newfoundland labrador hydro

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October 4, 2023

Board of Commissioners of Public Utilities
Prince Charles Building
120 Torbay Road, P.O. Box 21040
St. John's, NL A1A 5B2

Attention: Jo-Anne Galarneau
Executive Director and Board Secretary

Re: ***Reliability and Resource Adequacy Study Review***
Summary of Findings from L3501/2 Failure Investigations

At the technical conference on the *Reliability and Resource Adequacy Study Review* proceeding ("*RRA Study Review*") on May 1 and 2, 2023, Newfoundland and Labrador Hydro ("Hydro") provided an overview of all of the reports, studies, and analyses underway or planned for fulsome consideration of the next supply resource for the province. Following the technical conference, in correspondence dated May 5, 2023, the Board of Commissioners of Public Utilities ("Board") directed Hydro to file a number of updates regarding the studies and analyses ongoing within the *RRA Study Rev*iew. In particular:

1) Hydro shall file by May 19, 2023 a comprehensive list of all reports, studies and analyses it has currently underway or planned with respect to the reliability of the LIL, potential alternative generation resources, the load forecast, and any other issues raised in the 2022 RRAS Update and the May 1-2, 2023 technical conference. This list shall include a description of the scope of each study, report and analysis, the consultant or group undertaking the work and the schedule for completion.
2) Hydro shall file with the Board a copy of each report, study or analysis listed in response to number 1 above as it is completed.[1]

On May 25, 2023, Hydro provided the Board with a list of all reports, studies, and analyses currently underway or planned to support future filings in relation to the *RRA Study Review*.[2]

Enclosed with this letter is an overview of the findings and their impact on LIL reliability, as well as four documents summarizing the L3501/2 failure investigations, specifically:

- Turnbuckles on Structures 1872, 1806, and 1014;
- Optical ground wire tower peaks on Structures 1230 and 1231;
- Optical ground wire top plates on Structures 2135 and 2136; and
- Electrode conductors on Structures 513 to 515.

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[1] "Newfoundland and Labrador Hydro - Reliability and Resource Adequacy Study Review - To Parties - Further Process," Board of Commissioners of Public Utilities, May 5, 2023, p. 2.

[2] "*Reliability and Resource Adequacy Study Review* – Listing of Planned Reports, Studies, and Analyses," Newfoundland and Labrador Hydro, May 25, 2023, Table 1 and att. 1.

All repairs to L3501/2, pertaining to the aforementioned failures, necessary to return the line to service have been completed. Hydro is actively working to implement the recommendations resulting from the investigations.[3]

Should you have any questions, please contact the undersigned.

Yours truly,

NEWFOUNDLAND AND LABRADOR HYDRO

SWalsh

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Encl.

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Stephen F. Fitzgerald, Browne Fitzgerald Morgan & Avis
Sarah G. Fitzgerald, Browne Fitzgerald Morgan & Avis
Bernice Bailey, Browne Fitzgerald Morgan & Avis

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[3] On June 23, 2021, the Government of Newfoundland and Labrador announced that Nalcor operations would move under Hydro. For clarity, within the enclosed documents the use of "Hydro" is in reference to the entire company, including both Hydro and Nalcor. Although Nalcor now operates as a single entity under the Hydro brand, as of the date of this filing, Nalcor as a legal entity, its structure, and all of its subsidiaries remain unchanged.

Summary of Labrador-Island Link Failure Investigations

Line L3501/2

October 4, 2023

A report to the Board of Commissioners of Public Utilities

Introduction

The Labrador-Island Link ("LIL") is a 900 MW high-voltage direct current ("HVdc") transmission line that carries electricity from the Muskrat Falls Hydroelectric Generating Facility to the Soldiers Pond Terminal Station. Line L3501/2[1] is the 350 kV HVdc overland transmission line portion of the LIL. Construction of the 1,100 km LIL was completed in late 2017; power commenced flowing in 2018 and the asset was commissioned on April 14, 2023.

The LIL is an important transmission line for the provincial energy grid due to its power-carrying capacity, which will be used to deliver a large portion of the winter peak energy to meet demand on the Island Interconnected System. Although the LIL is one transmission line, it runs through vastly different geographic and climatic conditions with large variations in terms of wind and ice. As a result, the line consists of many different types of towers, each designed for the specific conditions of each geographic region.

As Figure 1 shows, the overland transmission line is a bipole line with a single conductor per pole, duel electrode conductors for a portion of the line,[2] and an optical ground wire ("OPGW") communication cable. The lines are supported by galvanized steel lattice towers. The LIL consists of 3,223 towers, of which 10% (327) are dead-end insulator assembly towers (Figure 2) and 90% (2,896) are suspension insulator assembly towers (Figure 3)

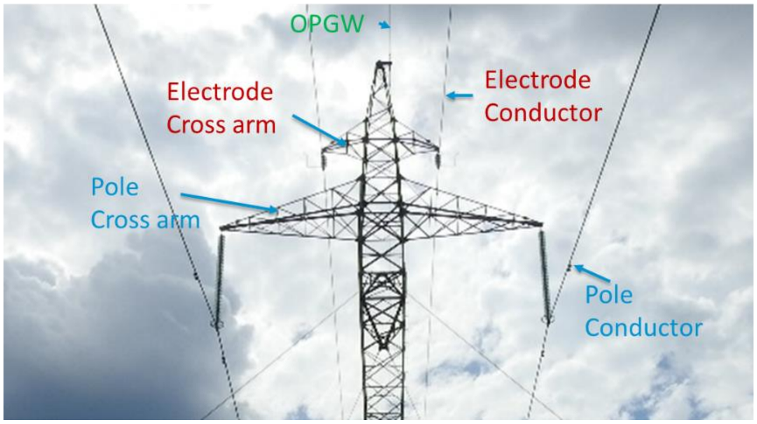

Figure 1: L3501/2 Structure Showing Wire Arrangement

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[1] L3501 and L3502 are Pole 1 and Pole 2 of the line, respectively.

[2] The electrode conductor system in Labrador is a redundant system that consists of two conductors supported on the 1,229 transmission line steel towers of the LIL and provides a connection between the converter station in Muskrat Falls to the grounding site in L'Anse au Diable. The electrode conductor system on the Island provides a connection between the converter stations in Soldiers Pond and the grounding site in Dowden's Point.

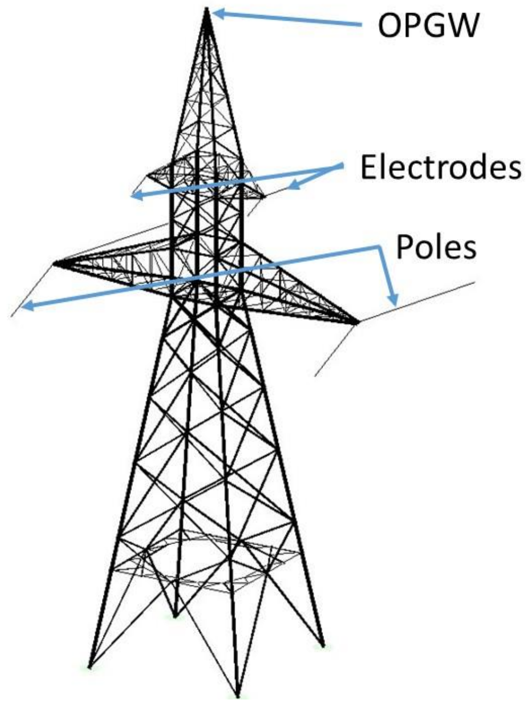

Figure 2: L3501/2 Dead-End Structure Showing Wire Arrangement

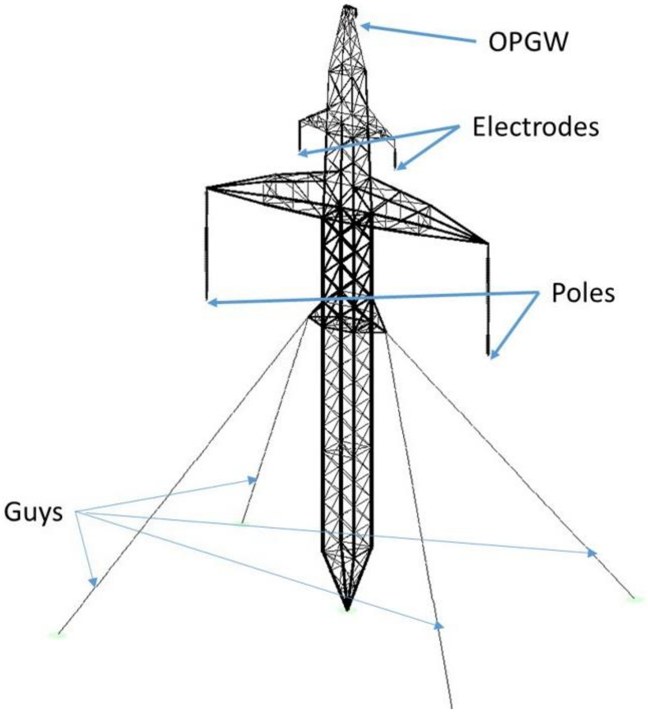

Figure 3: L3501/2 Suspension Structure Showing Wire Arrangement

Newfoundland and Labrador Hydro ("Hydro") has transmission assets that are located and operating in areas of harsh terrain across the Island and in Labrador. The LIL was also constructed in harsh terrain; it is subjected to heavy wind and ice loads and has experienced multiple winter seasons and weather events.

