2.5 mph towards the east in a subsequent 2.5 hour period before dropping to a negligible value in another three hours. Such a violent reversal of flow in such a large waterway is unprecedented in the author's experience and certainly has implication for the structural stability of this largely unsupported (except by erodible soil) pipeline.

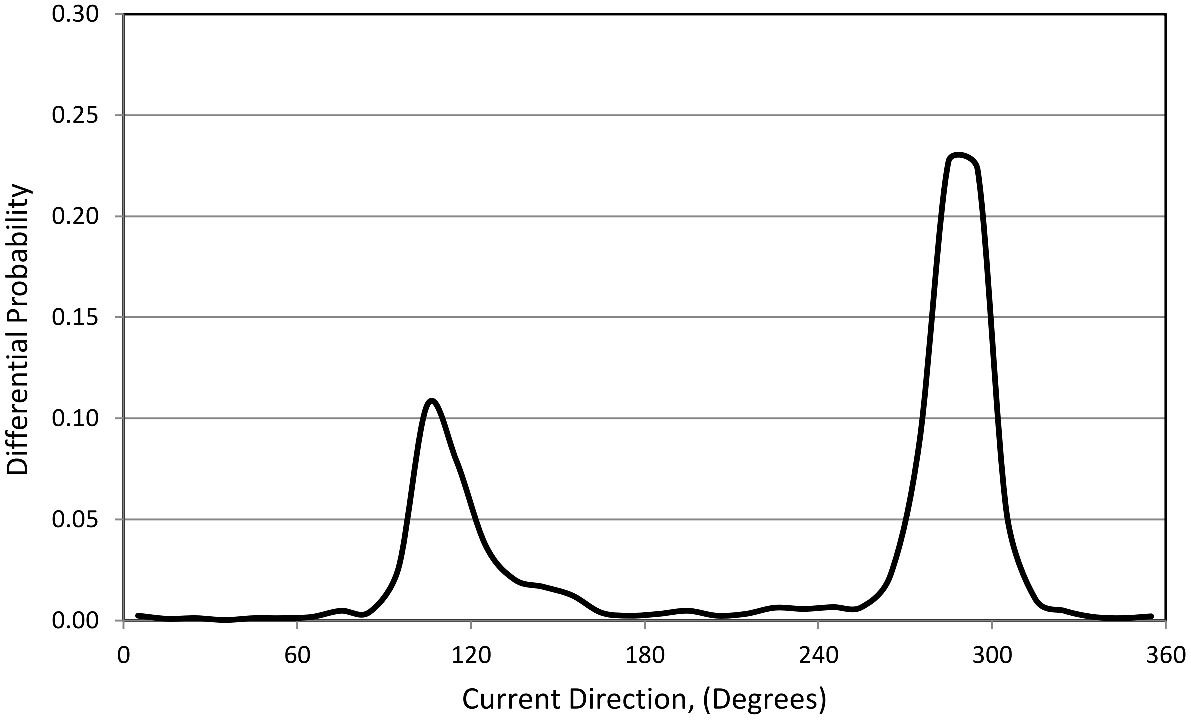


Figure 8. Differential Probability of Current Direction for Upper Quartile of Current Velocities for Buoy Data Set LM 02, Bin 1

Meadows Data, MTU, GLEC

NOAA Buoy 45175[15] is a part of the Great Lakes Observing System and is operated by Guy Meadows of the Great Lakes Research Center at Michigan Technological University. This buoy has collected data from 8/28/2015 through 10/27/16. Like LM 01 and LM 02, it is recovered during the winter because of ice formation in the Straits. The data abstracted from this data set for current measurements nearest the lake bottom comes from bin 27 and, because this buoy records data every ten minutes, consists of 22916 individual ten minute average measurements. The Buoy 45175, bin 27 data was analyzed similarly to the Saylor and Miller data sets. Figure 10, Figure 11 and Table 6 show the results of this analysis. Table 7 shows the current velocity measured at Buoy 45175, Bin 27 is estimated to be greater than the original design basis for maximum current velocity for 652 minutes each year or 695 hours since construction. Figure 12 again shows that these flows are primarily perpendicular to the pipeline, however, there is enough residual probability in non-perpendicular directions to indicate that flows along the length of the pipeline are not precluded.

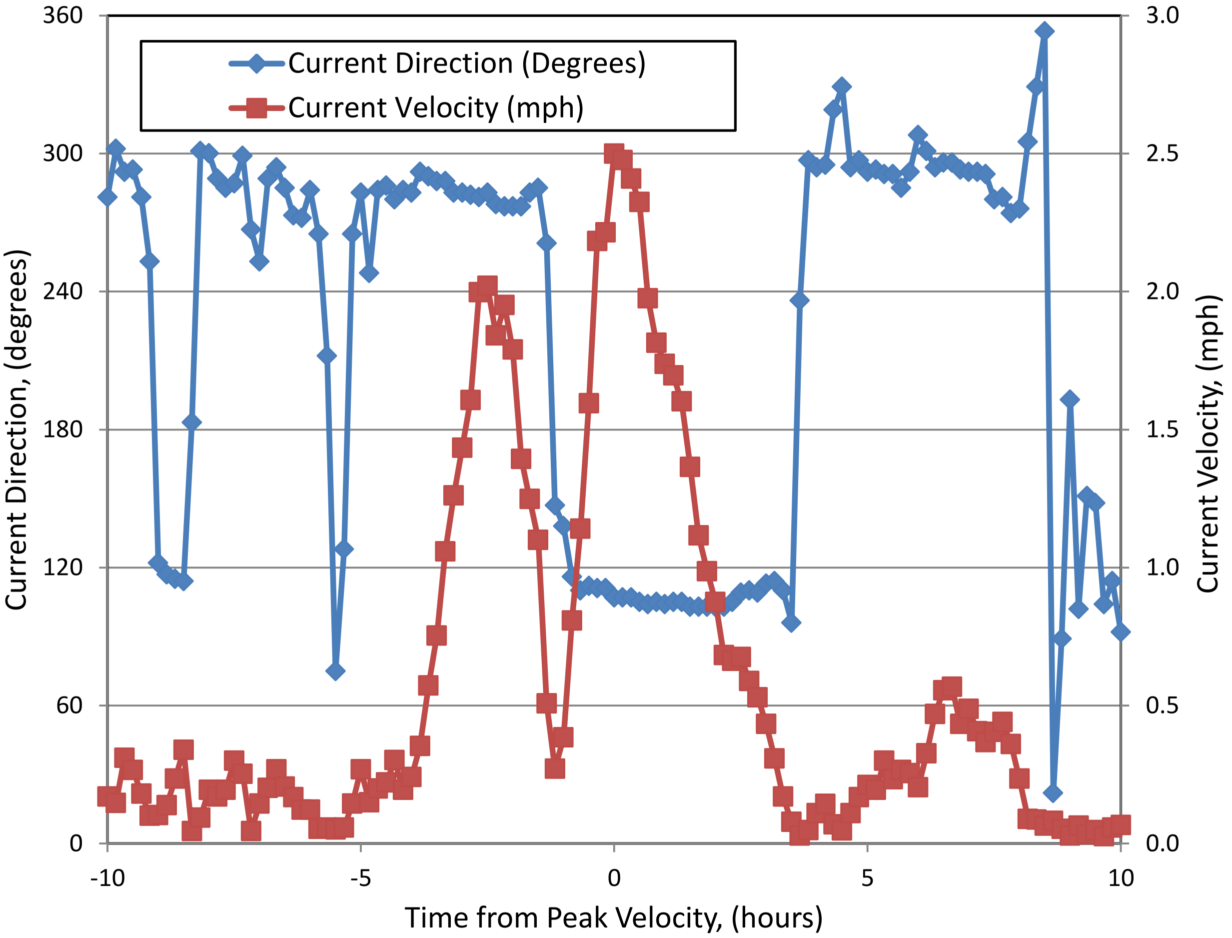


Figure 9. Current Velocity and Direction during a Peak Velocity Event for Buoy Data Set LM 02, Bin 1

Table 6. Weibull Fit Parameters for Current Velocity Data Set 45175, Bin 27

Fit Name	Weibull Offset Parameter, (mph)	Weibull Normalization Parameter, (mph)	Weibull Shape Parameter
LM 02, Bin 1, All Data	0.0201	0.3178	1.5358
LM 02, Bin 1, Upper 1%	0.7328	0.0016	0.2761

Table 7. Estimated Risk for Current Velocity Exceedances for Buoy Data Set 45175, Bin 27

Vtot, (mph)	Weibull Fit Cumulative Probability	Tail Risk	Minutes per Year
0	0.00000	1.0000E+00	525600
1	0.98413	1.5872E-02	8342
2	0.99828	1.7167E-03	902
3	0.99943	5.6611E-04	298
4	0.99974	2.5601E-04	135
5	0.99986	1.3598E-04	71
2.25	0.99876	1.2409E-03	652

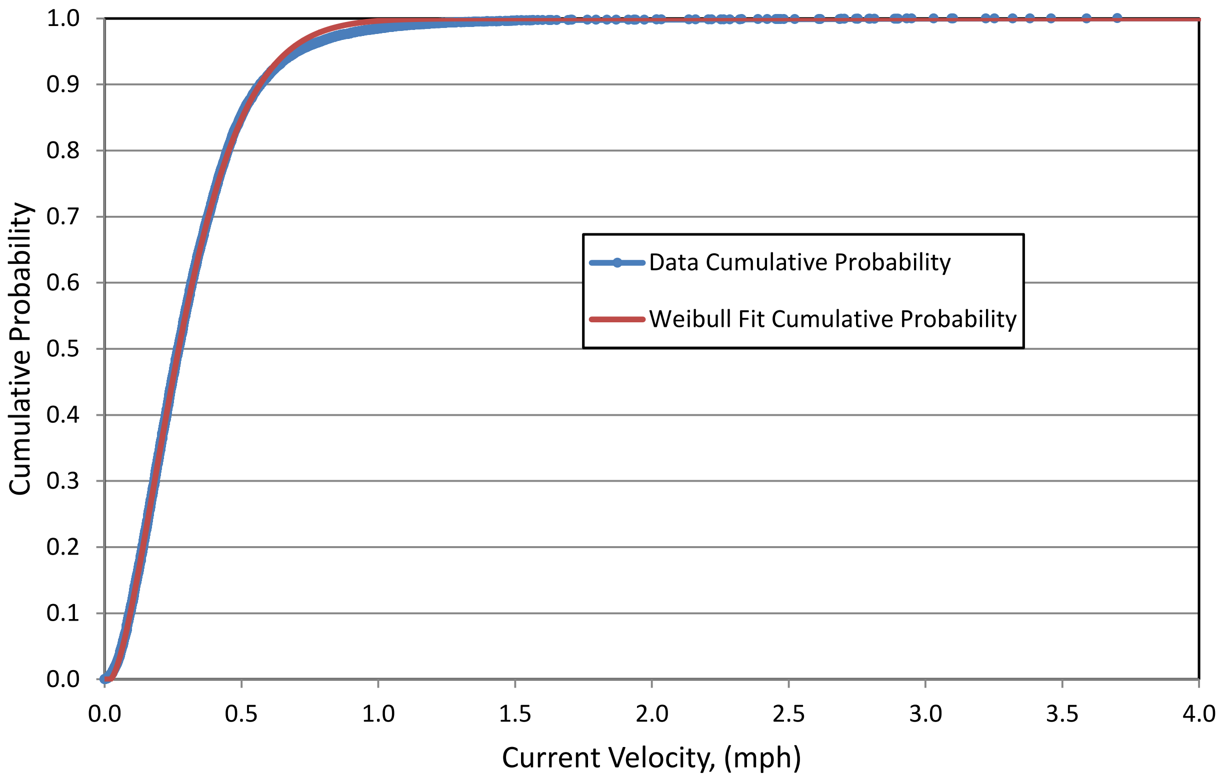


Figure 10. Data and Weibull Fit for the Cumulative Probability Density Function for Buoy 45175, Bin 27

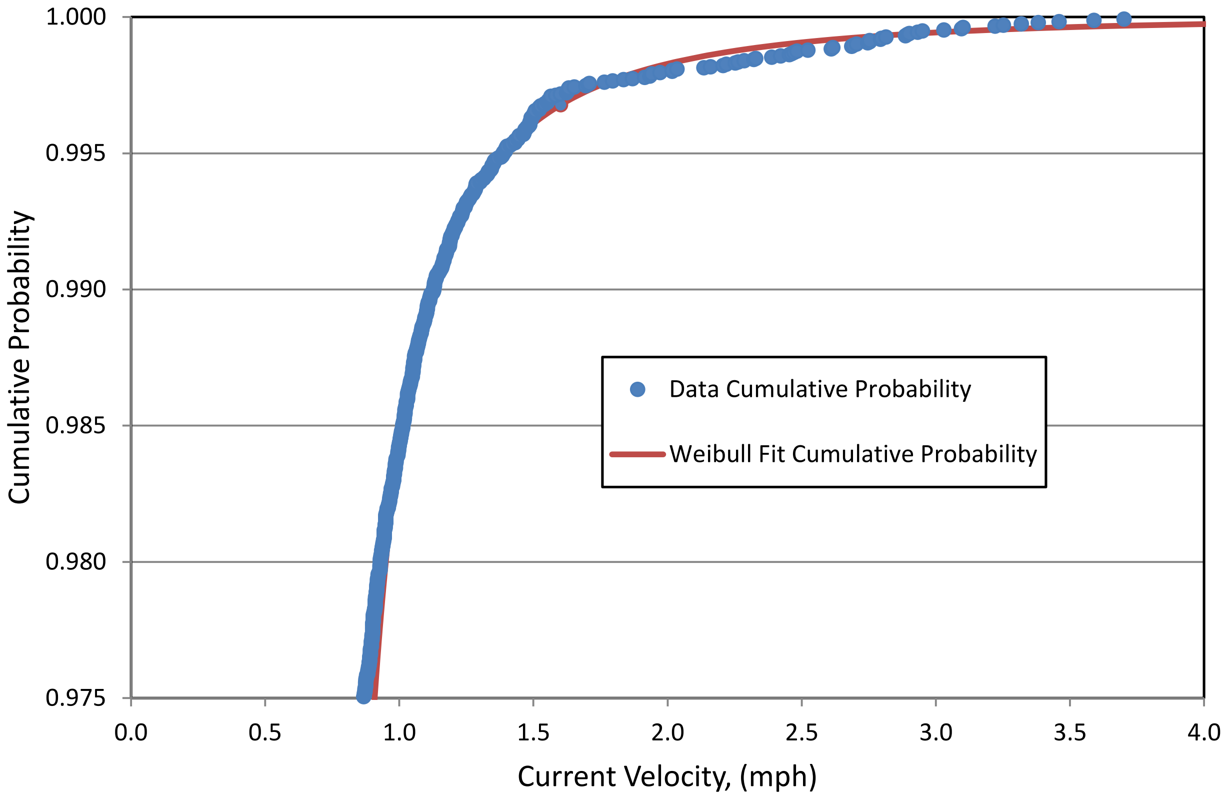


Figure 11. Data and Weibull Fit for the Cumulative Probability Density Function for Buoy 45175, Bin 27, Upper 1% of Data

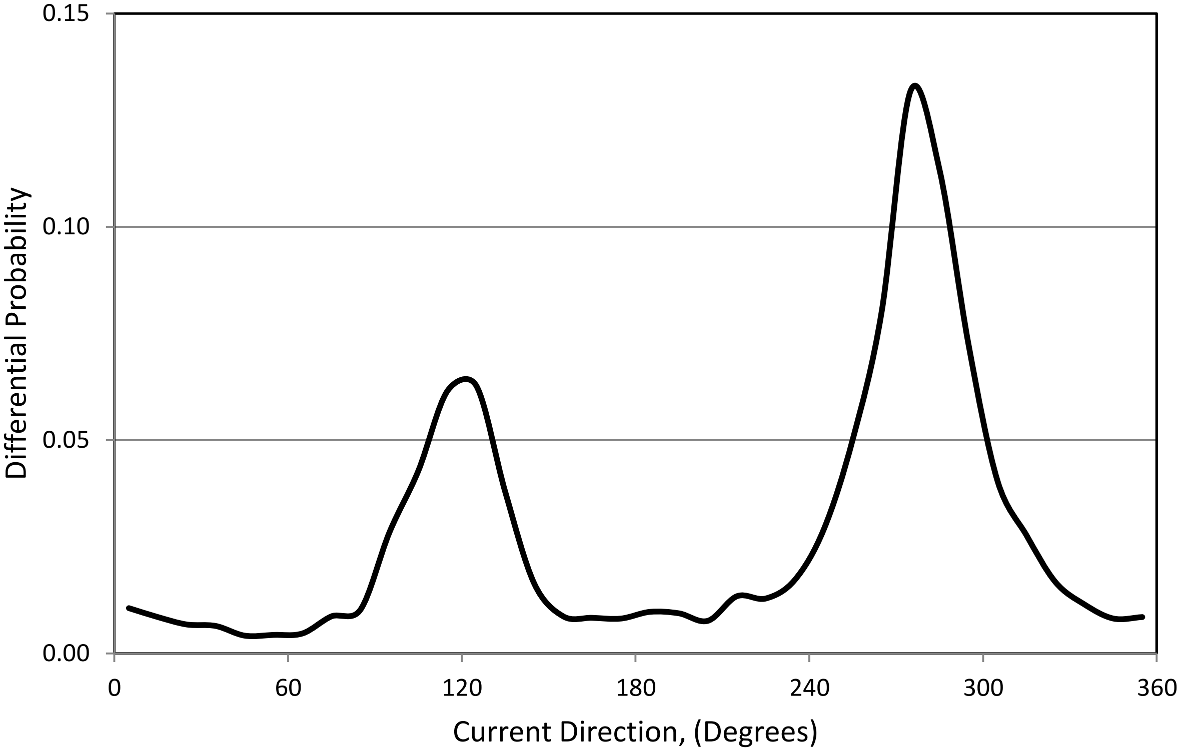


Figure 12. Differential Probability of Current Direction for Upper Quartile of Current Velocities for Buoy Data Set 45175, Bin 27

Anderson Data, NOAA, GLERL

NOAA Straits Buoy Data Set wh3748_2014_1S covers the period from 6/11/2014 through 5/21/2015 and the data from bin 1, the bin closest to the lake bottom, consists of 8246 observations including the only observations through the winter months. This buoy is located in deep water near the center of the ancient river bed but nearly two miles west of Line 5. This location is interesting because it is well past the “choke point” of minimum cross sectional area for the Straits unlike the other data discussed herein. Because Buoy wh3748_2014_1S is located closer to the open lake, current velocities would be expected to be lower than at the “choke point” locations previously discussed. This data set was analyzed following the procedures used for the other data considered in this study. Figures 13, 14, and 15 as well as Tables 8 and 9 display the result of this analysis.

