Appendix D

Technical Note

An Analysis of Errors and Omissions in the Dynamic Risk, Inc. Line 5 Alternatives Analysis, Option 5

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Introduction

The potential for an ecologically and economically disastrous rupture of Enbridge Energy Partners Line 5 under the Straits of Mackinac has resulted in an Alternatives Analysis commissioned by the State of Michigan and conducted by Dynamic Risk, Inc. The release of a draft[1] for comment of this analysis by the State's Pipeline Safety Advisory Board on June 29, 2017 started the clock on a public comment period concerning the substance of the Alternatives Analysis; this Technical Note addresses errors and omissions in the analysis of Option 5 therein. Option 5 in the Alternatives Analysis is the base case in the analysis to which other alternatives can be compared. This option is a "status quo" option intended to quantify the probability of a rupture and its consequences if the Straits sections of Line 5 are operated "as is" for an extended period into the future. It is critical for the purposes of the Alternatives Analysis that the probability of a rupture is determined through unimpeachable methodology since, if the rupture risk is incorrectly determined, comparisons to other options will be flawed
and the conclusions of the study will be questionable.

The twinned 20' pipelines on the bottom of the Straits of Mackinac were a pioneering effort in the construction of underwater pipelines. Constructed in 1953 by Bechtel, Inc., the two thick walled pipes were laid directly on the partially graded lake bottom without discrete support. The Alternatives Analysis attempts to quantify the risk of rupture or leakage into this critical waterway from several threats. Twelve different threat categories were considered in the Alternatives Analysis. Of these, four were found to be significant. Quoting[2] from this document:

"Operating Risk Analysis
In the risk assessment of the existing Straits Crossing segments, the principal threats that were found to contribute to the operating risk on the existing 20-in. Straits Crossing segments are, in order of decreasing contribution, anchor hooking, incorrect operations, vortex-induced vibration (VIV), and spanning stress."

The threats to Line 5 due to vortex-induced vibration and spanning stress result from the decision to lay the pipe directly on the partially graded lake bottom leaving unsupported spans of pipe subject to the forces of gravity and currents. Over time, currents have scoured the lake bottom from underneath the pipe causing unsupported pipe spans that may fail from bending stress and fatigue. This problem was recognized by both the designers of the pipe and the State of Michigan who granted an easement[3] for the pipe over state owned bottomlands. A recent review of what is publically known about the design and construction of Line 5 under the Straits as well as the threats to the pipe due to gravity and currents was released by Timm[4].

Following Timm's report, a report by Kiefner and Associates[5] was discovered that detailed the existence of very long unsupported spans and calculations about the structural stability of those spans. The Kiefner report revealed that Enbridge allowed unsupported spans to develop during the first 50 years of Line 5's operation that were much longer than those allowed under the easement (<75') or within the elastic limit of the pipe (~140'). This information necessitated an addendum[6] to the Timm report because these spans which were well beyond its elastic limit certainly resulted in plastic deformation of the pipe.

The Dynamic Risk Alternatives Report uses a Monte Carlo[7] simulation to calculate the probability of the pipe meeting a failure criterion. The necessary inputs to this simulation are a distribution of current velocities that impact the pipe and a distribution of unsupported span lengths that have occurred over the life to date of the pipe. Through numerous trials, the simulation repeatedly subjects a randomly chosen unsupported span to a randomly chosen mix of gravitational and drag forces then calculates the maximum principal stress resulting from this situation. If this stress exceeds the yield strength of the pipeline steel the trial is scored as failure and the process is repeated for a large (10^8) number of trials and the results are analyzed to give a "failure" probability". Quoting from the Alternatives Analysis:

"Spanning Assessment
The evaluation of threat attributes indicated that the Straits Crossing segments are potentially vulnerable to two separate failure mechanisms related to spanning:

i) fatigue caused by vortex-induced vibration (VIV) at span locations, resulting from near-lake-bottom water currents; and,
ii) over-strain caused by stresses due to unsupported span length (gravity and water current drag forces)

With respect to the threat of VIV, depending on pipeline design attributes and span lengths, even moderate currents can induce vortex shedding, at a rate determined by the velocity of water flowing around the pipe. Each time a vortex sheds, a force is generated, causing an oscillatory multi-mode vibration. Under some circumstances, this vortex-induced vibration can give rise to fatigue damage and failure of submarine pipeline spans. The threat of VIV was analyzed utilizing an amplitude response model in which input parameters of span length and upper-bound bottom-layer water currents along both the east and west Straits Crossing segments were represented as probability distributions. The span length distributions reflect observations that actual span lengths have exceeded (in some cases, by significant margins), the 75 ft. maximum stipulated in the Line 5 easement agreement. Using a total of 100,000,000 simulations in a Monte Carlo analysis, the probability that fatigue life would be exceeded for each of several future time periods was determined up to the year 2053.
As a separate analysis, a stress analysis was conducted that considered stresses arising from both gravity and drag forces in addition to those arising from operating pressure and temperature. As was done for the VIV analysis, input parameters of span length and upper-bound bottom-layer water currents along both the east and west Straits Crossing segments were represented as probability distributions. For the purposes of the spanning stress analysis, the probability of failure was defined as the fraction of simulations in which the maximum combined effective stress exceeded yield stress. Using a total of 100,000,000 simulations in a Monte Carlo analysis, the probability that

the pipe's yield strength would be exceeded by the maximum combined effective stress would be exceeded was determined. Although there is ample strain capacity beyond yield (and therefore, failure does not occur when the maximum combined effective stress reaches yield stress), yielding was selected as a failure criterion because it defines the onset of plasticity, which in a dynamic environment could give rise to high amplitude fatigue.
The analysis determined that the annual probability of failure associated with spanning-related threats was time-dependent, rising from 1.42x10-05 (3.1% of total, all-threat annual failure probability) in the year 2018 to 1.65x10-05 (3.5% of total, all-threat annual failure probability) in the year 2053."

As with any such analysis, if the input probability distributions are unrealistic, the output failure probabilities are not a true appraisal of the actual risk. This appears to be the case with the appraisal of both spanning and VIV failure mechanisms found in the Alternatives Analysis. With neither the Kiefner and Associates[5] report or both of the Timm[4,6] reports referenced or examined in Dynamic Risk's analysis, it appears as if there are both errors and omissions in the Alternatives Analysis which make its conclusions highly suspect. The following sections of this report will focus on these errors and omissions with the intent of providing guidance for a more realistic set of inputs for a robust Monte Carlo simulation of the risk of rupture of Line 5 under the Straits due to unsupported spans and vortex induced vibration.

Current Velocity Probability Distribution Discussion

When Bechtel's engineers were presented with the task of designing the segments of Line 5 under the Straits of Mackinac one of the first problems they faced was determining a realistic value for the maximum current velocity in the proposed location of the twin pipes. Based on unreported measurements, the Bechtel engineers concluded that the maximum current their design would have to withstand was 1.96 knots (~2.25 mph, 1.01 m/s). This value was used in the calculations of the maximum stress the design would have to withstand from many mechanisms. A review of these calculations can be found in the analysis by the famed structural engineer Mario Salvadori[8] in 1953. Foremost among the conclusions of this work is that an unsupported span of 140 feet is very close to the elastic limit of the pipe and this span should never be exceeded. This 140' span limit is supported by calculations made by Timm[9] at current velocities up to 2.25 mph. At current velocities above 2.25 mph the hydrodynamic drag from the current becomes a significant contributor to the bending force on the pipe as illustrated in Figure 1, taken from the Timm[9] report. Figure 1 shows that at the recommended span limit of 140' there is still some safety margin between the maximum combined stress and the elastic limit of the ASME Grade B (X35) steel used in the pipe which is given as 35,000 psi. Figure 1 also shows that the combined stress reaches the elastic limit at a 160' span impacted with a 3.6 mph current. Consequently, since it is known that spans of 160' and much longer developed over the 50 year period of 1953 to 2003 when Enbridge began significant efforts to add supports to the pipe, knowledge of the peak currents impacting these very long spans is critical to assessing the amount of plastic deformation accumulated over the years.

For these reasons, an accurate assessment of the rupture probability of the Straits sections of Line 5 depends on developing a good understanding of the fluid mechanical phenomena that characterize flow in the Straits. As thoroughly discussed in the Timm[4] report, flow in the Straits at any velocity beyond creeping flow is characterized as a developing mesoscale turbulent flow

similar to the flow fields found in the Gulf Stream or the Straits of Gibraltar. The flow is further complicated by the fact it is driven by weather systems that cross the Great Lakes basin in unpredictable ways. Since drag forces on the pipe respond to variations in flow velocity on the millisecond time scale, it is important to characterize maximum instantaneous flow velocities during extreme weather events to develop a realistic current velocity probability distribution for use in a Monte Carlo simulation of pipeline rupture risk. This task is yet further complicated by the fact that the turbulent flow in the Straits is far from homogeneous. Buoy ADCP data taken at differing locations in the Straits shows significant current velocity variation based on location as would be expected. Characterizing the flow field in the Straits using a single probability distribution for current velocity can only give an estimate of rupture risk that is biased low unless that distribution accurately includes the highest instantaneous velocities anywhere along the span of the pipeline.