Between December 2022 and January 2023, Hydro responded to failures resulting from four types of localized issues, each observed on a different section of the LIL. These included three failed turnbuckles,[3] damage to two OPGW tower peaks, one failed electrode conductor, and two damaged OPGW tower top plates. These issues did not affect Hydro's ability to provide customers on the Island with reliable service last winter; all critical repairs resulting from the failures have been completed.

These failures were localized issues each affecting a small amount of specific transmission line components. The turnbuckle failures were experienced on less than 1% of the LIL's dead-end structures or 0.2% of all installed turnbuckles. In the case of the two failed OPGW tower peaks, they represent less than 0.1% of all structures, and the LIL performed as expected under the loading conditions experienced.

Following the necessary repairs, Hydro completed investigations into the four types of issues observed on various sections of the LIL this past winter. The investigation results help Hydro understand the root cause of each incident so that proactive actions can be taken, where necessary, to mitigate against any impact on the long-term reliability of the LIL. The investigations were completed with expertise from Hydro's Transmission Engineering team and reviewed by third-party consultants for detailed calculations and modelling, material testing, and laboratory simulations, as well as the review of the process, findings, and recommendations. Hydro is actively implementing the recommendations, which are detailed within the summaries of the enclosed investigations.

As these early failures are identified, recommendations are addressed and components are replaced, Hydro anticipates that the performance of the LIL will be consistent with its designed return period.[4]

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[3] Turnbuckles are present only on dead-end towers (327 or 10% of towers), with each tower having four turnbuckles.

[4] Return period, also known as recurrence interval, is an estimate of the likelihood of a climatological event to occur. It is usually used for risk analysis (e.g., to design structures to withstand an event with a certain return period).

Summary of Failures and Investigations

The investigations examined four unrelated issues. Root causes and future recommendations have been determined for each. Implementation of the engineering recommendations will strengthen the long-term reliability of the Labrador-Island Link.

The primary cause for turnbuckle failures is galloping[5] on the transmission lines in isolated areas, whereas the remaining issues are primarily due to unbalanced ice load and ice shedding. Galloping has been studied in the transmission industry since the early 1900s.[6] There is no industry standard to design a transmission line that will not experience galloping; rather, galloping is addressed post-construction in areas of the line where it is observed. The presence of galloping on a transmission line is not a design flaw. Table 1 presents a detailed summary of each type of issue, including the root cause and engineering recommendations.

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[5] Galloping is a high-amplitude, low-frequency oscillation of overland power lines due to wind; it can be caused by specific wind conditions and is sometimes observed on lines with small amounts of icing.

[6] "State of the art of conductor Galloping," *Cigré-Brochure* 322, 2007.

Table 1: Summary of Findings for LIL Failure Investigations

	Turnbuckles	**OPGW Tower Peaks**	**Electrode Conductors**	**OPGW Top Plates**
Number of Structures	3 of 1,308	2 of 3,223	3 of 1,229	2 of 502
Failure Rate	< 1%	< 0.1%	0.2%	0.4%
Customer Impact (Outage)	Yes[7]	No	No	No
Long-Term Reliability Impact[8]	None	None	None	None
Primary Cause	Galloping	Unbalanced ice loads due to uneven ice shedding		Ice shedding and a design error for the A3 tower top plate
Action Items and Recommendations	• Galloping study complete identifying areas of higher priority. • Installation of airflow spoilers underway to mitigate galloping. Focusing on high-priority areas. • Increased field monitoring and reporting. • Replacement of turnbuckles underway with year one of four nearing completion. Focusing on high-priority areas.	• Increased monitoring of ice conditions along the transmission line. ○ Weather station installed in Labrador Straits. ○ Additional weather station planned for 2025 in central Labrador. ○ Information collection from ongoing line patrols and maintenance activities. • External consultant to study unbalanced ice loads, changes in weather patterns, and potential design changes to facilitate informed decision-making and proactive mitigation, where required.		• Consultant to redesign connection details for A3 towers and assess the bolted connection design of all tangent tower types in 2023. • Corrections to be implemented as required, starting in critical locations.

Although these issues impact a small amount of specific transmission line components, Hydro is taking proactive steps to mitigate the risk of customer impact resulting from failures in the long term, particularly where capital expenditures will improve the long-term reliability of the LIL. Specifically, for turnbuckle failures related to galloping, Hydro is mitigating possible failures and any potential customer

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[7] There was no customer impact associated with these failures; however, outages to the LIL were taken to complete repairs, from a work safety perspective.

[8] The expected impact of each type of failure on long-term reliability of the LIL once recommended action items have been completed.

impact by replacing all turnbuckles (1,308 in total). To date, Hydro is ahead of schedule within its capital program to replace the turnbuckles with all planned year 1 replacements having been completed. Based on the outcome of its galloping study, Hydro is also installing airflow spoilers on certain sections of the LIL to control galloping and mitigate further damage to turnbuckles. This scope of work is approximately 40% complete.

For the remaining failures, damage was isolated to system communications cables and the electrode conductor system, which are not required for power to flow and, as a result, would not cause a prolonged power interruption. To address these issues, Hydro has increased real-time monitoring of the ice conditions along the transmission line by installing a weather station in the Labrador Straits, with another slated for installation in central Labrador in 2025. Hydro has also increased line patrols and the collection of field observation data, as maintenance activities are performed. During maintenance activities, Hydro is proactively replacing any identified components that are deemed required for replacement arising from the failure investigation, such as the turnbuckles and OPGW top plates. Hydro will study the benefits and costs associated with changing or fortifying any other components and make decisions based on what is best for long-term reliability and Hydro's customers. Hydro has also engaged an external consultant to study unbalanced ice loads, changes in weather patterns, and potential design changes in 2024 to facilitate further informed decision-making for operations in the future.

All repairs resulting from the aforementioned failures have been completed and Hydro is actively implementing the recommendations detailed within each investigation report.

LIL Failures and Reliability

With the LIL in its early operation, the early level of reliability is anticipated to be lower than the long-term level of reliability, due to expected sources of potential failures associated with new assets, such as defective components or manufacturing issues. This phenomenon is known as the "bathtub curve." This concept, which theorizes a relationship between equipment age and failures, has been presented by The Liberty Consulting Group ("Liberty") in previous reliability assessments.

> ***Equipment failures in relation to equipment age generally exhibit a "bathtub-shaped curve." Incidents of failure tend to be high when equipment is new and again after 30-50 years, depending on equipment type.***
>
> ***-Liberty Consultants, Supply Outages and Power Review 2014***[9]

As shown in Figure 4, the bathtub curve has three regions—the first has a decreasing failure rate due to early failures that are found and corrected contributing to improved reliability, the middle is a constant failure rate due to normalized frequency of expected failures, and the last is an increasing failure rate due to end-of-life failures.

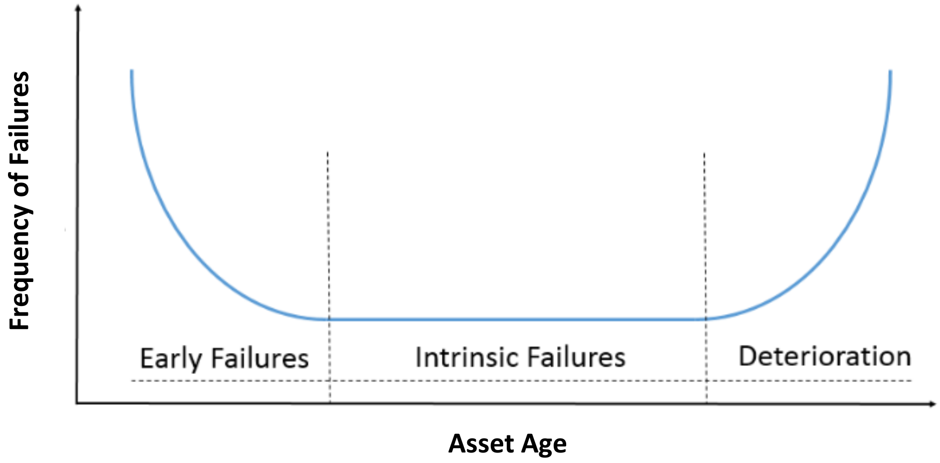

Figure 4: Bathtub Curve[10]

Early failures on the LIL have largely arisen due to items that were not considered during project design that have come to light during testing and early years of operation. Examples of such items include aspects of LIL software, LIL hardware, as well as with the overland line. In terms of LIL software, Hydro continues to work with General Electric to resolve known issues, which will be mitigated in the next revision. For LIL hardware, Hydro is undertaking efforts to replace DCCTs[11] to mitigate performance

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[9] "Supply Issues and Power Outages Review, Island Interconnected System, Executive Summary of Interim Report," The Liberty Consulting Group, April 24, 2014, sec. D, p. 57 <http://www.pub.nl.ca/applications/IslandInterconnectedSystem/files/reports/LibertyInterimReportApril24-2014.pdf>.