Table 8. Weibull Fit Parameters for Current Velocity Data Set wh3748_2014_1S, Bin 1

Fit Name	Weibull Offset Parameter, (mph)	Weibull Normalization Parameter, (mph)	Weibull Shape Parameter
wh3748_2014_1S, Bin 1, Bin 1, All Data	0.0177	0.3646	1.2460
wh3748_2014_1S, Bin 1, Upper 1%	0.0000	0.6361	2.0248

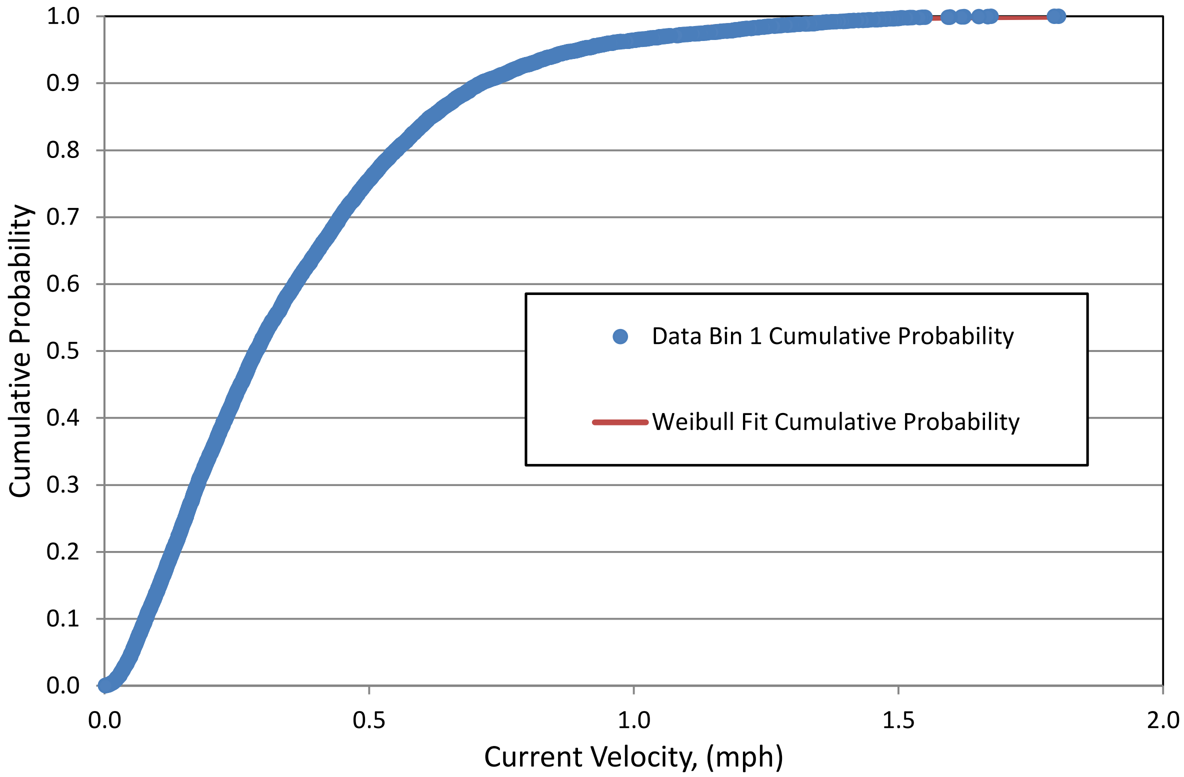


Figure 13. Data and Weibull Fit for the Cumulative Probability Density Function for Buoy wh3748_2014_1S, Bin 1

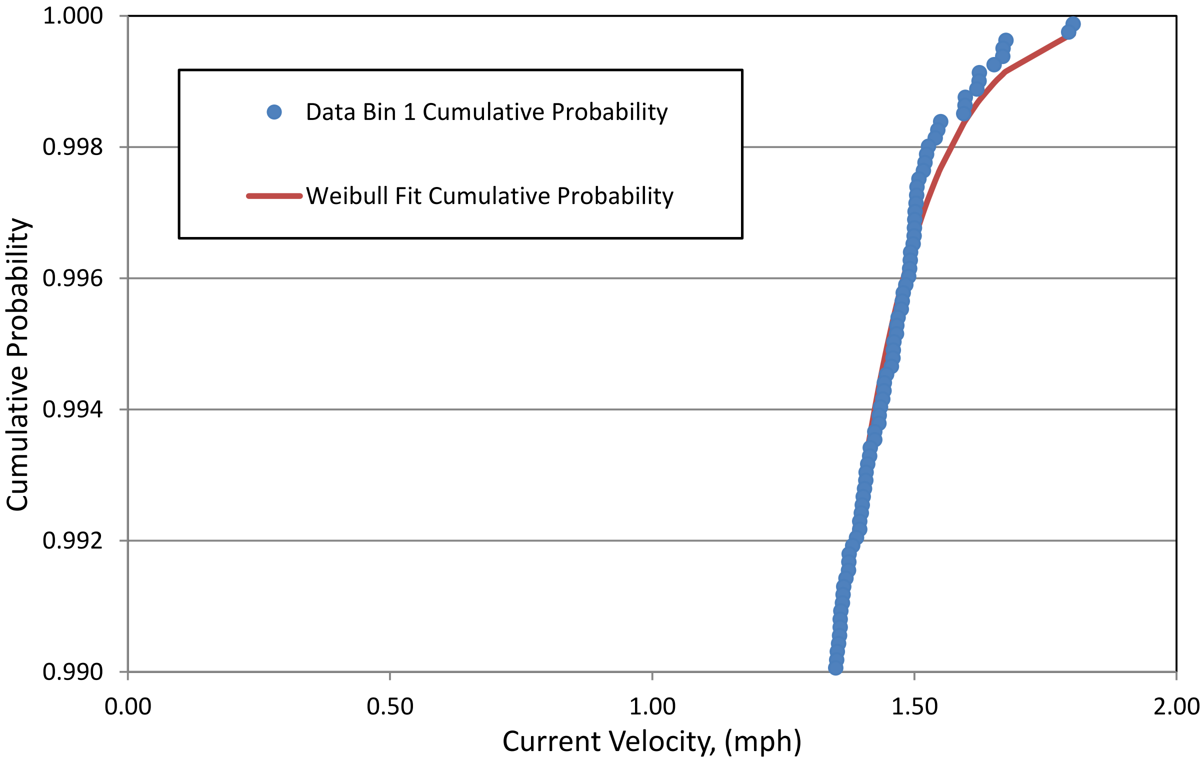


Figure 14. Data and Weibull Fit for the Cumulative Probability Density Function for Buoy wh3748_2014_1S, Bin 1, Upper 1% of Data

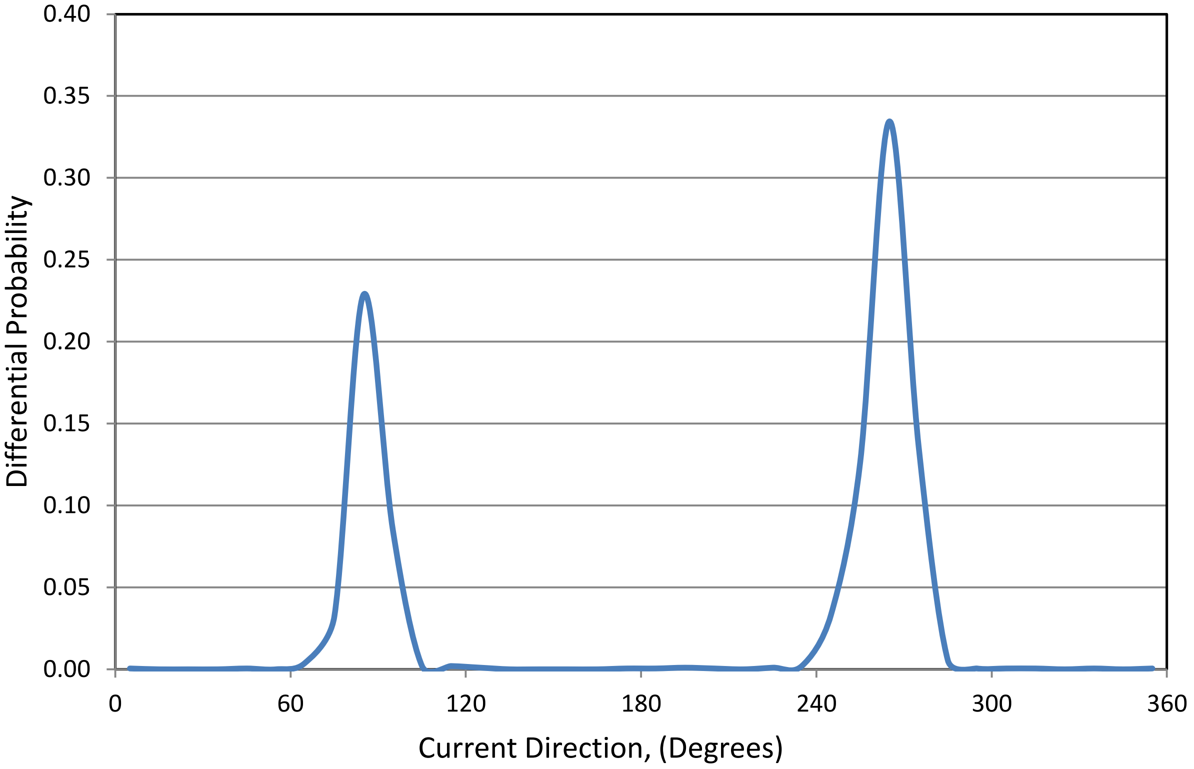


Figure 15. Differential Probability of Current Direction for Upper Quartile of Current Velocities for Buoy Data Set wh3748_2014_1S, Bin 1

Table 9. Estimated Risk for Current Velocity Exceedances for Buoy Data Set wh3748_2014_1S, Bin 1

Speed (mph)	Weibull Cumulative Probability	Tail Risk	Minutes per Year
0	0.0000%	100.00%	525600
1	91.7879%	8.2121%	43163
2	99.9962%	0.0038%	20
3	100.0000%	0.0000%	0
2.25	99.9998%	0.0002%	1.30

Compared to the data sets taken closer to Enbridge Line 5 which, understandably, crosses the Straits at its narrowest location, the amount of time the current velocity exceeds the design basis for the pipeline is much less. According to this analysis the total time this condition is met since the line was constructed is less than 2 hours which is statistically insignificant. Table 10 offers a comparison of this data with the other data sets analyzed in this study.

In the following fluid mechanical discussion, it is important to understand exactly what all these current velocity measurements are measuring. An ADCP determines the current velocity by measuring the Doppler shift of an emitted ultrasonic pulse that is reflected from particles and bubbles in the water column. Through a time of flight measurement the unit determines how far from the ultrasonic emitter the reflected pulse is. Combining this information with the beam angle allows the calculation of the depth from which the reflections come. A typical ADCP unit can be setup to “bin” the current information in a number of bins that represent the depth at which the current measurement is being made. Typically, an ADCP is set up with a number of bins, each representing a discrete range of current depths. Acoustic phenomena connected to the side lobes of the ultrasonic pulses prevent measurements directly at the surface or the bottom of a channel. Most ADCP's are set up with a “blanking distance”, typically two meters or more in depth, where no measurements are made.

Since each ultrasonic pulse results in an instantaneous measurement of current velocity that is somewhat imprecise, a number of pulses are averaged to get a meaningful signal to noise ratio. The current velocity numbers reported in this work are average current velocity over a significant time period and not instantaneous velocities. Not all of the studies examined in this work report this averaging time period. Anderson's buoy data set wh3748_2014_1S includes this information. This ADCP was set up to average the current velocities for 50 pulses or “pings” with a delay of 72 seconds between each ping group. Consequently, the current velocities reported by Anderson are average velocities over a one hour period. Similarly, the averaging period reported in Miller's work for buoy 45175 is reported to be 10 minutes. This information is not available for the work of Saylor and Miller but it is expected to be an average velocity over a time period that spans many minutes, most likely an hour.

Current velocities averaged over a significant time period are totally adequate for characterizing the bulk flow for hydrological purposes. When the subject of turbulence and the instantaneous drag on a submerged pipe is approached it must be understood that this data is an ensemble average for current velocity and not instantaneous data that can be used to characterize the turbulent flow field. Instantaneous data is best obtained using Laser Doppler Velocimetry (LDV) technology which is very difficult to operate in the field. In the following section of this report the nature of the flow field around the submerged spans of Enbridge Line 5 is discussed before attempting to calculate the effect this flow has on the structural integrity of the pipe. It should be noted from Table 10 that even these ensemble average current velocity measurements are above the design basis for current velocity for significant periods of time.

Table 10 Comparison of the Amount of Time the Current Velocity Exceeds the Design Basis of Enbridge Line 5 for all Buoy Data Sets

Data Set Name	Time Current Exceeds Design Basis, (min/yr)	Time Current Exceeds Design Basis Since Construction, (hr)
Buoy LM 01	818	873
Buoy LM 02	522	557
Buoy 45175	652	695
Buoy wh3748_2014_1S	1.3	1.4

The agreement between the current velocity design basis exceedances near the Straits choke point found in Table 10 appear to be consistent since these moorings are in waters of differing depths. The discussion of near bottom current data in the following section which concludes that this flow is turbulent in nature with large scale eddies that can be expected to flatten the current velocity profile during peak current events is consistent with the observations in Table 10.

Discussion of Near Bottom Current Data

The flow in natural rivers, streams and channels is classified as open channel flow by fluid mechanics professionals because the fluid in the channel has a free surface. Because of the large dimensions of such natural features, the Reynolds Number (Re) of these flow fields which is usually based on channel depth, is a very large number. Figure 16 is a plot of Re as a function of current speed for two channel depths. Reynolds numbers greater than ~7000 indicate that the flow in the channel will be turbulent instead of laminar. Clearly, the flow in any natural channel that is not microscopic is turbulent in nature. This fact has significant implications when the flow field around a pipeline is considered.

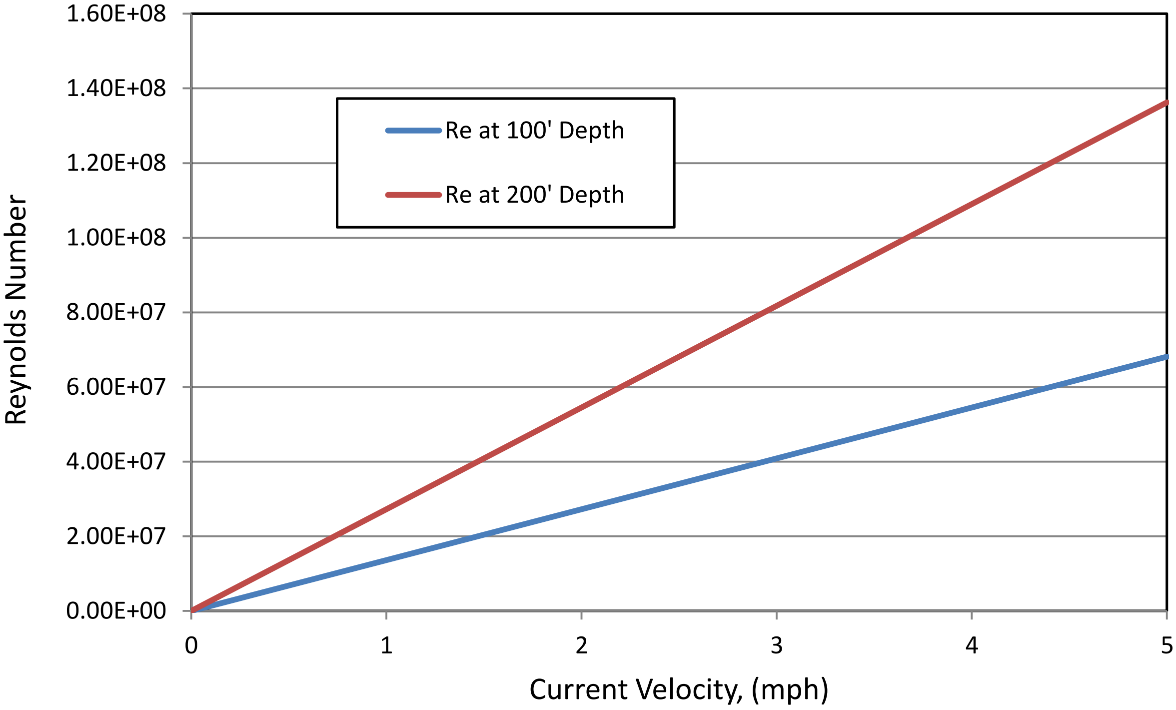


Figure 16. Reynolds Number for Flow in an Open Channel at 20^{o} Centigrade

The type of turbulence found in open channels is not classic fine scale Kolmogorov turbulence as is found in high velocity pipe flow. Rather, the turbulence found in these channels is called mesoscale turbulence and was first described by Matthes[16] in 1947. Matthes recognizes three types of turbulence as described by Edward J. Hickin of Simon Fraser University in unpublished course notes for a class entitled River Hydraulics and Channel Form. Quoting from these notes:

"(a) Rythmic and cyclic surges: the entire flow surges in response to waves in the flow and causes a shift in the mean velocity. These may be seasonal in nature, or related to storm events or to diurnal-scale processes. Included here might be surges related to choking or to the forming and reforming of hydraulic jumps (at relatively short timescales on the order of hours to minutes). These hourly to minute-long surges are very common in rivers although their cause often is very difficult to isolate.

(b) Continuous rotary motions, include separation eddies and von Karman vortex trails (or streets). Conventionally eddies have vertical axes of rotation while rollers have horizontal axes.

(c) Discontinuous or intermittent vortex action refers to the boils or 'kolks' commonly seen in the water surface of rivers. Vortices shed from the boundary reach the surface as eruptions (local water-surface elevation and outward spreading of flow). The origin of boils is not known although some (but not all) appear to be linked with the presence of dunes on the bed."

Not surprisingly, the previously cited references concerning flow in the Straits of Mackinac do not discuss the subject of turbulence and the computer models that describe this flow are bulk flow models averaged over time periods long enough that turbulent flow is not a factor. This observation is not intended as a criticism of these works because macroturbulence theory is not sufficiently developed to allow calculation of time dependent turbulence structures and, even if it was, the calculational capacity required to address the problem would require the largest of supercomputers.. Consequently, the following discussion will rely on data and empirical correlations to arrive at conclusions.

Van den Abeele and Vande Voorde[17] present a current approach to analyzing the stability of an offshore pipeline based on Morrison's equations. This computational approach requires software and computational capabilities that are beyond the resources of this author. Instead, this paper will use a similar approach to the methods used by the original designers of Line 5. In this approach, the drag force on the pipeline produced by the current will be added to the bending and pressure stresses imposed on the pipe resulting in a maximum stress that can be compared to the yield strength of the pipeline material. Calculating the drag force on the pipeline is done by the use of empirical drag coefficient (Cd) data and the current velocity data discussed previously. This drag coefficient data from Achenbach and Heinecke[18] is found in Figure 17 which is a reproduction of Achenbach and Heinecke's Figure 2.11.

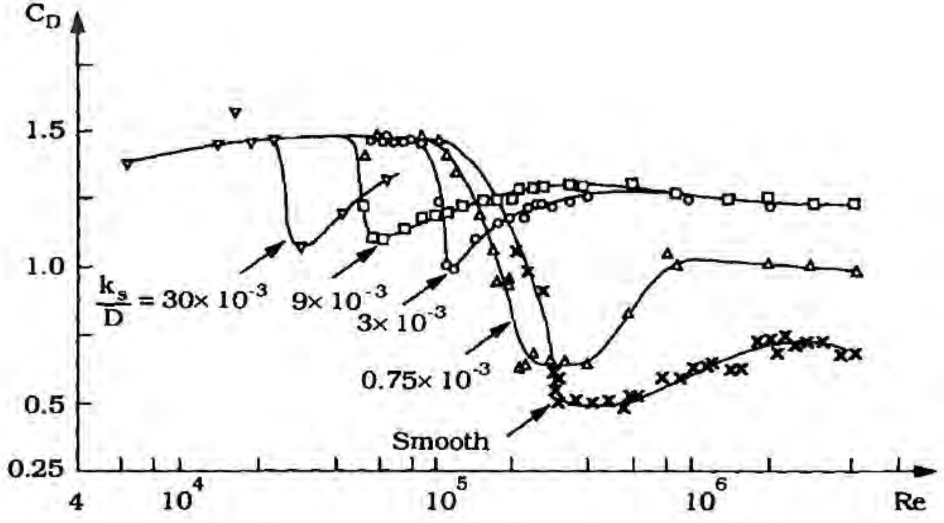


Figure 2.11 Drag coefficient of a circular cylinder at various surface roughness parameters k_s/D. Achenbach and Heinecke (1981).

Figure 17. Drag Coefficient Data from Achenbach and Heinecke

Drag coefficients determined from Figure 17 were based on a pipe diameter of 22 inches and a surface roughness of $30*10^{-3}$ which reflects a very rough pipe that is fouled with biota and sediment. The Reynolds numbers calculated for velocities in the range of interest range from 10^5 to 10^6, a range where the Cd's determined from Figure 17 are reliable.

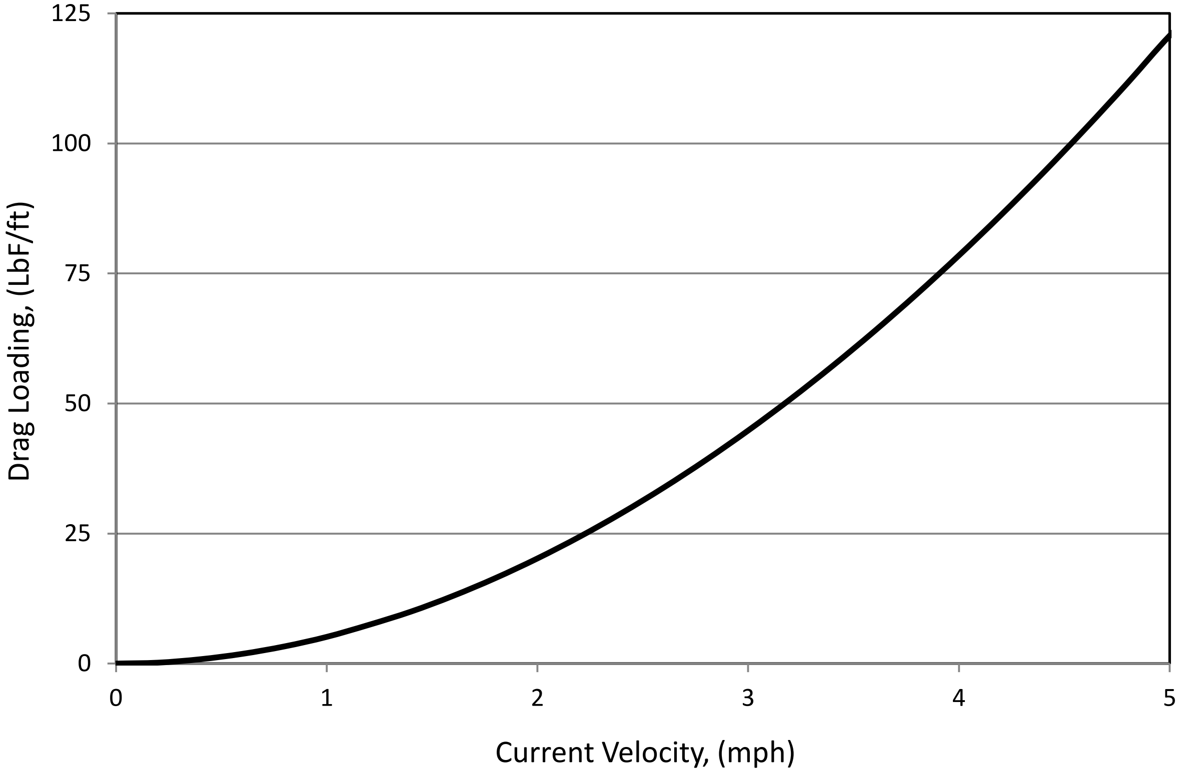


Figure 18. Drag Force on a Circular Cylinder with a 22 inch Diameter and a Surface Roughness of $30*10^{-3}$ at 10^0 C Water Temperature

Figure 17 applies to a cylinder in a free stream. Line 5 exists in a condition where it may be resting on the bottom or where an unsupported span may be many pipe diameters from the bottom. When the pipe is resting on the bottom, the flow around the pipe is stagnated and the drag force on the pipe results in a rolling moment on the pipe which induces a resisting torque. This situation was analyzed by Salvadori for velocities up to 2.25 mph and was found not problematic. Once the pipe is off the bottom, flow around the pipe results in a bending moment which must be considered together with the forces from internal pressure and gravity. Yang, Jeng, Gao and Wu[19] have analyzed the scenario where the pipe is supported at various distances from the lake bottom and found that if the pipe is further than about 80% of the pipe diameter from the bottom it acts as if it is in a free stream. The drag force values in Figure 18 are valid as long as this condition is met. When the pipe is closer to the lake bottom than 80% of the pipe diameter, the situation becomes complex and the drag forces may be either greater or lesser than those computed for Figure 18.

