Final Report

Evaluation of the Anchor Strike Risk Reduction System for the Line 5 Crossing of the Mackinac Straits

C-FER Technologies
A SUBSIDIARY OF ALBERTA INNOVATES

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Confidential to
Enbridge Energy, Limited Partnership

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Reviewed by
Mark Stephens, MSc, PEng

September 2020
M303

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Date 30-SEP-2020

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PROJECT TEAM

Evaluation of the Anchor Strike Risk Reduction System for the Line 5 Crossing of the Mackinac Straits	C-FER Project: M303	
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REVISION HISTORY

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EXECUTIVE SUMMARY

C-FER Technologies (1999) Inc. ("C-FER") was engaged by Enbridge Energy, Limited Partnership ("Enbridge") to update a previous assessment that evaluated the implications of using damage prevention measures to manage the potential for pipeline failure due to anchor strike for the Line 5 crossing in the Straits of Mackinac (herein referred to as "the Straits"). This study provides revised estimates of the annual failure rate for the crossing to reflect changes to the damage prevention measures analyzed in the previous study and to account for new preventative measures introduced since. The revised failure rate was calculated for both intentional anchor deployment by a vessel in response to an emergency situation and unintentional deployment by a vessel due to equipment failure or human error. The new preventative measures, collectively referred to here as the “coordinated anchor strike risk reduction system”, are primarily intended to reduce the failure rate due to unintentional deployment.

As with the previous study, the approach adopted in this study involved the use of quantitative fault tree analysis to estimate the probability of pipeline failure due to anchor strike. A fault tree is a deductive analysis model that identifies the logical combinations of basic events leading to the main accidental event being analyzed. In this study, the main accidental event of interest is failure of the pipelines at the crossing location due to anchor deployment. The events leading to this include:

- The deployment of an anchor from a vessel in proximity to the pipelines,
- The failure of measures to prevent anchor deployment,
- The conditions under which a deployed anchor will interact with the pipelines,
- The failure of measures to prevent interaction between the anchor and the pipelines, and
- The conditions under which interaction between an anchor and the pipelines will lead to pipeline failure.

A separate fault tree analysis was performed for unintentional and intentional anchor deployment. Information used to construct the fault tree and assign probabilities to the basic events included the operational protocols and history of the coordinated anchor strike risk reduction system to date, as well as public information collected on weather conditions, human error and equipment reliability. Where this information was insufficient, a formal expert opinion solicitation process was used to reach consensus-based estimates of selected event probabilities from maritime navigation consultants.

The calculated annual crossing failure rates attributable to both intentional and unintentional anchor deployment, before and after implementing the new preventative measures, are provided in Table 1 for three analysis cases.

The first analysis case establishes the annual crossing failure rate expected if no preventative measures were implemented, which was used as a baseline for comparison purposes.

The second analysis case considers the effect on failure rate of the Vesper Marine Guardian:protect system, which was first analyzed in the previous study and then revisited in this study. This system sends advisory messages to vessels entering the Straits and vessels displaying an intent to anchor near the pipelines. This damage prevention system is shown to reduce the total estimated pipeline crossing failure rate by 74% from 7.36×10^{-4} to 1.94×10^{-4} per year.

The final analysis case considers the combined effect of the Guardian:protect system and the new preventative measure that was the primary focus of this study, which consists of a coordinated anchor strike risk reduction system that monitors vessel traffic in the Straits, conducts visual observations of the vessels and communicates directly with the vessels over radio. Under this system, vessel communications include messages that advise vessel operators of the presence of the pipelines and requests that the vessel operators confirm that their anchors are secured. Visual observations of the vessels are made from patrol boats or from shore-based crews to confirm that the vessels do not have an unintentionally deployed anchor. Implementation of this additional damage prevention system, along with the Guardian:protect system, is shown to reduce the total estimated pipeline crossing failure rate by over 99% to 3.41×10^{-6} per year.

With the combined Guardian:protect and coordinated anchor strike risk reduction systems in operation, the total annual probability of pipeline failure at the crossing location was shown to be dominated by the contribution from unintentional anchor deployment, which accounts for 81% of the calculated annual crossing failure probability. Advisory messages, sent via the Guardian:protect system and radio communications, were found to be equally as effective as visual observations of anchor status in preventing unintentional deployment. Explicit requests to confirm anchor status sent to all vessels was found to have the largest effect on the overall failure rate by reducing the failure rate due to unintentional deployment by 94%.

Analysis Case	Failure Rate due to Intentional Anchor Deployment (per year)	Rate Reduction (% of no measures)	Failure Rate due to Unintentional Anchor Deployment (per year)	Rate Reduction (% of no measures)	Failure Rate due to Combined Anchor Deployments (per year)	Rate Reduction (% of no measures)
No preventative measures	1.27×10^{-6}	-	7.35×10^{-4}	-	7.36×10^{-4}	-
Guardian:protect advisory messages only	7.82×10^{-7}	38.0	1.93×10^{-4}	73.7	1.94×10^{-4}	73.6
Guardian:protect advisory messages and the coordinated anchor strike risk reduction system	6.70×10^{-7}	47.2	2.74×10^{-6}	99.6	3.41×10^{-6}	99.5

Table 1 Line 5 Crossing Failure Rates and Effect of Preventative Measure

1. INTRODUCTION

1.1 Terms of Reference

C-FER Technologies (1999) Inc. ("C-FER") was engaged by Enbridge Energy, Limited Partnership ("Enbridge") to update a previous assessment (1) that evaluated the implications of using damage prevention and protection options to manage the potential for pipeline failure due to anchor strike for the Line 5 crossing at the Straits of Mackinac (the "Straits").

1.2 Objectives

The specific objectives of this study were:

1. To review and update the inputs to the previous assessment to ensure alignment with current preventative measures.
2. To evaluate the additional reduction in failure probability expected to result from the creation and operation of a coordinated anchor strike risk reduction system (the "Coordinated System") that includes land- and water-based observations of, and direct communication with, vessel traffic passing through the Straits 24 hours per day (2).

1.3 Analysis Approach

As with the previous assessment, the approach adopted in this study involves the use of quantitative fault tree analysis to estimate the probability of pipeline failure due to anchor strike. A fault tree is a deductive analysis model that identifies the logical combinations of *basic events* leading to the main accidental event being analyzed (referred to as the *top event*). Construction of a fault tree is a top-down process in which the top event is identified and related to the events that contribute directly to its occurrence (called *intermediate events*). Each intermediate event is then related to its direct contributors until the basic events are reached at the bottom of the tree. A simple conceptual example of a fault tree is shown in Figure 1.1.

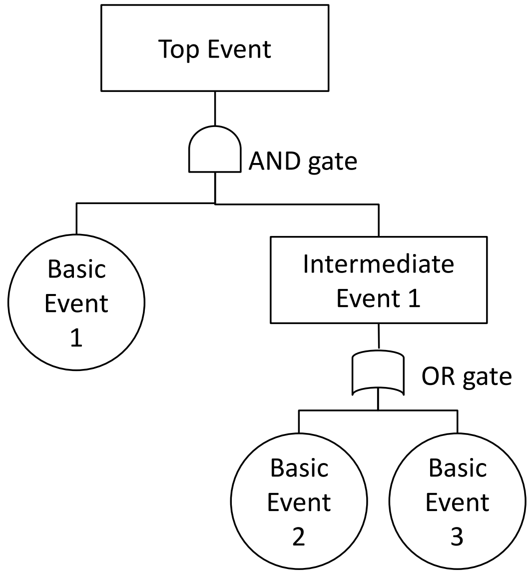


Figure 1.1 Fault Tree Structure and Notation

The two main types of event interactions considered in fault trees are:

- The OR relationship, which means that the occurrence of one or more events could cause the output event to occur. For example, in Figure 1.1, the occurrence of either Basic Event 2 OR Basic Event 3 is sufficient for Intermediate Event 1 to occur (and the probability of Intermediate Event 1 is equal to the probability of Basic Event 2 plus the probability of Basic Event 3[1]).
- The AND relationship, which means that a number of events must occur together for the output event to occur. For example, in Figure 1.1, both Basic Event 1 AND Intermediate Event 1 must occur for the Top Event to occur (and the probability of the Top Event is given by the probability of Basic Event 1 multiplied by the probability of Intermediate Event 1[2]).

If the basic events relevant to the occurrence of the Top Event can be identified and their relationships established, and if the probability associated with each basic event can be estimated, then the fault tree can be used to calculate the probability of the Top Event (in this application, the probability of pipeline failure due to anchor strike). It is noted that, if one of the top-level basic events in the fault tree is linked to the Top Event via an AND gate (e.g. Basic Event 1 in Figure 1.1) and that event is defined as an annual rate of occurrence (rather than a probability), the Top Event

[1] This additive relationship is strictly correct only for events that are mutually exclusive.
[2] This multiplicative relationship holds for events that are independent.

is similarly quantified in terms of its rate of occurrence (in this case, the frequency of pipeline failure due to anchor strike).

In the present application, the events leading to the Top Event include:

- The deployment of an anchor from a vessel in proximity to the pipeline,
- The failure of measures to prevent anchor deployment,
- The conditions under which a deployed anchor will interact with the pipeline,
- The failure of measures to prevent interaction between the anchor and the pipeline, and
- The conditions under which interaction between an anchor and the pipeline will lead to pipeline failure.

2. EFFECT OF THE GUARDIAN:PROTECT SYSTEM

2.1 Overview of Previous Study

In the previous study (1), the quantitative fault tree analysis approach was applied separately for two distinct anchor deployment scenarios. The first scenario involved intentional anchor deployment in response to a vessel emergency that warrants anchor deployment. The second scenario involved unintentional (or accidental) anchor deployment from a vessel underway due to equipment malfunction and/or human error. For both scenarios, the frequency of anchor deployment was based on the frequency of vessel crossings as obtained from marine traffic data. Only crossings by vessels whose size and anchor chain strength were sufficient to cause pipeline failure were considered. Separate fault trees were developed for each deployment scenario because: 1) the likelihoods of pipeline interaction with an intentionally or unintentionally deployed anchor are different; 2) the measures required to prevent deployment do not necessarily apply to both scenarios; and 3) the conditions under which the interaction between an anchor and the pipeline will lead to failure differ between the two deployment scenarios.

The analysis approach adopted in the previous study closely followed the approach developed by Det Norske Veritas (DNV), as set out in Appendix E of Revision 1 to DNV Report 2009-1115, *Recommended Failure Rates for Pipelines* (3). The analysis approach adopted for assessing intentional anchor deployment followed a similar approach, but it leverages other relevant information sources where appropriate.

The previous analysis evaluated the reduction of anchor strike failure probability expected to result from implementation of the following preventative and protective measures:

1. Implementation of a system, i.e. the Guardian:protect as developed and distributed by Vesper Marine, which automatically warns vessels displaying an intent to anchor of the presence of undersea pipelines and the associated deployment hazard. This system utilizes the Automatic Identification System (AIS), a vessel tracking and communications system that is required on all major vessels.

2. A modification of the above system that automatically sends AIS messages to vessels approaching the Straits, which warn the vessels of the anchor deployment hazard and request that the vessel check to ensure their anchors are properly stowed.

3. Two protective barrier options intended to prevent vessel anchors from contacting the pipelines.

Currently, measures 1 and 2 have been implemented in the Straits; however, the automatic message transmitted to vessels as part of measure 2 has been modified to remove the explicit request that vessels check for properly stowed anchors, leaving only a warning of the undersea pipeline hazard and anchoring restrictions. An explicit request to check for secured anchors is now included in the preventative measures, introduced since the previous study was completed, and it is analyzed in Section 3. The warnings transmitted by the Guardian:protect system through the AIS, as currently implemented, are referred to as "Guardian:protect advisory messages" in this study. The following section summarizes the results of the previous study and the revision made in this study to reflect the Guardian:protect advisory messaging currently in place in the Straits.