[10] Carroll, James & McDonald, Alasdair & Barrera, Oswaldo & Mcmillan, David & Bakhshi, Roozbeh. (2015). Offshore Wind Turbine Sub-Assembly Failure Rates Through Time.

[11] Direct-current current transformers ("DCCT")

issues that include measurement drifting in cold temperature conditions. As stated earlier, Hydro is taking action to understand and address the root causes of the overland line failures.

Each of the overland line failure incidents and subsequent investigations provide Hydro with critical data and information to better understand, and plan for, how the LIL will operate in the future. Through operational experience and strategic monitoring, Hydro will gain an understanding of the effectiveness of potential investments to upgrade LIL structures. Such investments have and will be made in consideration of risk and value-based assessments that will be better informed by other critical factors that impact system reliability, including response times for emergency repairs.

In the context of the *Reliability and Resource Adequacy Study Review* proceeding (*"RRA Study Review"*), the reliability of the LIL is a key consideration in terms of supply requirements for the Island Interconnected System. To this end, Hydro is undertaking efforts to understand the forced outage rate of the LIL based on operational data in consideration of the bathtub curve, the failures experienced during early operation, and the engineering solutions that are being implemented to mitigate failure modes and improve reliability.

In Hydro's "Reliability and Resource Adequacy Study Review – 2022 Update,"[12] for system planning purposes, Hydro quantified assumed LIL reliability using forced outage rates—from 1% (best case) to 10% (worst case) unavailability, with 5% as the base case. Hydro indicated that as LIL performance statistics become available in the coming years, the forced outage rate range can be narrowed in future filings.[13]

Hydro has begun compiling and analyzing reliability and outage data on the LIL. It is noted that this data is complicated in consideration of the relatively brief time since commissioning and the complexities of operational data prior to commissioning. However, Hydro will continue to monitor performance and, through the activities discussed herein, implement engineering solutions to continue to improve the reliability of the LIL. Through these efforts, improved LIL reliability can be expected as the LIL migrates to the second phase of the bathtub curve. It is the projected forced outage rate for this period that should be used by Hydro for long-term planning purposes.

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[12] "Reliability and Resource Adequacy Study – 2022 Update," Newfoundland and Labrador Hydro, October 3, 2023.

[13] Ibid, p. 16.

While it is premature to quantify forced outage rates or to develop firm conclusions based on the limited available reliability data, preliminary indications are that software considerations have had the most significant impact on LIL performance to date.

It is therefore expected that planned software fixes and the implementation of existing mitigating operating procedures will most significantly improve performance. Conversely, while there have been a series of performance issues with the overland line components of the LIL, the compounding effect of these failures has had a relatively minor impact on key reliability metrics.

As stated previously, it is too early to draw firm conclusions; however, Hydro will continue to collect and explore operational data to take the most effective measures to improve LIL performance.

Considering the Impact of Climate Change

Hydro makes its operational decisions based on known inputs, such as weather data; however, Hydro, and other utilities across Canada, must also manage the increasing impacts of climate change. These impacts, and the associated increase in frequency and severity of weather events, require Hydro to assess the resilience of its infrastructure—and adapt its planning, operation and response accordingly.

Hydro is proactively studying and will continue to monitor the impact of climate change on its operations, such as through the engagement of an external consultant to study unbalanced ice loads and changes in weather patterns, to ensure considerations are incorporated into operational decisions as it relates to the recommendations contained within this report and beyond.

Conclusion

Hydro is gaining operational experience with the LIL and is monitoring the performance of all aspects of the LIL, including software, hardware, and overland line considerations. Hydro is implementing engineering solutions that will effectively improve reliability and performance.

Hydro will continue to monitor performance and reliability drivers for the LIL and will report on the status of the action items arising from the overland line investigations in its quarterly LIL updates to the Board.

Hydro recognizes that an understanding of these parameters is critical to the *RRA Study Review* and future decision-making. Hydro is cognizant and sensitive to the time constraints and concerns of its stakeholders and is working diligently on a number of fronts to ensure all relevant information is gathered, analyzed, and incorporated into the larger examination of the viable and prudent solutions necessary to ensure safe, reliable, least-cost, environmentally responsible service to the province.

The enclosed investigation summaries provide an overview of four unrelated localized issues with the overland components of the LIL, which are typical of early failures. As stated herein, the compounding effect of these failures has had a relatively minor impact on key reliability metrics. Hydro will utilize the operational experience gained and information gathered within its *RRA Study Review* to take the most effective measures to improve system planning and reliability performance.

Summary of Findings from L3501/2 Failure Investigation

Turnbuckle Failures

Structures 1872, 1806, and 1014

October 4, 2023

A report to the Board of Commissioners of Public Utilities

Executive Summary

The Labrador-Island Link ("LIL") is a 900 MW high-voltage direct current ("HVdc") transmission line that carries electricity from the Muskrat Falls Hydroelectric Generating Facility to the Soldiers Pond Terminal Station. Line L3501/2[1] is the 350 kV HVdc overland transmission line portion of the LIL. Construction of the 1,100 km LIL was completed in late 2017; power commenced flowing in 2018 and the asset was commissioned on April 14, 2023.

The LIL is comprised of 3,223 towers, stretching over 1,100 km, of which 327 are dead-end[2] structures. Each dead-end structure contains a dead-end assembly[3] that includes four turnbuckles.[4] During December 2022, failures occurred on transmission line L3501/2 on Structures 1872, 1806, and 1014; less than 1% of Newfoundland and Labrador Hydro's ("Hydro") dead-end structures. The three failures, having occurred at different times on different structures in different locations, were similar—each failure consisted of a single turnbuckle failing in the pole conductor dead-end assembly, which is connected to a dead-end tower.[5] There was no customer impact associated with these failures; however, outages to the LIL were taken to complete repairs, from a work safety perspective. The repairs for each structure and the surrounding areas were primarily completed as recommended, with some revisions to the repair plans due to equipment and time constraints, material availability, and changes in priority based on inspections of the surrounding towers.

A detailed failure investigation was completed to determine the root cause of the failures and to identify recommendations to mitigate against the reoccurrence of this failure in the event of future major weather events or until all appropriate actions are completed. The primary cause of the failure of the turnbuckles on Structures 1872, 1806, and 1014 was fatigue failure, with galloping[6] believed to be the major contributing movement. A similar failure previously occurred in February 2021, in which the failure investigation concluded that fatigue failure likely as a result of galloping caused the turnbuckles

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[1] L3501 and L3502 are Pole 1 and Pole 2 of the line, respectively.
[2] A dead-end tower is a fully self-supporting structure used in the construction of overland power lines. A dead-end tower is a tower type at which the conductor ends at one side of the tower and another section of the conductor starts on the other side, with a jumper conductor in between to allow power to flow.
[3] A dead-end assembly is the hardware and insulator assembly that connects the dead-end conductor to the tower.
[4] A turnbuckle is a piece of hardware in the dead-end assembly that is used to adjust the sag and tension of the cable.
[5] Of the 1,308 turnbuckles, 3 turnbuckles failed, indicating a failure rate of approximately 0.2%.
[6] Galloping is a high-amplitude, low-frequency oscillation of overland power lines due to wind; it can be caused by specific wind conditions and is sometimes observed on lines with small amounts of icing.

to fail; therefore, it is logical to conclude that the primary cause of the failures in 2021 and 2022 are due to the same issue.

Although galloping is a common phenomenon in the transmission industry, it is not industry standard to design a transmission line that will mitigate galloping in all areas. Rather, galloping is addressed in affected areas upon observation after construction and during operation, normally in the early life stage of the line. Airflow spoilers have been used within the industry for many years to mitigate galloping, including on lines in Hydro's system. While they cannot be guaranteed to eliminate galloping, they have had positive results.

Given the investigation findings, the primary recommendation to prevent further failures on the line is to control galloping through the installation of airflow spoilers. Additional recommendations include increased field monitoring and reporting, replacing the turnbuckles, and installing hardware as a short-term solution if required.

To date, Hydro has progressed action on all recommendations included in the report. After the 2021 turnbuckle failure, a galloping study was performed to identify areas of the line that experience galloping. The results of the galloping study indicated areas of high priority and enabled the planning for the installation of airflow spoilers. A capital program is currently underway to complete the installation of airflow spoilers at the location of the turnbuckle failures at Structure 1872 and 1806, as well as other areas where galloping has been observed that have experienced line damage. Hydro has also increased field monitoring and reporting by implementing a process for line crews to report galloping when observed in the field during line monitoring and maintenance activities. In addition, a capital project to replace all turnbuckles with an extension link with two shackles is underway and will continue over four years to accommodate the operational requirements of the line. The first year of the project is nearing completion, with installation in 2023 focusing on areas of higher priority located in the Long Range Mountains and southern Labrador. Given the actions described herein, turnbuckle failures are not anticipated to impact the long-term reliability of the LIL.