The drag forces shown in Figure 18 are almost instantaneous in their response to changes in current velocity. This, along with the facts that ADCP cannot measure the current within about two meters from the bottom and the velocities determined in the previous section of this report are long term averages and not instantaneous measurements, complicates using Figure 18 in a straightforward stress analysis to determine if structural limits are being approached. As a rough approximation, the drag force on the pipe is equal to the gravitational force on the pipe at a current velocity of 5.5 mph.

ADCP's measure the current velocity throughout the water column except for near the top and bottom. The water depth and distance from the lake bottom for the data previously analyzed is contained in Table 11.

Table 11. Water Depths and Distance from Lake Bottom for ADCP Data

Data Set Name	Water Depth, (ft)	Depth to Centerline of Lowest Data Bin, (ft)	Distance from Bin Centerline to Bottom, (ft)
Buoy LM 01	115	105	10
Buoy LM 02	215	200	15
Buoy 45175	~120	102	~15
Buoy wh3748_2014_1S	242	219	23

Enbridge Line 5 mostly rests on the lake bottom. However, as explained in Appendix 1, several unsupported spans were left from the original construction or developed later due to bottom scouring or "washout". Figure 19 is a photograph taken from Enbridge's 2012 underwater inspection video that illustrates an unsupported span on the east leg near the south side of the ancient river bed that runs through the Straits. Although it is hard to exactly determine the distance from the pipe to the lake bottom it appears to be on the order of ten to fifteen feet. It also appears in this photo that the bottom is scoured clean of sediment since the marks left in the hardpan clay bottom by the teeth of the clamshell dredge used to level this area during construction in 1953 are still prominent.

Figure 19. Photo of Unsupported Span Clipped from Enbridge Underwater Inspection Video from the 2012 Inspection (East Leg, ~203 feet water depth)

Figure 20 is the velocity profile taken from buoy data set LM 02 during a peak current event. This velocity profile is a long term average as previously discussed and it shows the velocity at the lowest bin to be about 89% of the maximum velocities found at mid-depth. Since the lowest bin data is typically somewhat above the location of the pipe, a question remains regarding what the actual instantaneous velocity is in the immediate vicinity of the pipe.

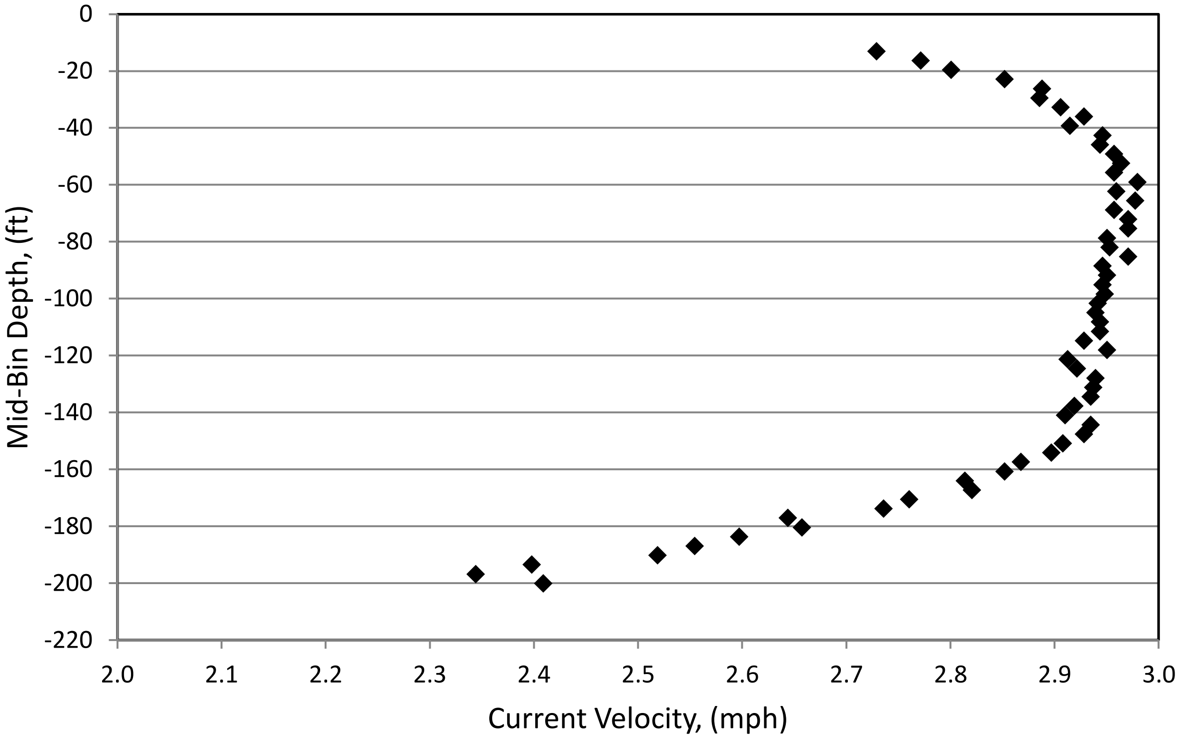


Figure 20. Velocity Profile Taken from Buoy Data Set LM 02 at the Time of a Peak Current Event.

The turbulent eddies that characterize mesoscale turbulence can range in size from centimeters to hundreds of kilometers. The Gulf Stream in the Gulf of Mexico is an example of very large mesoscale turbulent eddies. Since all the available data for current velocities in the Straits of Mackinac are long term averages, there is little direct evidence for mesoscale turbulence in the location of Enbridge Line 5.

Figure 21 shows the correlation of current direction and current velocity during a peak current event for buoy data set 45175. The ten minute average data shows a peak current of over four mph moving towards the north. This direction is nearly perpendicular to the axis of the Straits of Mackinac and generally along the axis of Line 5. That this event lasts for about ten hours argues for the existence of a large scale, persistent mesoturbulent eddy.

ADCP units are also capable of measuring z axis or vertical flows. Figure 22 is a scatter plot of vertical current velocity as a function of planar current velocity for the entirety of bin 1 data from buoy wh3748_2014_1S. The very low vertical current velocities measured at this location are at the limit of resolution for ADCP technology and generally do not show a significant correlation of vertical current velocity with planar current velocity.

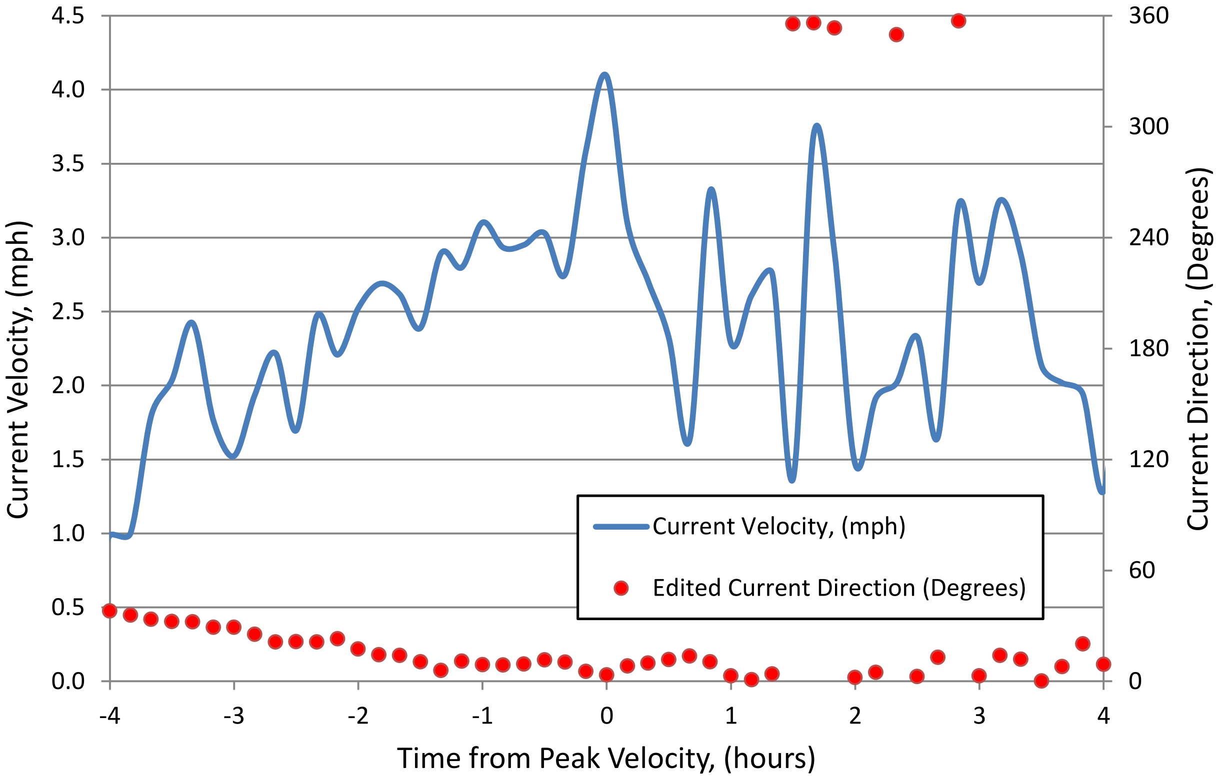


Figure 21. Correlation of Current Velocity and Current Direction During a Peak Current Event for Buoy Data Set 45175

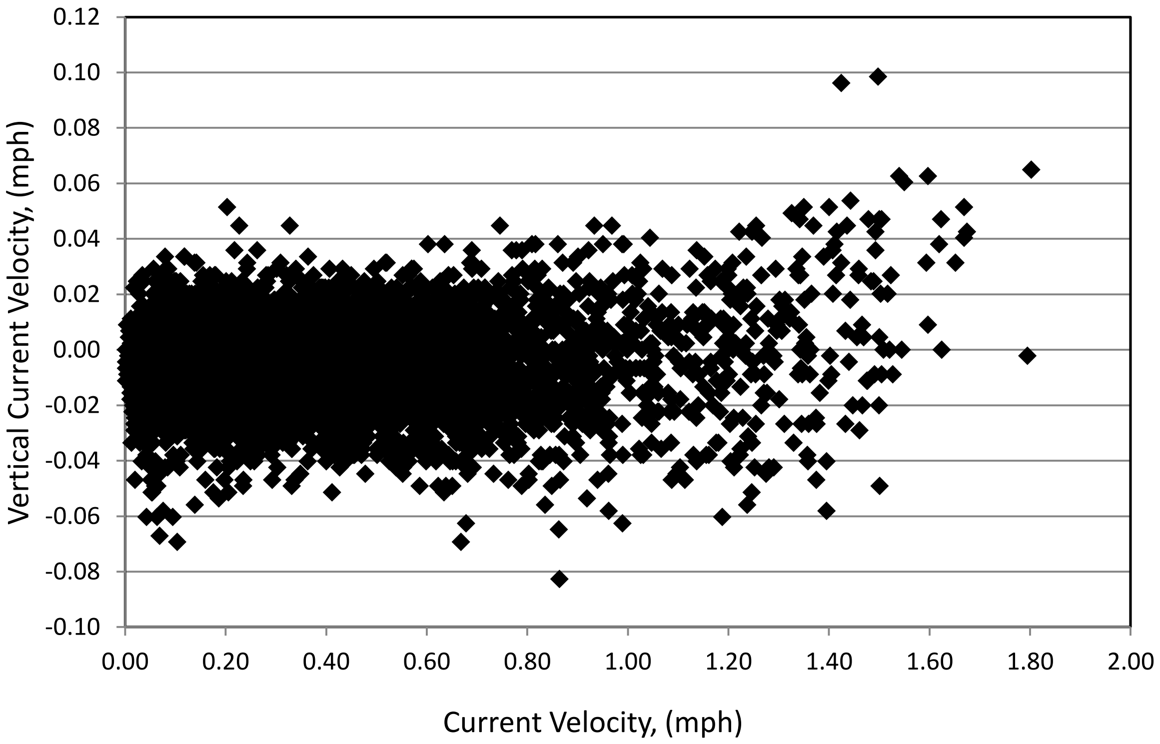


Figure 22. Scatter Plot Correlating Planar Current Velocity with Vertical Current Velocity for Buoy wh3748_2014_1S, Bin 1

Figure 23 is a scatter plot of vertical current velocity as a function of planar current velocity for the entirety of bin 1 data from buoy 45175. This plot shows a bifurcated correlation between vertical current velocity and the planer current velocity in this location. Although this vertical current velocity data is also at the limit of ADCP resolution, the correlation is significant because of the thousands of data points represented.

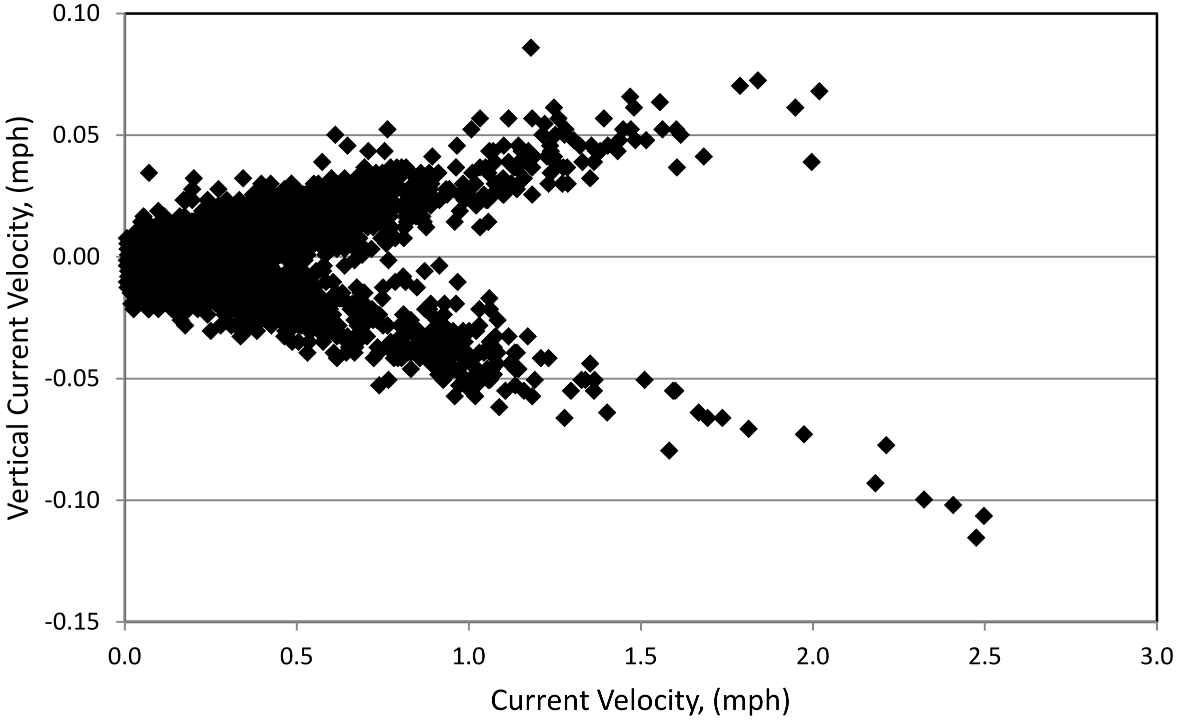


Figure 23. Scatter Plot Correlating Planar Current Velocity with Vertical Current Velocity for Buoy LM 02, Bin 1

The data in Figure 23 again argues for the existence of mesoscale turbulent eddies in the vicinity of Line 5. Buoy 45175 is located near the choke point of the Straits where the flow velocity is significantly greater than that taken where the Straits opens out at the location of buoy wh3748_2014_1S. It is probable that the change in current velocity as the bulk flow through the Straits accelerates or decelerates to maintain continuity as it approaches the choke point, initiates mesoscale turbulence with large scale three dimensional eddy structures that make the flow in the Straits far from an isopotential flow field. This finding is to be expected and is similar to the flow where Lake Huron empties into the St. Clair River creating a violent mesoscale turbulent flow field at the entrance to the river. Flow in this location has many of the features mentioned by Hickin previously.

A literature search has not revealed many references that investigate the peak-to-mean turbulence intensity in mesoscale turbulent eddies. This is an area of developing science and the literature is sparse to say the least. Thompson, et al[20] studied mesoscale turbulence at potential locations for tidal power turbines in two locations in Puget Sound on the five minute time scale. Figure 24 is taken from this work and provides experimental data about mesoscale turbulence intensity at two locations on Puget Sound, WA. Each data point is a set of instantaneous current velocity measurements taken over a 5 minute period and normalized by procedures discussed in Thompson's paper to give a fractional turbulence intensity.

Interestingly, a current velocity of 1 meter/second converts to 2.24 mph which is very close to the design basis for Line 5. At this current velocity the turbulence intensity is typically 10% although there are a significant number of data points up to 20% at the more turbulent Admiralty Head Location. At higher flow velocities ca. 4-5 mph, most of the data shows turbulence intensities less than 15% . It should be noted that because the drag force on the pipe is proportional to the velocity squared, a 15% velocity fluctuation results in a 22.5% drag force fluctuation.

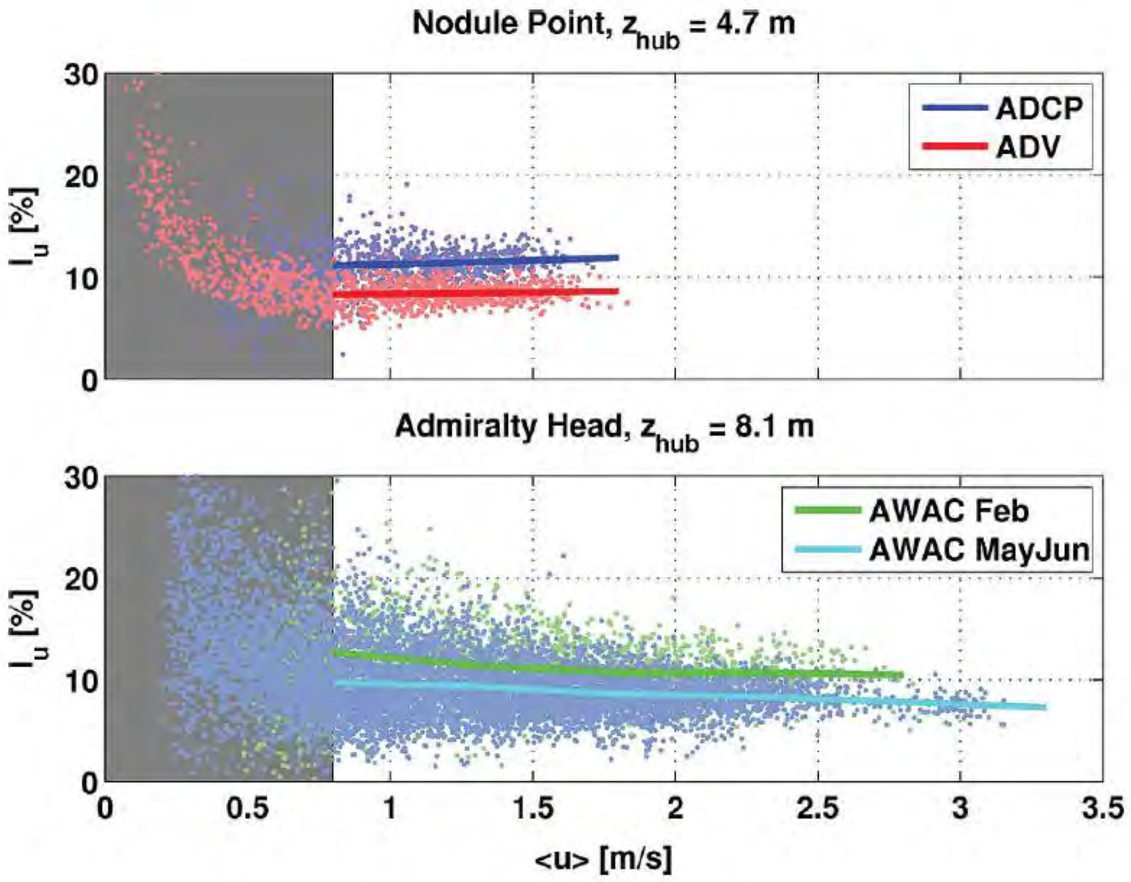


Figure 24. Fractional Turbulence Intensity of Horizontal Motion as a Function of length scale at Nodule Point and Admiralty Head. Thin Lines are Individual 5 Minute Records and Thick Lines are Non-Slack Averages.