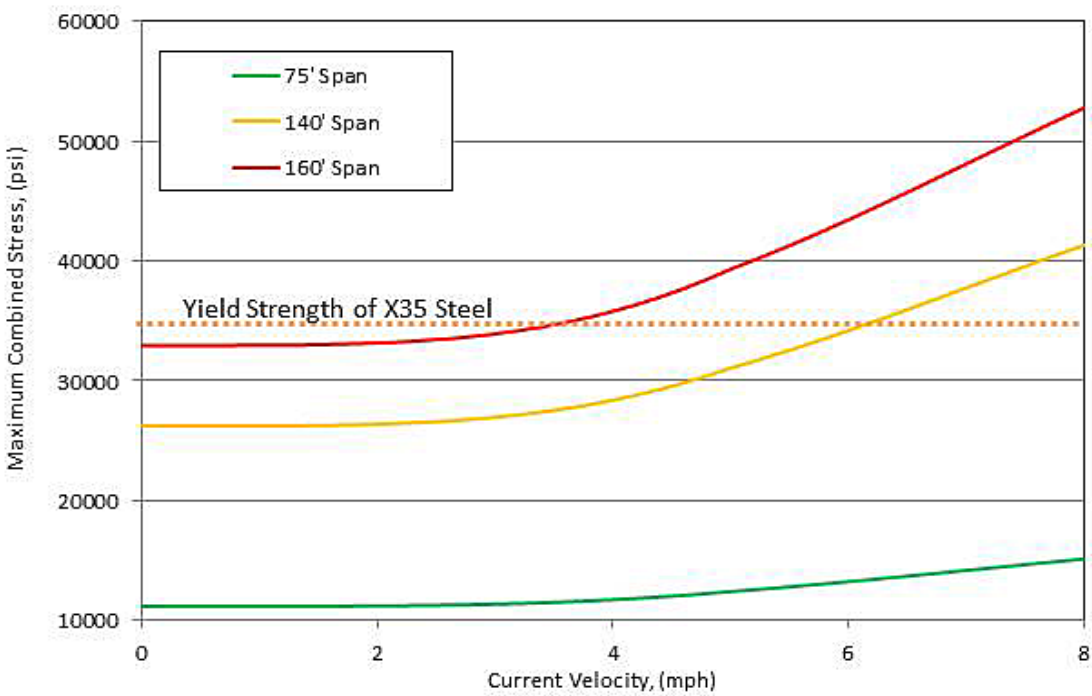

Figure 1. Maximum Combined Stress for Line 5 as a Function of Current Velocity

The Alternatives Analysis requires modeling of the flow in the Straits to explore the issues associated with hydrodynamic forces on Line 5 under the Straits of Mackinac and modeling the whole of the Lake Michigan/Lake Huron basin to explore the issues associated with oil dispersion in the event of a rupture. Dynamic Risk contracted with DHI, Inc.[10]. to develop these hydrodynamic models using their well-known MIKE 2 and MIKE 3 hydrodynamic modeling packages[11]. Appendix 5[12] of the Alternatives Analysis details this effort. The MIKE 3 hydrodynamic model of flow in the Straits used a variable mesh grid and a maximum 10 minute step time to model flow in the Straits based on a given set of meteorological forcing functions. After making an attempt to calibrate the model against existing buoy ADCP data sets, the model was run in monthly increments for a year to develop a velocity field data set representing velocities expected to be experienced in the vicinity of Line 5. Velocity probability distributions were then fitted to this synthetic data from several locations along the pipe and generalized into two probability distributions representing the east and west legs of the pipeline. Ignoring for a moment the fact that the ten minute step time of the model makes it

impossible to accurately model the mesoscale turbulence characteristics of flow in the Straits, there are several reasons to question the accuracy of this effort.

Figure 2 is an annotated comparison of velocity data taken over a twelve day period beginning October 15, 2015 at the -20 m level from NOAA Buoy 45175 with the predictions of the MIKE 3 model. On a separate plot, the wind speed and barometric pressure measured by Buoy 45175 during this period is depicted.

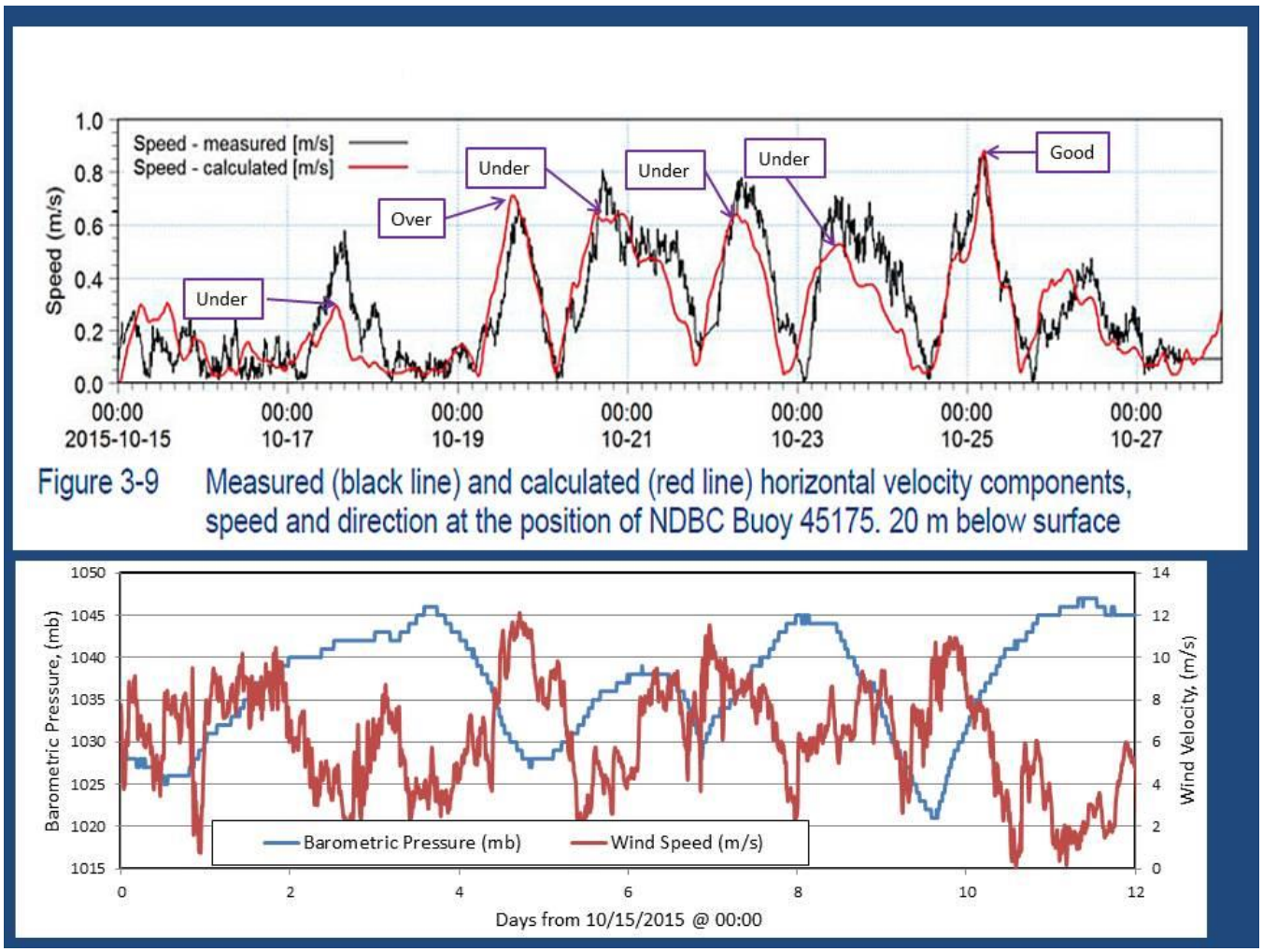

Figure 2. Comparison of Measured and Predicted Current Velocity at NOAA Buoy 45175 along with Corresponding Meteorological Conditions

Figure 6 shows that while the MIKE 3 model predicts currents that generally correspond with the measured velocities, it fails to predict the critical peak current velocities necessary to predict maximum stresses on the pipe. Of the six current excursions depicted in Figure 2, one is correctly predicted, one is over-predicted by ~15%, three are under-predicted by ~20% and one is under-predicted by ~50%. The meteorological information shown on Figure 2 describes a period of generally moderate weather for October on the Great Lakes with high pressure and winds not exceeding 24 mph. Given that hydrodynamic forces on Line 5 generally scale with the square of current velocity, these predictions of peak current velocity are insufficiently robust to be the basis for examining the rupture risk of the single most critical oil pipeline in the

Great Lakes Basin. A further complication with this modeling effort can be found in the following paragraph[13]:

"4.1 Selection of Production Period
Following consultation with the project team, the 1 year time period of time extending from 1st of July 2014 to 30th of June 2015 was adopted for the model production runs. The following considerations were put forward when selecting this timeframe:
• Advantageous to start the model simulation in summer to allow a well-developed model solution (in terms of flow and water levels) prior to any ice effects influencing the model results
• Ice cover: the winter of 2014/2015 is a winter with fairly high ice coverage in Lakes Michigan and Huron; however, the period with significant ice cover is brief (not like in winter 2013/14, for example, with a prolonged period of ice cover)
• Wind conditions are fairly average compared to other years, without any particular high wind events or extreme situations.
• The selection of the simulation period has been based on the last 10 years, rather than further in the past"

This decision by the unidentified "project team" (Dynamic Risk ?, DHI ?, Enbridge ?) to use meteorological forcing data from a period where "Wind conditions are fairly average compared to other years, without any particular high wind events or extreme situations." defies common sense. Even laity certainly understand that structures don't fail during nice weather! To exclude the very conditions that would be expected to lead to a rupture of Line 5 and then using the model output to attempt to predict rupture risk is a decision by the "project team" that is neither explained in the Alternatives Analysis nor realistic. The only explanation for this decision that occurs to this author is that the MIKE 3 model cannot be reasonably converged when faced with extreme but historical meteorological forcing conditions as would have been found with years like 1913, 1975 or other years memorable for very severe weather[14]. Regardless of the reasons for the decision to base the Alternatives Analysis on a year with only mild weather conditions, this decision alone makes the risk estimates for spanning and vortex induced vibration based failures extremely suspect.