Contents

1.0 Introduction

During December 2022, there were three failures on Structures 1872, 1806, and 1014 on transmission line L3501/2. While each of the failures occurred at different structures, times, and locations along the line, they were similar in failure type. All three consisted of a turnbuckle failing in the pole conductor dead-end assembly, which is connected to a dead-end tower. A turnbuckle is a piece of hardware in this assembly that is used to adjust the sag and tension of the cable. A dead-end assembly and the location of the break are shown, highlighted in blue, in Figure 1.

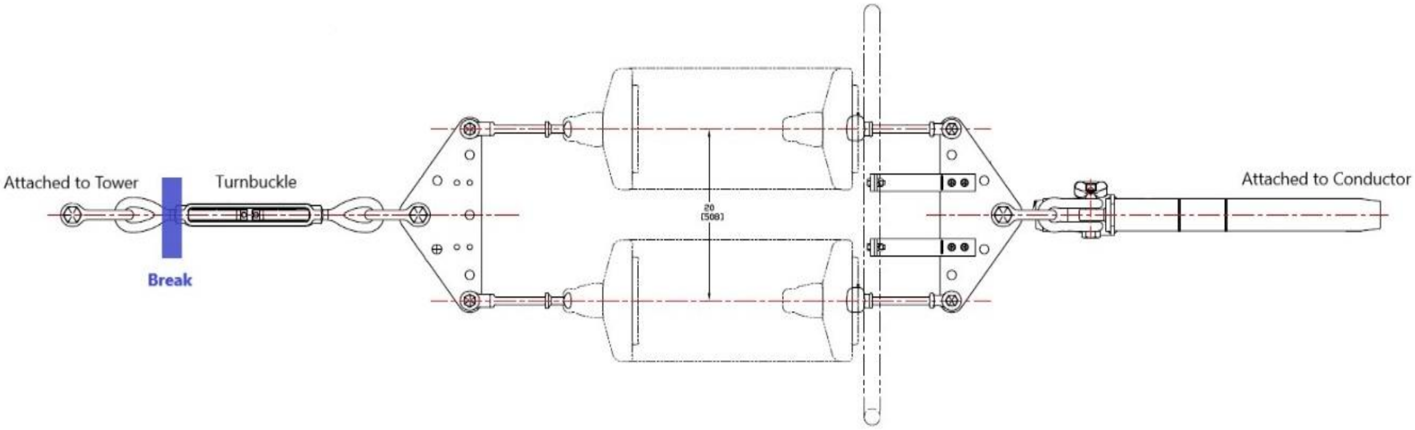

Figure 1: Dead-End Assembly

2.0 Background

The LIL is an important transmission line for the provincial energy grid due to its power-carrying capacity, which will be used to deliver a large portion of the winter peak energy to meet demand on the Island Interconnected System. Line L3501/2 is the 350 kV HVdc overland transmission line portion of LIL, traversing a distance of approximately 1,100 km. As Figure 2 shows, the overland transmission line is a bipole line with a single conductor per pole, duel electrode conductors[7] for a portion of the line, and an optical ground wire ("OPGW") communication cable. The lines are supported by galvanized steel lattice towers. The LIL was constructed in harsh terrain; it is subjected to heavy wind and ice loads and has experienced multiple winter seasons and weather events.

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[7] The electrode conductor is attached to the lattice towers until about 384 km southeast of Muskrat Falls (Structures 1 to 1229), where it diverts to a separate right-of-way on wood poles to an electrode site located in the L'Anse au Diable area. Sections of L3501/2 without the electrode on the towers do not have electrode crossarms.

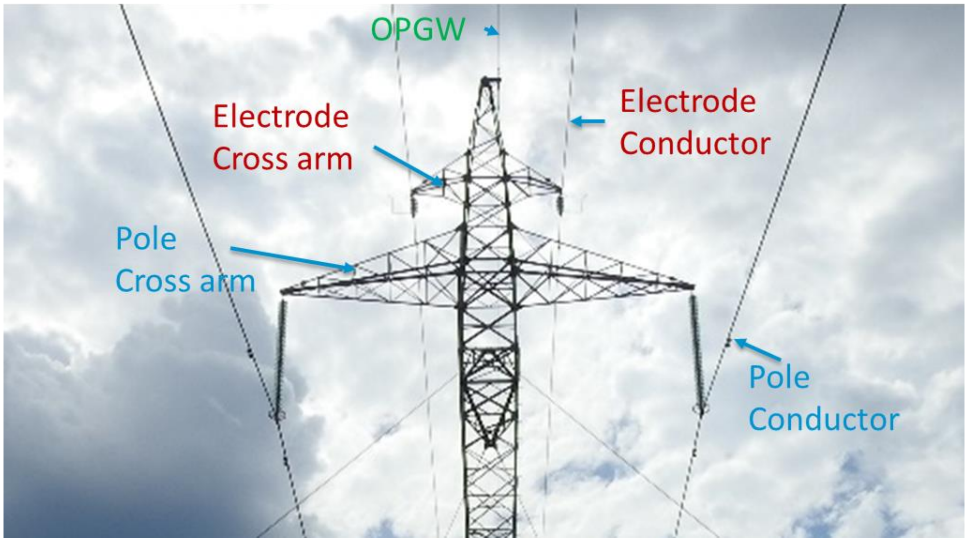

Figure 2: L3501/2 Structure Showing Wire Arrangement

The HVdc transmission line corridor has been divided into three major meteorological loading zones (average, alpine, and eastern) in combination with eight further subcategories related to meteorological loads, pollution levels (inland and coastal), and geographic location. The resulting combinations lead to the HVdc line consisting of 19 separate loading zones. There are 11 tower types (A1, A2, A3, A4, B1, B2, C1, C2, D1, D2, and E1) that were designed to meet the loading requirements applied to the line, which consist of a specified wind load, ice load, and combination of both. The tower types consist of both guyed towers and self-support towers. The tower types are summarized in Table 1.

Table 1: Tower Types

Tower Type	Structure Type	Insulator Assembly Type	Deflection Angle Limit (Degree)
A1, A2, A3, A4	Guyed	Suspension	0–1
B1	Guyed	Suspension	0–3
B2	Self Support	Suspension	0–3
C1, C2	Self Support	Dead End	0–30
D1, D2	Self Support	Dead End	0–45
E1	Self Support	Dead End	45–90

As shown in Chart 1, only 10% of all towers on the L3501/2 are dead-end towers that utilize turnbuckles (types C1, C2, D1, D2, and E1).[8] Chart 1 breaks down the tower distribution on L3501/2.

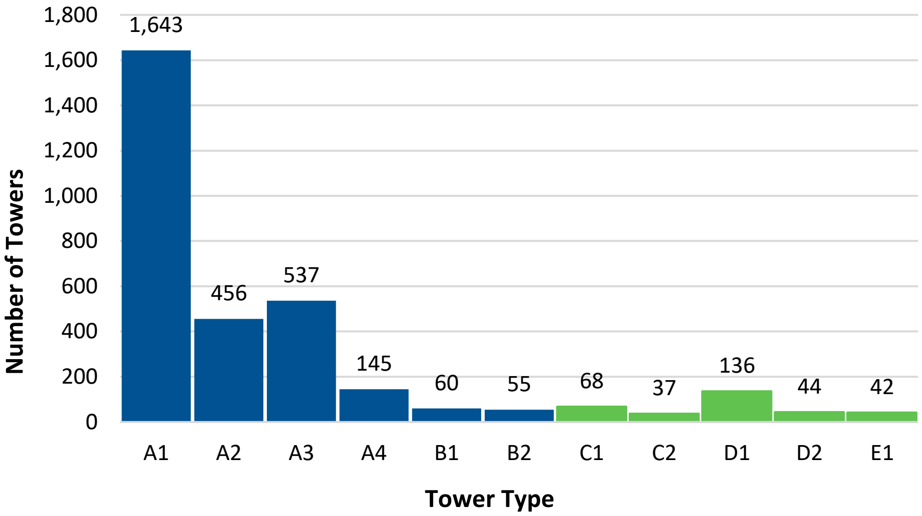

Chart 1: Distribution of Tower Types on L3501/2

3.0 Investigation Overview

To understand the line's performance in severe weather conditions, a detailed failure investigation was completed to determine the root cause of the failures and to conclude what actions can be taken to mitigate against further failures, including damage to the line, and to provide appropriate remediation.

The investigation will be described in detail herein and includes the following components:

- Failure description;
- Weather information;
- Immediate repairs;
- Construction quality and maintenance review;
- Similarity to past failure;
- Galloping and damper issues;

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[8] Suspension towers do not have turnbuckles.