Figure 25 is also taken from Thompson's work and shows the fractional turbulence intensity of horizontal motion as a function of length scale at Nodule Point and Admiralty Head. Although the turbulent eddies found in this mesoscale turbulence have a very broad wavelength spectrum, the spectrums show peaks at about 50 m (164 ft) at Nodule Point and 150 m (492 ft) at Admiralty Head. At the design specification current velocity for Line 5 which is close to 1 m/s these values correspond to turbulent fluctuation frequencies of 0.02 Hz to 0.0067 Hz. An average value for turbulent fluctuation frequency is 0.01 Hz.

A characteristic of flow around bluff bodies is the formation of a vortex street on the downstream side of the pipe. This vortex shedding results in transverse forces on the pipe as illustrated in Figure 26. Pipeline vibration causing metal fatigue is a factor in pipeline failures.

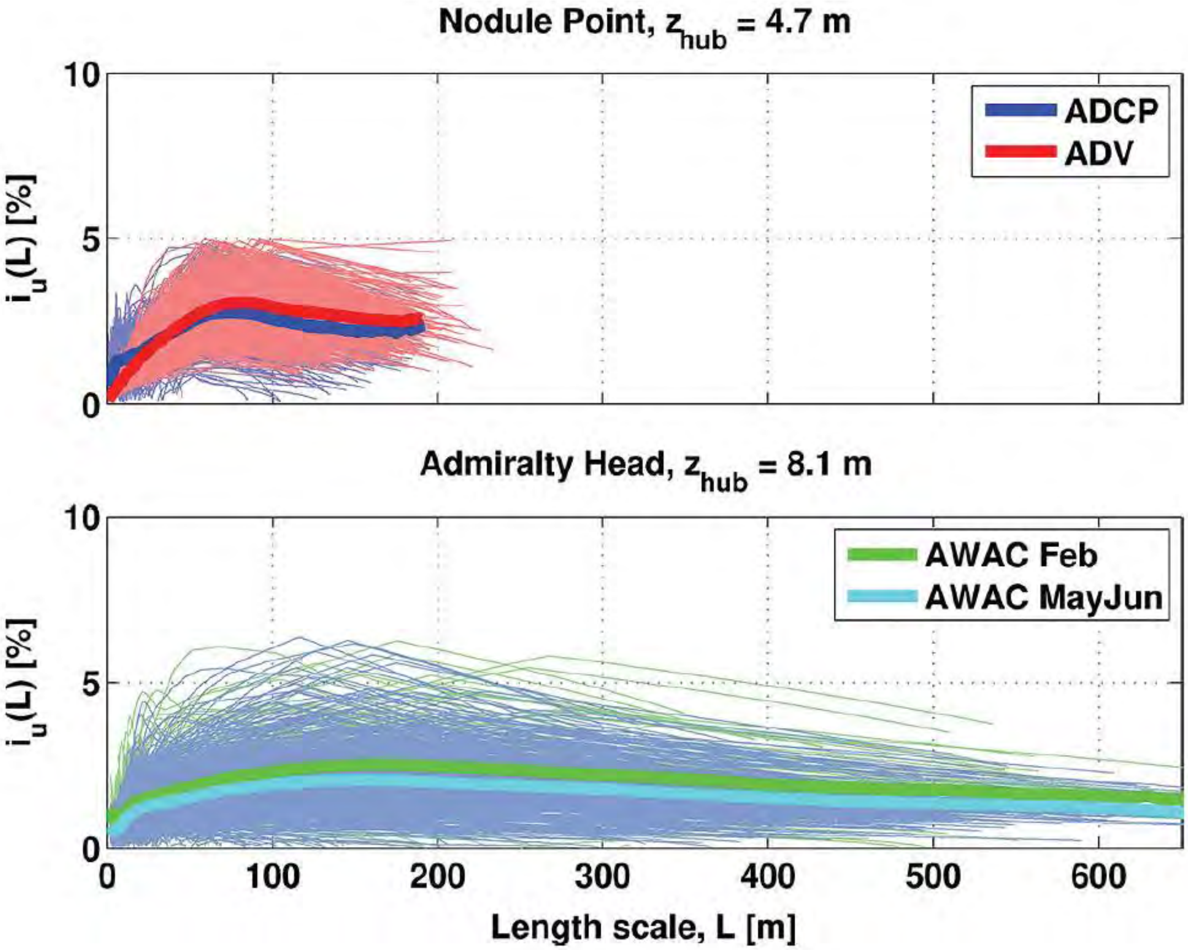


Figure 25. Fractional Turbulence Intensity of Horizontal Motion as a Function of Length Scale at Nodule Point and Admiralty Head. Thin Lines are Individual 5 Minute Records and Thick Lines are Non-Slack Averages

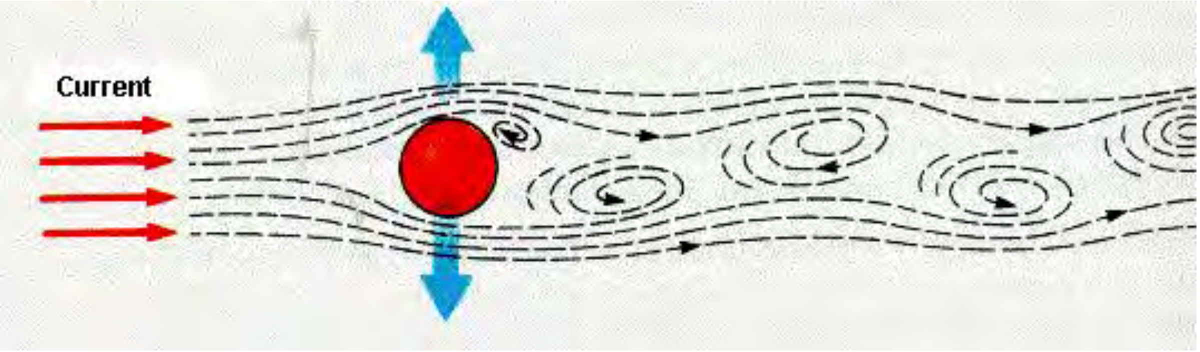


Figure 26. Drawing of Fluid Flow Induced Transverse Forces on a Pipeline due to Vortex Shedding

In October, 2012 ExxonMobil's Silvertip pipeline completely ruptured where it crosses the Yellowstone River and released 1500 barrels of crude oil into the waterway. The PHMSA investigation[21] concluded that the cause was girth weld failure due to metal fatigue caused by vortex shedding induced vibration. Quoting from this report:

"The pipeline failed at a girth weld as a result of the effects of external loading that occurred due to exposure to flood conditions. The failure mechanism was fatigue crack growth adjacent to a girth weld, followed by ductile fracture of the remaining section due to tensile overload. The fatigue crack that precipitated the failure originated at the interior of the pipe adjacent to the weld root bead at the bottom of the pipe. A second, smaller fatigue crack originating adjacent to the root bead in the top quadrant of the pipe was present on the fracture surface. A fatigue crack was also discovered in the first downstream girth weld. The cracks initiated and grew by fatigue due to vortex-induced vibration (VIV) of the exposed pipe in the river current. The final fracture occurred due to tensile overload of the remaining uncracked pipe section."

Figure 27 is a correlation plot of dimensionless vortex shedding frequency (Strouhal Number) as a function of dimensionless flow velocity (Reynolds Number) taken from Achenbach and Heinecke.[18] Data taken from this plot will be used to calculate the vortex shedding frequency for Line 5. These calculations use a surface roughness value of 30*10-3 as was used for the previously discussed drag coefficient (Cd) information taken from the same reference. It should be noted that in the current velocity region of interest, the Reynolds number is in the range of 10^5 to 10^6. In this region, the vortex shedding frequency is not a single value but can be thought of as the center of a power density spectrum.

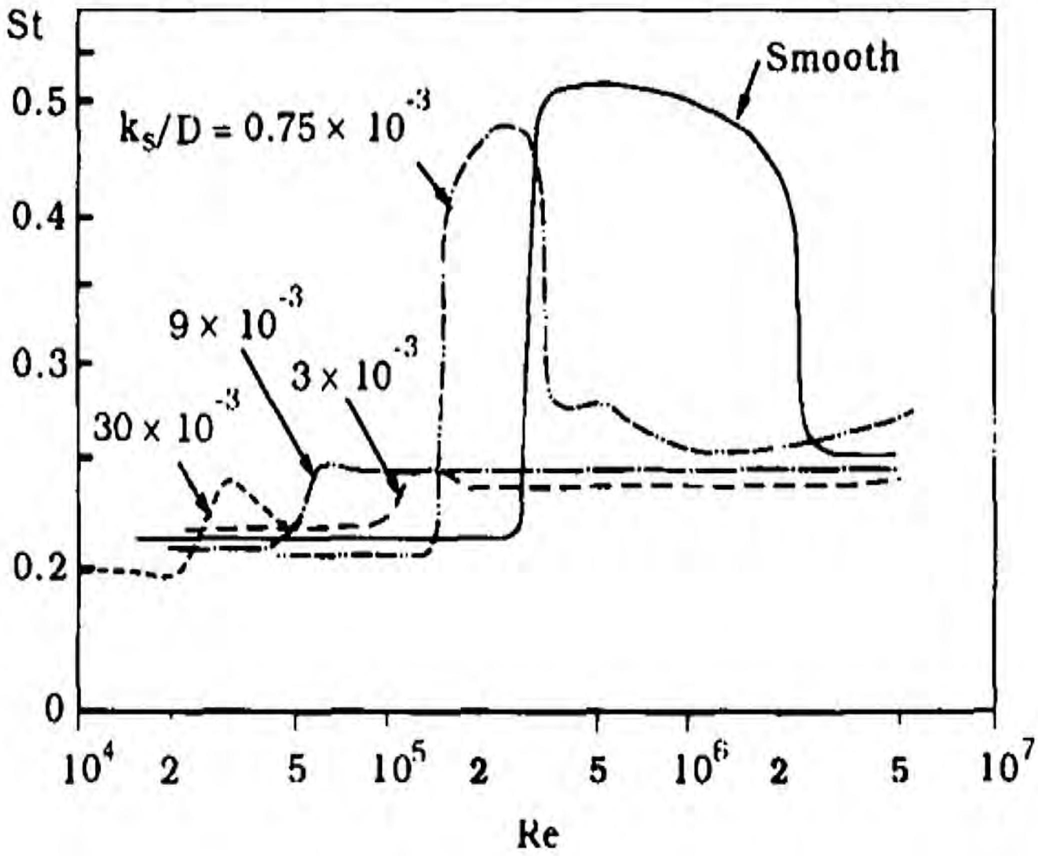


Figure 27. Correlation Plot of Strouhal Number as a Function of Reynolds Number

Current Caused Stresses on Enbridge Line 5

The intent of this section is to draw conclusions whether or not Line 5 has ever been stressed to beyond its yield strength and, if so, how many fatigue cycles may have accumulated in unsupported spans. Three cases will be considered and each will be evaluated using the current data from the three buoys closest to Line 5.

1. The effect of reversing bulk flow currents,
2. The effect of mesoscale turbulence during peak flow events,
3. The possibility of vortex shedding lock-in resulting in the accumulation of many fatigue cycles during peak flow events.

Construction Background

Before consideration of the above subjects it is necessary to discuss some aspects of the construction of Enbridge Line 5. Like any pioneering large scale construction project, the construction of Line 5 was problematic. As noted in Appendix 1, the Michigan Petroleum Pipeline Task Force concluded in its final report[22] that further study was required. This led to the formation of the Michigan Pipeline Safety Advisory Board and the release of a great deal of historical documentation about the construction of the pipeline. A full discussion of this documentation is beyond the scope of this text, but it includes as built blueprints, construction logs, dredging logs, inspection reports, dive reports and other historical information. A thorough reading of all this material as well as discussions with Bruce Trudgen, a young engineer who worked on the project as a surveyor had resulted in the following conclusions about the construction of Line 5. Of particular importance is an article written by Trudgen[23] in 1954. The following conclusions are based on all publically available documentation.

1. The design intent was to bury the pipeline on both sides of the Straits where it is in water less than 65 feet in depth to protect from ice damage and anchor strikes. In deeper water, the intent was to prepare a smooth “bed” that would provide continuous support for the line as it was placed on the bottom. In fact, it was recognized that the topography of the Straits bottomlands and the variety of soils and rocks encountered in the path of the pipeline would not allow for a perfectly flat pipeline bed and that unsupported spans would occur because of dredging and filling problems. The easement[3] granted by the State of Michigan mandated that unsupported spans up to 75 feet in length were considered acceptable and in an engineering analysis[7] it was concluded that unsupported spans of over 140 feet were likely to be structurally unstable. These unsupported span distances were set before the line became encrusted with mussels, sediment and algae which increase the gravitational and drag loading.

2. One specification set forth the in the easement was that “The minimum curvature of any section of pipe shall be no less than two thousand and fifty (2,050) foot radius.” This specification was stricter that the one recommended by Salvadori in his engineering analysis where he recommended a minimum radius of curvature of 1750 feet. Calculation shows that the outer fiber of the pipe will reach yield at a radius of 690 feet. Both of these specifications were intended to prevent the welded pipe strings from being bent to a radius that would cause yielding and the accumulation of fatigue cycles during the pipe laying process. Figure 28 uses a photograph taken by Bruce Trudgen in 1953 that shows the pipe being pulled from the St. Ignace shoreline during the launching process. By carefully scaling the photo, it is clear that the pipe was yielded during launch by bending to a radius of curvature of ~300 feet. More importantly, as Trudgen mentions in his Spartan Engineer[23] article, the 2500 foot welded pipe

strings were moved around in the marshalling yard without respect to the 1750 foot radius limit. During a personal discussion with the author he mentioned that the operation where the pipe strings were moved onto the launch way by running a “shoe” suspended from a crane down the length of the string “bent the hell out of the pipe.” A black and white photograph of this operation is shown as Figure 29. Additional discussion focused on problems with the pipe pulling operation where the pipe strings were pulled across the Straits in 2500 foot increments as they were welded revealed other opportunities for yielding. It is also clear from the as-built blueprints discussed in Appendix 1 that the bed prepared for the pipeline had significant discontinuities causing the pipe to be yielded into place in several locations. In some areas clay fill was used to fill these discontinuities and some of it appears to have been placed after the pipe was yielded into place in order to meet easement support requirements. Figure 30 is an example of one of these clay piles taken from Enbridge’s 2012 underwater inspection video and it does not appear as if the clay piled on top of the pipe was placed after the clay under the pipe. What actually went on regarding the fifteen clay piles placed under the west leg of the pipe and the seven clay piles placed under the east leg of the pipe is lost to history and adds uncertainty about the yielding history in the segments of the pipe supported by these clay piles. It does appear as if several of these clay piles violate restriction (13) in the easement: “(13) In locations where fill is used, the top of the fill shall be no less than fifty (50) feet wide”.

Calculation of Radius of Curvature During Line 5 Straits Pipelaying Operation

Image, Bruce Trugen 000010370007.tif Taken summer, 1953

Figure 28. Estimation of Radius of Curvature During the Pipe Laying Operation in 1953 Figure 28. Estimation of Radius of Curvature During the Pipe Laying Operation in 1953

Figure 29. 1953 Photograph Showing Curvature of Pipe String as it is Moved onto the Launch Way Using a Crane

3. Appendix 1 discusses the history of Line 5 unsupported spans. Because the referenced as built drawings were traced in1964 from an original Bechtel, Inc. drawing from 1963 and updated after 1972, 1975 and 1979 underwater inspections, they are the best references available about unsupported spans dating from the construction of Line 5. It appears from consideration of this document that that two 150 foot unsupported spans and one 160 foot unsupported span existed from the date of construction until Enbridge started shoring up Line 5 using screw anchor supports in 2001. It is unlikely the grout filled canvas bags employed in early efforts to support the pipe were effective,

Much of the remainder of this section regarding current caused stresses and fatigue of Line 5 will focus on these spans which are in excess of Salvadori's considered guidance.

The Effect of Reversing Bulk Flow Currents

Figure 9, showing data from buoy data set LM 02, shows an event where the current goes from slack water, to a maximum of 2 mph towards the east, to slack water, to a maximum of 2.5 mph towards the west and back to slack water in an eight hour period. Events like this offer the possibility of yielding the pipe in one direction then, shortly later, yielding the pipe in the opposite direction. Figure 31 shows the maximum combined stress for line 5 based on a publication by Vakharia and Farook[25] and drag coefficient data from reference 18. Longitudinal stresses are not included since they are not known. Input data for this calculation include:

1. Pipe is seamless, schedule 60, 20 inch diameter made from X35 steel with < 0.25% C in hot formed condition.
2. Pipe is filled with Enbridge type CNS synthetic light crude oil, has a ¼" thick protective coating and is fouled with a 2" layer of biofouling giving an immersed weight of 172.5 lbf/foot.
3. The gauge pressure in the pipe is 500 psi which becomes a 400 psi differential pressure at a depth of about 200 feet. This value is a typical maximum operating pressures and well below the allowed 600 psi MAOP.

Figure 30. Frame Grab from Enbridge 2012 Underwater Inspection Video[24] of the East Leg of Line 5 under the Straits of Mackinac Depicting a Clay Pile

Figure 31 shows the maximum combined stress from pressure, gravitational and drag forces as a function of current velocity. Up to about the design specification current velocity (2.25 mph), the current has little effect on combined stress. X35 steel has a specification yield stress of 35,000 lb/in^2. At the easement specified minimum unsupported span of 75', the structure has a safety margin of ~three compared to the yield strength of the steel. At Salvadori's recommended maximum unsupported span of 140 the design is at 75% of the yield strength which is greater than the ASME B31.4 code requirement of 72% maximum. At the 160' unsupported span that is found on the 1964 as built blueprints and not fully corrected until 2001, the design is at 97% of yield. Referring to Figure 30, a current of 3.6 mph will push the design to yield at 35000 lb/in^2 stress. These calculations show the rationale for the 75' easement limit and the wisdom of Salvadori's 140' absolute maximum span limitation.

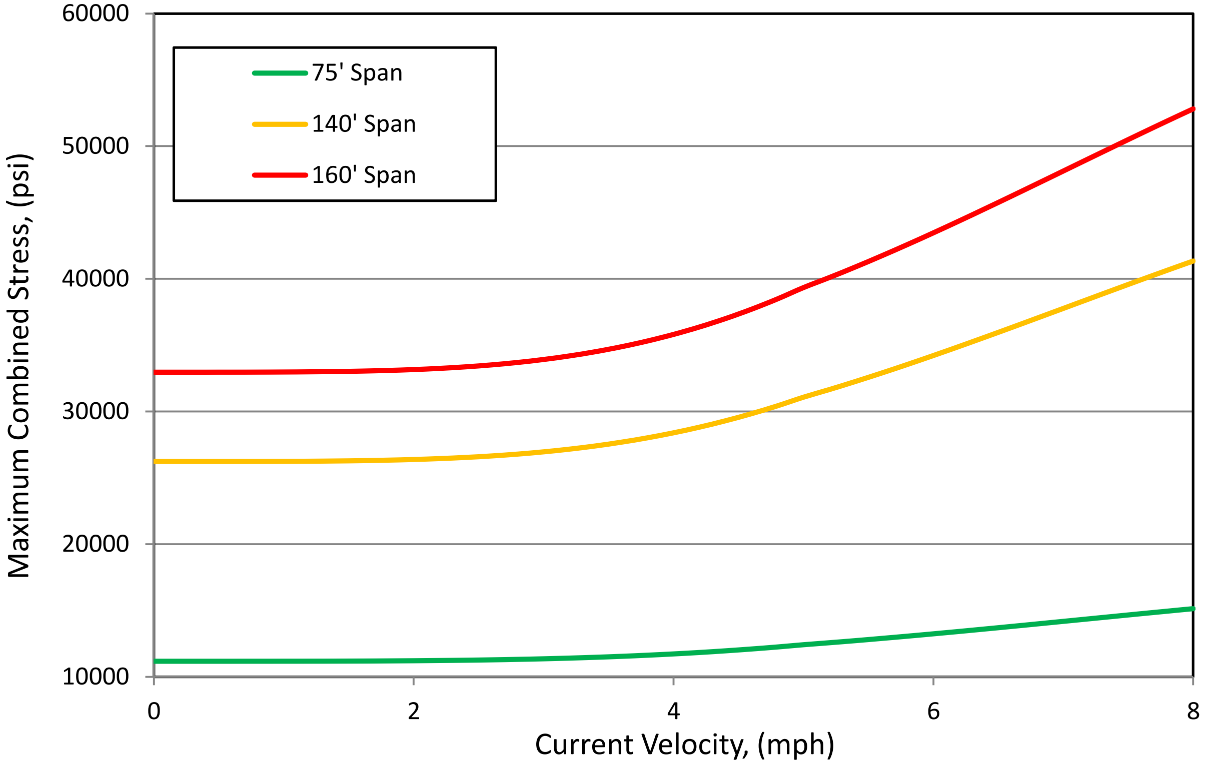


Figure 31. Maximum Combined Stress for Line 5 as a Function of Current Velocity

Table 12. Depth and Location of Long Unsupported Spans on the West Leg of Line 5

Span Unsupported Length, (ft)	Bechtel Station (ft)	Water Depth, (ft)
150	7600	225
150	10800	175
160	11800	130

Figure 32 is a detail clipped from the as built blueprints of Line 5 under the Straits that are discussed in Appendix 1. Figure 32 shows that two 150' unsupported spans and one 160' unsupported spans that resulted from insufficient grading of the lake bottom during construction. Based on all publically available information, these spans were not properly supported until Enbridge started using screw anchor supports in 2001, so that these spans were exposed to currents for a period of 48 years. Table 12 gives the water depth and Bechtel station number for these spans. As mentioned earlier in this paper, exact current velocity information at these locations is not known but based on the information in Table 13 it is likely that the two 150' unsupported spans were exposed to current velocities more typical of those measured by buoy LM 02 while the more critical 160' unsupported span was exposed to current velocities typical of those measured by buoys LM 01 and 45175. In the following sections of this report, computations will use the data from all three buoy data sets to illustrate the range of possible results due to uncertainty in current velocity measurement.