2.2 Failure Due to Intentional Anchor Deployment

2.2.1 Fault Tree

As discussed in the previous study (1), pipeline failure due to intentional anchor deployment is the potential result of a response to a vessel emergency that is deemed sufficiently serious by the vessel operator to warrant anchor deployment. Such vessel emergency events could include collision, contact, grounding, fires, explosions and heavy weather. The fault tree developed to estimate the pipeline failure frequency due to intentional anchor deployment in the previous study (1), including consideration of the preventative measures listed in Section 2.1 that are currently in place, is shown in Figure 2.1. A list of all events evaluated in this fault tree is also provided in Appendix A.

Effect of the Guardian:protect System

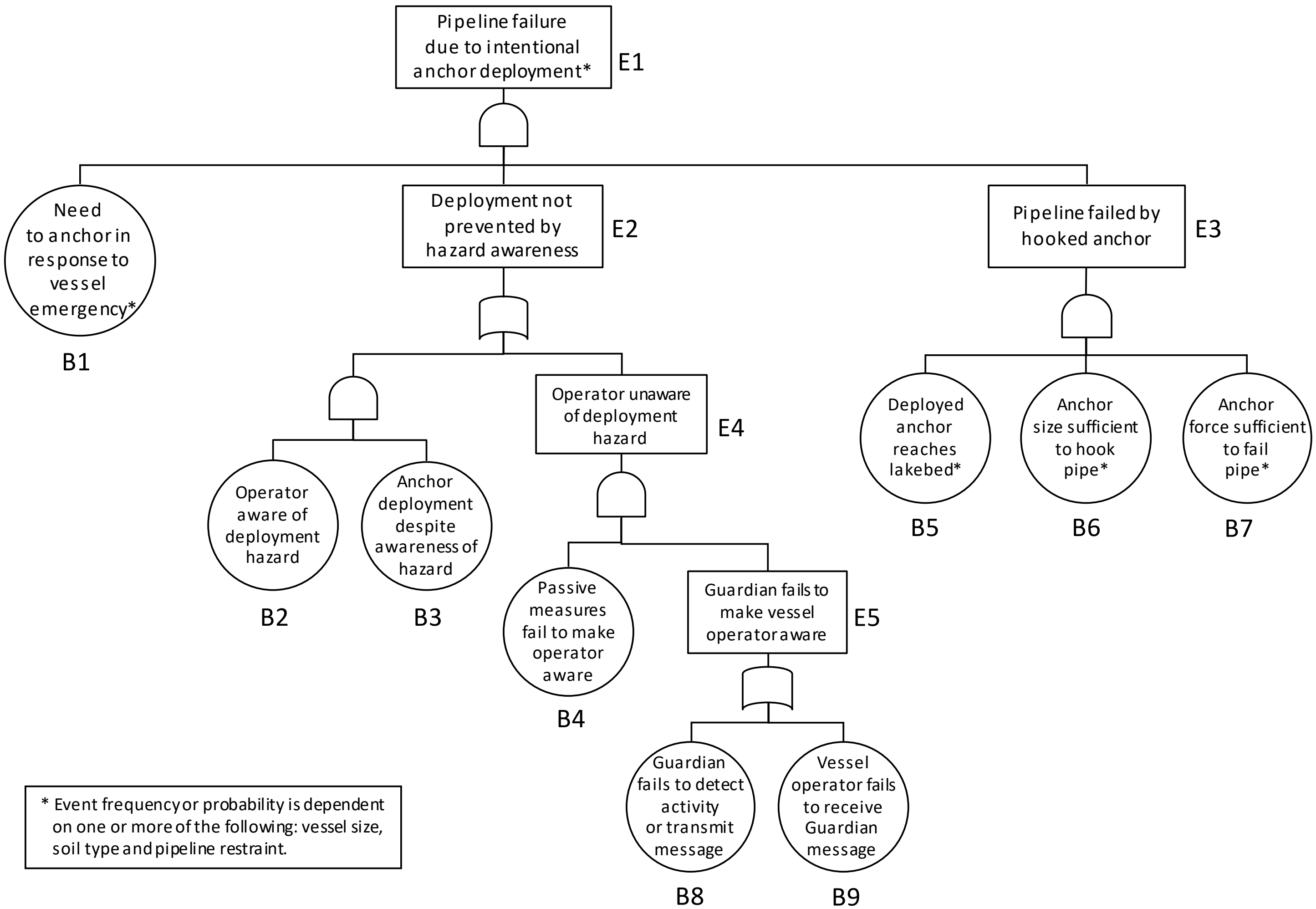


Figure 2.1 Fault Tree for Pipeline Failure Due to Intentional Deployment – Crossing with Guardian:protect Advisory Messages

This fault tree structure indicates that failure is the product of three outcomes: 1) the need to deploy an anchor in response to a vessel emergency within the interaction distance (Basic Event B1); 2) the intent to anchor not being prevented by hazard awareness (Event E2); and 3) pipeline failure by anchor hooking (Event E3). The derivation of all event frequencies in Figure 2.1 is discussed in the previous study and summarized in Section 2.2.2. No changes to these event occurrence rates were required to reflect current conditions in the Straits.

2.2.2 Event Probabilities and Results

The frequency of Basic Event B1 and all events connected below Event E3 (referred to as the "E3 branch" in this study) are independent of the preventative measures employed at the Straits. The probability assigned to each of these events was calculated in the previous study for each combination of vessel size, soil type and pipeline restraint that was expected in the Straits. Three years of vessel traffic data in the Straits, including the size and expected anchor dragging force of each crossing, was then used to derive the annual occurrence rates for Basic Events B1, B5, B6 and B7. These values remain unchanged.

The events within the E2 branch of the fault tree reflect the probability that the vessel operator is unaware of the hazard when there is a need to deploy the anchor in an emergency and the probability that the vessel operator deploys an anchor despite awareness of the hazard. The Guardian:protect system influences this branch of the tree by reminding the operators of vessels displaying an intent to anchor that a deployment hazard exists. Potential for this system to fail exists if the vessel activity is undetected or the message fails to be transmitted or received. As this function is currently implemented as analyzed in the previous study, no changes to the fault tree events were necessary to reflect its operation. The pipeline failure rate due to intentional anchor deployment therefore remains the same as it was in the previous study at 7.82×10^{-7} failures per year.

2.3 Failure Due to Unintentional Anchor Deployment

2.3.1 Fault Tree

As discussed earlier, pipeline failure due to unintentional anchor deployment is the potential result of an accident caused by anchor equipment malfunction and/or human error. The fault tree developed in the previous study, modified to remove the protective barriers that have not been implemented, is shown in Figure 2.2. A list of all events used in this fault tree is also provided in Appendix A.

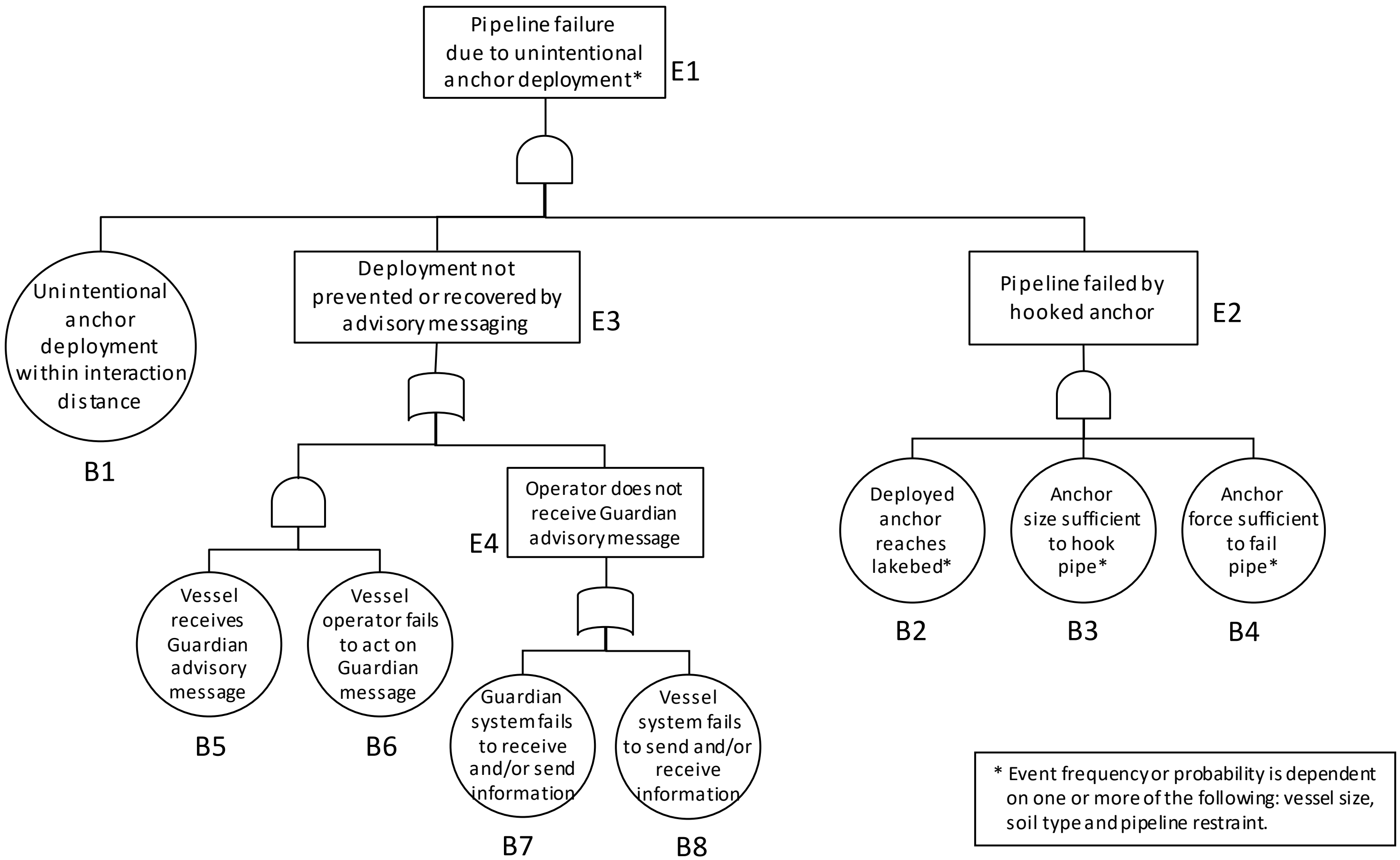


Figure 2.2 Fault Tree for Pipeline Failure Due to Unintentional Deployment - Crossing with Guardian:protect Advisory Messages

Effect of the Guardian:protect System

The fault tree structure indicates that failure is the product of three outcomes: 1) the unintentional deployment of an anchor within the interaction distance (Basic Event B1); 2) the unintentional deployment not being prevented or the unintentionally deployed anchor not being recovered as a result of advisory messaging (Event E3); and 3) pipeline failure by anchor hooking (Event E2). Updates to the basic event occurrence rates required to reflect current conditions and their effect on the overall failure rate are discussed in Section 2.3.2

2.3.2 Updated Event Probabilities and Results

The frequency of all events within the B1 and E2 branches of the fault tree are independent of the preventative measures employed at the Straits. The probability assigned to Basic Events B2, B3 and B4 were calculated in the previous study for each combination of vessel size, soil type and pipeline restraint that was expected in the Straits. Three years of vessel traffic data in the Straits, including the size and expected anchor dragging force of each crossing, was then used to derive the annual rates for Basic Events B1, B5, B6 and B7. These values remain unchanged.