- Material testing;
- Summary of root cause; and
- Recommendations.

4.0 Failure Description

At approximately 2330 hours on December 1, 2022, a line trip was reported on L3502. The line tripped upon energization; however, as it had not been in service since November 24, 2022, the actual time of failure is unknown. On December 2, 2022, the failure was identified at Structure 1872. As Figure 3 shows, the back span[9] of pole conductor Pole 2 ("P2") was on the ground. The point of failure was the turnbuckle, which was located on the tower side of the dead-end assembly. The break was located in the threaded portion of the turnbuckle just below the eye, as shown in Figure 4 and Figure 5.

Figure 3: Structure 1872 with Failed Dead-End Assembly

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[9] The back span is the span between Structures 1871 and 1872.

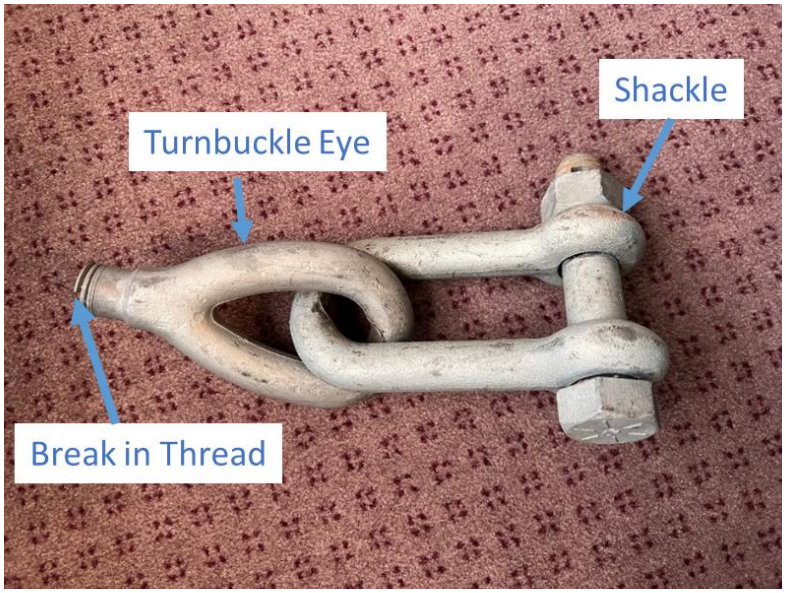

Figure 4: Failed Turnbuckle and Shackle

Figure 5: Failed Turnbuckle Eye and Shackle

At approximately 1030 hours on December 27, 2022, the line tripped on the Island section of L3501. On December 30, 2022, a failure was identified at Structure 1806. The back span of pole conductor Pole 1

("P1") was on the ground, as shown in Figure 6 and Figure 7. Similar to Structure 1872, the failure was located on the turnbuckle of the pole conductor assembly. Once the failure was identified, the necessary repairs were made and the line was put back into service.

Figure 6: Failed Dead-End Assembly at Structure 1806

Figure 7: Failed Turnbuckle on the Ground at Structure 1806

At approximately 1645 hours on December 29, 2022, the line tripped in the Labrador section of L3501. Later that same day, the failure was identified at Structure 1014. The ahead span of the pole conductor was on the ground, as shown in Figure 8. Similar to Structures 1872 and 1806, the failure was located on the turnbuckle of the pole conductor assembly. Once the failure was identified, the necessary repairs were made and the line was put back into service.

Figure 8: Failed Dead-End Assembly at Structure 1014

4.1 Failure Location

Structures are numbered sequentially along the line, starting at Muskrat Falls. As Figure 9 shows, Structures 1872 and 1806 are located 60 km and 75 km from the highway, respectively, in a remote location in the Long Range Mountains, which is only accessible by the transmission line access roads. The access roads are cleared of snow if winter access to the towers is required.

Figure 9: Map of the Island Showing the Locations of Turnbuckle Failures on Structures 1872 and 1806

4.1.1 Loading Zone

As discussed in Section 2.0, the LIL is divided into 19 loading zones. Structures 1872 and 1806 are located in loading Zone 7c (High Alpine Zone) and Zone 7b (Extreme Alpine), respectively. The wind and ice conditions for which these zones are designed are summarized in Table 2 and Table 3. Due to the elevation of this area, these zones experience rime ice.[10]

Table 2: Zones 7a and 7c Wind and Ice Design Loading

Load	Design Loading
Maximum Ice	115 mm radial rime, 0.5 g/cm^3 density
Maximum Wind	180 km/h (10-minute average wind speed at 10 m height above ground)
Combined Ice and Wind	60 mm radial rime, 0.5 g/cm^3 density 125 km/h (10-minute average wind speed at 10 m height above ground)

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[10] Rime ice, also known as in-cloud icing, is a type of ice that can form in higher elevations, occurring when moisture in the air freezes on objects such as transmission lines.

As Figure 10 shows, Structure 1014 is located in Labrador, near the southwest coast. The structure is located in a remote location 60 km from the closest highway, requiring access via transmission line access roads.

Figure 10: Map of Labrador Showing Location of Turnbuckle Failure on Structure 1014

Structure 1014 is located in loading Zone 2b (Labrador Extreme Alpine). The wind and ice conditions that this zone is designed for are summarized in Table 3.

Table 3: Zone 7b Wind and Ice Design Loading

Load	Design Loading
Maximum Ice	135 mm radial rime, 0.5 g/cm^3 density
Maximum Wind	135 km/h (10-minute average wind speed at 10 m height above ground)
Combined Ice and Wind	70 mm radial rime, 0.5 g/cm^3 density 95 km/h (10-minute average wind speed at 10 m height above ground)

5.0 Weather Information

5.1 Structure 1872

There was snow on the ground in the area of Structure 1872 at the time of failure. As Figure 11 shows, snow clearing was required to access the structure. There was some ice on the lines in the vicinity of the failure; however, the quantities observed were far less than the design thickness of 115 mm of radial rime ice for this section of the line.

Figure 11: Snow Conditions at Structure 1872

The weather station with hourly data closest to Structure 1872 is located approximately 36 km away in Daniel's Harbour. The mountainous landscape surrounding Structure 1872 has a significant effect on the localized weather.

The wind speed at Daniel's Harbour on the day of the failure, December 1, 2022, ranged from 5 km/h to 52 km/h, with an average speed of 26 km/h. Winds on the day of the failure were not extreme or above design loads, which is indicative of fatigue failure due to movement over the life of the line. The wind direction varied from east to south, as shown in Chart 2.

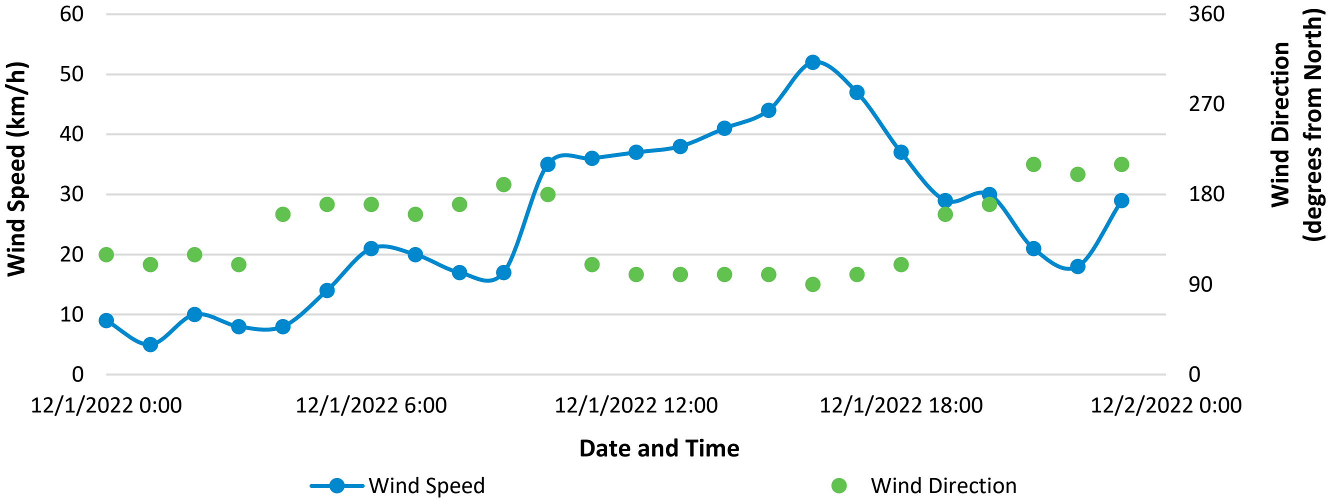

Chart 2: Daniel's Harbour Wind Data for December 1, 2022

As Chart 3 shows, the temperature at Daniel’s Harbour on December 1, 2022 ranged from -6°C to 8°C.