Table 13 shows the amount of time that the current velocity is estimated to be greater than 3.6 mph, the condition where a 160 foot unsupported span will reach the yield stress of X35 steel. Reference to Figure 21 shows that peak current events of significant magnitude typically last for about 20-30 minutes. Using the value of 30 minutes per peak current event results in the number of possible fatigue cycles due to bulk flow during extreme current events at three buoy locations for a 160 foot unsupported span. Based on this assumption, it is likely that the 160' unsupported span located at Bechtel Station 11800 has been subjected to between 200 and 300 reversing bending cycles over the 48 year period it was out of compliance with easement conditions and Salvadori's calculations.

Table 13. Estimates of Elapsed Time that Current Velocity Exceeds 3.6 mph at Three Locations

Data Set Name	Annual Time Current is > 3.6 mph, (min/yr)	Total Time Current is > 3.6 mph over 48 Years, (hr)	Total Fatigue cycles over 48 years
Buoy LM 01	169	135	270
Buoy LM 02	14.7	11.8	24
Buoy 45175	180	144	288

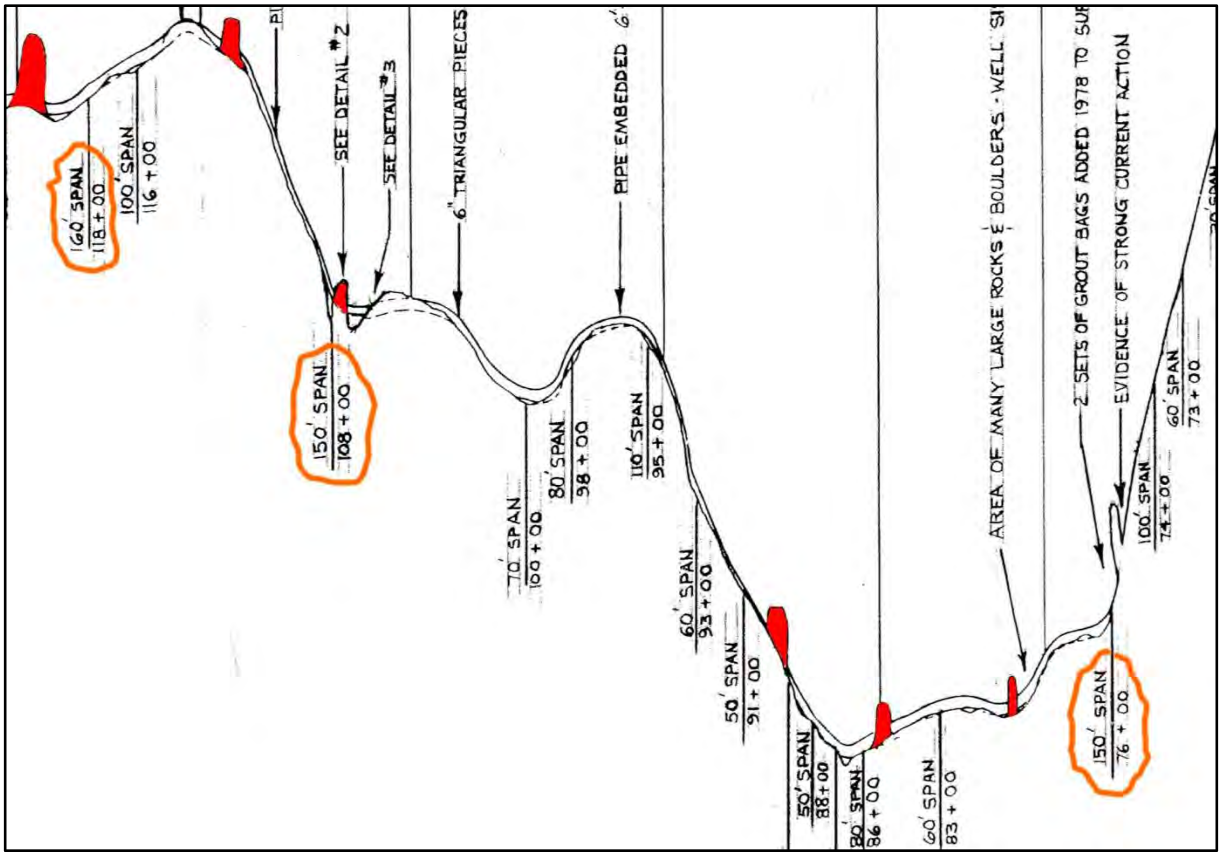


Figure 32. Detail Clipped from As Built Blueprint for the West Leg of Line 5 under the Straits as Referenced in Appendix 1 (Clay Piles Annotated in Orange)

The Effect of Mesoscale Turbulence During Peak Flow Events

The preceding analysis is predicated on slowly varying bulk flow and does not take into consideration the effect of mesoscale turbulence. A flow field that is turbulent on the mesoscale consists of large eddies that create a continuously varying velocity at any given point in the flow field. As the work of Thompson has shown, these turbulent velocity fluctuations are on the order of 10 – 20% of the mean flow velocity and have wavelengths measured to be about 50 m (164 ft) to 150 m (492 ft) at the peak of their spectral density.

Considering the case where the peak velocity in a turbulent eddy is just fast enough to create enough drag to create a combined stress equal to the yield stress of the structural steel in the pipe, it is possible to calculate how often this has happened over a time period for a given unsupported span length. Figures 31 and 32 can be used to give a range of estimates for how many yield cycles the documented 160’ unsupported span of Line 5 was cycled through in the 48 years before it was shored up. Entering Figure 31 on the right ordinate at 160’ and moving horizontally to the red line results in an ordinate value of 3.32 mph mean current velocity at which the yield condition will be met at the peak turbulent velocity. Then moving vertically from a mean current velocity of 3.32 mph to the red, green and blue lines gives the respective number of fatigue cycles for current velocities determined from buoys LM 01, buoy LM 02 and 45175. Figure 32 is a similar graph that uses Thompson’s Admiralty Head data instead of the Nodule Point data used in the example above.

Table 14 shows the results from these mesoscale turbulence calculations as applied to a 160’ unsupported span using the buoy data from Buoys LM 01, LM 02 and 45175. Table 15 shows similar results for a 150’ unsupported span. In both cases, Line 5 has experienced a significant number of fatigue cycles. Even the case of a 140’ unsupported span appears to experience significant fatigue when subjected to currents like those measured by buoys LM 01 and 45175 due to turbulence effects. This finding somewhat supports Salvadori’s finding that a >140’ unsupported span presents unacceptable risk even though the knowledge necessary to calculate these scenarios was not available in 1953. This does not mean that all unsupported spans less than 140’ in length have not been cycled to stresses that affect their fatigue life, but rather they have been flexed to stresses less than the yield stress on X35 steel.

Table 14. Fatigue Cycles from Mesoscale Turbulence for a 160 foot Unsupported Span over an Elapsed Time of 48 Years

Data Set Name	Fatigue Cycles in 48 Years with Turbulence Wavelength of 492 feet	Fatigue Cycles in 48 Years with Turbulence Wavelength of 164 feet
Buoy LM 01	6425	19514
Buoy LM 02	969	2944
Buoy 45175	6570	19954

Table 15. Fatigue Cycles from Mesoscale Turbulence for a 150 foot Unsupported Span over an Elapsed Time of 48 Years

Data Set Name	Fatigue Cycles in 48 Years with Turbulence Wavelength of 492 feet	Fatigue Cycles in 48 Years with Turbulence Wavelength of 164 feet
Buoy LM 01	3241	9842
Buoy LM 02	62	188
Buoy 45175	3767	11441

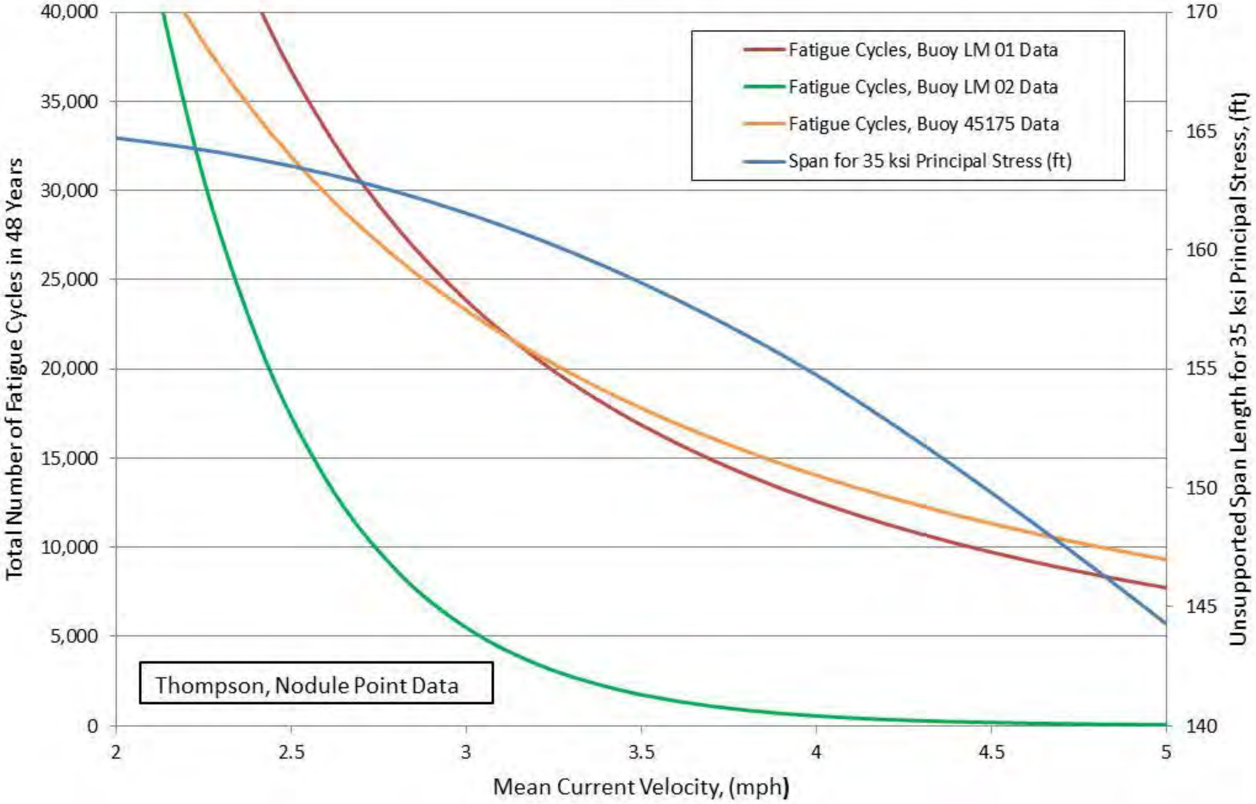


Figure 33. Total Number of Yield Cycles and Unsupported Span Length as a Function of Current Velocity for a Turbulence Wavelength of 164' (50 m)

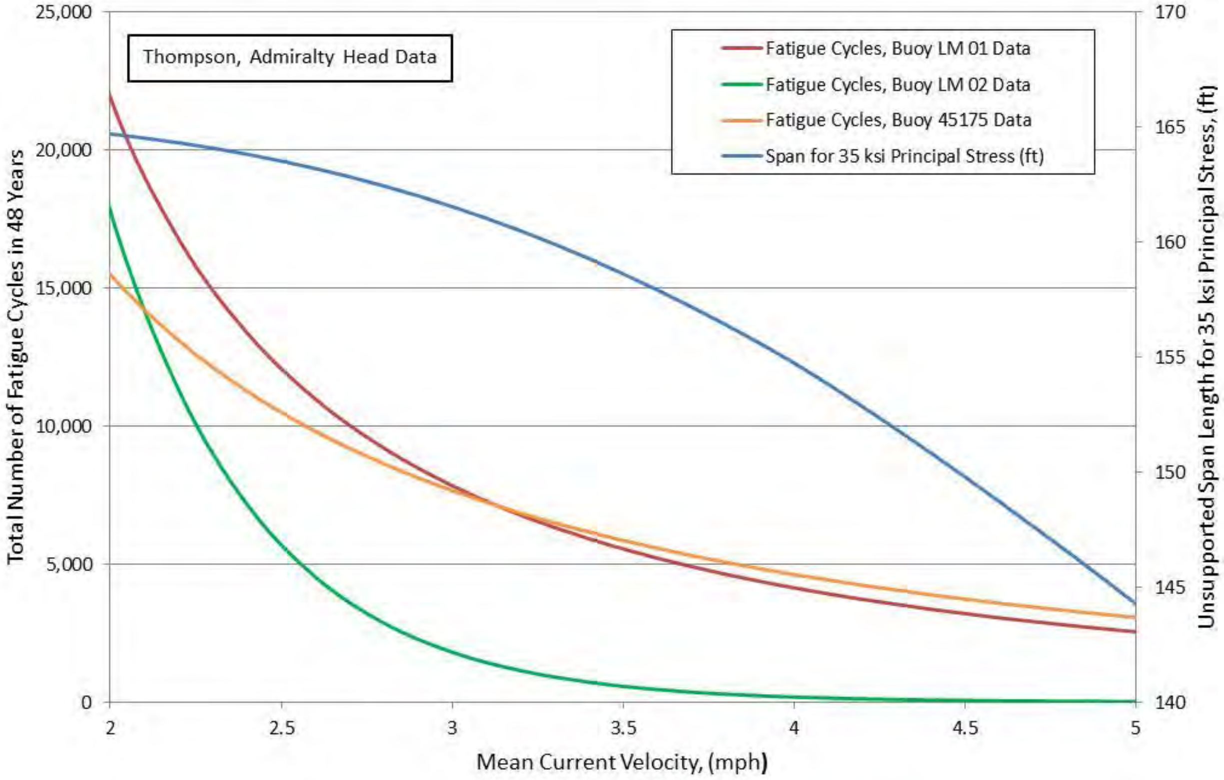


Figure 34. Total Number of Yield Cycles and Unsupported Span Length as a Function of Current Velocity for a Turbulence Wavelength of 492' (150 m)

The Possibility of Vortex Shedding Resonant Lock-In Condition

As mentioned on page 31, pipelines have failed catastrophically due to cyclic stressing by vibrations induced by vortex shedding that coincide with the fundamental resonant frequency of the structure. The spectacular failure of the Tacoma Narrows suspension bridge over the Tacoma Narrows of Puget Sound is often attributed to vortex shedding resonant lock-in but actually this failure was due to related fluid mechanical phenomena called aeroelastic flutter.

Vortex shedding frequencies for Line 5 in the same condition as used for the previous drag calculations were computed using the data in Figure 27. The first fundamental transverse vibration frequency for the pipe was calculated according to Blevins[26]. Figure 33 is a plot of the results of these computations. It can be seen from this figure that at a current velocity of 4.6 mph and an unsupported span length of 185', vortex shedding lock-in will occur at a frequency of 0.88 Hz.

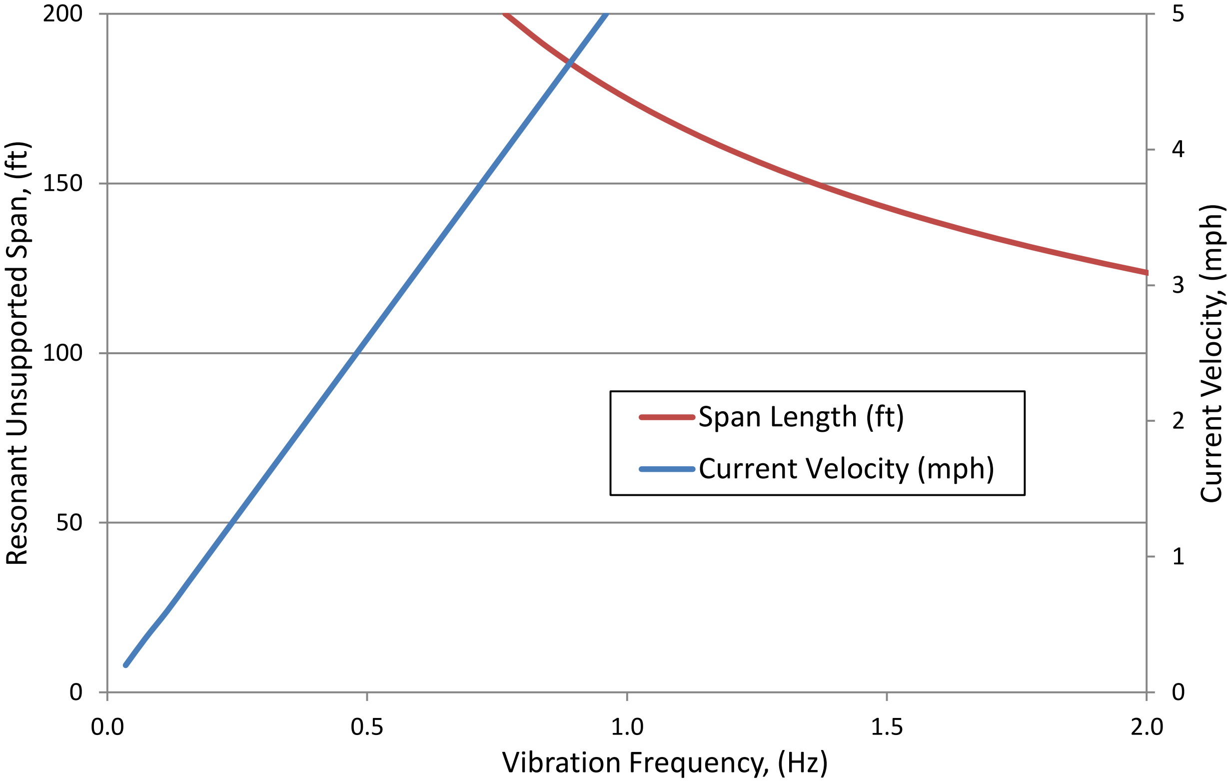


Figure 35. Resonant Unsupported Span Length and Current Velocity for Vortex Shedding as a Function of Frequency

Table 16. Elapsed Time Current Velocity is Greater Than 4.6 mph at Buoy Locations

Data Set Name	Annual Time Current is > 4.6 mph, (min/yr)	Total Time Current is > 4.6 mph over 48 Years, (hr)	Possible Fatigue Cycles over 48 years
Buoy LM 01	77	96	$3.04 * 10^5$
Buoy LM 02	1.2	1.5	$4.75 * 10^3$
Buoy 45175	91	114	$3.61 * 10^5$

It is recognized that there is no data that show an unsupported span of 185' or greater ever existed over the history of Line 5 although there is reason to believe that such spans did exist during construction before low lying areas were filled with clay. However, because the excitation frequency caused by vortex shedding and the resonant response frequency of the pipe are not single valued, but rather the peaks of broad spectrums or response, the possibility that the longer unsupported spans have been subject to resonant vibration cannot be dismissed. Because the extreme current values necessary to cause lock-in also result in very high stresses in the pipe, if such an event has occurred it would be extremely damaging.

Table 16 shows the total elapsed time that current velocities have been above 4.6 mph at three buoy locations. Although the amount of time elapsed at current velocities over 4.6 mph at buoy LM 02 is not statistically significant, this is not true for buoys LM 01 and 45175. Because of the very large number of fatigue cycles that can be imposed on long unsupported spans by the vortex shedding resonant lock in mechanism, this mechanism should not be discounted as a possibility for sections of Enbridge Line 5 that were allowed to go unsupported over an extended period of time.

Discussion and Conclusions

An old adage describes an Engineer as someone who does precision guesswork based on unreliable data from people of questionable knowledge. This paper is intended to be the polar opposite of that description, it is based on the best data and analysis available from researchers with unimpeachable credentials. I consider this work to be a pathfinding attempt to investigate mathematically the substance of Bruce Trudgen's supposition that Enbridge Line 5 under the Straits of Mackinac has been structurally compromised by buffeting from currents, corrosion and lack of maintenance. Bruce Trudgen died at the age of 84 in December, 2016 but, as the only experienced mechanical engineer that actually worked on the construction of the Straits sections of Enbridge Line 5 and is not directly associated with its operation, his opinion is significant.