Similarly, it can be seen that the MIKE 2 hydrodynamic model, used to predict wave heights for the purpose of oil dispersion modeling, under-predicts wave heights during relatively benign October weather conditions. Figure 3 is reproduced from Appendix 5 of the Alternatives Analysis[15]. It too shows that the MIKE 2 model does a very poor job of predicting peak significant wave heights in conditions where the largest measured significant wave height is under two meters. Reference to the data available online from NOAA Buoy 45175[16] for October 10, 2015 at 19:40 shows a significant wave height of 2.509 m. This value is not reflected in Figure 3 which shows a predicted significant wave height of 1.3 m or about half of the actual value. This kind of disagreement between the model and actual measurement of peak wave heights makes relying on model predicted values instead of actual data likely to result in under-prediction of dispersion phenomena related to oil spill modeling. A likely cause of this misleading information from the MIKE 2 hydrodynamic model is the model is run with a maximum time step of 30 minutes while Buoy 45175 takes data every ten minutes. Once again, awareness of the averaging time used in model simulation and buoy measurements is necessary to prevent incorrect conclusions about the severity of extreme peak events from

being drawn based on information that does not have the time resolution necessary to expose extreme peaks.

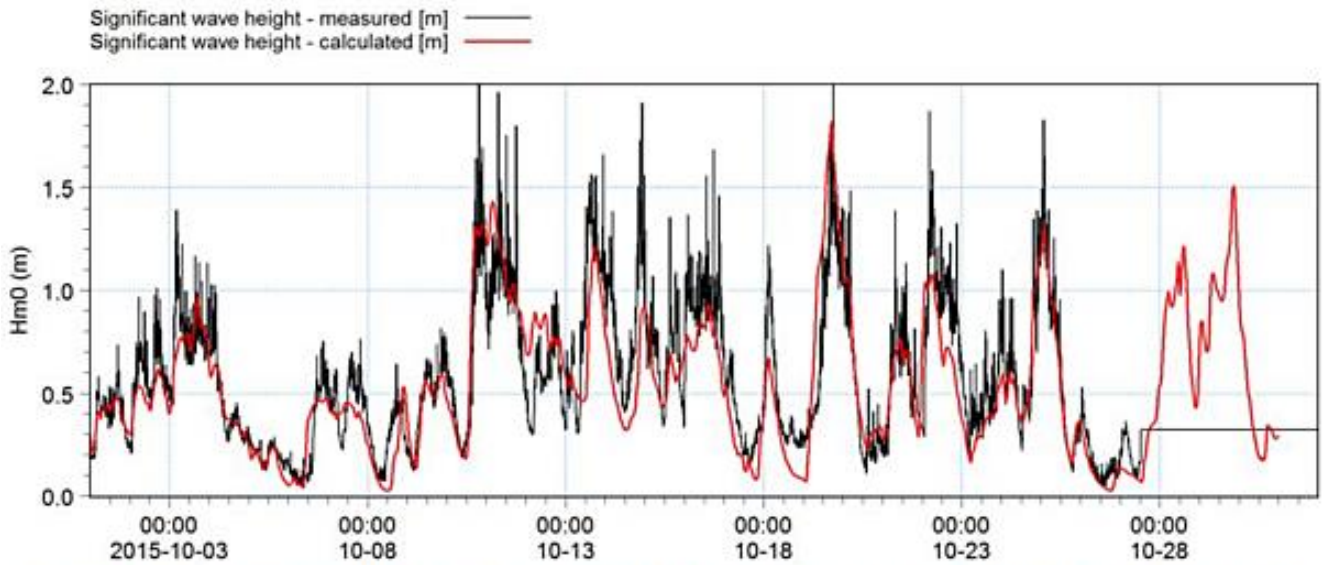

Figure 3-32 Measured (black line) and calculated (red line) significant wave height, peak wave period and mean wave direction at the position of NDBC Buoy 45175. October 2015

Figure 3. Comparison of Measured and Predicted Significant Wave Height at NOAA Buoy 45175

The current velocity probability distributions used in the Monte Carlo simulation intended to calculate the risk of rupture from both spanning and vortex induced vibration are described in the Alternatives Analysis report[17]. Following is a description of these distributions:

Accordingly, an extract of modeled hourly current velocity values over a one-year period was obtained from the bottom layer that corresponded to the position along both the East and West Straits crossing segments with the highest current velocity. These data extracts were used to fit probability density functions describing upper-bound temporal bottom-layer current velocity for both the East and West Straits Crossing segments. For the East segment, a Gamma distribution, having a Shape Parameter of 1.6861 and a Scale Parameter of 0.1051 was obtained, while for the West segment, a Lognormal distribution, having a mean of -2.1623 and a standard deviation of 0.7708 was obtained.

Since it is extreme values of the current velocity that will apply potentially damaging forces to the Straits segments of Line 5, a comparison of actual data with these calculated distributions in the upper tail region is warranted. Figure 4 is a cumulative probability plot of data taken from buoys 45175, LM 01 and the unreported measurements revealed in the Kiefner report with the current velocity fits resulting from the one year duration run of the MIKE 3 model. This figure shows that the tail risk for current velocity between data taken from Buoys 45175 and LM 01 is similar to the risk calculated from the MIKE 3 model for the West Leg of Line 5. The agreement between the buoy data and the MIKE 3 model for the East Leg as well as the Kiefner data is not nearly so impressive. Given that Buoys 45175 and LM 01 straddle the location of the pipeline, are placed in water of similar depths and give quite similar risk results;

the fact that the MIKE3 model gives very different tail risk for these two locations is puzzling. The Kiefner measurements are expected to predict lower velocities because they are apparently three hour average data as opposed to LM 01 which has a one hour averaging period and 45175 which has a ten minute averaging time.

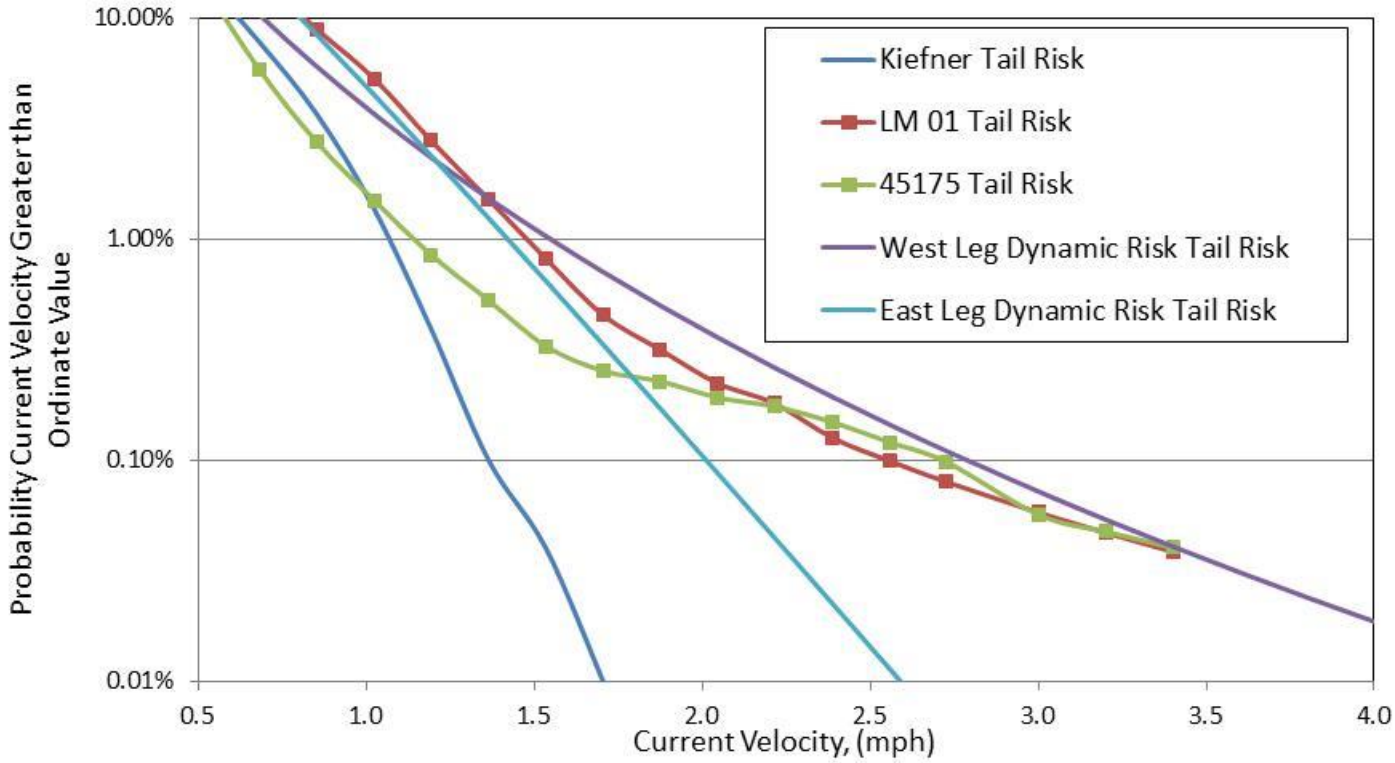

Figure 4. Comparison of the Tail Risk as a Function of Current Velocity

Conversion of the information displayed in Figure 4 into the expected amount of time the current velocity exceeds the Bechtel design basis for Line 5 under the Straits gives a more obvious indication of how the design basis compares with measurement and modeling based results. It should be noted that none of the measured data comes from a particularly stormy year and the model output was specifically restricted to quiescent conditions due to the choice of meteorological forcing conditions.