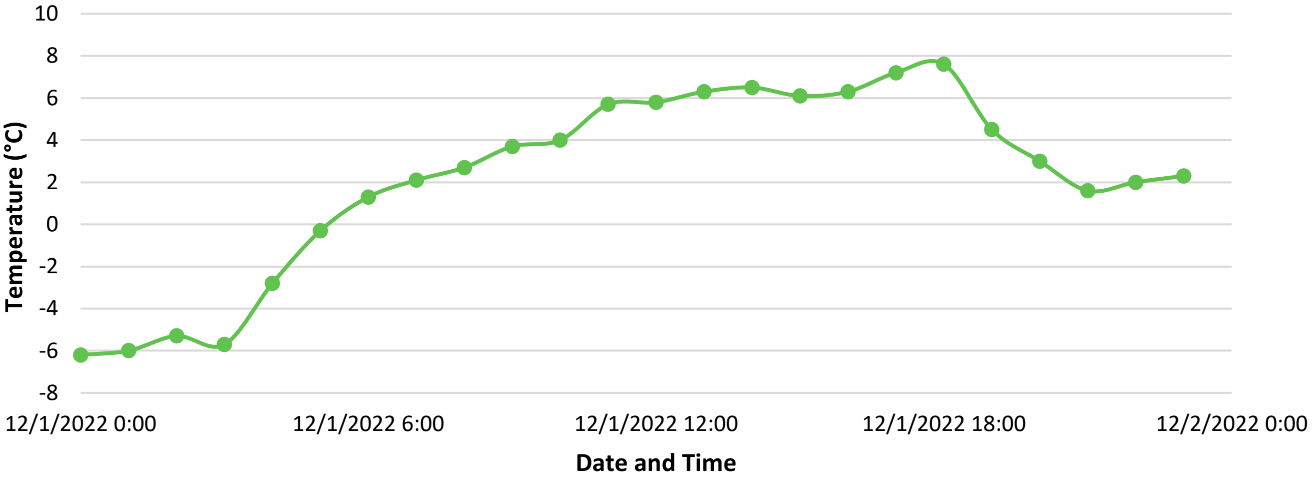

Chart 3: Daniel's Harbour Temperature Data for December 1, 2022

5.2 Structure 1806

There was significant snow on the ground in the area of Structure 1806, as shown in Figure 12. Snow clearing to access the structure took several days and continued effort was required to keep the access road open. There was a small amount of ice on the lines in the vicinity of the failure; however, the quantities observed were far less than the design thickness of 135 mm of radial rime ice for this location.

Figure 12: Snow Conditions at Site near Structure 1806

The weather station with hourly data closest to Structure 1806 is located approximately 27 km away in Daniel's Harbour. The mountainous landscape surrounding Structure 1806 has a significant effect on the localized weather.

The wind speed at Daniel's Harbour on the day of the failure, December 27, 2022, ranged from 18 km/h to 35 km/h, with an average speed of 26 km/h. Winds on the day of the failure were not extreme or above design loads, which is indicative of fatigue failure due to movement over the life of the line. The wind direction varied from west to north, as shown in Chart 4.

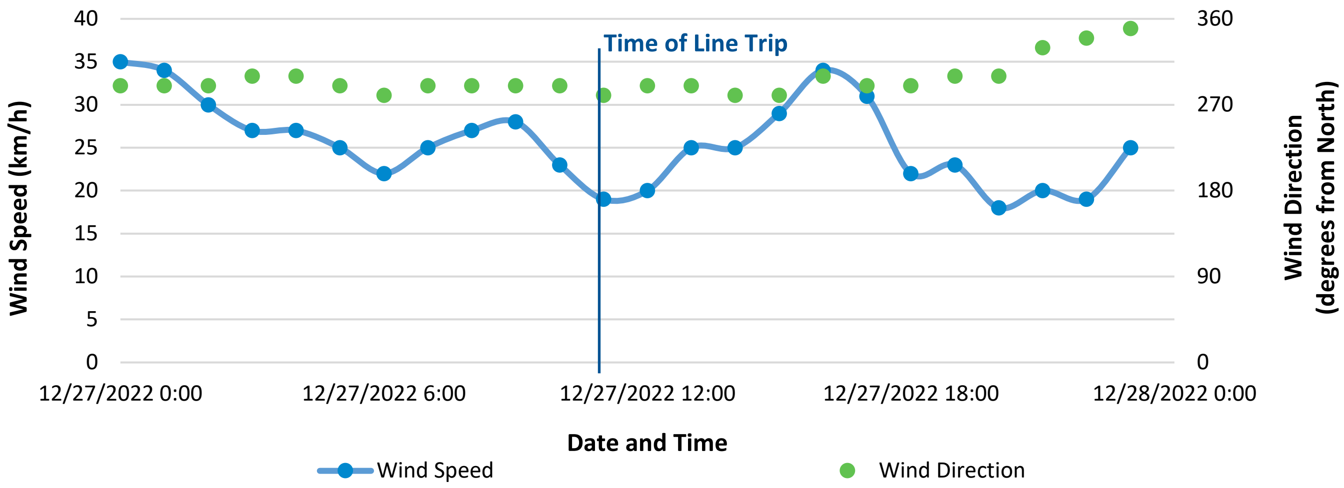

Chart 4: Daniel's Harbour Wind Data for December 27, 2022

The temperature at Daniel's Harbour on December 27, 2022, ranged from -6°C to -2°C, as shown in Chart 5.

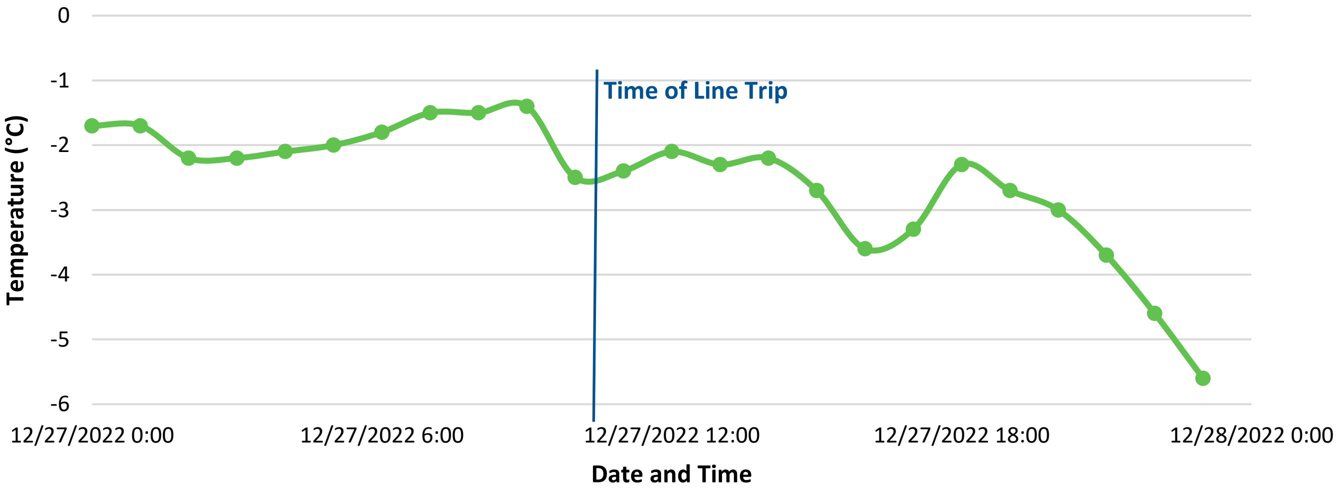

Chart 5: Daniel's Harbour Temperature Data for December 27, 2022

5.3 Structure 1014

There was significant snow and ice in the area of Structure 1014 at the time of failure, as shown in Figure 13 and Figure 14. The ice on the lines was observed to be nearing but not in exceedance of the design thickness of 135 mm of radial rime ice.