There are a number of criticisms that can be made of the work in this paper. Many of the relevant details concerning the design and construction of Line 5 are either lost to history or not publically available. Long term average current data has been statistically analyzed to give insight into phenomena that occur infrequently and very quickly. Mesoscale turbulence data has been applied to a different geography and flow situation from where it was taken and the possibility of vortex shedding lock-in is discussed in broad terms without specific data. Nevertheless, this paper is intended to bring analytical rigor to a subject that, previously, has only been discussed in the broadest of terms or dismissed outright without supporting data.

Figure 36 is a typical fatigue curve for carbon steel as tested using a rotary bending test apparatus. For the 0.02% carbon hot rolled steel that is similar to the X35 steel used in Line 5, an endurance limit of about 30,000 cycles is found at a bending stress of 35000 psi. At this stress level, the metal is being plastically deformed on the microscale, and the total strain and strain rate sensitivity found in low cycle fatigue phenomena come into play. Additionally, laboratory fatigue testing uses small test specimens and the test only applies the maximum stress to a small volume of those samples. Fatigue life analysis of large welded structures is possible using finite element analysis where the strain history of every element is analyzed. These studies show that the fatigue life of a large structure is reached when one element of that structure reaches its fatigue limit and initiates cracking. Such a study is beyond the scope of this document and would be unwise considering the uncertainties in the stress and strain history of the underwater sections of Line 5.

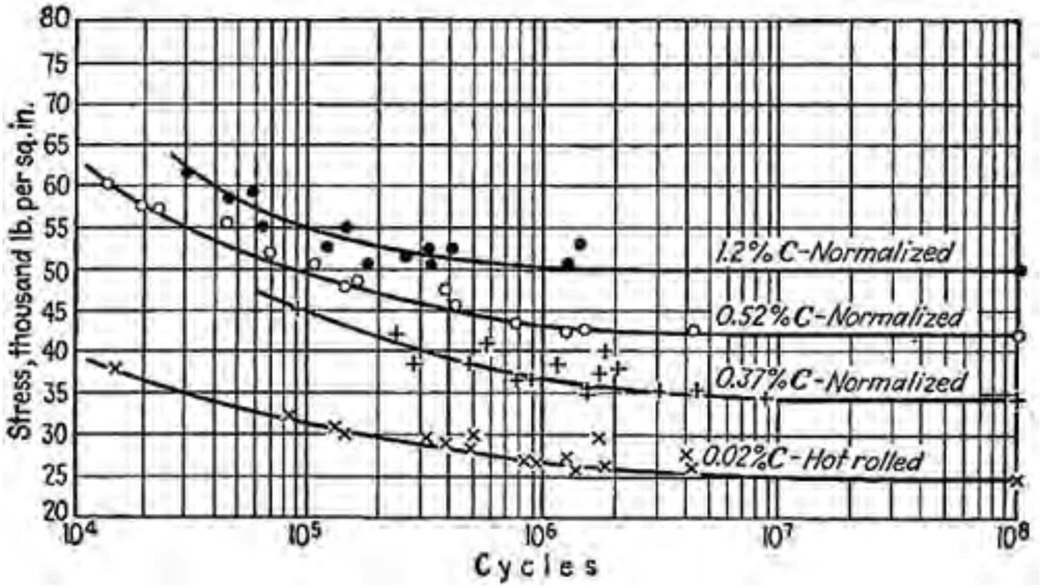


Figure 36. Typical Fatigue Curve for Carbon Steel

Throughout this paper, calculations concerning current induced stresses have been done using data from the three buoy locations closest to the pipeline and near the choke point of the Straits. Figure 37 shows the locations of these buoys in relation to the three unsupported spans identified in Appendix 1 and discussed in this work. In this figure, the locations of the buoys has been superimposed along the axis of the Straits onto an annotated version of Saylor and Miller's location cross section. From this figure, it is apparent that the longest unsupported span discussed here (160') is quite close to the streamline of buoy LM 01. The two 150' unsupported spans are located deeper and not near a buoy streamline. The following sections of this paper will discuss the stress history of the 160' unsupported span using data from buoy LM 01.

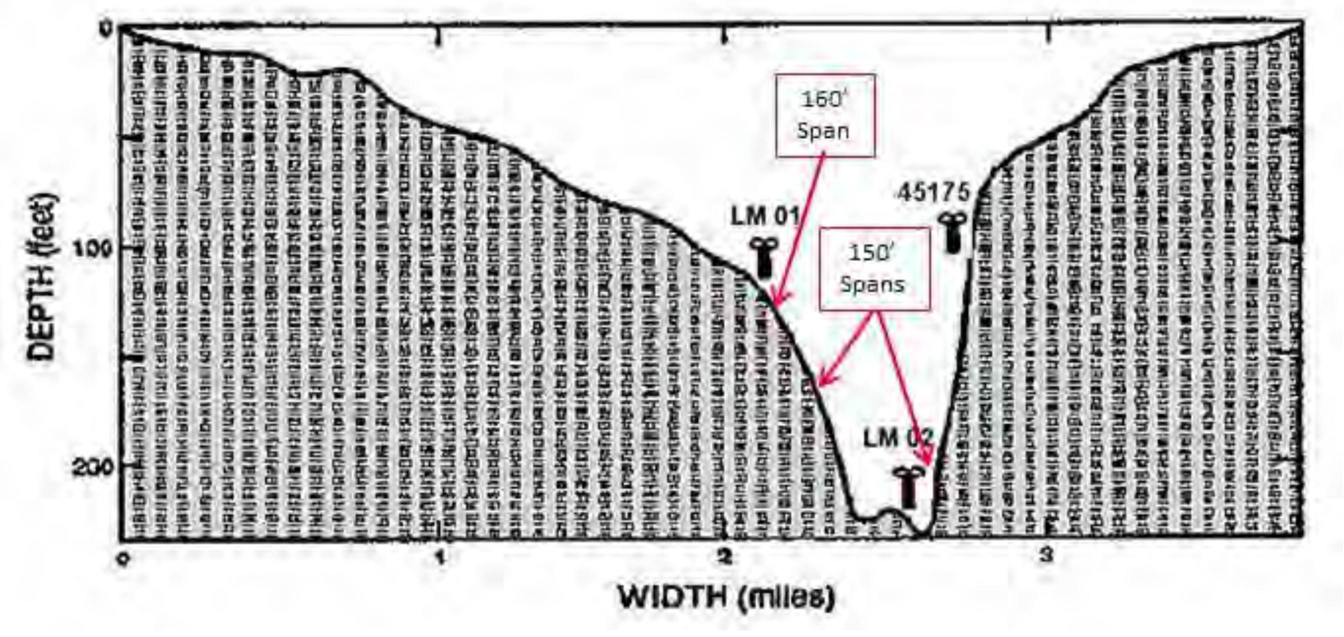


Figure 37. Cross Sectional View of the Straits of Mackinac Showing Locations of Long Unsupported Spans in Relation to Buoy Positions

The calculations in this paper raise the possibility that some portions of the exposed underwater segments of Enbridge Line 5 have been cycled beyond the yield stress of X35 steel by four mechanisms. Focusing on the 160' unsupported span documented to be at the Bechtel station located 11,800 feet from the northern datum of the west leg of Line 5 under the Straits, each of the following mechanisms may have contributed the following number of plastic fatigue cycles to this pipeline.

1 The effect of plastic deformation during construction, < 10 cycles
2. The effect of reversing bulk flow currents, 270 cycles
3. The effect of mesoscale turbulence during peak flow events, 3240-19510 cycles
4. The possibility of vortex shedding lock-in events, $3.04*10^5$ cycles

It would be possible to construct a finite element model of a welded structure like Line 5 and submit it to all the insults enumerated above. Without the information such a study would produce, it is impossible to conclude how much of the fatigue life the longest unsupported spans of Enbridge Line 5 have used up. What can be concluded is that the pipe has experienced a significant number of plastic deformation cycles based on all the available current data and that the possibility of fatigue crack initiation and growth cannot be discounted without additional study.

In a review of In Line Inspection (ILI) data commissioned by Oak Ridge National Laboratory, the Lamontagne Pipeline Assessment Corporation issued a report[27] that summarized the data from several recent in line inspections of Line 5 under the Straits. It should be noted that Lamontagne explicitly stated that this was not a "fitness for service" determination. .Quoting from this report:

"Crack-Like Anomalies

The 2014 ultrasonic inspection for circumferential "crack-like" anomalies identified 39 that were all at the minimum tool reporting depth of 5%, save one at 6%. Sixteen were described as potential notches. Three were excavated for field interpretation and found to be innocuous manufacturing related marks on the pipe. A fatigue analysis was made employing the most recent years' operating pressures. All of the delineated anomalies had a remaining life of greater than 50 years."

It is clear from this report that the possibility of metal fatigue from bending stresses due to current velocities that exceed the design basis of the pipeline were not considered when determining that this pipe has a remaining fatigue life of greater than 50 years. It may well be that the scope of work for the Lamontagne assessment precluded study of historical current induced metal fatigue. The fact that there are a number of crack like anomalies known to exist in Line 5 that are at the limit of detection of the ILI tools used, raises additional questions about the fatigue history of Line 5 and its fitness for service. Based on all the evidence presented in this work, it is not a reasonable proposition that the exposed underwater sections of Enbridge Line 5 under the Straits of Mackinac can be considered fit for service without a thorough examination of all the issues raised here. The knowledge that current induced fatigue cracking has caused the catastrophic failure of other underwater pipelines and the knowledge that the currents under the Straits of Mackinac are much stronger and more complex than contemplated by Line 5's design engineers strengthen this opinion.

An additional concern regarding the condition of these long unsupported spans can be raised by Figure 38. A document[28] released by the Michigan Pipeline Task Force shows an annotated histogram of metal loss features in the west leg of Line 5 as measured during a 2013 MFL inspection scan. The locations of the long unsupported spans discussed in this report have been superimposed on this figure. Figure 38 groups the number of metal loss features into 500' long sections of the pipe and gives the metal loss depth histogram for each 500' section inspected. It can be seen from Figure 38 that each section that includes long unsupported spans also includes a number of metal loss features with depths ranging up to 30% of the pipe wall thickness. These metal loss features have been assigned by the ILI contractor as "mill defects" but, if any of these features are included in the unsupported spans discussed here, they could have a significant impact on the fatigue life of the welded structure. The resolution of Figure 38 is insufficient to draw a conclusion about this and the features are not located precisely due to differing chainage measurements between different contractors, but all the ILI data available should be examined at the highest resolution to look for any suggestion that fatigue cracking exists in these sections.

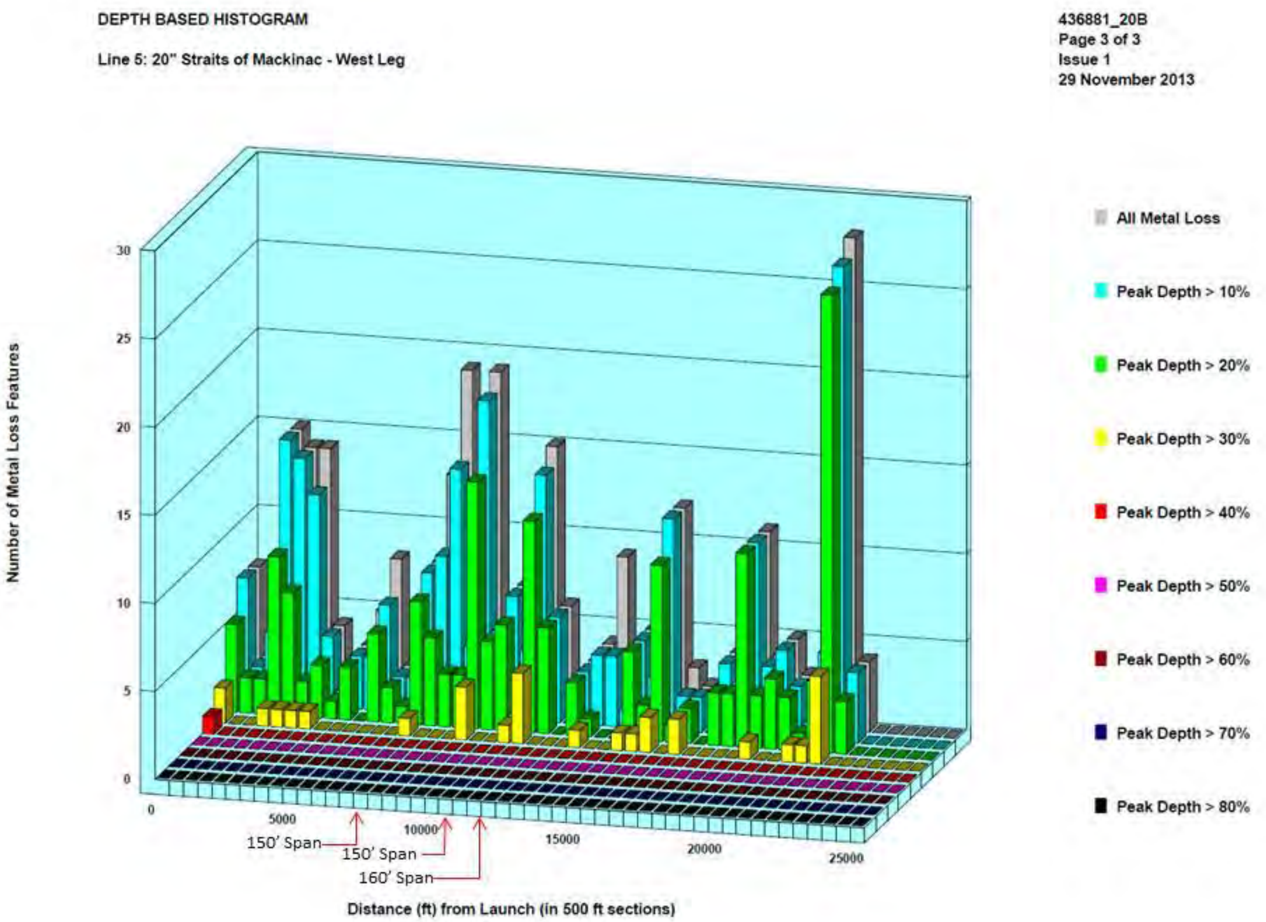


Figure 38. Annotated Histogram of Metal Loss Features in the West Leg of Line 5 from a 2013 MFL Inspection Report[28].

As a result of the circumstances leading to the catastrophic rupture of Enbridge Line 6b in 2010, the United States and Enbridge are negotiating a consent decree[29] which includes conditions mandating a study[30] of the structural stability of Line 5. This study includes work to characterize the bioaccumulation on the pipe, the integrity of the coating system and an engineering analysis that incorporates this information with a goal of characterizing the structural stability of the pipeline. Following is a description of the engineering analysis taken from reference 30.

> **3.4 Engineering Stress Analysis**
> A structural engineering firm will be engaged to conduct an engineering stress analysis considering the impact of biota on the integrity of the pipelines suspended above the floor at the Straits. The analysis will include the following:
>
> - An allowable suspended span length of the pipeline will be calculated to include the biomass along with operating loads, drag forces, buoyant weight, etc. A sensitivity analysis will be also completed on the impact of the biota mass to allowable span length.
> - Vortex induced vibration ("VIV") assessment will be also performed to determine the mode shape and associated vibration periods of pipe free spans with various lengths and the assessed biomass. A sensitivity analysis will also be completed on the impact of the biota mass to allowable span length as part of the VIV assessment

This mandated analysis is remarkably similar to the analysis done in this this paper and will face the same uncertainties described here. Because of the inadequacy of the available current data, the accurate calculation of drag loadings and the possibility of vortex shedding resonant lock in (VIV in the terminology of reference 30) will require the development of an instantaneous current velocity database measured at several locations along both legs of the pipeline, a subject is discussed further in the next section of this report.

Recommendations

This work has concluded that the complexities of construction and intensity of currents under the Straits of Mackinac may well have resulted in a significant low cycle fatigue history for certain portions of Line 5. A review of all publically available inspection logs and data shows that this history has not been taken into account in Enbridge's fitness for service determinations for this pipeline. Given the exceedingly critical location of this pair of pipes in what David Schwab has called the worst possible place for an oil spill in the Great Lakes, the following recommendations should be implemented.

1. Instantaneous current velocity data at critical locations along the Straits crossing of the twin Line 5 pipes should be acquired starting in the spring of 2017. Thompson, et al[20] have studied available instrumentation and fully developed techniques for acquiring and analyzing this data. Appropriate acoustic Doppler instrumentation should be installed directly on Line 5 at critical locations and a database of the intensity and duration of peak current events should be logged over the course of a year to provide hard data about the stresses imposed on Line 5 by currents. Six to eight instruments, logging data that can be correlated with meteorological and hydrological records, would provide the database necessary to implement a detailed finite element fatigue model of selected sections of Line 5. This would allow for accurate calculation of the fatigue history of these sections of Line 5 which could be used, along with ILI data, to produce a meaningful fitness for service evaluation of these pipes.

2. While the data acquisition program discussed in the previous recommendation is being developed, a reputable pipeline integrity analysis firm with significant underwater pipeline experience should be engaged to use the current data developed in this paper to further examine the stress mechanisms discussed in this paper and how they affect Enbridge's current determination that the twinned sections of Line 5 under the Straits of Mackinac are fit for service. After a year's worth of data has been acquired about peak current events in the Straits, this firm could then examine the fitness for service of these Line 5 sections based on instantaneous mesoscale turbulence data. DNV (Det Norsk Veritas, Oslo, Norway) is one firm with exceptional experience in this area. Testing of some sections of these pipes for residual stress and fatigue damage may also be warranted in this study.

3. Based on Appendix 2 in this work, a full evaluation of the condition of the protective coating on Line 5 coupled with additional analysis of all relevant ILI data should be conducted to determine the extent of external corrosion and cracking on Line 5. Internal ILI data should also be reviewed. If, as it appears in Appendix 2, the protective coating on Line 5 is severely compromised, this knowledge will be necessary for accurate fatigue life predictions. Special emphasis should be given to the corrosion environment found under the mussels and biofouling present on Line 5 and its potential for acerbating stress corrosion cracking.

4. Because all previous fitness for service evaluations for these critical pipes can be considered suspect due to their omission of an adequate analysis of historical low cycle fatigue issues, consideration should be given to implementing a protocol where the twinned pipes of Line 5 are shut down and given a thorough ultrasonic ILI inspection that can be compared to other inspections to determine crack sizes and growth rates whenever a peak current event is detected in the waters of the Straits of Mackinac. NOAA Buoy 45175 continuously monitors and reports current data from a location near Line 5 and this data could be the basis for a protocol that requires shutdown and inspection directly after a severe peak current event. The work in this paper can be used to set conditional parameters for initiating such a protocol. Since it can be argued from this work, that certain sections of the twinned sections of Line 5 under the Straits may be only one peak current event away from catastrophic failure, this is a reasonable and prudent interim measure that could be required by the State of Michigan under the easement agreement that allowed the placement of these pipes in 1953.

5. Computational modeling efforts of the flow field in the Straits during peak current events should be accelerated. These efforts should be directed at better understanding the peak flows in the Straits of Mackinac and their breakdown into mesoscale turbulence. These efforts would be useful in understanding these flows and would feed into the analysis recommended in recommendation 2. Additionally, the impact of climate change on the frequency of peak current events should be considered.

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Appendix 1

Technical Note

Regarding Enbridge Line 5 Non-Compliance with 1953 Easement Requirements A Mechanistic Analysis of Straits Pipeline Washout Phenomena

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The two legs of Enbridge's line 5 that lie on the bottom of the Straits of Mackinac are constructed of very heavy 20" pipe and must be supported to prevent collapse due to gravitational force. A review of the original design calculations[1] conducted by famed structural engineer, Dr. Mario G. Salvadori, approved the design analysis made by Bechtel Inc. personnel and set limits on maximum unsupported span lengths. Based on both Bechtel's original design and Dr. Salvadori's calculations, the State of Michigan set a maximum unsupported span distance of 75 feet when it granted the easement[2] under the Straits. Dr. Salvadori additionally noted in his report that any unsupported span over 140 feet was dangerous and that the pipe should not be allowed to sag to a radius of curvature of less than 1750 feet during construction. These values were based on information provided to Dr. Salvatore and assumed that the maximum current under the Straits was 1.96 knots (2.26 mph). These calculations did not anticipate or include loads on the pipe due to biofouling and the mussel growth that started after the opening of the St. Lawrence Seaway in 1958. A review of these documents also reveals that the possibility that currents would erode the supporting soil under the pipe leading to 'washouts" was not considered.

When the Straits sections of Line 5 were designed by Bechtel engineers the engineering science of underwater pipeline design was in its infancy. Many design efforts involving short river crossings where the pipe is buried in the river bottom had proven successful but there was little experience with longer crossings where the pipe was placed on the bottom of a body of water without burial. As the offshore oil industry developed in the 1960's the need for such pipelines drove engineering understanding and the problem with currents washing away the bottomlands that support an underwater pipeline was recognized. In retrospect, the mis-estimation of the magnitude of currents under the Straits coupled with the lack of understanding about the soil entrainment processes that cause washouts can be seen as a fatal flaw in the design of the Line 5 Straits crossing.