Table 1. Comparison of the Expected Duration of Currents Exceeding the Design Velocity of Line 5.

Current Velocity, (mph)	Kiefner Duration (hr/yr)	LM 01 Duration (hr/yr)	45175 Duration (hr/yr)	West Leg Dynamic Risk Duration (hr/yr)	East Leg Dynamic Risk Duration (hr/yr)
2.22	0	16	15	23	4

From Table 1, it appears as if the current velocity probability distribution used in the Alternatives Analysis for the West leg Monte Carlo simulation agrees reasonably well with buoy data taken with averaging periods similar to the maximum time step used in the MIKE 3 model. The fit for the East Leg does not agree well and, since both pipes are less than 1200' feet apart, this disparity may be an indication of a violation of the continuity constraint. In

either case, measurements of turbulence intensity as discussed in the Timm[4] report and detailed by Thompson[18] are necessary to truly characterize the instantaneous velocities impacting Line 5. Thompson's work indicates that peak velocities approaching 20% higher than the averaged values are likely to be found in the mesoscale turbulent fluctuations that characterize the flow field in the Straits. Any analysis that does not address this subject, as is the case with the Alternatives Analysis, is suspect as a basis for making a well-informed decision of enormous ecological and economic consequence. Real instantaneous current velocity data taken directly near both legs of Line 5 is a much more robust basis for calculating the risk of rupture of this pipe. The fact that the West Leg current velocity probability distribution derived in the Alternatives Analysis is similar to those used in Timm's analysis leads credence to Timm's thesis that currents that exceed the design basis of Line 5 under the Straits exist and are capable of affecting the integrity of the pipeline.

Unsupported Span Length Probability Distribution

Through a series of Enbridge document releases in compliance with the requests of both the Michigan Pipeline Task Force and the Federal Court negotiating the consent decree settlement over Enbridge's Line 6b rupture, the history of unsupported spans in Line 5 under the Straits has been reconstructed. When the Michigan Conservation Commission negotiated the easement allowing construction across State bottomlands in the Straits, it laid down three conditions that read on unsupported spans and construction practice. These are:

"(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.
(4) The minimum curvature of any section of pipe shall be no less than two thousand and fifty (2,050) foot radius.
(10) The maximum span or length of pipe unsupported shall not exceed seventy-five (75) feet.
(13) In locations where fill is used, the top of the fill shall be no less than fifty (50) feet wide."

The history of unsupported spans on the two legs of Line 5 under the Straits can be divided into five periods as follows:

Period 1, the period starting with the beginning of dredging and construction and ending when each pipe was flooded with water to sink it into the bottom of the Straits. The date of the end of this period for each leg is immediately after the pipes were pulled across the Straits. Reference to the "as built" profile drawings of the pipe resting on the bottom of the Straits do not allow determination of the distribution of unsupported spans immediately following the pipe laying operation but Bechtel engineers realized the freshly laid pipe did not sag into final contact with the dredged bottomland to a degree they found acceptable. Remedial action was required and the evidence supports many violations of the radius of curvature requirement in the easement (4) that was intended to prevent plastic deformation of the pipe as it was placed. Remediation of these long unsupported spans was accomplished by piling clay fill on top of the pipe resulting in many clay piles along the pipe path. At least 15 spans along the West Leg and at least 10 spans on the East Leg were remediated in this fashion. Figure 5 is a photograph of a typical clay pile near the South end of the West Leg location taken from the 2012 underwater

inspection video. Careful review of all of the 2012 inspection video reveals that easement requirement (13) is consistently violated by all observed clay fill piles. Some of these clay piles are quite large with lengths approaching 100' and heights over 20'. They appear to have been placed by dumping the clay chunks onto the pipe perhaps using a hopper barge.

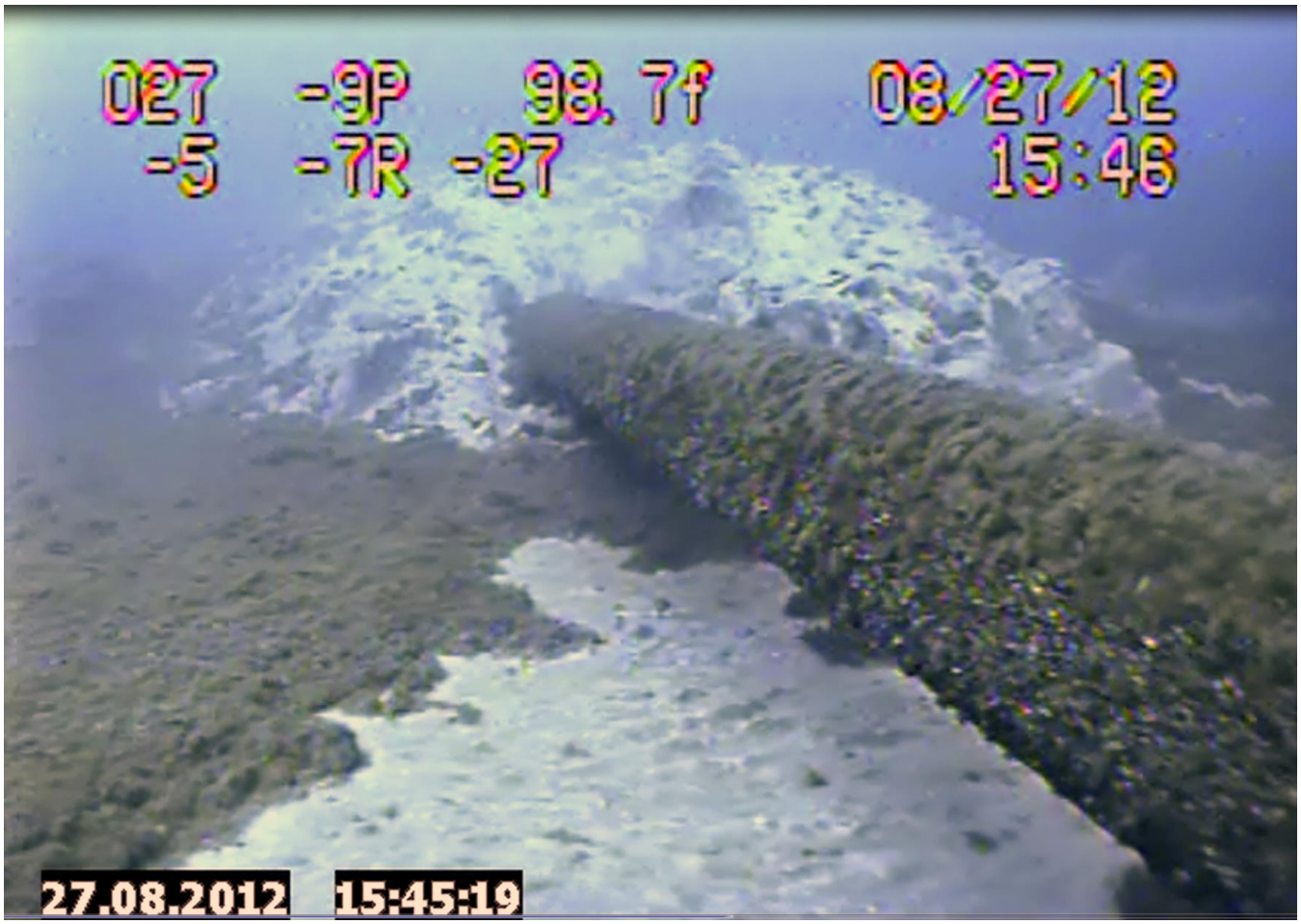

Figure 5. Typical Clay Fill Pile Placed in 1953 to Remediate an Unacceptably Long Unsupported span.

Period 2, the period that ends with the cessation of construction activities in November, 1953. As documented by the "as built"[19,20] drawings of the pipeline's profile that were traced from Bechtel originals in 1964 and updated with information about span distributions and remedial actions through 1979. It can be seen in these drawings that many long unsupported spans remained after the clay dumping operation but the exact distribution of spans following the cessation of construction in 1953 cannot be reliably determined because the updating process for the drawings is not well noted.