The events within the E3 branch of this fault tree reflect the probability that an unintentionally dragging anchor is not prevented or recovered by the vessel operator checking on their anchor(s) after receiving an advisory message via the vessel's AIS system. Changes to the content of this automated message require changes to the probability assigned in the previous study to Basic Event B6 (vessel operator fails to act on Guardian:protect advisory message).

The previous study assumed the message would contain an explicit request for vessel operators to check that their anchors were properly stowed. A relatively low probability of 10% was chosen as the probability that the operator would ignore this message and not initiate a check of anchor status. After completion of the previous study, in the process of implementing the Guardian:protect system, it was deemed that a request for an anchor check was too onerous on vessel operators and was unlikely to get approval from the United States Coast Guard (USCG). An updated message that does not contain this explicit request, and instead reminds vessel operators of the undersea pipeline hazard and associated anchoring restrictions, was implemented. This message is less likely to trigger a physical check of anchor status by the vessel operator. Through the expert solicitation process described in Section 3.2, a new value of 25% was chosen for Basic Event B6. While the value of Top Event E1 in the previous study was 8.45×10^{-5} failures per year, this change resulted in a failure rate increase of 2.3 times to 1.93×10^{-4} per year. A summary of the pipeline failure rates considering the preventative measures analyzed in the previous study that are currently implemented are shown in Table 2.1. As in the previous study, the total combined annual failure rate is overwhelmingly dominated by the failure potential attributable to unintentional anchor deployment. As a result, the focus of the preventative measures and modelling efforts discussed in Section 3 is on those measures intended to reduce the probability of failure due to unintentional anchor deployment.

Damage Mechanism	Previous Study	Current Study
Intentional Deployment	7.82×10^{-7} per yr	7.82×10^{-7} per yr
Unintentional Deployment	8.45×10^{-5} per yr	1.93×10^{-4} per yr
Total Combined	8.53×10^{-5} per yr	1.94×10^{-4} per yr

Table 2.1 Line 5 Crossing Failure Rate Due to Intentional and Unintentional Anchor Deployment with Guardian:protect Advisory Messages in Place

3. EFFECT OF THE RISK REDUCTION PROGRAM

3.1 Overview of Risk Reduction Program

To reduce the risk of pipeline failure due to anchor deployment, Enbridge has implemented the coordinated anchor strike risk reduction system (herein referred to as the "Coordinated System") (2). This Coordinated System is operated by Marine Pollution Control Corp. (MPC) from the land-based Enbridge Straits Maritime Operation Center (ESMOC) located in Mackinaw City, Michigan. Operating 24 hours per day, 7 days per week, ESMOC reduces the risk of damage to the Line 5 pipelines from anchor strikes through visual observation and vessel communication, both of which are explained in more detail below:

- **Visual observation**: The crew at ESMOC, led by the Shore Captain, utilizes AIS and other vessel traffic monitoring systems to identify vessels transiting the Straits. All vessels that pose a threat to the Line 5 pipelines, as determined by the vessel type and size, are assigned an event number and continuously tracked throughout their transit of the Straits. An observation of each of these vessels to check for an unintentionally deployed anchor is then planned and conducted. An observation can consist of either:
  - *Shore-based observations* conducted by an Observer Team from predetermined points along the shore of the Straits using high-resolution optics; or
  - *On-water observations* conducted by one of three MPC-operated patrol boats dedicated to the Coordinated System (the "Patrol Boats").
- **Vessel communication:** The crew of ESMOC and the Patrol Boats uses radio to communicate directly with vessel operators. Communication via radio occurs for all vessels assigned an event number and consists of:
  - *An advisory message*, which alerts vessel operators to the location of the Line 5 crossing and indicates that ESMOC will be conducting observations of the vessel; and
  - *An anchor check request* that asks the vessel operator to confirm that their anchors are secured.

The choice of observation is made at the discretion of the Shore Captain. However, C-FER's discussions with Enbridge and MPC personnel have indicated how the Shore Captain's decisions will be influenced by factors such as weather conditions. From this, the intended operational logic for the Coordinated System was captured sufficiently for quantitative fault tree analysis. The process flow logic, indicating when and what type of vessel observations and communications are made, is illustrated in Figure 3.1.

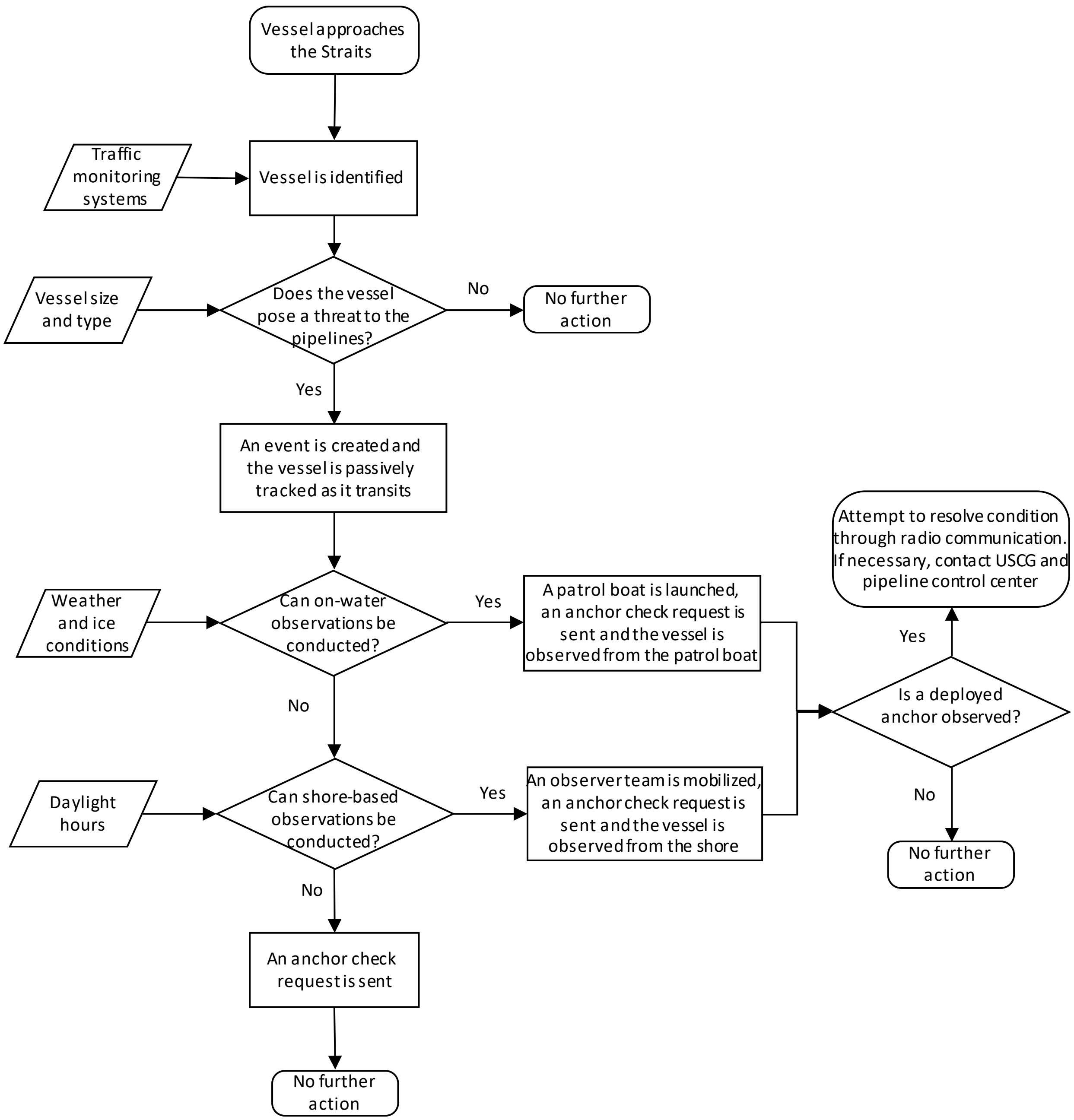


Figure 3.1 Illustrative Process Flow Diagram for Coordinated System Operations

On-water observations using the Patrol Boats is the preferred observation type for all vessel crossings. It is assumed that an on-water observation will be attempted whenever weather and water conditions permit. During on-water observations, the Patrol Boat crew will communicate directly with the vessel operator to send an advisory message and anchor check request. If on-water observation cannot be conducted, the Shore Captain may direct a shore-based observation, daylight permitting. The Shore Captain or the Observer Team will then communicate directly with the vessel to send an advisory message and anchor check request. If either an on-water or shore-based observation observes a deployed anchor, the vessel operator will be immediately contacted. If neither type of observation can be completed, the Shore Captain will communicate directly with the vessel operator to send an advisory message and anchor check request.

3.2 Expert Opinion Solicitation Process

The probabilities assigned to the basic events in the fault tree analysis were derived from historical data and engineering models whenever possible. However, the behavioral or highly situation-specific nature of many events made finding applicable data or developing suitable models infeasible within the scope of the project. Subject matter expert opinion was, therefore, sought to address the information gaps using a structured approach called the 'Delphi' method[3] (4).

The primary sources of expert opinion were two independent maritime navigation consultants ("Experts"). The solicitation process involved two rounds of questions and answers. In the first round, each Expert was given a list of events and asked to estimate the probability of these events occurring. Answers were developed and received independently from each Expert. To ensure consistency in the language used while quantifying the probability of these events, each Expert was given guidance on the use of calibrated language for characterizing uncertainties based on Mastrandea et al. (5). After receiving answers from both Experts, C-FER aggregated the responses and identified the answers that differed significantly between Experts. The second round focused on the questions that elicited significant differences in the responses from the Experts. During this round, the Experts were also given a summary of the previous responses for each question and asked if they would like to revise their answer based on this information. After the second round of questions and answers, the response disparity between the Experts was reduced for all questions and the expert opinion solicitation process was stopped. The specific questions and answers used to develop the basic event probabilities are discussed in Sections 3.3.2 and 3.4.2. A summary of the expert opinion solicitation process is presented in Appendix B.

[3] In the Delphi method, a questionnaire is sent to an independent panel of experts, soliciting their opinion on the likelihood of events. The responses are collected and summarized, and in the next round of questionnaires, the experts are given an opportunity to update their response based on the summary of the responses from the previous round. The number of rounds of questioning will depend on reaching consensus among the experts. Experts remain anonymous to each other throughout the process.

3.3 Failure Due to Intentional Anchor Deployment

3.3.1 Fault Tree

The fault tree developed to estimate the pipeline failure frequency due to intentional anchor deployment for the pipeline crossing, accounting for the preventative measures currently employed by Enbridge, is shown in Figure 3.2. In addition to the Guardian:protect advisory messages analyzed in the previous study and updated in Section 2.2, this fault tree accounts for the additional hazard awareness created from direct contact between the vessel operators and the ESMOC personnel. A list of all fault tree events, and their final values, is given in Appendix C.