Although much has been published about the problem with washouts under Line 5 with resultant lack of support and easement violations, it does not appear that the mechanism causing this problem has been previously elucidated. Washouts occur because of currents that are fast enough to entrain soil particles and move them away from beneath the pipe. Figure 1, calculated from the Levillain[3] equation, illustrates the extremely nonlinear nature of the soil entrainment process. This figure shows that at currents below the design maximum of 2.26 mph no soil particles larger than 0.5mm can be entrained. This velocity is sufficient to entrain silt and small sand particles but is not capable of moving most soil particles. Because the Levillain equation is highly nonlinear, current speeds greater than this value have a disproportional impact on the size of soil particles that can be entrained and transported. A three mph current will entrain particles with diameters on the scale of a millimeter which includes typical lake bottom sand and a six mph current can transport small rocks with diameters on the order of one half inch. This knowledge leads to the conclusion that pipeline washouts occur during events that cause extreme currents which are most likely found in turbulent eddy flows resulting from exceptional weather events across the Great Lakes basin.

During its 63 year lifetime, the Straits sections of Line 5 have been consistently out of compliance with the easement's 75 foot maximum unsupported span requirement. Table 1, taken from copies of the "as built" drawings of the two Straits legs of Line 5 updated through the 1979 underwater inspection[4,5] shows a total of 17 spans that exceed the 75 foot maximum unsupported span distance and three spans that exceed the 140 foot structural damage threshold. Table 2, taken from another document filed by Enbridge at the request of the Michigan Attorney General under the terms of the 1953 easement[6], outlines the numerous campaigns undertaken from 1962 through 2012 to inspect and add support to the pipes. This information shows a lack of urgency on Enbridge's part to insure that Line 5 is both safe and complies with applicable language in the 1953 easement. In spite of all the non-compliances shown in Table 1 which was current as of January, 1980, Table 2 shows that no action was taken by Enbridge until 1987 to remedy this dangerous situation. In 1987, Enbridge began campaigns to insure adequate support under line 5, but, as can be seen from Table 2, the 1987 effort only added support to seven unsupported spans out of the seventeen noncompliant spans that were documented in the 1980 drawings. This 1987 effort certainly did not bring Line 5 into compliance with the easement.

Beginning in 2001 and continuing today, Enbridge has made efforts to add modern screw anchor supports to Line 5 to bring it into compliance with the easement and, more importantly, prevent damage to the line.
As can be seen from Table 2, a total of 106 supports were added to Line 5 through 2012. A 2014 campaign by Enbridge found 40 spans that violated easement requirements. Following this campaign Enbridge stated that there were no unsupported spans over 75 feet and the average unsupported span was 50 feet. This calculates to a total supported distance of 1.38 miles out of a total exposed distance of 4.4 miles (2.3 miles West leg, 2.1 miles East leg) which means only about 31% of the pipe has discrete supports and is not subject to washout. A recent (7/2016) underwater survey of Line 5 has found four more spans that are out of compliance with the easement and eighteen spans that Enbridge plans to support proactively to prevent future non-compliance. This information is documented in a construction permit application to the State filed in August, 2016 with a planned work start date in September, 2016. The ongoing nature of washouts under Line 5 with resulting easement non-compliances demonstrates conclusively that strong currents and a shifting bottom under the Straits requires continuous vigilance to prevent excessive spans that could result in collapse of Line 5. A careful analysis of all the documentation publicly available about this issue leads to the conclusion that the Straits segments of Line 5 never met the easement support and curvature requirements as constructed in 1953 and have been consistently and sometimes dangerously out of compliance since that date. It may be that Enbridge's support efforts have brought the line into compliance with easement requirements for brief periods but it is certain that easement requirements have not been met for the great majority of its life to date.

An analysis of the current data taken in the Straits by Saylor and Miller in 1991[7] shows that the original designers of Line 5 seriously underestimated the strength of the currents impacting the structure. This data shows that
currents near Line 5 can exceed the design basis for several hours each year and that at some times the currents exceed 4 mph. It is probable that Line 5 washouts are caused by local turbulent eddies with peak velocities over 6 mph that occur infrequently likely during seiche inducing Derecho events or other extreme weather events. Due to the limited data available about extreme currents under the Straits and the probabilistic nature of the washout process, it is very difficult to predict when and where washouts will occur. Additionally, because of both marine fouling and current loadings well beyond the design basis, it is likely that the original stress calculations that resulted in the 75 foot maximum unsupported span requirement underestimate stresses in the pipe and the 75 foot requirement no longer results in the safety margins originally contemplated in the 1953 easement agreement. These errors also affect the calculation that predicts severe consequences should an unsupported span over 140 feet develop. Given currents above the design basis and severe biofouling, the stresses predicted to occur at a 140 foot span are underestimated and severe consequences may occur at unsupported spans less than this length.

The finding that Line 5 needs more supports that resulted from Enbridge's 2016 underwater inspection and resultant construction permit application is, once again, an admission that Enbridge has consistently violated the easement allowing construction of Line 5. Apparently, after the 2014 support campaign by Enbridge, assurances were given to the State of Michigan that, in the future, no further easement non-compliances would occur. The fact that four such non-compliances were found and eighteen more supports are required to prevent potential future non-compliances has called into question Enbridge's assurances regarding their engineering competence and ability to comply. In an August 3, 2016 letter, Michigan's Attorney General, Bill Schuette[8], notified Enbridge that, under the terms of the easement, they had to provide information about their ongoing inspection and repair program. Quoting from this letter:

> "First, please provide as soon as possible, and in any event within 14 days of this letter, the results of the most recent underwater inspection of the Straits Pipelines in 2016. This includes a detailed description of the methods used to conduct the inspection, as well as the findings regarding pipeline support locations, span lengths observed, and changes to the conditions reported in 2014 that have led to the current situation where the four spans now exceed 75 feet. Specifically, please explain why and how the span lengths Enbridge represented existed in 2014 are now missing in those locations.
>
> Second, please provide, within 14 days from this letter: (a) a detailed description of the predictive maintenance model that Enbridge relied upon and referred to in its November, 2014 letter; (b) a detailed explanation of how and why that model failed; and (c) a new span monitoring and preventative maintenance plan to ensure future and continuing compliance with the Easement pipeline support requirement. That plan should include, as needed, increased inspection frequency and proactive pipeline support repair, installation and replacement to prevent any spans greater than 75 feet before they occur."

Based on my analysis of current data and knowledge of hydrodynamics, it is probable that a model to predict future washouts that does not take into account current data will not be reliable. As shown by Anderson and Schwab[9], the oscillating flows through the Straits are driven by atmospheric pressure differences and reach extreme values during severe weather events like a Derecho induced seiche. Without taking this information into account, it is likely that washouts can occur that will go undetected by Enbridge's two year underwater survey schedule. Because a truly extreme weather event could produce a washout that exceeds the 140 foot limit for structural damage to Line 5, the risk of a rupture in Line 5 in its current condition cannot be said to be negligible. This observation raises the question of what action should be taken by the State of Michigan to assure the safety of the Straits sections of Line 5 given Enbridge's continuous inability to comply with easement support requirements since before 1975.

Allowing Enbridge's current process of bi-annual underwater inspection followed by repair to continue under these circumstances guarantees that the Straits sections of Line 5 will not be in compliance with easement requirements most of the time. Indeed, there is a finite possibility that the probabilistic nature of the washout process will result in a dangerously long unsupported span that could go undetected for over a year. This approach seems neither reasonable nor prudent since a rupture and large oil spill in the Straits would be incomprehensibly damaging to Michigan's economy and ecology. If the obvious remedy of shutting down this pipeline is judged to be too extreme based on economic concerns, it would be reasonable and prudent to take an approach that incorporates the technical arguments made in this document to reduce risk.

Since routinely scheduled (2 year) underwater inspections cannot guarantee the level of reliability that may be necessary in such a critical waterway, an event triggered approach may be useful. Real time monitoring of weather events and currents in the most vulnerable areas of the pipeline in conjunction with a Straits flow model like that of Anderson and Schwab could provide the data necessary to determine when currents reach values that threaten pipeline stability. When such a condition is reached, it would be prudent to either shut down Line 5 or restrict it to non-oil cargo until an underwater inspection could be made. These event triggered inspections along with ameliorative action would provide a level of safety unobtainable through regular inspections at reasonable cost. This approach is used in many other safety critical situations with good results. For example, commercial airliners continually record flight information and any event that causes an airplane to exceed preset limits triggers a thorough inspection, review and repair/replace decision by the operator. This approach could be used to make sure the frequent, unpredicted washouts that plague the Straits sections of Line 5 would not result in rupture when pressurized with crude oil during an extreme current event.

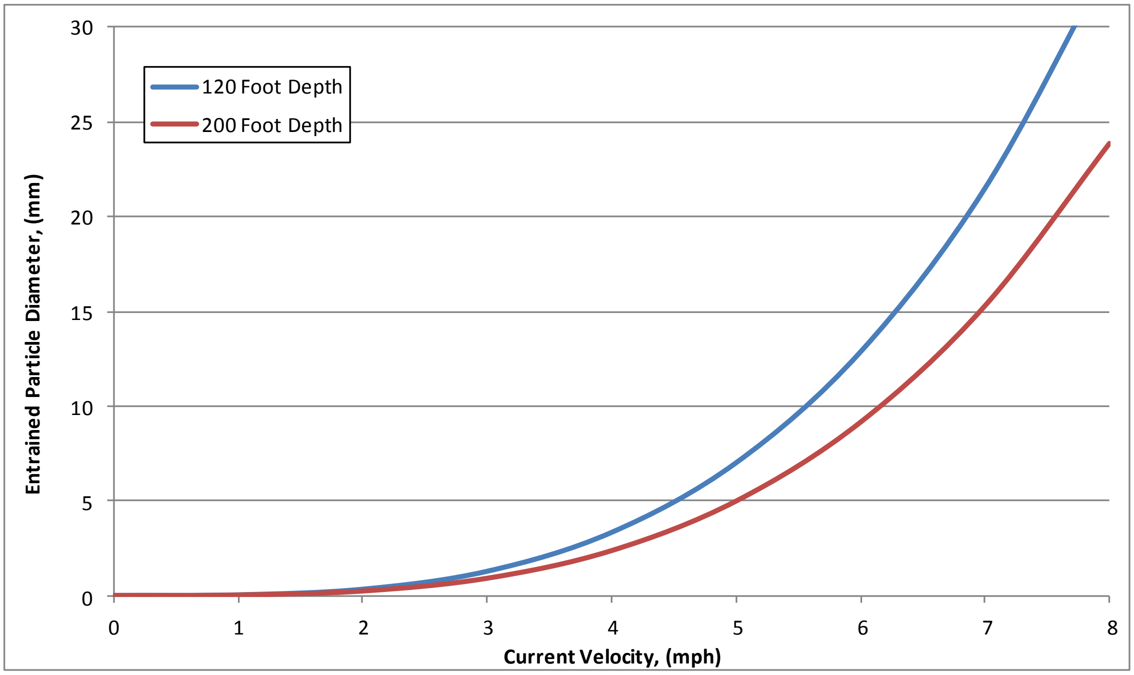


Figure 1. Soil Particle Entrainment Velocity as a Function of Underwater Current Velocity

Table 1. Summary of Spans and Supports as of the 1979 Underwater Inspection of Line 5

1. Data taken from Lakehead Pipeline Company, Inc drawings released by Michigan Attorney General
2. Drawing originally dated 4/14/64 and noted as being traced from Bechtel, Inc drawing dated 11/63
3. Drawing updated through 1980 including revisions following 1972, 1975 and 1979 underwater inspections
4. Unsupported spans over 75 feet are prohibited by 1953 easement agreement with the State of Michigan
5. Unsupported spans over 140 feet were calculated to be dangerous to line integrity by original designers at Bechtel

Summary of non-Compliant Unsupported Spans as of 1980

Location	Spans > 75 feet	Spans > 140 feet
West Leg	10	3
East Leg	7	0

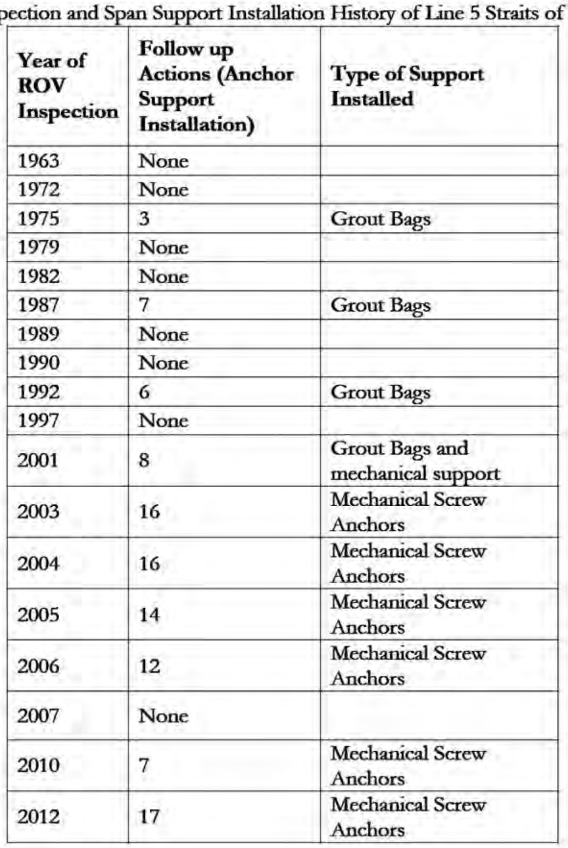
West Leg Spans and Supports

Feature Description	Approximate Bechtel Chainage	Approximate Depth	Unsupported span Length (feet)	Notes
Beginning	5140	65		
Span	6800	105	60	
Span	7000	130	70	
Clay Pile	7050	135		
Span	7100	135	30	
Span	7300	165	60	
Span	7400	180	100	
Clay Pile	7500	210		Evidence of strong current action
Span	7600	240	150	Two sets of grout filled bags placed in 1978 to support span.
Note	8000			Area of many large rocks and boulders, well silted
Clay Pile	8100	240		
Span	8300	235	60	
Clay Pile	8560	242		
Span	8600	245	80	
Span	8700	245	70	
Span	8800	240	50	
Span	8900	225	85	
Span	9100	220	50	
Span	9300	205	60	
Span	9500	180	110	
Burial	9650	175		Pipe embedded 6-8 feet
Span	9800	180	80	
Span	10000	185	70	
Note	10300	170		6" triangular pieces of coating chipped off during 1978 construction
Span	10800	170	150	Two details on drawing showing pipe sideways movement and pipe unsupported in trench
Clay Pile	11200	130		
Span	11600	130	100	
Span	11800	135	160	
Clay Pile	12000	135		
Span	12250	135	70	
Clay Pile	12350	135		
Span	12450	135	40	
Span	12700	130	40	
Clay Pile	12900	130		
Clay Pile	13100	130		
Span	13200	130	60	
Note	13350	130		Cable mark on pipe, no damage
Span	13500	130	90	
Span	13900	95	35	
Clay Pile	14050	95		
Span	14300	95	50	Two small clay piles appear to have
Span	14400	95	50	been placed to create these three spans
Span	14500	95	20	from one original
Span	15200	80	40	Several small clay piles appear to have
Span	15600	75	40	been used to support pipe in area of non
Span	16400	75	10	
End	17260	65		

East Leg Spans and Supports

Feature Description	Approximate Bechtel Chainage	Approximate Depth	Unsupported span Length (feet)	Notes
Beginning	5040	65		
Span	5510	70	80	Two sets of grout bags added in 1978 to
Span	5650	70	70	suppoirt spans
Span	6000	115	70	
Note	6350	160		Large Rock
Note	6400	160		Gravel Ridge
Span	6450	160	70	
Span	7060	210	80	Evidence of strong current action
Clay Pile	7500	220		
Span	7720	220	80	
Trench	8050	225		
Span	8120	232	80	
Clay Pile	8160	232		
Span	8200	232	90	
Span	8510	190	90	
Span	8740	165	60	
Span	8880	140	70	
Span	8950	130	60	
Trench	9000	130		
Clay Pile	9210	130		
Trench	9270	130		
Clay Pile	9590	140		
Span	9600	140	50	
Trench	9800	140		
Clay Pile	9990	140		
Span	10450	120	70	
Span	10740	110	60	
Clay Pile	10950	105		
Span	11400	95	70	
Span	11930	100	90	Span well anchored
Clay Pile	12150	95		
Span	12400	105	80	
Clay Pile	12500	105		
Span	13300	90	80	
Span	13600	80	70	
Clay Pile	14100	70		
Span	14480	75	50	Pipe is 5 to 6 feet off bottom in this area
Span	14800	80	50	
Clay Pile	15300	75		
Span	15720	70	60	
End	17200	50		

Table 2 ROV Inspection and Span Support Installation History of Line 5 Straits of Mackinac



Year of ROV Inspection	Follow up Actions (Anchor Support Installation)	Type of Support Installed
1963	None	
1972	None	
1975	3	Grout Bags
1979	None	
1982	None	
1987	7	Grout Bags
1989	None	
1990	None	
1992	6	Grout Bags
1997	None	
2001	8	Grout Bags and mechanical support
2003	16	Mechanical Screw Anchors
2004	16	Mechanical Screw Anchors
2005	14	Mechanical Screw Anchors
2006	12	Mechanical Screw Anchors
2007	None	
2010	7	Mechanical Screw Anchors
2012	17	Mechanical Screw Anchors

References

[1] “Report on the Structural Analysis of the Subaqueous Crossing of the Mackinac Straits”, Salvadori, Mario G., PE, Department of Civil Engineering, Columbia University, New York 27, NY, January 19, 1953.
Also released by the State of Michigan as: “Engineering and Construction Considerations for the Mackinac Pipeline Company’s Crossing of the Straits of Mackinac” and “Report on the Structural Analysis of the Subaqueous Crossing of the Mackinac Straits,” submitted by Mackinac Pipeline Company/Lakehead Pipeline Company to the Michigan Department of Conservation, January, 1953 http://www.michigan.gov/documents/deq/Appendix_A.2_493980_7.pdf

[2] “Straits of Mackinac Pipeline Easement”, Conservation Commission of the State of Michigan, April 23, 1953.

[3] “Critical Soil Particle Entrainment Velocity”, Stability and Operation of Jackups, Chapter 4.5.1.2, pages 222-223, Pierre Le Tirant and Christian Perol, Editors, Design Guides for Offshore Structures, Editions TECHNIP, Paris, France 1993.

[4] “East Line Profile, Mackinaw Straits Crossing, Underwater Inspection”, Lakehead Pipeline Company, Inc., 4/14/64, Updated 1972, 1975 and 1979, http://www.michigan.gov/documents/ag/164-00-1_700-10483-01_523921_7.pdf?20160819195501

[5] “West Line Profile, Mackinaw Straits Crossing, Underwater Inspection”, Lakehead Pipeline Company, Inc., 4/14/64, Updated 1972, 1975 and 1979, http://www.michigan.gov/documents/ag/164-00-1_700-10483-01_523922_7.pdf?20160819195501

[6] “Table 2 ROV Inspection and Span Support Installation History of Line 5, Straits of Mackinac”, Appendix 2B, Table 2, p. 4 (document Appendix_B4_493991_7.pdf, MPP Task Force Record).

[7] “Current flow through the Straits of Mackinac”, James Saylor and Gerald Miller, Great Lakes Environmental Research Laboratory Ann Arbor, Michigan, Technical Report, 1991

[8] “Re: *Enbridge Lakehead System Line 5 Pipelines at the Straits of Mackinac”,* Letter from Michigan Attorney General Bill Schuette to Brad Shamla, Vice President U. S. Operations, Enbridge Energy Limited Partnership, August 3, 2016.

[9] ” Predicting the oscillating bi-directional exchange flow in the Straits of Mackinac”, Eric J. Anderson and David J. Schwab, Journal of Great Lakes Research, December, 2013.

Appendix 2
Technical Note

Regarding Enbridge Line 5 Coating Condition and Related Observations

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Carbon steel pipelines are susceptible to corrosion and stress corrosion cracking. They must be protected from their surrounding environment by a coating system that precludes corrosive attack. Coating technology for steel pipelines has been an evolving area of technology since the infancy of the pipeline industry and improvements have not always stood the test of time. In this technical note the coating system used on Enbridge Line 5 under the Straits of Mackinac will be discussed based on historical documentation and an assessment of the current condition of the coating system on this pipe will be attempted.

There are three primary historical references regarding the coating technology used in 1953 when Line 5 under the Straits was constructed. These are:

1. A 1953 order by the Michigan Public Service commission that granted permission for the construction of Line 5 across the State of Michigan[1],
2. A 1953 easement granted by the State of Michigan to cross the bottomlands of the Straits of Mackinac[2],
3. A pair of engineering reports by famed structural engineer Mario G. Salvadori of Columbia University that review the design of Line 5 by Bechtel Inc. engineers[3].

The following descriptions of the coating system used to protect Line 5 from the submarine environment are taken from these documents.

1953 MPSC Order Regarding Corrosion Protection

"The entire pipe line will be properly cleaned, primed, and coated with a single application of coal tar. The coating will be reinforced by a spiral wrap of glass material and covered by a spiral wrap of special glass outer wrap. Penetrations will be made for cathodic protection."