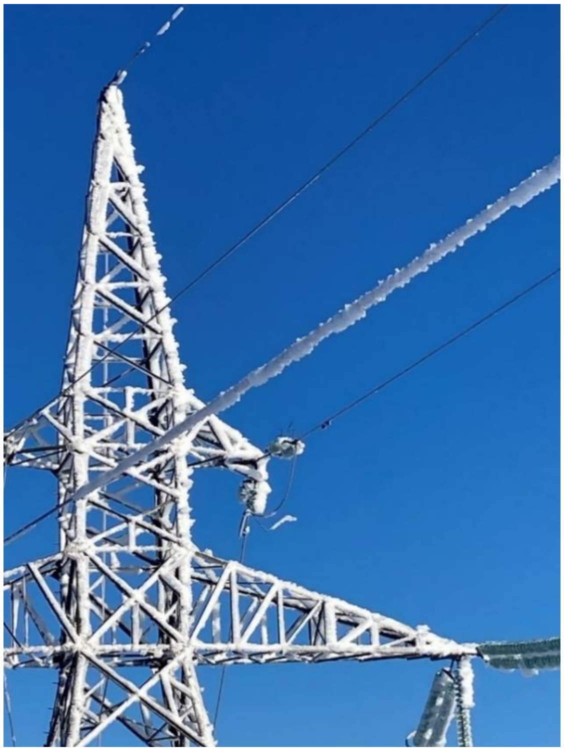

Figure 13: Ice on Lines near Structure 1014 Failure

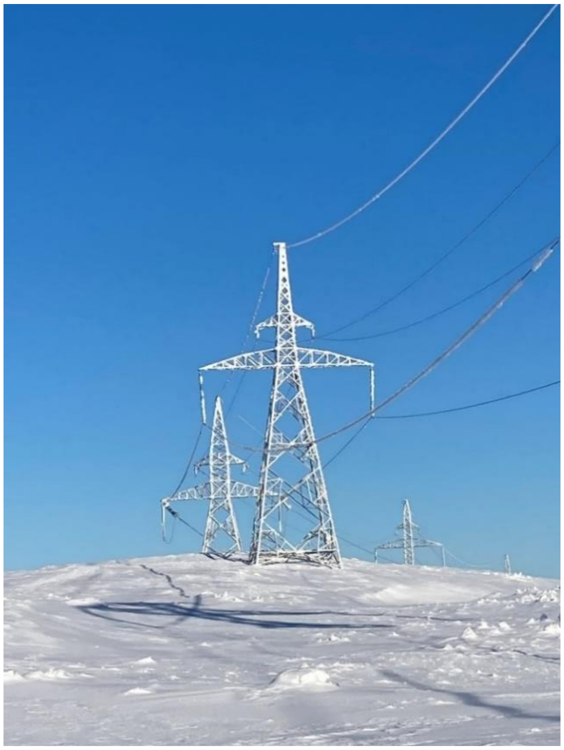

Figure 14: Snow at Site near Structure 1014 Failure

The weather station with hourly data closest to Structure 1014 is located approximately 58 km away in Blanc-Sablon, Quebec. The hilly landscape surrounding Structure 1014 will have a significant effect on the localized weather.

The wind speed at Blanc-Sablon on the day of the failure, December 29, 2022, ranged from 7 km/h to 28 km/h, with an average speed of 17 km/h. Winds on the day of the failure were not extreme or above design loads, which is indicative of fatigue failure due to movement over the life of the line. The wind direction varied from west to northwest, as shown in Chart 6.

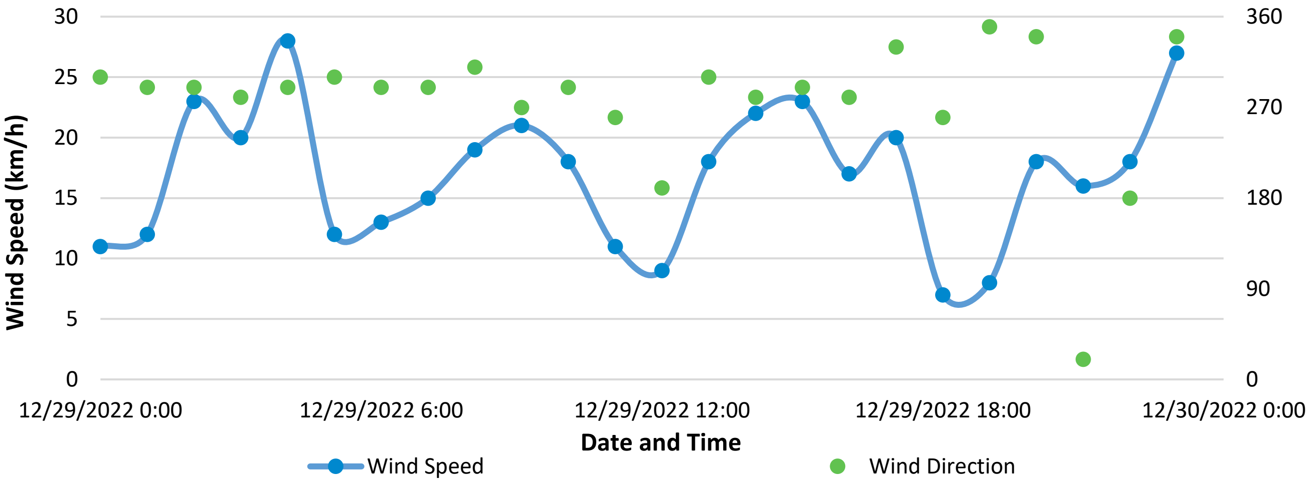

Chart 6: Blanc-Sablon Wind Data for December 29, 2022

The temperature at Blanc-Sablon on December 29, 2022 ranged from -16°C to -10°C, as shown in Chart 7.

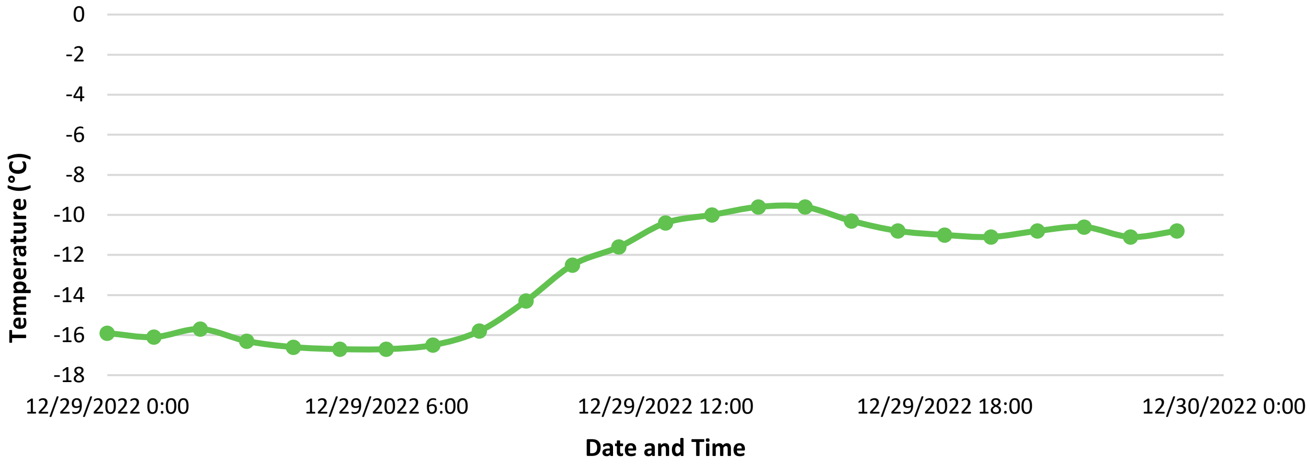

Chart 7: Blanc-Sablon Temperature Data for December 29, 2022

6.0 Immediate Repairs

6.1 Engineering Recommendations

The primary goal of the restoration work was to replace the failed turnbuckles and restore power. The surrounding structures were also inspected for damage and repaired as required. Any opportunities to strengthen the line that were practical within the timeframe of repairs were also implemented. The following are the engineering recommendations for immediate repairs and line strengthening based on the information available at the time of the failures.

The recommendation for repairs for failed dead-end structures was to replace the turnbuckle in the assembly with a chain link. The chain link is much shorter than the turnbuckle and is in one piece, so it would be less likely to fail under bending. A chain link was part of the original design of the pole dead-end assembly, as shown in Figure 15; however, the assembly design was revised to include the turnbuckle; this would allow adjustability to the initial sag of the line and better control over the vertical clearance between the conductors and the ground.

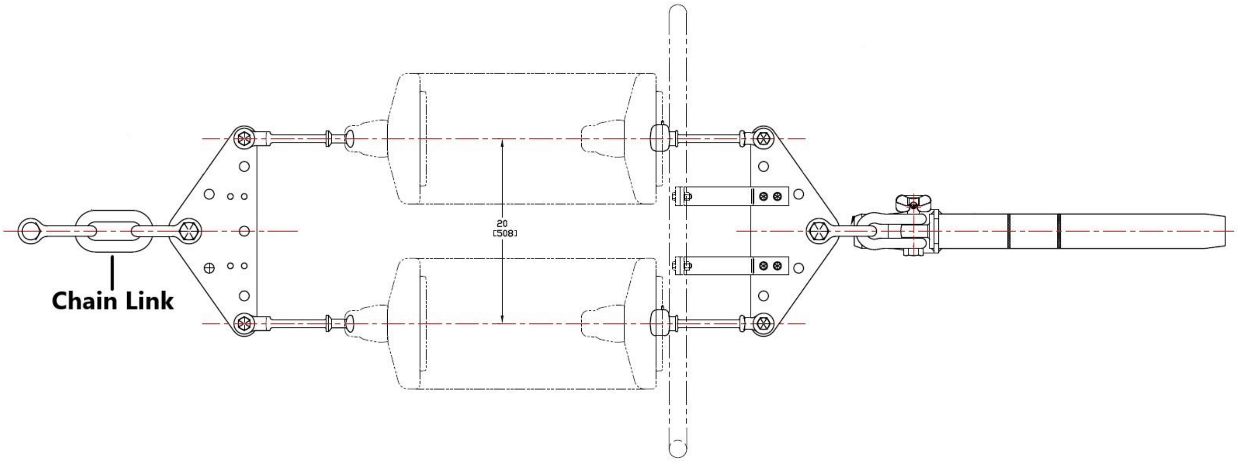

Figure 15: Pole Conductor Dead-End Assembly with Chain Link

It was recommended that the turnbuckles on adjacent dead ends be replaced as part of the immediate repairs. This recommendation is because nearby dead-end structures were likely subjected to similar loads as that of the failed turnbuckles and, as such, could be experiencing fatigue and wear, although they have not yet failed.