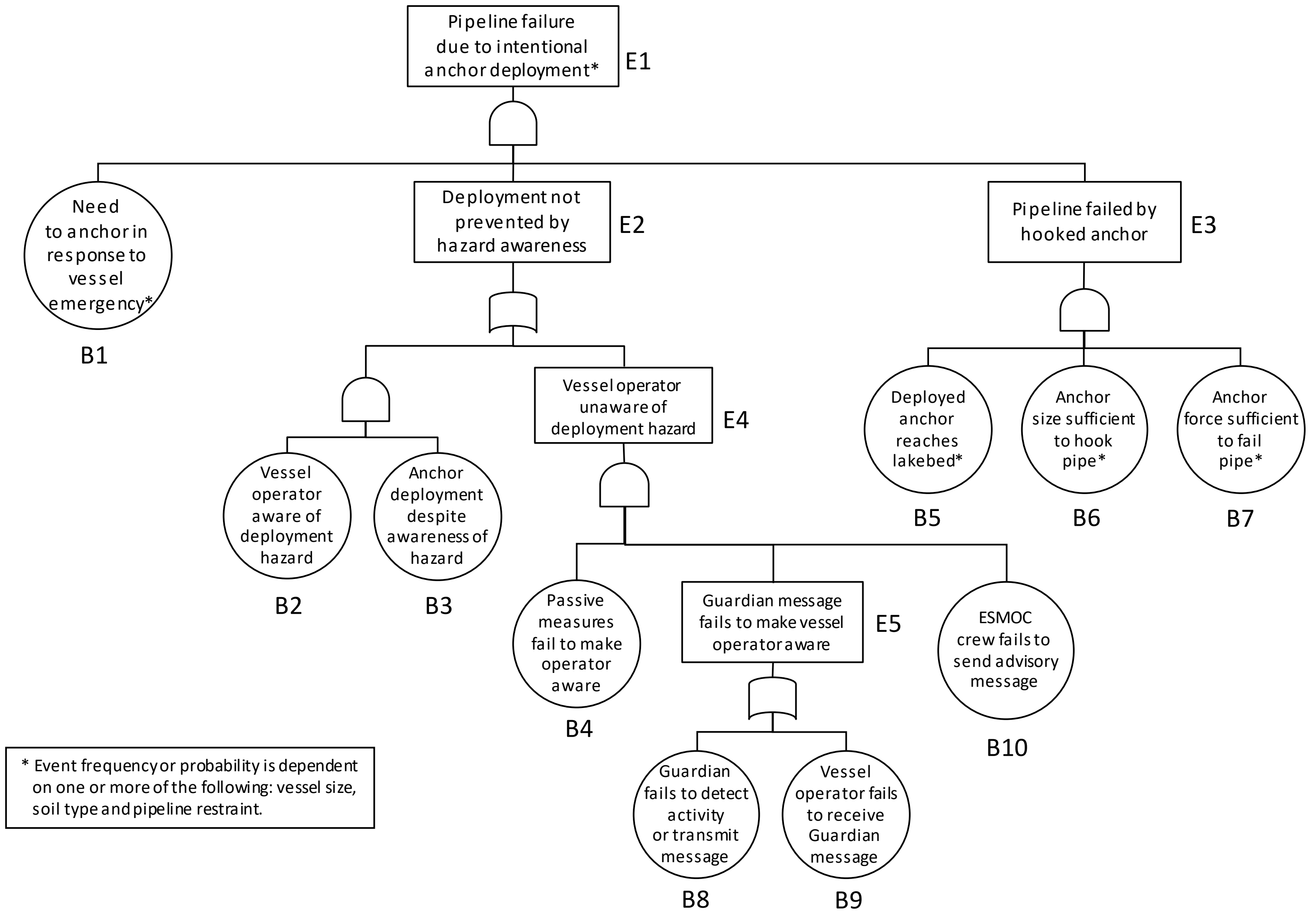


Figure 3.2 Fault Tree for Pipeline Failure Due to Intentional Deployment - Crossing with Guardian:protect Advisory Messages and the Coordinated System

The only difference between this fault tree and that presented in Section 2.2 is the addition of Basic Event B10, which represents the probability that the ESMOC crew fails to send an advisory message. These messages serve to make the vessel operator aware of the anchor deployment hazard (Event E4) in parallel with the Guardian:protect advisory message sent to vessels displaying an intent to anchor and with passive measures, such as navigation charts and operator certification.

3.3.2 Fault Tree Event Probabilities and Results

Direct communication with the vessel operator is required by the Coordinated System operation protocols. Either the Shore Captain, Observer Team or the Patrol Boat crew are required to be in contact with the vessel operator to advise them of the pipelines and the observation procedure. Two radio systems are available to conduct these communications. Therefore, the probability assigned to Basic Event B10 was assumed to be dominated by the probability of the crew of the Coordinated System failing to follow the protocols and communicate with the vessel, either intentionally or unintentionally. This type of human error was assumed to be exceptionally unlikely and assigned a reference probability of 1% based on the mapping between likelihood ranges and reference probabilities in Mastrandea et al. (5).

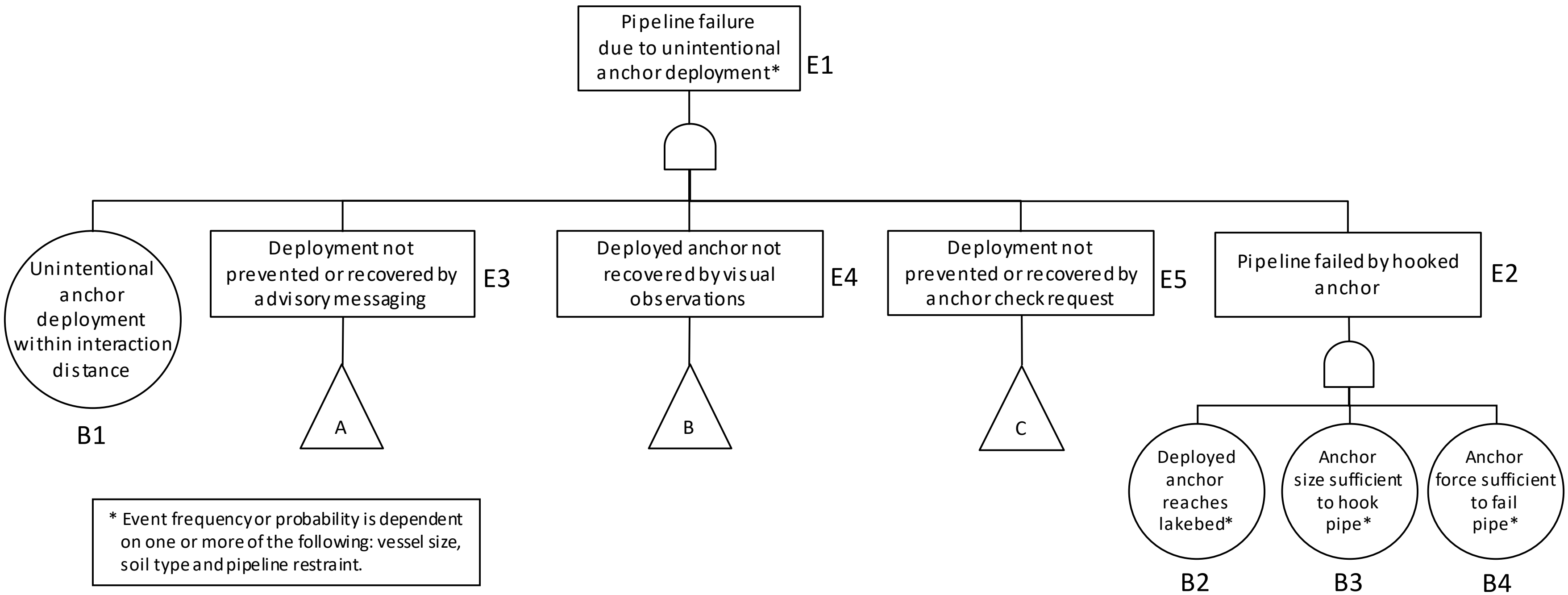
The awareness of the deployment hazard brought about by direct communication with the ESMOC crew serves the same purpose as the awareness resulting from passive measures and the Guardian:protect advisory messages. As found in the previous study (1), Event E2, the failure of hazard awareness to prevent intentional anchor deployment, is less sensitive to the probability of the vessel operator having awareness of the hazard (Event E4) than it is to the probability that the vessel operator deploys their anchor despite awareness of the hazard (Event B3). As a result, the total probability of failure due to intentional anchor deployment is not sensitive to the probability assigned to Basic Event B10. Top Event E1 had a probability of 7.82×10^{-7} with only the AIS messaging in place and is reduced by 20% to 6.70×10^{-7} when accounting for the effect of the Coordinated System by introducing Basic Event B10.

3.4 Failure Due to Unintentional Anchor Deployment

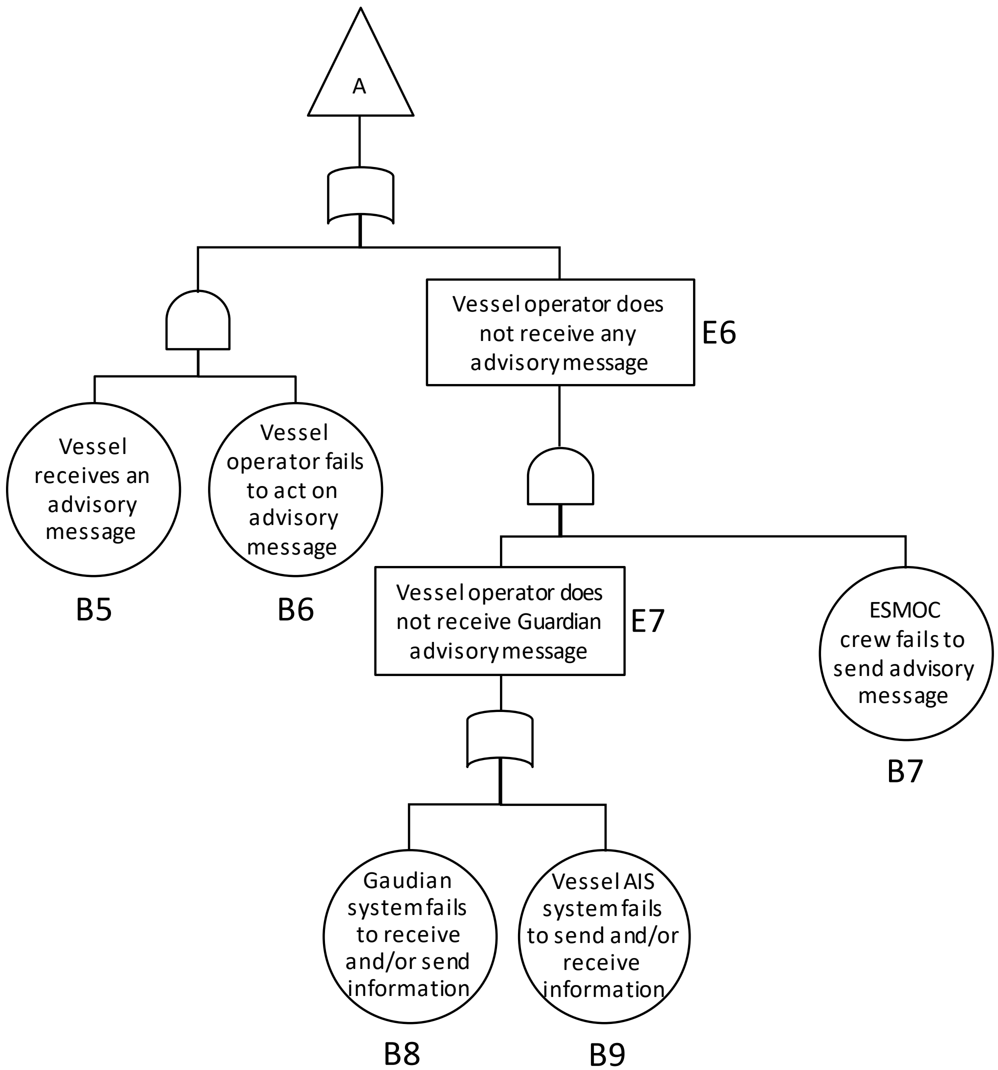
3.4.1 Fault Tree

The fault tree developed to estimate the pipeline failure frequency due to unintentional anchor deployment, accounting for the preventative measures currently employed by Enbridge, is shown in Figure 3.3. The top-level structure shown in Figure 3.3a differs from that of the fault tree in Section 2.3.1 by the addition of two branches: one reflecting anchor deployment recovery through visual observations (corresponding to Event E4 and expanded in Figure 3.3c), and one reflecting anchor deployment recovery or prevention through anchor check requests (corresponding to