1953 Easement Restrictions Regarding Corrosion Protection and Support

("8) Cathodic protection shall be installed to prevent deterioration of the pipe

(9) All pipe shall be protected by asphalt primer coat, by inner wrap and outer wrap composed of glass fiber fabric material and one inch by four inch (1" x 4") slats prior to installation."

Engineering and Construction Considerations for the Mackinac Pipeline Company's Crossing of the Straits of Mackinac" submitted by Mackinac Pipeline Company/Lakehead Pipeline Company to the Michigan Department of Conservation, January, 1953

“After coating with asphalt primer, fiberglass inner wrap and an asbestos felt outer wrap, and after attaching 1” x 4” wood slats to the full circumference of the pipe, it will be lowered onto a previously prepared “bed” on the floor of the Straits.”

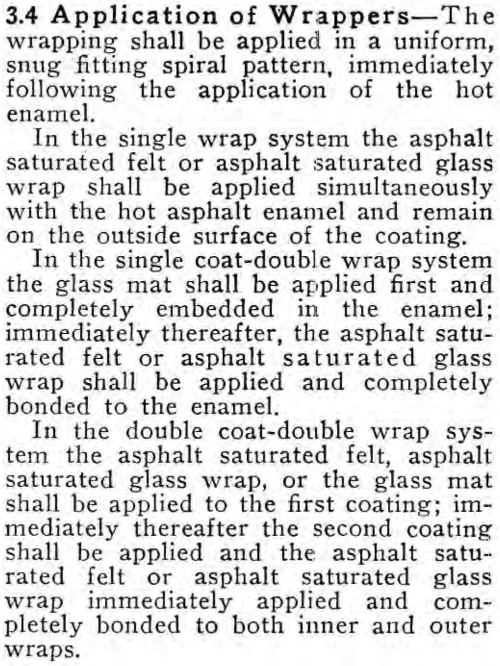
Two documents released by Enbridge give a contemporary account of Line 5’s coating system.

In a 2014 document entitled “Enbridge Energy Limited Partners, Operational Reliability Plan, Line 5 and Line 5 Straits of Mackinac Crossing”[4], a specification table entitled “Table 1: Line 5 Pipeline Construction Specifications” states that the pipe is coated with coal tar enamel while on page 12 of this document it states “The particular material,an extract of coal or asphalt, is highly impermeable to water and is reinforced with a fiber wrapping for added strength.”

There is contradiction and ambiguity between these sources of information about the coating system on the Straits portion of Line 5. The owner of the line, Enbridge, states that the coating could be either coal tar or asphalt based, the 1953 MPSC order states that the coating is coal tar and both the easement and Salvadoris’s reports state that the coating is asphalt based. To make matters more confusing, the two layers of wrapping materials are cited to be glass fiber fabric except in Salvadori’s opinion which states the outer wrap is to be asbestos felt.

A series of color photographs taken by Bruce Trudgen, a young MSU engineer who worked on the Line 5 project and wrote about it[5] offer insight into the coating and wrapping system used on Line 5. Figure 1 shows the pipe cleaning machine which used a rotating brush assembly to clean the surface of the pipe and Figure 2 shows the pipe wrapping machine which was used to spiral wrap the pipe with reinforcing cloth.

A reference[6] from the time Line 5 was constructed (1957) documents good coating practice using asphalt enamel and provides and context for coating technology at the time of Line 5’s construction. The following text is taken from this document.



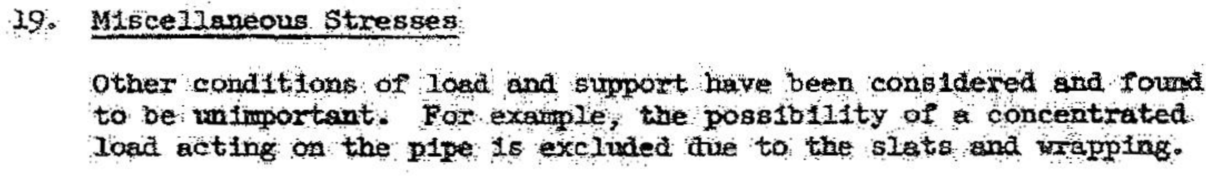
3.4 Application of Wrappers—The wrapping shall be applied in a uniform, snug fitting spiral pattern, immediately following the application of the hot enamel.

In the single wrap system the asphalt saturated felt or asphalt saturated glass wrap shall be applied simultaneously with the hot asphalt enamel and remain on the outside surface of the coating.

In the single coat-double wrap system the glass mat shall be applied first and completely embedded in the enamel; immediately thereafter, the asphalt saturated felt or asphalt saturated glass wrap shall be applied and completely bonded to the enamel.

In the double coat-double wrap system the asphalt saturated felt, asphalt saturated glass wrap, or the glass mat shall be applied to the first coating; immediately thereafter the second coating shall be applied and the asphalt saturated felt or asphalt saturated glass wrap immediately applied and completely bonded to both inner and outer wraps.

Based on this document and Figure 2, which shows the pipe wrapping machine loaded with four rolls of similar, presumably asphalt saturated glass fiber fabric, it is probable that Line 5's coating system consists of a solvent based asphalt primer, two layers of asphalt saturated glass fiber fabric and a white protective overlayer of white craft paper bonded with asphalt enamel. The craft paper layer was intended to provide some abrasion protection to the underlayers and protect the wrapped pipe from the heat of the sun as described in reference 6. In addition to these layers, the pipe was intended to be wrapped with 1' x 4" wooden slats held on by encircling bands. A hint regarding the purpose of this wooden lagging can be found in Salvadori's report during a discussion of miscellaneous stresses on the pipe. It is believed that the purpose of these slats was to protect the coating from abrasion due to scrubbing on the lake bottom and to protect the pipe from point loading.



19. Miscellaneous Stresses

Other conditions of load and support have been considered and found to be unimportant. For example, the possibility of a concentrated load acting on the pipe is excluded due to the slats and wrapping.

Figure 3 is a detail clipped from Figure 2 that shows the end of the cleaned and wrapped pipe and Figure 4 shows the assembled, coated pipe strings including one on the launchway prior to pulling them across the Straits. Figure 5 shows the welding operation that joined the 2500' strings together as the line was launched. Approximately eight such girth welds had to be made and coated in the 60-65 hour time it took to launch the pipes across the Straits. No details are available of how the pipe was preheated prior to welding or coated after welding in this operation where time was of the essence. It is notable that in Figure 5, the 1" x 4" wooden slats that were supposed to encircle the pipe are only covering the bottom third of the pipe as opposed to those pipes seen in Figure 4. According to Bruce Trudgen, this change was made to ease assembly of the pipe strings midway in the construction process. It is also apparent in Figure 5 that the presumed Kraft paper protective layer is only on the top third of the pipe. As in all construction projects, field changes to a design are inevitable, but no documentation has been discovered regarding field change procedures on the Line 5 project and their approval by engineering personnel.

Discussion

The previous section of this report details what is publically known about the coating system used on Enbridge Line 5 under the Straits of Mackinac and how it was applied in 1953. As of 2016, Jason Manshum, an Enbridge spokesman has taken the position that this pipe is in "like new condition." It is not clear what criteria were used to arrive at this judgement but, as the following section of this report documents, "like new condition" isn't what it used to be.

The 1" x 4" wooden slats that were supposed to encircle the pipe and prevent coating abrasion and point load protection were found to be largely missing in 1964. Two as built drawings of the pipeline (Appendix 1, References 4 and 5) show notations that indicate most of the slats were damaged during the pipe laying operation. Figure 6 is a photograph clipped from the Enbridge 2012 underwater inspection video of Line 5 that, typically, shows these slats lying on the bottom surrounding the pipe. A review of all the video from the 2012 inspection does not show any slats encircling the line throughout its entire exposed length.

Figure 1. Trudgen Photo of Pipe Cleaning Machine (00010370013.tif)

Figure 2. Trudgen Photo of Pipe Wrapping Machine (00010370012.tif)

Figure 3. Detail Enlarged from Trudgen Photo of Pipe Wrapping Machine Showing Wrapped Pipe (00010370012.tif)

Figure 4. Trudgen Photo of Pipe Stockyard (00010370011.tif)

Figure 5. Trudgen Photo of Pipe String Assembly Welding (0001037005.tif)

Figure 6. Photo Clipped from Enbridge 2012 Underwater Inspection Video of the West Line Taken on 8/24/2012 at 12:01:06 Showing Detached Slats.

Judging the condition of the asphalt enamel saturated glass fiber coating system is difficult because the entirety of Line 5 is encrusted with biofouling comprised of mussels, algae and sediment. Bill Scheuette, Hydrographics Manager for Veolia ES Special Services, Inc. noted in his report[7] to Enbridge following his firm's 2007 underwater inspection "The exposed portion of the pipeline is heavily covered in zebra mussel growth, making a detailed analysis of the coating and actual pipe condition impossible." Figures 7, 8, 9, 10 and 11 are clipped from Enbridge's 2012 underwater inspection video and show features where it appears the coating is either partially or totally missing or disbonded from the pipe. Figure 11 is especially interesting because it was taken at one of the few times the survey vehicle turned on its lights revealing true color. Video taken below about 60 feet deep only shows blue/grey monochrome images because red light is entirely filtered out by the water at this depth. There may be another interpretations of Figure 11, but it appears to this author as if the coating is compromised in many areas and the pipe appears rusty with apparent pitting corrosion when viewed in true color.

Asphalt coatings have been used since historical times as a waterproofing and corrosion preventative coating. They are frequently used in roofing materials and asphalt shingles. The asphalt used in these applications is made up of molecules of widely varying molecular weights and pipeline coating grade asphalt is chemically processed to remove low molecular weight species. Molecular weight distribution control is necessary to ensure that the finished product will have a desirable balance of low temperature plasticity and high temperature flowability. A common problem with such natural polymeric materials is that, over time, the low molecular weight species that provide plasticity both migrate into the environment and react together reducing plasticity and causing shrinkage which results in cracks. This is why old asphalt shingles shrink and crack. It is unlikely a 64 year old underwater pipeline coating is immune to these phenomena.

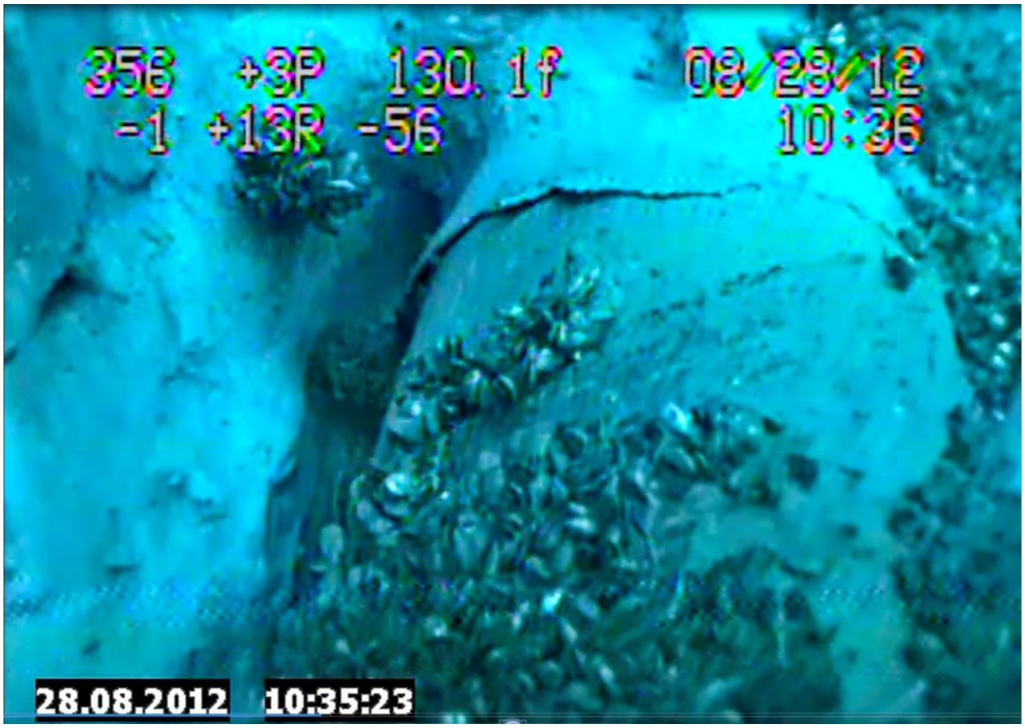


Figure 7. Photo Clipped from Enbridge 2012 Underwater Inspection Video of the East Line Taken on 8/28/2012 at 10:35:23 Showing Missing and Disbonded Coating

Figure 8. Photo Clipped from Enbridge 2012 Underwater Inspection Video of the East Line Taken on 8/24/2012 at 11:44:26 Showing Missing and Disbonded Coating

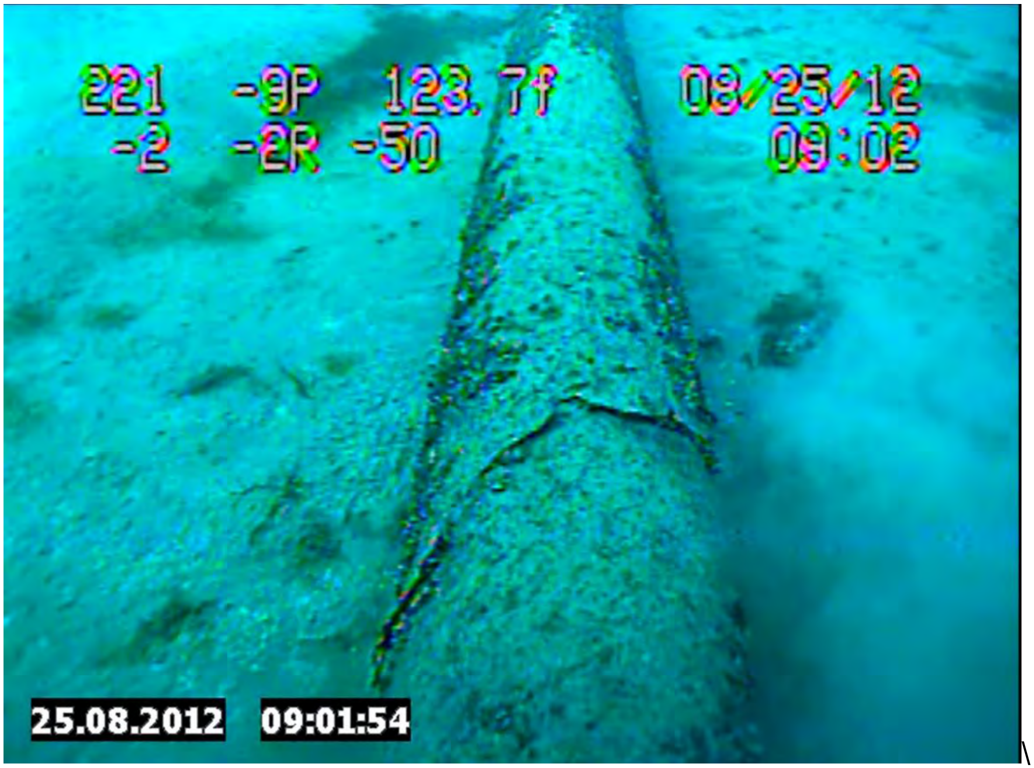


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Figure 9. Photo Clipped from Enbridge 2012 Underwater Inspection Video of the East Line Taken on 8/25/2012 at 09:01:54 Showing Missing and Disbonded Coating

Figure 10. Detail from Photo Clipped from Enbridge 2012 Underwater Inspection Video of the West Line Taken on 8/25/2012 at 15:58:44 Showing Disbonded Coating and Broken Band

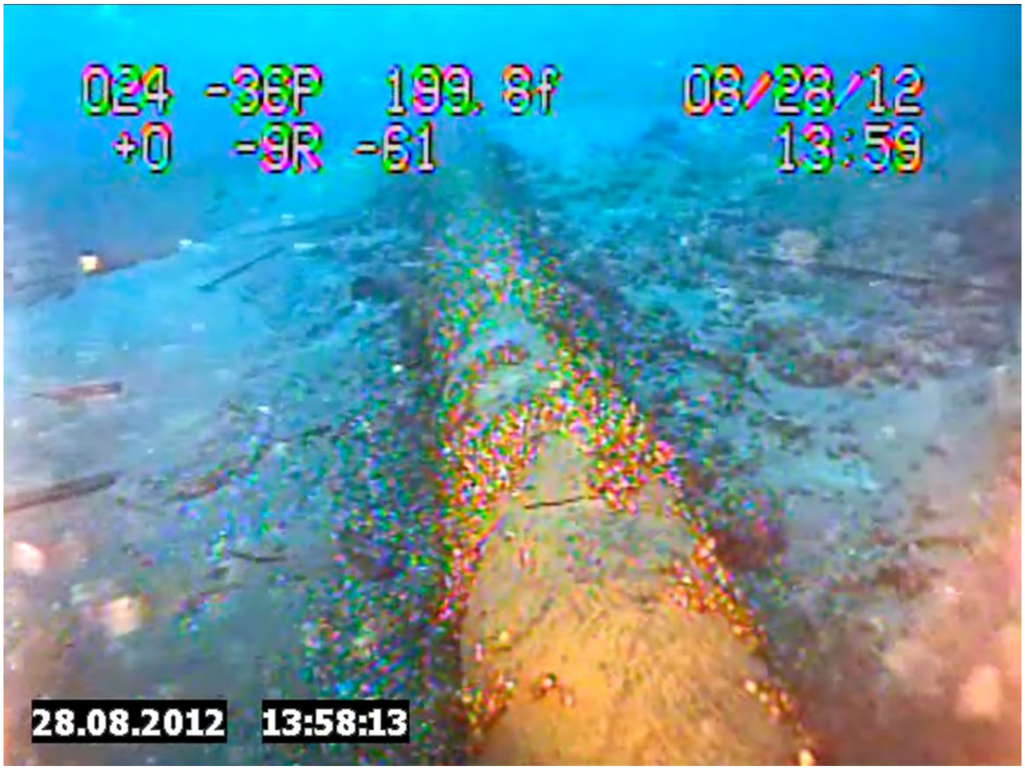

Figure 11. True Color Photo Clipped from Enbridge 2012 Underwater Inspection Video of the East Line Taken on 8/28/2012 at 13:58:13 Showing Missing and Disbonded Coating and Rusty Coloration of Pipe with Apparent Pitting Corrosion

Conclusions

The coating system used on Enbridge Line 5 under the Straits of Mackinac would not have been considered to be the best available practice in 1953 for two reasons. First, the coating system was field applied even though it was recognized at the time that coatings applied in a controlled environment at the pipe factory are of superior quality with fewer coating holidays. Second, coal tar coatings are recognized as having superior properties to asphalt based coatings but, even in 1953, the industrial hygiene problems with coal tar (coal tar is a known human carcinogen) precluded its use in the field. A good review of the challenges faced by operators of vintage pipelines due to coating issues was presented by Didas[8] at a recent NIST symposium. Figure 12 is taken from this document and shows how a disbonded coating can lead to a very corrosive environment under the disbonded coating. The similarity of this illustration to the apparently disbonded coatings found in Figures 7-11 is apparent.

Coating failure with resultant corrosion is the prime cause of vintage pipeline failure and, because of the unpredictability of coatings and corrosion phenomena, no insurance carrier will insure a pipeline against corrosion damage. Coating lifetimes are uncertain and even the best current coating technology, fusion bonded epoxy, is not warranted by manufacturers as to expected lifetime. A recent product brochure from 3M Corporation contains the following language: *"All statements, technical information and recommendations related to 3M Products are based on information believed to be reliable, but the accuracy or completeness is not guaranteed. Before using the 3M Product, you must evaluate it and determine if it is suitable for your intended* *application. Because conditions of Product use are outside of our control and vary widely you assume all risks and liability associated with such use."*

Figure 12. Typical Corrosion Found Under a Disbonded Coating as Reveled by Light Abrasive Blasting

Based on knowledge of the coating system used on Line 5 and the photographic evidence presented in Figures 7-11, the asphalt enamel based coating system on Enbridge Line 5 under the Straits is compromised or missing on many areas of the pipe. Because of biofouling and the lack of true color underwater survey videos, it is impossible to judge how much of the coating system is compromised. It is known that the 1" x 4" wooden slats, designed to protect from point loads and abrasion, are entirely missing. Cathodic protection survey data, which could be interpreted to give an indication of the integrity of this electrically shielded coating system, is not publically available.

Even though the pipe used in Line 5 under the Straits has very thick walls and is a favorable alloy, it is not immune to corrosion and stress corrosion cracking. The biofouling on the pipe has been documented[9] to produce a very corrosive environment is some situations. It is clear that the coating system on Line 5 under the Straits has exceeded its useful life and no longer provides the level of corrosion protection expected by the original designers. A full study of the integrity of the coating system and the impact of biofouling on Line 5 is required as an integral part of any fitness for service evaluation made of this pipe. Recommendations as to the design of this study are beyond the scope of this Appendix but would involve biofouling sampling and characterization, coating sampling and characterization, pipeline cleaning and inspection and other work intended to elucidate the exact condition of the coating on Enbridge Line 5 under the Straits of Mackinac. In this study, special attention should be paid to the condition of the eight girth welds that were used to join the 2500' pipe strings as they were being pulled across the Straits. The lack of any documentation regarding how these joints were quickly coated as the pulling operation progressed under time pressure makes this a particularly important concern.

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