Period 3, the period beginning when the as built drawing were updated through 1979 and approved on January 15, 1980. An accurate distribution of unsupported spans can be determined from these updated drawings and a review of this subject is found in the Timm report, Appendix 1[4] and the Supplemental Addendum[6] to the Timm report. As of the beginning of 1980 the unsupported span distribution in Table 2 was determined.

Table 2. Unsupported Span Distribution as of January, 1980

Location	Spans > 75 feet	Spans > 140 feet	Maximum Span
West Leg	10	3	160
East Leg	7	0	90

Period 4 is the period beginning in 1980 and ending in 2003. The Kiefner report[5,] which was issued in 2016 but originally drafted in 2003 and released in draft form to Enbridge in 2005, is the next source of the information about unsupported span distributions. The following brief summary of the number of unsupported spans is taken from this report:

"The 2003 survey identified 7 spans longer than140 feet in the east leg, with the longest being 224 feet, and 9 spans longer than 140 feet in the west leg, with the longest being 286 feet (due to a failed grout bag support)."

Table 3 summarizes this fragmentary information similarly to Table 2.

Table 3. Unsupported Span Distribution as of 2003

Location	Spans > 140 feet	Maximum Span
West Leg	9	286
East Leg	7	224

A comparison of Tables 2 and 3 shows that Enbridge's efforts at span remediation were woefully deficient during the 23 year period beginning in 1980 and ending in 2003. The shockingly long unsupported spans that were allowed to develop during this time period are far beyond the elastic limit of the pipe and permanent bending occurred. According to calculations in the Kiefner report, the 20", Schedule 60 pipe used to construct the twin legs of Line 5 under the Straits will reach full catenary mode where there is no compressive stress along the inside radius of the sagged pipe at a span length of ~190 feet. At an unsupported span length approaching 300' the pipe will sag until it either touches down on the bottom or ruptures. Exact calculation of the failure mechanisms for these very long spans cannot be done because exact information about the material properties of the steel used in the pipe and weld joint efficiency are not available. Most importantly, no data seems to exist that documents the fracture toughness of the steel and welded joints in the Straits sections of Line 5 which means detailed, accurate analysis of pipe rupture mechanics cannot be calculated.

Period 5 of the history of unsupported spans begins in 2003 when Enbridge started a major effort to shore up Line 5. The history of Enbridge's efforts to provide support is shown in Table 4. This table reveals that Enbridge switched from ineffective grout filled bags placed under the pipe to provide support to modern screw anchors in a significant way in 2003. Period 5 runs through 2016. In 2016 Enbridge added four screw anchors to the pipeline and requested a permit to place 22 more anchors in 2017 to rectify developing unsupported spans that were expected to exceed the Easement's 75' limit. At the end of 2016, underwater inspection showed no spans that exceeded the 75' easement requirement.

Table 4. History of Enbridge's Campaigns to Support Line 5 under the Straits

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

Line 5 under the Straits was out of compliance with the 75' unsupported span requirement from the time the pipe was sunk to the bottom until sometime after 2003 when compliance was finally achieved using screw anchor supports. During the period from 2003 until the end of 2016 compliance was sporadic due to the ongoing problem of extreme currents scouring the bottomland from under the pipe leaving washouts. An extensive spreadsheet[21] documenting the span remediation efforts from 2005 through 2016 was released by Enbridge at the request of the State of Michigan.

The two Monte Carlo simulations used in the Alternatives Analysis to estimate the risks of rupture due to spanning and fatigue from vortex induced vibration use span length probability distributions for each leg based on data from the period 2005 through 2016 found in Reference 21. Following is a description of these distributions as taken from the Alternatives Analysis[22].

"Span Length Distribution
Based on a review of information obtained from seven underwater inspections of the East and West segments spanning the years 2005 – 2016, it was observed that the lengths of individual spans change over time. [82] While the terms and conditions of the April 23, 1953 Straits of Mackinac Pipeline Easement limit allowable span length to 75 ft., and maintenance activities have been undertaken to maintain span lengths to less than that limit, span lengths have varied both below and above that limit over time. Therefore, for modeling purposes, it would be non-conservative to assume that span

lengths will be limited to 75 ft. on a go-forward basis. Instead, the results of the seven inspections performed between 2005 – 2016 were used to generate separate span length distributions for each of the East and West segments. A total of 715 separate span length measurements were used to generate a span length distribution on the East segment, and 691 separate span length measurements were used to generate a span length distribution on the West segment. In both cases, Weibull distributions were found to provide the best fit to these data."

Figure 6 is a plot of the probability a span will be greater than a given length for both legs. At the scale of Figure 6, the fitted Weibull cumulative probability distributions appear to be identical.

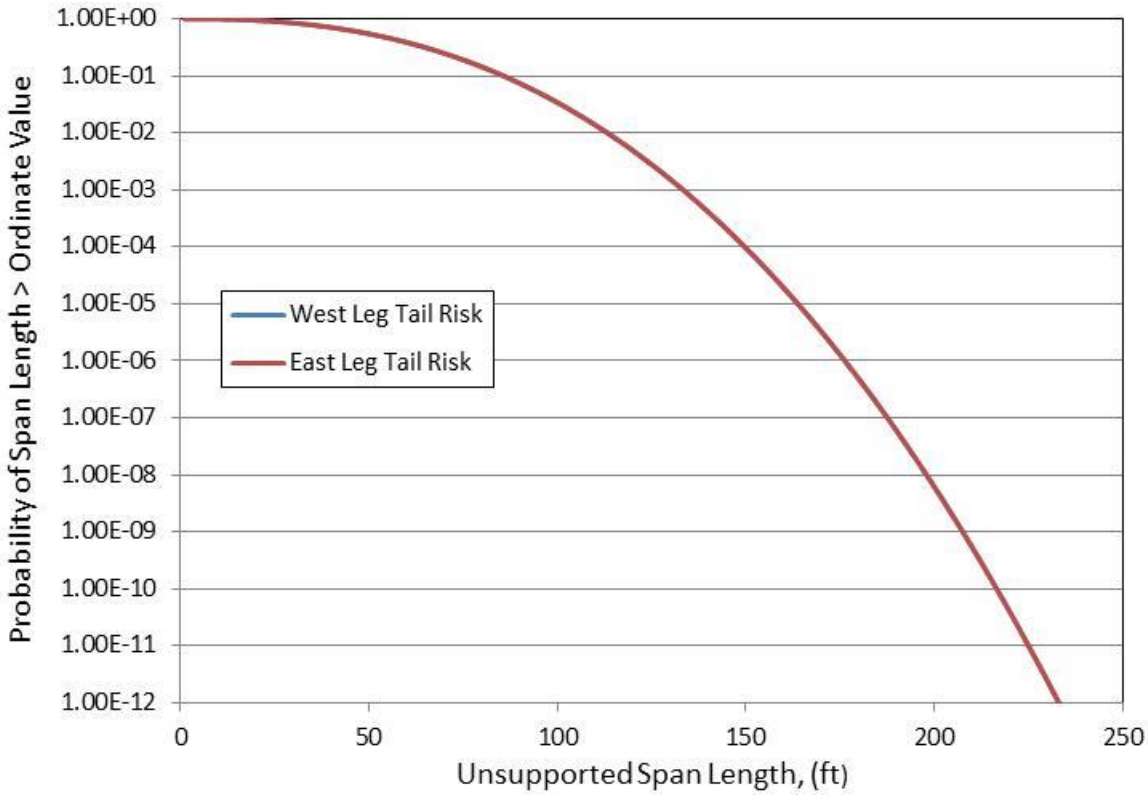

Figure 6. Probability an Unsupported Span is Longer than Ordinate Value for East and West Legs of Line 5 for the Period 2005-2016

These distributions are a very good fit to the span data revealed in Reference 21 but when used in a Monte Carlo analysis to estimate risk, the authors of the Alternatives Analysis appear to have made a serious mathematical error. The 715 East Leg span length measurements and the 691 West Leg span length measurements result from pooling data taken during inspections in 2005, 2006, 2007, 2010, 2012, 2014 and 2016. Each individual dataset contains a differing number of spans both because of new washouts and the addition of new supports. This means that while the distribution functions plotted above may be relatively time invariant over the period 2005-2016, the ensemble of spans existing during each time interval between inspections is different. Because a random selection of current velocity in the Monte Carlo impacts all the spans in an ensemble, each span in that ensemble must be tested for the failure criteria not just one randomly selected span. Because extreme current events are quite rare but each such event tests a large number of spans, multiple failures may occur for each

random current velocity selection. **This physical fact results in a much larger number of failures than the Monte Carlo implementation apparently done in the Alternatives Analysis and the estimates of risk derived from this analysis are erroneously underestimated by a large margin!** This problem affects both the spanning risk Monte Carlo and the vortex induced vibration Monte Carlo analysis

Although the ensemble error mentioned previously is a disqualifying error, it is much less serious than an erroneous assumption that also greatly biases the rupture probability estimates for the Straits sections of Line 5. Assuming the ensemble error was fixed by developing representative span length ensembles for each period data is available and completing a correct Monte Carlo analysis, there is a problem with the failure criteria used in each iteration of the analysis. For both the spanning analysis and the vortex induced vibration analysis, the failure criteria requires knowledge of material properties that are affected by the fatigue history of the span of pipe being examined. Following is a short discussion of both spanning and VIV failure mechanisms.