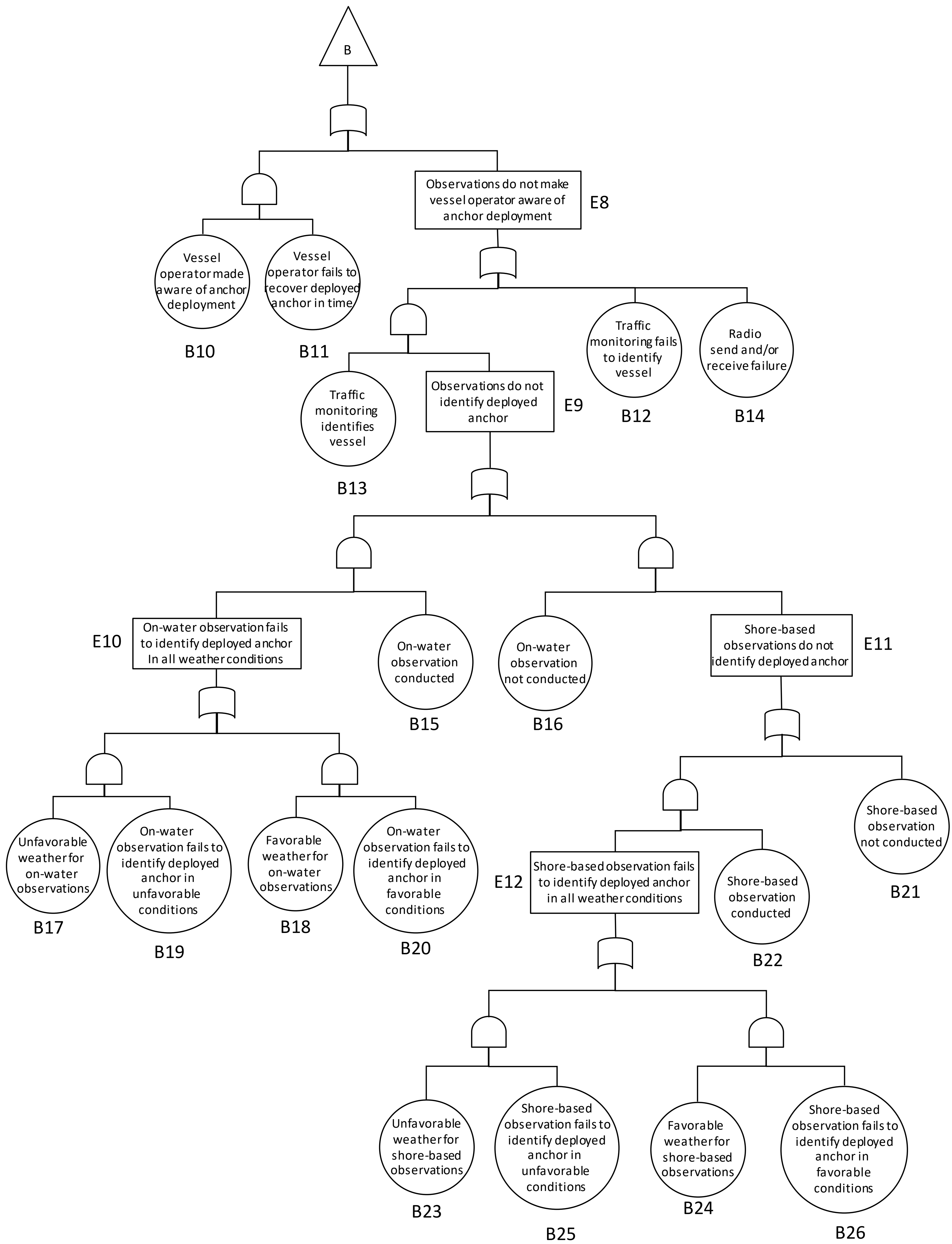
Event E5 and expanded in Figure 3.3d). The E3 branch, representing anchor deployment recovery or prevention through advisory messaging, has been modified to reflect the advisory messages received by the vessel operators as part of the Coordinated System (shown in Figure 3.3b). The E4 branch accounts for visual observations using either shore-based or on-water observations. A list of all fault tree events, and their final values, is given in Appendix C.



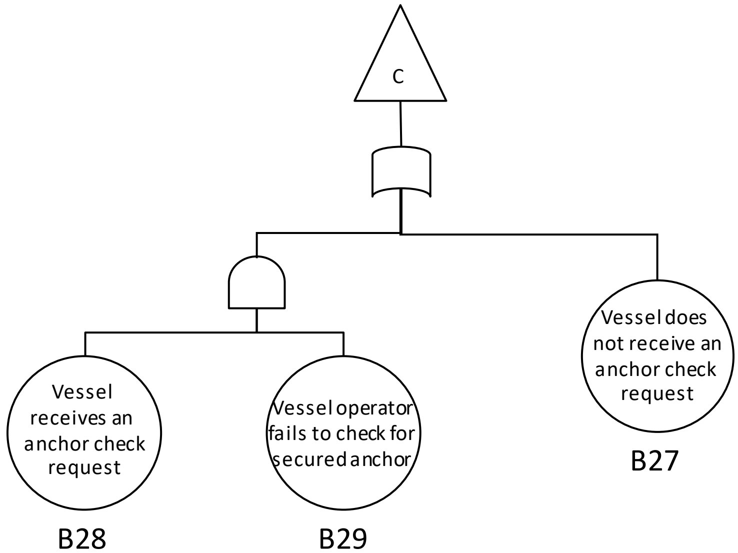
a) High-level Events



b) Advisory Messages



c) Visual Observations



d) Anchor Check Requests

Figure 3.3 Fault Tree for Pipeline Failure Due to Unintentional Deployment - Crossing with Guardian:protect Advisory Messages and the Coordinated System

3.4.2 Fault Tree Event Probabilities

3.4.2.1 Effect of Advisory Messages

The fault tree branch shown in Figure 3.3b indicates that unintentional anchor deployment will not be prevented or recovered by advisory messages (Event E3) if the vessel operator does not receive any advisory messages (Event E6), or if the vessel operator does receive an advisory message (Basic Event B5) and fails to act (Basic Event B6). The fault tree further indicates that the vessel operator will not receive an advisory message if the Guardian:protect advisory message is not received by the vessel's AIS system (Event E7) and the crew of the Coordinated System fails to send an advisory radio message (Basic Event B7).

Event E7 in the modified fault tree is equivalent to Event E4 in the previous study, calculated as the probability of either the Guardian:protect or vessel AIS system failing to send or receive information. Based on the estimated reliability of the components of the AIS systems, Event E7 was calculated to have a probability of 1.61% in the previous study. This value was not changed in the modified fault tree.

Basic Event B7 in the modified fault tree for unintentional anchor deployment is equivalent to Basic Event B10 in the modified fault tree for intentional anchor deployment (Figure 3.2). As discussed in Section 3.3.2, the probability that the crew of the Coordinated System fails to send an advisory radio message is assumed to be 1%. The probability of the vessel operator not receiving any advisory messages, either as an AIS message or via direct radio communication, is then calculated as:

$$\text{Event E6} = \text{E7} \times \text{B7} = 0.0161 \times 0.01 = 1.61 \times 10^{-4}$$

The probability that the vessel operator receives an advisory message, Basic Event B5, is taken as one minus the probability of Event E6. The probability of the vessel operator failing to check for proper stowage of their anchors following receipt of an advisory message, Basic Event B6, was developed using expert opinion on the expected behavior of vessel operators. Through the process described in Section 3.2, the Experts suggested that an advisory message, indicating the presence of the Line 5 crossing and reminding operators of the anchoring restriction, would trigger a voluntary check of vessel anchor status 50% or 75% of the time if the request came through the vessel AIS system or radio hail, respectively. The fault tree structure assumes that the response of a vessel operator to an advisory message will be the same regardless of the source of the message. As advisory radio communications happen after the Guardian:protect advisory messages are transmitted and have a higher probability of being received by the vessel operator, the response to this type of message was assumed to be the dominant factor when assigning a probability to Basic Event B6. Therefore, it was assumed that the vessel operators would fail to check for proper anchor stowage in response to an advisory message 25% of the time.

Instead of assuming the vessel response would be the same for advisory messages received via AIS or radio communication, each type of advisory message could have been modelled as a separate branch under Top Event E1, with each being able to independently prevent or recover an unintentionally deployed anchor. However, modelling the behavior of the vessel operator as such would have been unconservative as it is extremely unlikely that a separate check of anchor status would be triggered after each advisory message. Furthermore, a vessel operator that does not respond to one advisory message by checking the status of their anchor would be more likely to not respond to the second advisory message as well. As the responses to each advisory message could not be considered independent, they were combined in the modified fault tree, conservatively giving the vessel operator only one opportunity to prevent or recover a deployed anchor after either one or both advisory messages. On this basis, the probability of advisory messaging failing to prevent or recover a deployed anchor (Event E3) is given by:

$$\begin{aligned}\text{Event E3} &= \text{E6} + (\text{B5} \times \text{B6}) = \text{E6} + ((1 - \text{E6}) \times \text{B6}) = 1.61 \times 10^{-4} + (1 - 1.61 \times 10^{-4}) \times 0.25 \\ &= 0.250\end{aligned}$$

3.4.2.2 Effect of Visual Observations

The fault tree branch shown in Figure 3.3c indicates that unintentional anchor deployment will not be recovered by visual observations if the observations fail to make the vessel operator aware of the anchor deployment (Event E8), or if the vessel operator is made aware of the anchor deployment (Basic Event B10) but is unable to recover the deployed anchor in time (Basic Event B11). Basic Event B10 is taken as one minus the probability of Event E8. The probability assigned to Basic Event B11 was based on expert opinion of the time required to stop or slow vessels sufficiently to raise anchor versus the expected notice given by the Patrol Boat crew observing the vessel. The largest vessels posing a threat to the Line 5 crossing are Panamax Bulk carriers, which the Experts indicated could take 10 to 15 minutes to stop or slow sufficiently to begin raising an unintentionally deployed anchor. During this time, these vessels may travel 2 to 3 nautical miles towards the pipelines along their original course and may travel up to 0.5 nautical miles perpendicular to their course, if prevailing conditions and traffic within the Straits allow this course. According to the protocols of the Coordinated System, all visual observations are intended to confirm the anchor status of each vessel when they are at least 15 minutes, or approximately 3 nautical miles, away from the pipeline crossing. As a result, the Experts indicated that it would be extremely unlikely for a vessel to be unable to raise their anchor in time if given at least 15 minutes of notice. Using the mappings between likelihood statements and representative probabilities in Mastrandea et al. (5), Basic Event B11 was assigned a 5% probability of occurrence.

The fault tree structure indicates that the observations will not make the vessel operator aware of anchor deployment if the Coordinated System fails to identify the vessel through traffic monitoring (Basic Event B12), the radio systems of the Coordinated System and/or vessel fail to send and/or receive messages (Basic Event B14), or if the Coordinated System does identify the vessel (Basic Event B13) but the observations do not identify a deployed anchor (Event E9). The Coordinated System uses multiple methods to identify vessels approaching the Straits and track their course (AIS tracking systems from Vesper, Marine Traffic, and VHF/GPS Chartplotter, as well as radio monitoring). With these redundant tracking systems in place, it was assumed to be exceptionally unlikely for a vessel of a size that poses a threat to the pipelines to enter the Straits and cross Line 5 without being identified by the Coordinated System. Therefore, Basic Event B12 was assigned a 1% probability. Basic Event B13 was taken as one minus this probability. The probability of Basic Event B14 was based on the expected equipment reliability of radios operated by the Coordinated System and vessels, which were assumed to have two radio systems each. Each radio was assigned an expected mean time between failures of 5,000 hours and a mean time to repair of one week according to Quanterion Solutions (6). The estimated proportion of time that either the Coordinated System's or vessel's radio would be unavailable was calculated as 0.211% and assigned to Basic Event B14 as the probability.

Based on the modified fault tree structure, visual observations will not identify a deployed anchor (Event E9) if on-water observations are conducted (Basic Event B15) but fail to identify a deployed anchor (Event E10), or on-water observations are not conducted (Basic Event B16) and shore-based observations do not identify a deployed anchor (Event E11). Following the Coordinated System protocols discussed in Section 3.1, on-water observations were assumed to occur unless weather and water conditions prohibited operations of the Patrol Boats. Two conditions were identified as being the primary factors preventing Patrol Boat operations: heavy ice conditions and strong winds. Based on Great Lakes ice cover data (7) and the operation history of the Coordinated System, it was estimated that the Straits would be largely iced over during the months of January, February and March, preventing Patrol Boat operation entirely within that time. Although this represents 25% of the year, the analysis of vessel traffic for the previous study indicated that only 4% of vessel crossings occur within these months as icy conditions also prevent commercial ship traffic. In addition to iced-over periods, it was assumed that days with gale-force wind warnings (winds speed greater than 38.5 mph) would prevent Patrol Boat operations for the duration of that day. Data on the wind speed collected from multiple buoys in the Straits and surrounding areas (8) indicated that the recorded daily maximum wind speed exceeded this threshold at one or more of the observation stations with an annual average of 7.7%. This probability was seen to align with the number of on-water observations that were not possible due to strong winds, as indicated by the operating history of the Coordinated System. With these two contributing factors, it was assumed that 11.5% of the annual vessel crossings could not be observed using the Patrol Boats (Basic Event B16). Basic Event B15 was taken as one minus this probability.

The probability that an on-water observation fails to identify a deployed anchor was assumed to be dependent on the weather and water conditions present at the Straits. Weather conditions were classified as either favorable or unfavorable. An on-water observation will fail to identify a deployed anchor (Event E10) if there are favorable conditions (Basic Event B18) and the observation fails under these conditions (Basic Event B20), or there are unfavorable conditions (Basic Event B17) and the observation fails under these conditions (Basic Event B19). The presence of unfavorable conditions for on-water observations was taken as the probability of elevated wind speeds during the observation. Elevated wind speeds would increase the relative motion between the Patrol Boat and observation vessel, as well as reduce the visibility of an anchor chain, which indicates a deployed anchor. Elevated wind speeds were taken as speeds above the small-craft warning (31.1 mph) but below the gale-force warning that would prevent Patrol Boat operation. Based on the data available, these conditions exist on 15% of the recorded days. Other factors, such as fog, precipitation and daylight were considered for inclusion as unfavorable weather. However, the ability of the Patrol Boats to control their distance from the vessel and the use of thermal imaging cameras on the Patrol Boats was expected to reduce the influence these factors have on anchor visibility. The 15% probability assigned to Basic Event B17 was also considered conservative as, although the maximum wind speed was considered elevated on 15% of the days, these conditions would likely not be persistent throughout the day and would, therefore, not affect every observation during that day. Basic Event B18 was taken as one minus this probability. The visibility of a deployed anchor under favorable and unfavorable conditions was based on expert opinion after the Experts were provided with details on the equipment used in the observation and the expected distance of the observation. After two rounds of solicitation, the Experts assigned a value of 25% to the probability that on-water observations will fail to identify a deployed anchor in unfavorable conditions (Basic Event B19), and a value of 10% to the probability that on-water observations fail to identify a deployed anchor in favorable conditions (Basic

Event B20). The probability that on-water observations fail to identify a deployed anchor in all conditions is given by:

$$\begin{aligned}\text{Event E10} &= (B17 \times B19) + (B18 \times B20) = (B17 \times B19) + ((1 - B17) \times B20) \\ &= (0.15 \times 0.25) + ((1 - 0.15) \times 0.1) \\ &= 0.123\end{aligned}$$

The modified fault tree indicates that shore-based observations will not identify a deployed anchor if shore-based observations are not conducted (Basic Event B21), or a shore-based observation is conducted (Basic Event B22) and the shore-based observation fails to identify a deployed anchor (Event E12). According to the operation protocols of the Coordinated System, shore-based observations will only take place during the day when high-powered optics can be used to observe vessels from extended distances. Based on the annual daylight hours at the Straits, a probability of 50% was assigned to Basic Event B21. Basic Event B22, taken as one minus the probability of Basic Event B21, was therefore also assigned a value of 50%.

Mirroring the process used to derive the probability of Event E10, the probability of a shore-based observation failing to identify a deployed anchor is a combination of there being favorable or unfavorable conditions for these types of observations and the ability of the shore-based crew to identify a deployed anchor under these conditions. As shore-based observations occur from fixed locations further away from the vessel than on-water observations, the conditions between the observer and vessel will have more of an impact on the visibility of a deployed anchor. The presence of unfavorable conditions for shore-based observation (Basic Event B23) was assumed to occur whenever strong winds (greater than 31.1 mph), significant rainfall (greater than 1 inch) or significant snowfall (greater than 3 inches) occurred over the course of the day. The existence of these conditions was only considered on days when gale-force winds or ice were present that would prevent an on-water observation from being conducted. Based on the wind and rain data collected (9,10), one or more of the weather types necessary to create unfavorable shore-based observation conditions were present on 30% of all applicable days. Basic Event B23 was assigned this probability and Basic Event B24 was taken as one minus this probability. While fog was initially considered to create unfavorable shore-based observation weather, it was found that, on days of gale-force warnings, fog occurred much less frequently (less than 2%) than the other weather criteria. For the months with iced-over conditions, fog was accompanied by other unfavorable weather criteria frequently (greater than 75%) and had little effect on the overall estimated annual occurrence rate of unfavorable weather conditions.

As with on-water observations, the ability of shore-based observations to identify a deployed anchor in favorable and unfavorable conditions was derived directly from expert opinion. Shore-based observations were estimated to be far less successful than on-water observations, with failure to identify a deployed anchor occurring 50% of the time in favorable conditions (Basic Event B26) and 90% of the time in unfavorable conditions (Basic Event B25). The probability that shore-based observations fail to identify a deployed anchor in all conditions is then given by:

$$\begin{aligned} \text{Event E12} &= (\text{B23} \times \text{B25}) + (\text{B24} \times \text{B26}) = (\text{B23} \times \text{B25}) + ((1 - \text{B23}) \times \text{B26}) \\ &= (0.30 \times 0.90) + ((1 - 0.30) \times 0.50) \\ &= 0.620 \end{aligned}$$

After considering the probability that a shore-based observation cannot be conducted due to a night-time crossing, the probability of shore-based observations not identifying a deployed anchor is given by:

$$\begin{aligned} \text{Event E11} &= (\text{E12} \times \text{B22}) + \text{B21} = (\text{E12} \times (1\text{-B21})) + \text{B21} \\ &= (0.62 \times (1\text{-}0.50)) + 0.50 \\ &= 0.810 \end{aligned}$$

With the probability of success using both observation types, the total probability of observations not identifying a deployed anchor becomes:

$$\begin{aligned} \text{Event E9} &= (\text{E10} \times \text{B15}) + (\text{E11} \times \text{B16}) = (\text{E10} \times (1 - \text{B16})) + (\text{E11} \times \text{B16}) \\ &= (0.123 \times (1 - 0.115)) + (0.81 \times 0.115) \\ &= 0.202 \end{aligned}$$

This calculation indicates that all visual observations have an expected failure rate of 20%. After accounting for the probability that the vessel is not flagged for observation or the probability that the radio systems fail to relay the indication of a deployed anchor, the probability that visual observations do not make the vessel operator aware of deployment is given by:

$$\begin{aligned} \text{Event E8} &= \text{B12} + \text{B14} + (\text{B13} \times \text{E9}) = \text{B12} + \text{B14} + ((1 - \text{B12}) \times \text{E9}) \\ &= 0.01 + 0.00211 + ((1 - 0.01) \times 0.202) \\ &= 0.212 \end{aligned}$$

Finally, the probability that the visual observations of vessel anchor status will fail to recover an unintentionally deployed anchor is calculated as:

$$\begin{aligned} \text{Event E4} &= (\text{B10} \times \text{B11}) + \text{E8} = ((1 - \text{E8}) \times \text{B11}) + \text{E8} \\ &= ((1 - 0.212) \times 0.05) + 0.212 \\ &= 0.251 \end{aligned}$$

The probability of visual observations failing to lead to recovery of a deployed anchor is coincidentally the same as the probability of advisory messages preventing or recovering a deployed anchor, which indicates that advisory messages and visual observations have approximately the same influence on the overall probability of failure due to unintentionally deployed anchors. It should be noted that, unlike advisory messages, visual observations can only lead to the recovery of anchors that have already been deployed. They cannot check for proper anchor stowage, which would prevent an anchor deployment from happening in between the time of the observation and the time of the vessel crossing over the Line 5 pipes. While not explicitly modelled in this study, the probability of such a deployment was considered to be exceedingly low due to the short time-span between observation and vessel crossing. Additionally, the operational protocols of the Coordinated System indicate that there are to be additional patrol boats stationed directly over the Line 5 crossing at all times. These patrols boats would observe all traffic within the Straits and would likely identify a recently deployed anchor.

3.4.2.3 Effect of Anchor Check Requests

The fault tree branch shown in Figure 3.3d indicates that unintentional anchor deployment will not be prevented or recovered by an anchor check request if the vessel operator does not receive a request from the Coordinated System (Basic Event B27), or if the vessel operator receives the request (Basic Event B28) and fails to perform a check for secured anchors (Basic Event B29). Under the operation protocols for the Coordinated System, a radio hail from ESMOC asking for a vessel operator to initiate a physical check to ensure their anchors are not deployed and are properly secured is required for all vessels assigned an event number.

As anchor check requests are required to be sent to each vessel regardless of observation type, and multiple radio systems are available to the ESMOC crew, the dominant reason for a vessel not receiving an anchor check request was assumed to be failure of the ESMOC crew to follow protocols and send the request. As discussed in Section 3.3.2, this type of human error was assumed to be exceptionally unlikely and Basic Event B27 was, therefore, assigned a probability of 1%. This is the same probability that was assigned to Basic Event B7 for failure of the ESMOC crew to send an advisory message. Although the advisory message and anchor check request may occur as part of the same vessel communication, they are assumed to be independent processes. The probability that the vessel receives an anchor check request (Basic Event B28) is taken as one minus the probability of Basic Event B27.