As discussed in the Timm report, the bidirectional nature of the currents in the Straits raise the possibility that a long span may well be bent back and forth by the currents causing low cycle, high strain fatigue damage to the pipe. Therefore, it is necessary to know the stress-strain history of the pipe in order to know if the pipe is close to its fatigue limit. A heavily fatigued pipe may well fail at a stress well below the elastic limit of virgin material so the failure criteria must take into account what has gone before. Similarly, the vortex induced vibration failure criteria is based on the number and severity of vibratory cycles. Again, the analysis must start from a time when the material in the pipe has zero fatigue cycles so that cycles can be accurately counted as the fatigue failure limit is approached.

From the preceding discussions, one problem with the Monte Carlo risk estimates in the Alternatives Analysis is that they don't start from the pipeline's construction in 1953. Instead, Dynamic Risk assumes the material making up the pipe is in virgin condition when they start their analysis in 2018 and use it to predict a risk of rupture extrapolated to 2053. In fact, the pipe has endured five different periods of spanning history with each adding its quanta of damage as the years pass. Essentially, Dynamic Risk has chosen to ignore the first 50 years of Line 5 under the Straits history, a history that includes little or no span maintenance with spans growing to at least 286', and then begins its calculations starting in 2018 assuming virgin material properties. Any risk estimate based on this methodology is so erroneous an equally accurate estimate could be produced using black cat bones and fuzzy dice! A correct Monte Carlo risk estimate would require doing separate year by year analyses each featuring a realistic current velocity distribution, span length probability distribution and number of spans. This would result in over sixty different Monte Carlo risk estimates which could be added up starting in 1954 to the current date then projected forward to get a realistic estimate of risk for any year in the future.

A very simple risk estimate for the whole of the underwater section of Line 5 can be done based on the average failure rate for all DOT 195 pipelines from all causes. This risk is given as 0.89 failures/(1000 mi * yr)[23]. Using this figure, the risk of failure for the 8.15 miles of twinned lines under the Straits gives a failure rate of $7.25*10^{-3}$ per year. Adding up the failure probability on a yearly basis gives the 2017 failure probability at 46.4% and the 2053 failure probability at 72.5%. These figures are very different from the Alternatives Analysis estimate

of 1.6% by 2053. This means that Line 5 under the Straits is 45 times safer than a typical buried DOT 195 pipeline, a conclusion that defies sense.

Evidence of Damage to Line 5 under the Straits

The Monte Carlo analysis spanning risk failure criterion is when the combined stress in the pipe reaches the elastic limit. Quoting from the Alternatives Analysis[24]:

"For the purposes of the analysis, the probability of failure was defined as the fraction of simulations in which the Von Mises maximum combined effective stress exceeded yield stress. This condition was selected as a failure criterion because although there is ample strain capacity beyond yield (and therefore, failure does not occur when the maximum combined effective stress reaches yield stress), it defines the onset of plasticity. In a dynamic environment, characterized by changing water currents, span lengths and gap ratios, there is potential for the maximum combined effective stress to vary with time in a repetitive manner, as the variables that control the stresses vary over time. Under such conditions, the potential for plasticity creates the potential for plastic fatigue, under which conditions, progression to failure can occur after relatively few cycles."

The unpredictability of what happens next once a structure reaches its elastic limit is why engineers rarely design a structure where stresses approach plasticity. An example of plastic failure in Line 5 under the Straits appears to have been discovered through careful comparison of Enbridge and other documents.

If the theory proposed by Timm that extreme currents have structurally compromised Line 5 under the Straits is correct, there should be evidence of post construction plastic deformation of the pipe. This evidence would not be found in MFL or ultrasonic inspection records but should be discernable in inspection records of the physical location of the twin legs. Plastic deformation caused by currents and gravity would result in bends and in extreme cases ovaling of the pipe. Following are two statements taken from the Alternatives Analysis[25] that reveal the existence of such features.

"The analysis of inertial data identified 20 bends on the East Crossing and 23 bends on the West Crossing with an angle larger than 1.5° and a radius of curvature less than 100x diameter. There were no bends on either crossing segment that were characterized as tight (having bend radii of 5x diameter or less).
Of the 20 bends on the East Crossing, only two (BND 10 and BND 11) were located in the portion of the pipeline where the pipeline was installed on top of the lakebed; the rest were located in the trenched portions of the crossing. Of the 23 bends on the West Crossing, only 5 (BND 9 to BND 13, inclusive) were located in the portion of the pipeline where the pipeline was installed on top of the lakebed. While it was not possible to determine the origin of each bend, it is likely that bends located on the onshore portions of the crossing are field or factory bends that are part of the design. The remainder of the bends may have been intentionally or unintentionally created as part of the installation process."

"In the West Straits Crossing segment, two features (both ovalities) were identified that exceeded the reporting criteria. One ovality had a maximum deflection of 8.75% nominal

OD, and the other had a maximum deflection of 5.45% nominal OD. While significant ovalities can, under certain circumstances impair the passage of in-line inspection tools, the strain associated with these features is normally broadly distributed around the pipe circumference, and thus, ovality is not generally considered to be a feature that poses an integrity threat."

The Alternatives Analysis states that the bends found in the exposed underwater sections of the pipe (Bends 10 and 11 in the East Leg, Bends 9 through 13 on the West Leg) are of unknown origin but "may have been intentionally or unintentionally created as part of the installation process." This statement is speculation on the part of the authors of the Alternatives Analysis and potential evidence of damage should not be dismissed without a full examination of the evidence.

Information from three sources has been pooled in order to investigate the cause of damage to the exposed lakebed portion of the West Leg of Line 5. Figure 7 is a composite drawing of the area where Bends 9-13 are located. The 2016 profile view of this section of the pipe is taken from Figure 5 in the Biota[26] report, the 1979 profile view[20] was released by the Michigan Pipeline Task Force and the geometric inspection information is taken from the 2013 Baker-Hughes Geopig[27] geometry inspection report. Figure 7 shows the locations of the five bends and two ovals found by Baker-Hughes on the bottom profile view taken from the Biota report. Four of these bends are within a 250' section of pipe and the two ovals are both the result of bending as shown by their coincidence with Bends 11 and 12. Both ovals have primary axes that do not coincide with the vertical direction and all bends have a lateral component as well as a vertical component. These features are not consistent with "sag bends" that form as a pipeline is sagged into place along a poorly graded path but rather appear to have been bent both vertically and laterally which is what would be expected if they had been formed by the combined forces of gravity and currents. It is exceedingly unlikely that these bends were formed during construction since the pipe was pulled along the bottom of the Straits using great force, a process that would insure a straight path. These bends are not mentioned on the 1979 profile drawing of the pipe which includes many notes about the condition of the pipe at that date.

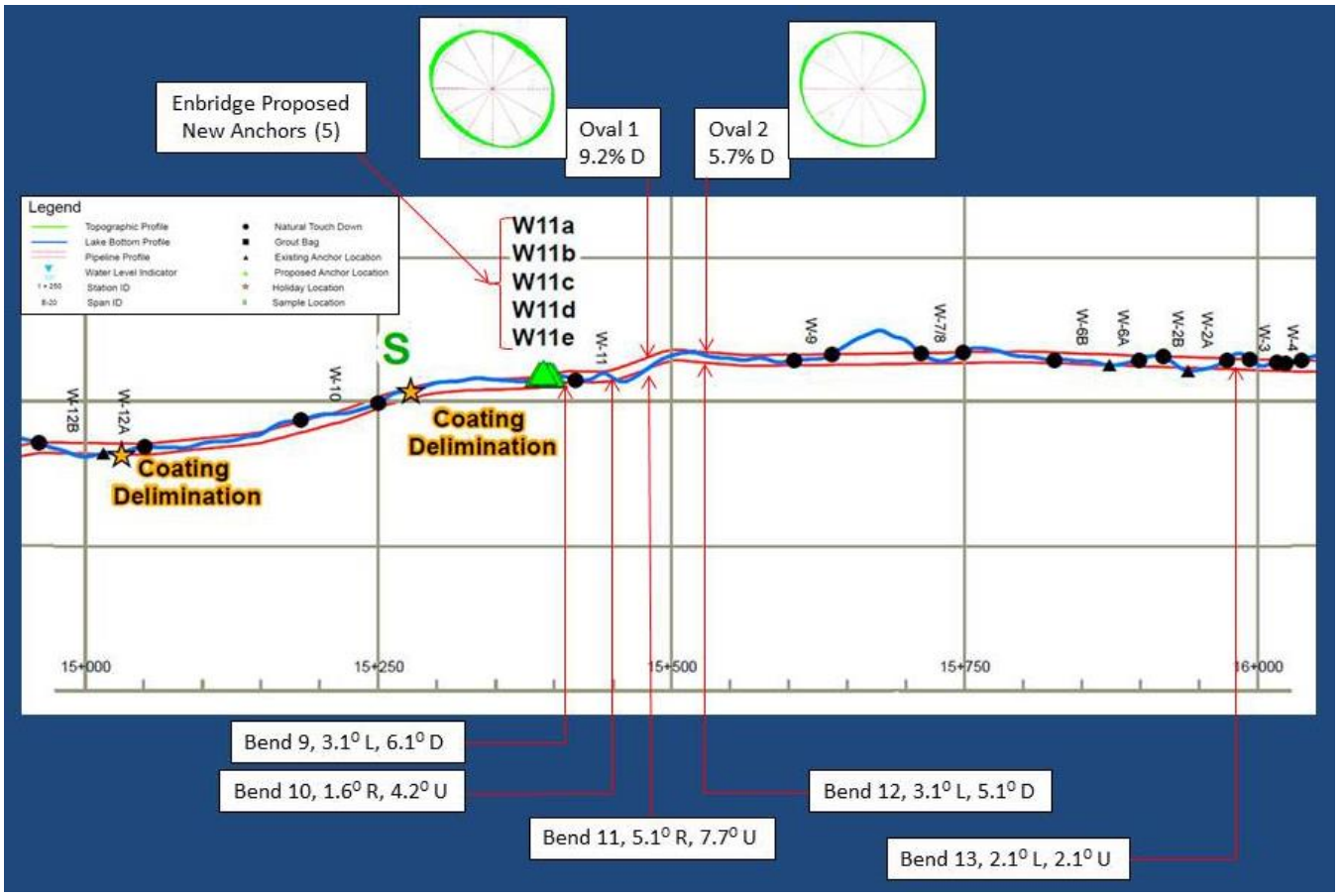

Figure 7. Overlay of Pipe Deformation Information from the 2016 Baker-Hughes Geopig Inspection on Figure 5 from the Biota Report.

A more probable explanation than the one given in the Alternatives Analysis for the existence of these features can be found in Figure 8. In Figure 8, the top drawing is the 2016 bottom profile which has been flipped end to end so that south side of the Straits is oriented to the left similarly to the 1979 profile drawing. Both profile drawings have been stretched horizontally and vertically so that they are scaled similarly. Additionally, using the 1953 Lake Michigan water level datum of 581 feet elevation allows depths to be compared and the 70' depth level is plotted on both profiles. The profile drawings have been offset to compensate for the differences between the Bechtel chainage length scale used in 1979 and the absolute length scale used in 2016.

The green dotted line on the 2016 profile drawing labelled "2016 Average Grade" has been carefully transferred to the 1979 profile drawing. The light blue area marked "Scour" on the 1979 drawing shows the volume of bottomland that appears to have been scoured away between 1979 and 2016. The obvious interpretation of Figure 8 is that the washouts noted in the 1979 drawing appear to have merged into one long span (~300 feet) sufficiently long to have caused the pipe to collapse to the bottom profile shown in 2016 bending it and ovaling it in the process.

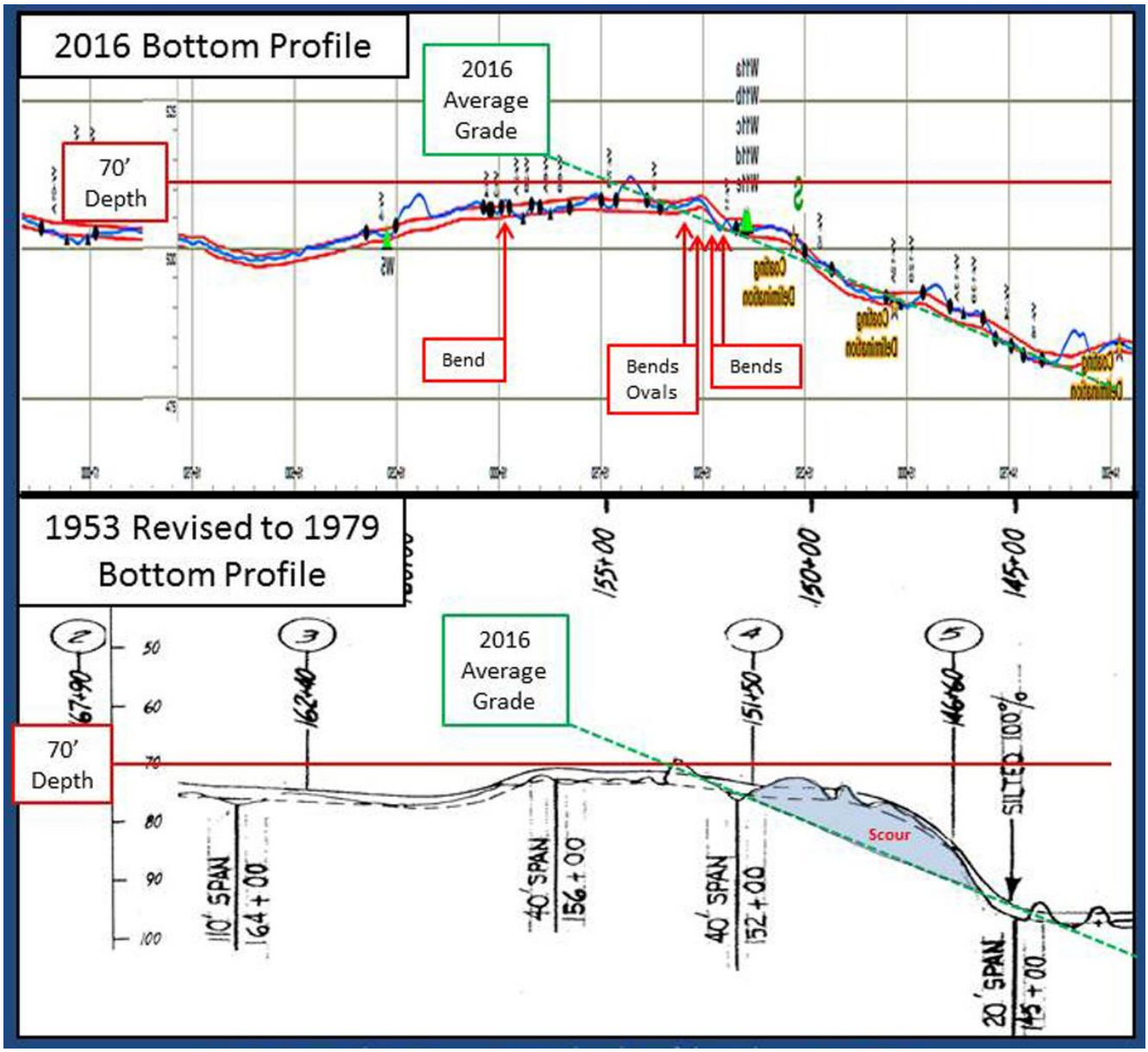

Figure 8. Comparison of West Leg, South End Lake Bottom Profile Drawings from 1979 and 2016

Given the long geometric in line inspection history that begins in 1987 as detailed in Table 2 of the Enbridge Operational Reliability Plan[28] and access to Enbridge's archives of Bechtel's construction documentation, it should be a simple task for Dynamic Risk to prove the speculative assertation made in the Alternatives Analysis that the bends and ovals found in the West Leg are a result of construction. Lacking such proof, the alternative hypothesis put forward here, that these bends and ovals are evidence of periodic uncontrolled bending due to the forces of gravity and currents, becomes very reasonable. A further argument follows.

In 2016, Enbridge applied to the State of Michigan for a construction permit[29] to place a number of new screw anchor supports on Line 5 under the Straits because of unsupported spans detected during the 2016 underwater inspection. Of the requested 22 new screw anchor supports, four were required to remediate spans over 75' and the rest were to be

placed prophylactically to prevent ongoing washouts from growing into excessive spans. As can be seen from Figure 7, five of these supports (W11a-W11e) are to be placed in the area of the pipe where bends and ovals exist. Enbridge's support permit application makes no exceptional mention of these supports in their support permit request. A clip from a recent Enbridge spreadsheet that details the span history of Line 5 provides some detail on the W11 span and is shown as Table 5.

Table 5. Span History of the W11 Span Dating from 2005

* All Measurments given in feet* Span Identifier	2016 Length	2016 Span Height (Approximate)	2016 Support Length	2014 Length	2012 Length	2010 Length	2007 Length	2006 Length	2005 Length
W-11	52	2.5	107 to W-9^	48	52	47	40	46	49

Touch Down Position and Type (Year Install)	Support Depth	Notes	Anchors Proposed in 2016 (not yet installed)
South/Sand	75	Install anchors to support deflection area just south of span W-11	5
North/Sand	80		

This information about the W11 span shows that no span over 52 feet exists and there does not seem to be progressively increasing span length warranting additional support. However, it is noted in the comments column of the spreadsheet that Table 5 is taken from: "Install anchors to support deflection area just south of span W11". That five anchors are being planned for installation in an area of the pipe suspected of damage but without excessive spans requires explanation and lends credence to the theory that Line 5 under the Straits was damaged due to the forces of gravity and currents sometime after construction. This conclusion is consistent with the findings of the Timm report[4] and the Supplemental Addendum to the Timm[6] report that incorporates the findings of the Kiefner report[5].

Other Subjects of Concern Raised by the Alternatives Analysis

Girth Welds and Welding Practice

Although the Straits sections of Line 5 had their girth welds inspected both visually and by gamma ray radiography, questions remain about the joint efficiency of the welds produced using 1950's technology. The Alternatives Analysis[30] states:

"In the February 06, 2016 tethered PipeScan / WeldScan Inspection Report for the West Straits Crossing, it was noted that the girth welds displayed significant amounts of porosity, slag and lack-of-fusion, typical of vintage manual welding. There were two indications that exceeded the above reporting thresholds."