The Experts were consulted to estimate the probability that an anchor check via the radio triggers a physical check of anchor status. As this request is more direct and explicit than that of the advisory messages, the Experts estimated that it would be more likely to initiate an anchor check, with failure to do so only 5% of the time. The probability that a deployed anchor is not prevented or recovered by an anchor check request is given as:

$$\begin{aligned}\text{Event E5} &= (\text{B28} \times \text{B29}) + \text{B27} = ((1 - \text{B27}) \times \text{B29}) + \text{B27} \\ &= ((1 - 0.01) \times 0.05) + 0.01 \\ &= 0.0595\end{aligned}$$

3.4.2.4 Top Event Probability

Based on the fault tree logic shown in Figure 3.3a, the rate of Top Event E1, the annual probability of pipeline failure due to an unintentionally deployed anchor, is given by:

$$\begin{aligned} \text{Event E1} &= (\text{B1} \times \text{E2}) \times \text{E3} \times \text{E4} \times \text{E5} \\ &= (7.35 \times 10^{-4} \text{ per year}) \times 0.250 \times 0.251 \times 0.0595 \\ &= 2.74 \times 10^{-6} \text{ per year} \end{aligned}$$

As calculated in the previous assessment, the probabilities assigned to Basic Event B1 and the E2 branch were calculated based on the expected frequency of unintentionally deployed anchors from vessels that carry anchors of sufficient size to fail the pipelines. These values were kept the same for this study.

3.4.3 Event Sensitivity

The sensitivity of the Top Event E1 probability to modelling assumptions was investigated for a select group of basic events, which were derived from expert opinion or historical weather data. For each of these events, an alternative value was considered and the resulting change in the probability of failure due to unintentional anchor deployment was determined. The results of the sensitivity study are summarized in Table 3.1, showing the original value of the basic event probability, the alternative value, the value of Top Event E1 using this alternative value and the percent change from the original value of Top Event E1 (2.74×10^{-6} per year).

Basic Event	Current Value	Alternative Value	Top Event using Alternative Value (per year)	Change in Top Event (%)
B6: Vessel operator fails to act on advisory message	0.25	0.50	5.48×10^{-6}	+100
B16: On-water observation not conducted	0.12	0.04	2.21×10^{-6}	-19.3
B17: Unfavorable weather for on-water observations	0.15	0.30	2.95×10^{-6}	+7.7
B19: On-water observation fails to identify deployed anchor in favorable weather	0.10	0.25	3.90×10^{-6}	+42.3
B23: Unfavorable weather for shore-based observations	0.30	0.15	2.71×10^{-6}	-1.1
B26: Shore-based observation fails to identify deployed anchor in favorable weather	0.50	0.25	2.64×10^{-6}	-3.6
B27: Vessel does not receive an anchor check request	0.01	0.05	4.49×10^{-6}	+63.9
B29: Vessel operator fails to check for secured anchor	0.05	0.10	5.02×10^{-6}	+83.2

Table 3.1 Sensitivity of Unintentional Anchor Deployment Probability of Failure to Basic Event Probabilities

As seen in the previous study, the probability of failure due to unintentional anchor deployment is highly sensitive to Basic Event B6, representing the probability that a vessel operator does not initiate a check of anchor status after receiving an advisory message. Doubling the probability assigned to this basic event also doubles the probability of Top Event E1 occurring. The current probability assigned to this basic event was derived using expert opinion and the alternative value of 50% used in Table 3.1 represents the upper end of the estimated values obtained by the Experts after the first round of solicitation. After the second round, the consensus-based estimate was 25%. When estimating these values, the Experts used their knowledge of vessel crew performance in light of standard maritime navigation conventions. Public sentiment or navigation procedures in the Straits may cause vessel operators to behave differently and affect the probability that an anchor status check is performed after receiving an advisory message.

The weather conditions used in this study were collected between 2009 and 2019 and may not be representative of the future conditions within the Straits. Furthermore, assumptions on what weather conditions would prevent observations or create unfavorable conditions were made by C-FER and used to estimate the basic event probabilities based on the number of days experiencing these conditions. In reality, the performance of the observations will depend on multiple weather-related factors, which could change throughout the course of a day. To understand the implications of these assumptions, a sample of the weather-derived basic event probabilities were included in the sensitivity analysis. Basic Event B16, which represents the probability that on-water observations cannot be conducted, was assigned an alternative value of 4%. This represents the proportion of vessel crossings that occur in January, February and March when it was assumed that icy conditions would prevent Patrol Boat operation, and it ignores the probability of any other weather conditions preventing Patrol Boat operation. The probability of the Top Event E1 decreased by 19% after applying this alternative value, showing it can be moderately altered if the probability of an on-water observation not being conducted deviates significantly from the 12% estimated in this study. However, given that the current probability closely matches the number of observations that were not possible from the event logs of the Coordinated System, it was determined to be a reasonable estimate.

Basic Events B17 and B23 represent the probability that the weather creates unfavorable conditions for on-water or shore-based observations. These values were derived from historical wind levels for on-water observations, and historical precipitation and wind levels for shore-based observations. Table 3.1 indicates that changing these probabilities by a factor of two changes the Top Event E1 probability by less than 10%, demonstrating low sensitivity to these values. The Basic Events B19 and B26 represent the probability of observations failing to identify a deployed anchor and were taken directly from expert opinion. The alternative values used in Table 3.1 are the original estimate from the first round of expert solicitation that differed most from the final consensus-based estimate. As on-water observations are the preferred observation method and happen more frequently, a higher sensitivity to the success of this action was observed, with the total probability of failure increasing by 42% after changing the probability assigned to Basic Event B19 from 10% to 25%. Top Event E1 showed little sensitivity to the probability of failure of shore-based observations.

As shown in in Table 3.1, the probability of pipeline failure is highly sensitive to the events within the anchor check request (E5) branch of the fault tree. If the probability of vessels not receiving an anchor check request (Basic Event B27) is assumed to be 5% instead of 1% (being representative of an extremely unlikely event instead of an exceptionally unlikely event according to Mastrandea et al. (5)), the probability of failure increases by 64%. As the probability of a vessel operator receiving an anchor check request (Basic Event B28) is high, the vessel operator's response to the anchor check request has a large impact on Top Event E1's probability. As with the response to an advisory message (Basic Event B6), the probability used for Basic Event B29 was derived using expert opinion on vessel operator response to anchor check requests. The alternative value of 10% in Table 3.1 represents the upper bound of the estimates after the first round of solicitation. After the second round, the current value of 5% was agreed upon by the Experts. Doubling the probability of vessel operators failing to check for secured anchors increases the probability of failure by 83%. While the above reinforces the importance of the probability assignments that pertain to the anchor check request branch of the fault tree, the consensus-based probability estimates obtained from the Experts remain the most defensible basis for the characterization of probability of Basic Event B29.

3.5 Combined Failure Frequencies

The Line 5 crossing failure rates, attributable to both intentional and unintentional anchor deployment, with consideration of the Guardian:protect advisory messages and the Coordinated System, are summarized in Table 3.2 and compared to those of the previously calculated scenarios.

Analysis Case	Failure Rate due to Intentional Anchor Deployment (per year)	Rate Reduction (% of no measures)	Failure Rate due to Unintentional Anchor Deployment (per year)	Rate Reduction (% of no measures)	Failure Rate due to Combined Anchor Deployments (per year)	Rate Reduction (% of no measures)
No preventative measures	1.27×10^{-6}	-	7.35×10^{-4}	-	7.36×10^{-4}	-
Guardian:protect advisory messages only	7.82×10^{-7}	38.0	1.93×10^{-4}	73.7	1.94×10^{-4}	73.6
Guardian:protect advisory messages and the Coordinated System	6.70×10^{-7}	47.2	2.74×10^{-6}	99.6	3.41×10^{-6}	99.5

Table 3.2 Effect of Preventative Measures on Line 5 Crossing Failure Rate

4. SUMMARY OF RESULTS

The previous study estimating the failure rate of the Line 5 pipeline crossing has been updated to reflect the new and modified preventative measures taken by Enbridge at the Straits of Mackinac. Updates were made to the estimates of failure due to both intentional and unintentional anchor deployment. As failure due to the latter was found to dominate in the previous study, the focuses of this study and the new preventative measures were to identify vessels that are unintentionally dragging their anchors and to attempt to resolve the situation before the vessel crosses the pipelines. The modified preventative measures consist of AIS messages from the Guardian:protect system to alert vessels of the presence of the pipelines. The new preventative measures analyzed in this study are a system of visual anchor status verifications and vessel communications performed by personnel in patrol boats and an integrated operation center.

To evaluate the effectiveness of these systems, C-FER collected information from Enbridge, public data sources and two maritime navigation consultants. Sources of failure considered in this study included human error, equipment failure and inclement weather. Using a quantitative fault tree analysis approach, the failure of the Line 5 pipeline crossing was expressed as logical combinations of contributing events leading to failure. The probabilities assigned to the individual events were derived from historical data or objective models whenever possible. An expert opinion solicitation process was used to assign values to events where appropriate information or models could not be found.

Considering only the effect of the Guardian:protect advisory messages, the estimated total failure rate was 1.94×10^{-4} per year. The failure rate due to intentional and unintentional anchor deployment was reduced by 38.4% and 73.7%, respectively, when compared to crossing without any preventative measures in place. With the Guardian:protect advisory messages and the Coordinated System in place, these reductions increased to 47.2% and 99.6% for intentional and unintentional anchor deployment, respectively. The failure rates considering all preventative measures were estimated to be 6.70×10^{-7} per year for intentional anchor deployment and 2.74×10^{-6} per year for unintentional anchor deployment. The total failure rate of 3.41×10^{-6} per year represents a reduction of 99.5% when compared to that without any preventative measures in place. Advisory messages, sent via AIS and radio communications, were found to be equally as effective as visual observations of anchor status, reducing the unintentional anchor deployment failure probability by 75% each. Explicit communications with all vessel operators requesting them to confirm their anchor status were found to be the most effective preventative measure, reducing the probability of failure due to unintentional anchor deployment by 94%.

5. REFERENCES

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APPENDIX A – FAULT TREE EVENTS FROM PREVIOUS STUDY

A.1 OVERVIEW

This appendix provides a list of the fault tree events created in the previous study[1], and that were modified in this study, to model pipeline failure due to anchor deployment considering the effect of the Guardian:protect system. Event lists are presented separately for intentional and unintentional anchor deployment.

A.2 INTENTIONAL ANCHOR DEPLOYMENT

ID	Description
E1	Pipeline failure due to intentional anchor deployment
E2	Deployment not prevented by hazard awareness
E3	Pipeline failed by hooked anchor
E4	Operator unaware of deployment hazard
E5	Guardian fails to make vessel operator aware
B1	Need to anchor in response to vessel emergency*
B2	Operator aware of deployment hazard
B3	Anchor deployment despite awareness of hazard
B4	Passive measures fail to make operator aware
B5	Deployed anchor reaches lakebed*
B6	Anchor size sufficient to hook pipe*
B7	Anchor force sufficient to fail pipe*
B8	Guardian fails to detect activity or transmit message
B9	Vessel operator fails to receive Guardian message

*only crossings by vessels with potential to fail pipeline were considered

Table A.1 Events for Pipeline Failure Due to Intentional Anchor Deployment

[1] Stephens M, Adianto R, Nessim M. Evaluation of anchor strike prevention and protection measures for the Line 5 crossing of the Mackinac Straits. Edmonton (AB): C FER Technologies; 2018. Report no. M268. Prepared for Enbridge Energy, Limited Partnership.