A similar revelation is made about the East Leg. Although the Alternatives Analysis goes on to dismiss concerns about the quality of the vintage girth welds in Line 5, the lack of data concerning these welds makes these conclusions suspect. No data has been publically released about the testing procedures used to qualify welds or the mechanical properties of the welds such as tensile properties or fracture toughness. Without this information, it is impossible to accurately model the processes where a departure from elastic behavior into plastic behavior can result in tensile failures and fatigue damage. Of particular concern are the

girth welds used to join the 2500' pipe strings during the operation where the line was actually pulled across the Straits. Another subject of concern is whether the pre-welding preheat procedures discussed in some of the early documentation about Line 5 were actually implemented. Given the importance of girth weld integrity and the fact that poor girth welding techniques have led to problems with many vintage pipelines, a full examination of the knowledge base concerning Line 5 welding procedures including the examination of testing data from weld qualification samples is necessary to assure the models of Line 5's structural integrity are realistic.

Coating Integrity and Cathodic Protection

Both the Timm report and the Biota report document the fact that the coating system on the Straits sections of Line 5 are deteriorating with sheets of the fiberglass wrap intended to protect the base coating from abrasion delaminating from the base coating. Enbridge has contended that the base coating on Line 5 maintains its integrity and offers as proof cathodic protection surveys from Baker-Hughes that show very little current is flowing through the cathodic protection system that applies electrical polarization to the pipe. A review of Baker-Hughes literature offers no insight into the sensitivity of the Baker-Hughes CPCM™ inspection tool or this unique use of the tool to inspect an underwater pipeline submerged in low conductivity fresh water. An investigation into the sensitivity and limits of detection for a coating holiday using this inspection tool is necessary before drawing the conclusion that a newly developed inspection methodology used on a unique pipeline in an unusual environment proves anything at all about the integrity of the coating. Although numerous MFL inspections of the Straits sections of Line 5 have been conducted that show little metal loss corrosion it should be noted that MFL technology has a limit of detection for metal loss of about 10% of the wall thickness of the pipe. Because of the extremely thick walls of Line 5 (0.812"), this limitation means that corrosion damage of 0.080" is the detection threshold in this situation and significant metal loss and pitting could exist just below the detection threshold of MFL inspection technology. Further information will be available regarding corrosion and the condition of the coating on Line 5 under the Straits following the completion of the ongoing Biota[25] report.

Thermal Expansion and Pipe Movement

The Kiefner report[31] goes into great detail in the examination of a subject that is barely addressed in the Alternatives Analysis. The oil pumped under the Straits is warmer than the surrounding underwater environment. This means the pipe expands when oil is pumped into the pipe after it has been shut down for long enough to cool and vice versa. The temperature swing that occurs is on the order of 20-30 ^{o}F and the total longitudinal expansion of the unburied sections of line 5 under the Straits is around four feet. In its original conception, this thermal expansion was accommodated by the bends that naturally occurred during the pipe laying process which prevents the buildup of compressive stress and buckling. Now that the pipe is rigidly supported by screw anchor supports for long distances, the question of how thermal expansion stress will be accommodated in this new configuration becomes relevant. Quoting from the Kiefner report:

"An analysis of the deflection and stresses in the spans considered that the pipes are in a state

of compression caused by differential thermal expansion due to the crude oil product in the pipe being warmer than the water temperature of 40 F. This led to the finding that spans must exceed 120 ft in length in order to fully relieve the thermal compression. Longer spans develop catenary behavior from the thermally relieved sag configuration, with resistance to additional vertical sag developed through increased axial tension rather than additional bending stress. In fact, recognition of this phenomenon led to greater allowable spans than would be the case without any initial thermal compression on the pipeline. It follows that if the flow is shut-in for a sufficiently long period of time prior to the span correction, the lines would cool to the ambient water temperature and the thermal compressive stress would be lost. This would result in more tension in the spans and reduced sag. If the supports were to be installed with the line in this condition, then when product flow is restored and the pipe warms to the product temperature, the supports would become loaded by the additional sag induced by thermal expansion of the pipe.

It should be noted that the analysis also showed that without thermal expansion, spans of 140 ft are at the limit of acceptable lengths based on traditional Code stress criteria. This means that after cooling down, the existing long spans that are currently safe but longer than the 140-ft service lengths Enbridge plans to allow, would then be in excess of acceptable stress limits for the period of time between when the line cools down and when the supports are installed. It is likely that the longest spans could experience longitudinal stresses in excess of the yield strength. There are a number of reasons why this is probably not a real structural integrity concern but the safety margins are difficult to quantify with the information available. Thus shutting in the lines while they are full of product is not recommended even though doing so would lead to more effective span support."

Clearly, thermal expansion accommodation in Line 5's new, supported configuration becomes a problem as the number of supports is increased. The Kiefner report suggests that the pipe sag between supports may help accommodate thermal expansion stress but it assumes the supports are perfectly rigid. In fact, the supports which are adequately strong to support the weight of the pipe are quite flexible laterally compared to the forces that can develop due to thermal expansion. Since the supports are clamped rigidly to the pipe it is also possible that the supports could be bending laterally due to thermal or other forces. Figure 9 shows images clipped from the 2012 and 2016 underwater inspection videos that appear to prove that lateral flexion of the pipe supports is occurring.

The images in Figure 9 raise serious concern about the long term prospects for screw anchor supports that are flexed laterally, a condition they were not designed to accommodate. Insufficient information exists to properly assess the magnitude of this threat but the fact that the Alternatives Analysis does not recognize this phenomena as a potential cause of excessive stress on Line 5 under the Straits is a serious omission.

Also omitted from consideration in the Alternatives Analysis is a previously undiscussed mechanism affecting the integrity of the pipe. As significant lengths of pipe are supported off the bottom in a long assemblage, current forces induce an overturning moment on the whole structure. This moment must be resisted by a combination of lateral forces from the pipeline supports plus and increase in tension in the pipe as the whole assemblage tilts out of plumb in response to current drag force. How serious this problem becomes, with the result of uprooted/bent pipe supports and unknown tensile forces in the pipe, as more and more

supports are added requires analysis. Failure to address this unanalyzed integrity threat as well as the difficult subject of thermal expansion stress accommodation are further reasons to suspect the conclusions of the Alternatives Analysis.

Looking West Looking East

Figure 9. Images of Laterally Deflected Screw Anchor Supports from 2012 (left) and 2016 (right) Underwater Inspection Videos. Images are believed to be of two different anchors.

Conclusions and Recommendations

The Alternatives Analysis authored by Dynamic Risk, Inc. is a complex work that incorporates risk modeling, oil spill dispersion modeling and economic analysis in an effort to provide insight into alternatives to Line 5 under the Straits as well as estimate the risk of operating Line 5 as is. My Technical Note, "An Analysis of Errors and Omissions in the Dynamic Risk, Inc. Line 5 Alternatives Analysis, Option 5", attempts to address some of the shortcomings that make sections of the Alternatives Analysis incorrect. Errors and omissions in the analysis of the rupture risk associated with Line 5 under the Straits affect conclusions drawn about the condition of this critical pipe and in the comparison of Option 5 to other options. Among the errors and omissions discussed here are:

1. A conceptual mathematical error in the construction of the Monte Carlo risk analyses that results in risk estimates orders of magnitude less than would be estimated using a properly constructed analysis.

2. A non-existent understanding of the bidirectional mesoscale turbulent flow field in the Straits and how averaged current data under-predicts the peak current velocities,

3. Failure to take into consideration the very long unsupported spans that evolved over the first fifty years of the line's lifetime and the possibility that these spans were fatigued and otherwise damaged by the combination of bidirectional currents and gravity,

4. The use of an unproven hydrodynamic model with an inappropriate choice of input meteorological forcing data to derive current velocity extremes impacting the unsupported spans of the pipeline,

5. The use of material property information appropriate for virgin pipeline steel in the simulations of spanning and vortex induced vibration risk even though evidence shows the pipe has experienced fifty years of neglect and abuse,

6. Failure to consider integrity threats that result from the addition of supports to a pipeline designed without support. Thermal expansion stresses and assemblage overturning moment forces resulting from the pipelines new configuration require consideration, analysis and quantification before they can be dismissed as insignificant threats to the integrity of Line 5 under the Straits.

The Alternatives Analysis is a very complex work that incorporates a great deal of good information and calculation concerning the alternatives to Line 5 as it exists today. Unfortunately the errors and omissions in the analysis of the risk associated with the “do nothing” Option 5 compromise many of the conclusions of the Alternatives Analysis making the document as a whole a very flawed work. In general, the plethora of questionable assumptions and unsupported conclusions found in the sections of the Alternatives Analysis intended to support the fitness for service of Line 5 under the Straits, raise questions about the lack of intellectual curiosity and objectiveness necessary for this kind of work to be credible. As a result of these errors and omissions, at a minimum, it is recommended that an interdisciplinary group of technical experts drawn from a range of industry and non-industry sources be assembled to recommend a path towards a robust examination of the future fitness for service of Line 5 under the Straits.

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