A.3 UNINTENTIONAL ANCHOR DEPLOYMENT

ID	Description
E1	Pipeline failure due to intentional anchor deployment*
E2	Pipeline failed by hooked anchor
E3	Deployment not prevented or recovered by advisory messaging
E4	Operator does not receive Guardian advisory message
B1	Unintentional anchor deployment within interaction distance
B2	Deployed anchor reaches lakebed*
B3	Anchor size sufficient to hook pipe*
B4	Anchor force sufficient to fail pipe*
B5	Vessel receives Guardian advisory message
B6	Vessel operator fails to act on Guardian message
B7	Guardian system fails to receive and/or send information
B8	Vessel system fails to send and/or receive information

*only crossings by vessels with potential to fail pipeline were considered

Table A.2 Events for Pipeline Failure Due to Unintentional Anchor Deployment

APPENDIX B – EXPERT OPINION SOLICITATION

Table B.1 provides the list of questions that were posed to the independent marine navigation consultants (i.e. the Experts) to derive the probabilities assigned to basic events within the quantitative fault tree analysis. For each question, the final consensus-based estimate achieved after two rounds of solicitation, if necessary, is given.

Question	Expert Response
How likely would an automated AIS message be to trigger a physical check of anchor deployment status–where message includes notification of approach to pipeline crossing and reminder that the Strait is a no anchor zone?	50%
How likely would a radio hail from the Enbridge Straits Operations Center be to trigger a physical check of anchor deployment status–where message includes notification of approach to pipeline crossing and reminder that the Strait is a no anchor zone?	75%
How likely would a radio hail from the Enbridge Straits Operations Center be to trigger a physical check of anchor deployment status–where message requests that the vessel captain confirm that the vessel's anchors are all properly stowed and not deployed, assuming the message is worded to make it clear that a physical check for proper anchor stowage is requested?	95%
How likely is an observation from a patrol boat to identify a deployed anchor under favorable conditions?	90%
How likely is an observation from a patrol boat to identify a deployed anchor under unfavorable conditions?	75%
How likely is an observation from the shoreline to identify a deployed anchor under favorable conditions?	50%
How likely is an observation from the shoreline to identify a deployed anchor under unfavorable conditions?	10%
If an anchor deployment is detected 15 minutes from the pipeline crossing (at the current speed), how likely would a typical cargo vessel be able to either stop, or slow down sufficiently, and weigh anchor before reaching the crossing?	95%

Table B.1 Expert Opinion Solicitation Questions and Answers

APPENDIX C – FAULT TREE EVENTS

C.1 OVERVIEW

This appendix provides a list of the fault tree events that were created to model pipeline failure due to anchor deployment. For each intentional and unintentional anchor deployment, a simplified version of the fault tree presented in Section 3 is provided, along with a table of events and their assigned or calculated probabilities.

C.2 INTENTIONAL ANCHOR DEPLOYMENT

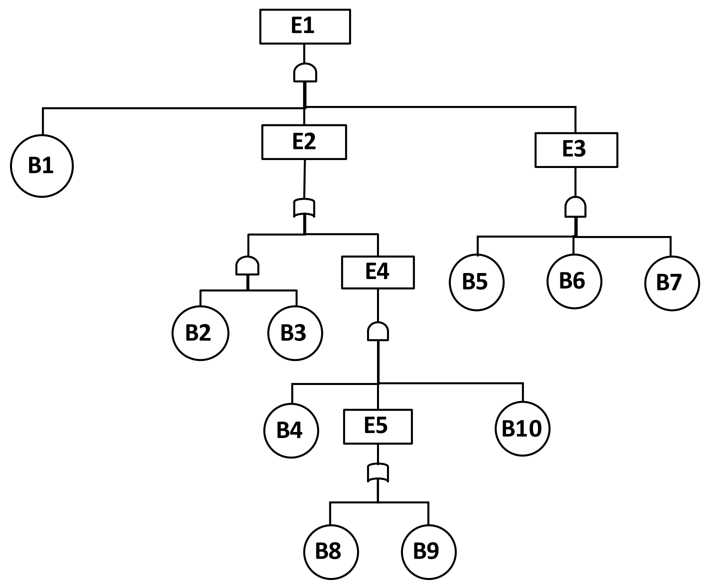

Figure C.1 Fault Tree for Pipeline Failure Due to Intentional Deployment

ID	Description	Value
B1	Need to anchor in response to vessel emergency	6.7×10^{-6} per year*
B2	Vessel operator aware of deployment hazard	0.9996
B3	Anchor deployment despite awareness of hazard	0.1
B4	Passive measures fail to make operator aware	0.1
B5	Deployed anchor reaches lakebed	1*
B6	Anchor size sufficient to hook pipe	1*
B7	Anchor force sufficient to fail pipe	1*
B8	Guardian fails to detect activity or transmit message	0.1
B9	Vessel operator fails to receive Guardian message	0.1
B10	ESMOC crew fails to send advisory message	0.01
E1	Pipeline failure due to intentional anchor deployment	6.70×10^{-7} per year
E2	Deployment not prevented by hazard awareness	0.1
E3	Pipeline failed by hooked anchor	1*
E4	Vessel operator unaware of deployment hazard	1.9×10^{-4}
E5	Guardian message fails to make vessel operator aware	0.19

*only crossings by vessels with potential to fail pipeline were considered

Table C.1 Events for Pipeline Failure Due to Intentional Anchor Deployment

C.3 UNINTENTIONAL ANCHOR DEPLOYMENT

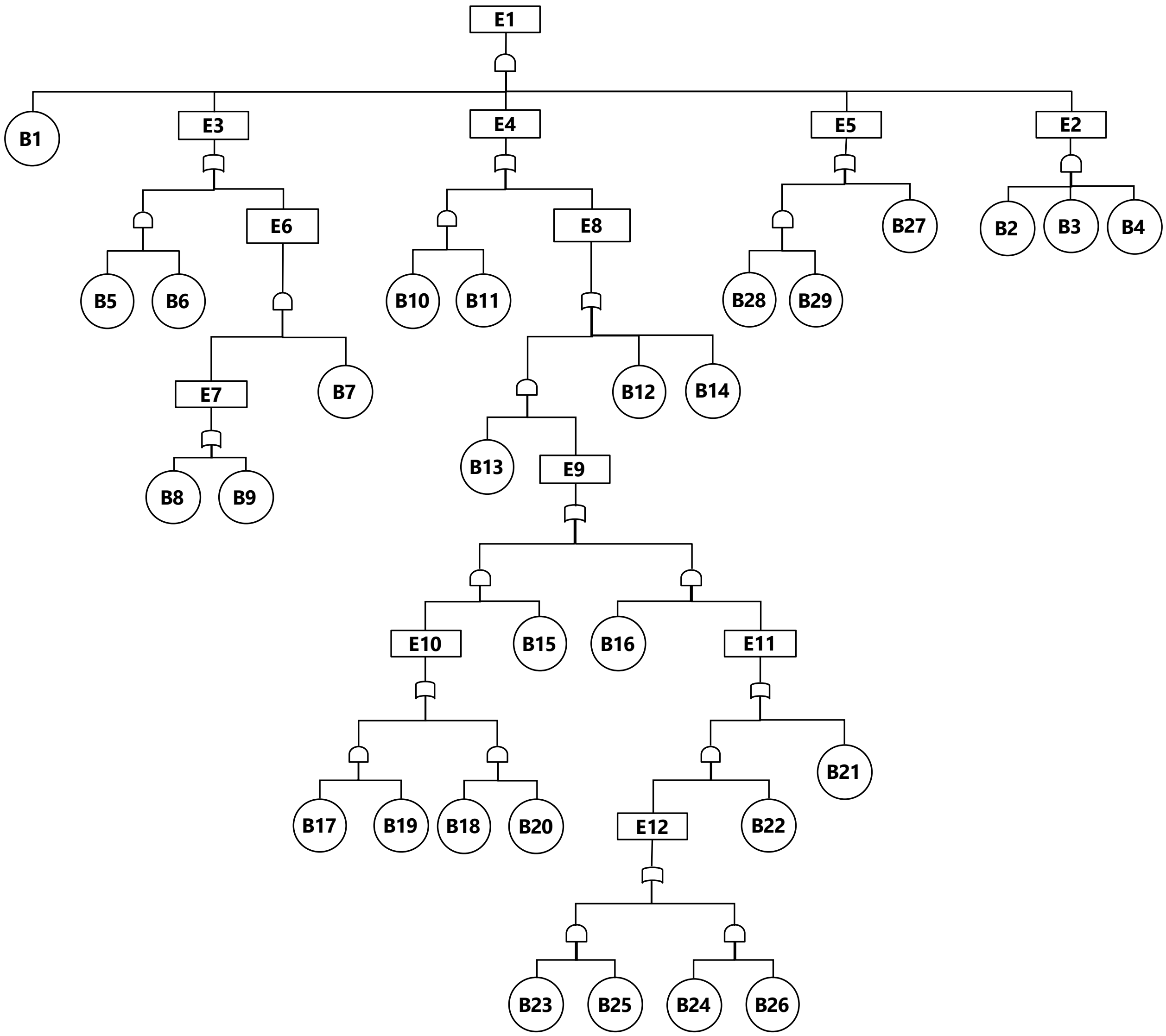

Figure C.2 Fault Tree for Pipeline Failure Due to Unintentional Anchor Deployment

Appendix C – Fault Tree Events

ID	Description	Value
B1	Unintentional anchor deployment within interaction distance	7.35×10^{-4} per year
B2	Deployed anchor reaches lakebed	1*
B3	Anchor size sufficient to hook pipe	1*
B4	Anchor force sufficient to fail pipe	1*
B5	Vessel receives an advisory message	0.9998
B6	Vessel operator fails to act on advisory message	0.25
B7	ESMOC crews fails to send advisory radio message	0.01
B8	Guardian system fails to receive and/or send information	0.01
B9	Vessel AIS system fails to send and/or receive information	4.2×10^{-3}
B10	Vessel operator made aware of anchor deployment	0.79
B11	Vessel operator fails to recover deployed anchor in time	0.05
B12	Traffic monitoring fails to identify vessel	0.01
B13	Traffic monitoring identifies vessel	0.99
B14	Radio send and/or receive failure	2.1×10^{-3}
B15	On-water observation conducted	0.89
B16	On-water observation not conducted	0.12
B17	Unfavorable weather for on-water observations	0.15
B18	Favorable weather for on-water observations	0.85
B19	On-water observation fails to identify deployed anchor in unfavorable conditions	0.25
B20	On-water observation fails to identify deployed anchor in favorable conditions	0.10
B21	Shore-based observation not conducted	0.50
B22	Shore-based observation conducted	0.50
B23	Unfavorable weather for shore-based observations	0.30
B24	Favorable weather for shore-based observations	0.70
B25	Shore-based observation fails to identify deployed anchor in unfavorable conditions	0.90
B26	Shore-based observation fails to identify deployed anchor in favorable conditions	0.50
B27	Vessel does not receive an anchor check request	0.01
B28	Vessel receives an anchor check request	0.99
B29	Vessel operator fails to check for secured anchor	0.05

ID	Description	Value
E1	Pipeline failure due to unintentional anchor deployment	2.74×10^{-6} per year
E2	Pipeline failed by hooked anchor	1*
E3	Deployment not prevented or recovered by advisory messaging	0.25
E4	Deployment not recovered by visual observations	0.25
E5	Deployment not recovered or prevented by anchor check request	0.06
E6	Vessel operator does not receive any advisory message	1.6×10^{-4}
E7	Vessel operator does not receive Guardian advisory message	0.02
E8	Observations do not make vessel operator aware of anchor deployment	0.21
E9	Observations do not identify deployed anchor	0.20
E10	On-water observation fails to identify deployed anchor in all weather conditions	0.12
E11	Shore-based observations do not identify deployed anchor	0.81
E12	Shore-based observation fails to identify deployed anchor in all weather conditions	0.62

*only crossings by vessels with potential to fail pipeline were considered

Table C.2 Events for Pipeline Failure Due to Unintentional Anchor Deployment