In addition, it was recommended that airflow spoilers be installed on the front and back spans of the structures with failures to help control galloping. Galloping was identified as a primary contributing factor to the fatigue failures in February 2021.

For other structures in the area of the failures, it was further recommended to add shackles to the holes adjacent to the turnbuckle attachment on the tower plate and yoke plate, as shown in Figure 16. Locks and chains were attached to the shackles as a safety feature. If the turnbuckle were to break, the shackle, lock, and chain mechanism would catch the pole conductor and prevent it from falling to the ground.

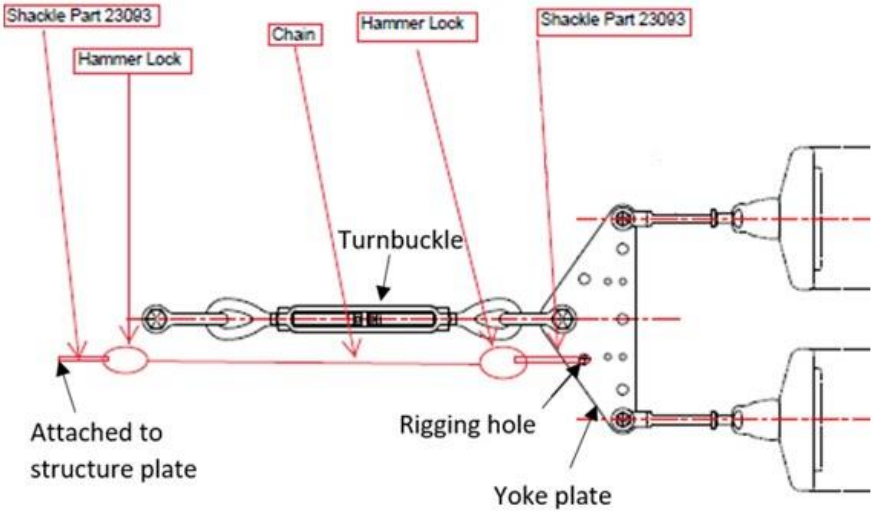

Figure 16: Sketch for Installation of Shackles, Locks, and Chains

6.2 Restoration Summary

The recommended repairs to Structures 1872, 1806, and 1014 were primarily completed as recommended due to equipment and time constraints. Some alternative strengthening options were used, such as replacing a turnbuckle with a new turnbuckle instead of a chain link or leaving the original turnbuckle in place and adding safety chains. Figure 17 shows an assembly with a safety chain installed.

Figure 17: Dead-End Assembly with Newly Installed Safety Chain

Some of the revisions to the repair plan were also due to a change in priority based on drone inspections of the surrounding towers. For example, turnbuckles on Structures 1883 and 1884 were deemed a higher priority than some of the turnbuckles on Structures 1866 and 1879 after inspection. Alternative strengthening options were also completed on Structures 1817, 1800, 1006, and 1022. While chain link assemblies are considered a permanent solution, those structures with replacement or reinforced turnbuckles are considered temporary and will be included in the upcoming capital projects for replacement, as detailed in Section 12.0.

7.0 Construction Quality and Maintenance Review

Construction quality reports were reviewed to determine if any issues were present that may have contributed to the failure. The review confirmed that there were no known defects or non-conformances from the engineering specifications, during either manufacturing or installation of the turnbuckles. No non-conformance reports were submitted on the dead-end assemblies of Structures 1872, 1806, or 1014 during construction and no corrective work orders were submitted for these structures prior to the turnbuckle failures.

8.0 Similarity to Past Failure

In February 2021, there were two turnbuckle failures on L3502 at Structures 1209 and 1229, after which a failure investigation was completed ("February 2021 Failure Investigation").[11]

The failures in 2021 occurred under similar conditions to the most recent failures, with some wind and little-to-no ice. The failed face of the turnbuckle was similar in appearance to the current failures, occurring close to the eye on the tower side of the turnbuckle within the threaded portion. As Figure 18 shows, in both the February 2021 and December 2022 failures, there was considerable wear on the shackle and turnbuckle eye next to the break, suggesting excessive movement.

Figure 18: Failed Turnbuckle Faces from February 2021 (left) and December 2022 (right)

Given the similarities in the failures, it is reasonable to assume the cause of the failure is the same. The February 2021 Failure Investigation concluded that the turnbuckles failed due to fatigue cracking caused by reverse bending; the movement of the dead-end assembly that would likely cause the turnbuckle to

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[11] The "Failure Investigation Report – L3501/2 Pole Assembly Turnbuckle Failure – Failure Event February 2021 in Labrador," Nalcor Energy, May 28, 2021 was filed as an attachment to the "*Reliability and Resource Adequacy Study Review* – Labrador-Island Link Failure Investigation Reports," Newfoundland and Labrador Hydro, May 31, 2023. <http://www.pub.nl.ca/applications/NLH2018ReliabilityAdequacy/correspondence/From%20NLH%20-%20Labrador-Island%20Link%20Failure%20Investigation%20Reports%20-%20January%20and%20February%202021%20-%202021-05-31.PDF>.

be subjected to repeat reverse bending is galloping.[12] There were no material issues found in the turnbuckles in the February 2021 Failure Investigation; each failed turnbuckle was replaced and safety chains were added for extra security in this location, airflow spoilers were procured and are planned to be added under the capital project that is currently underway.

9.0 Galloping and Damper Issues

Galloping has been studied in the transmission industry since the early 1900s;[13] however, while there have been advances in the understanding and controlling of galloping, there is no industry standard to design a line that will not experience galloping.

Galloping has been observed on the line since construction; causing extreme movement of the conductor, often vertically, but occasionally horizontally. The towers on L3501/02 have been designed so the wires can gallop without flashover[14] between them. Galloping will also cause fatigue and wear on hardware and conductors over time. Wear on the eyes of the turnbuckles and the shackle to which they are connected is a sign of galloping.

A review of the available methods to reduce galloping determined the most effective option for L3501/2 is airflow spoilers. Airflow spoilers have been used within the transmission line industry for many years, including on lines in Hydro’s system. While they cannot be guaranteed to eliminate galloping, they have had positive results.

One of the recommendations of the February 2021 Failure Investigation was to complete a galloping study to determine the sections of the line that are the most prone to galloping.[15] This information will be used to help monitor for galloping and to install airflow spoilers as required.

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[12] “Failure Investigation Report – L3501/2 Pole Assembly Turnbuckle Failure – Failure Event February 2021 in Labrador,” Nalcor Energy, May 28, 2021, sec. 10, p. 13.

[13] “State of the art of conductor Galloping,” *Cigré-Brochure* 322, 2007.

[14] Flashovers between phases are the most immediate, and frequently damaging, effect of galloping.

[15] “Failure Investigation Report – L3501/2 Pole Assembly Turnbuckle Failure – Failure Event February 2021 in Labrador,” Nalcor Energy, May 28, 2021, sec. 11, p. 14.

As stated in Section 6.1, it was recommended that airflow spoilers be installed at the locations of turnbuckle failures during repairs. Due to timing and equipment restraints, this work was only completed for Structure 1014.

As noted in the February 2021 Failure Investigation, the line has also experienced issues with the Stockbridge dampers that are installed on the line to control Aeolian vibration.[16,17] Through testing of the dampers and vibration monitoring of the line, it was determined the dampers currently installed on the electrode conductors and OPGW are not adequately controlling the vibration. It was noted during the assessment that there are far fewer failures of the dampers installed on the pole conductors. There is a capital project proposed for 2024 to specify new damper requirements and purchase new dampers for the line.

10.0 Material Testing

During the February 2021 Failure Investigation, the root cause of the failure of the turnbuckles was fatigue cracking due to reverse bending.[18] Galloping was determined to be the cause of this bending. It was also determined through material testing that there were no material issues with the turnbuckles, and they meet the design specifications.

To confirm that the December 2022 failures were due to the same cause, material testing was completed on a sample of turnbuckles[19] to confirm that they met design specifications and that no material issues could contribute to the failure. The consultant concludes that the turnbuckles met the minimum design specifications; however, it also identified a contributory cause for the fractured turnbuckle were indications[20] created during the manufacturing process due to an environmentally assisted cracking mechanism, most probably hydrogen embrittlement. Similar to the February 2021

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[16] Aeolian vibration is a high-frequency, low-amplitude oscillation of the overland power lines that is caused by low-velocity, steady wind.

[17] "Failure Investigation Report – L3501/2 Pole Assembly Turnbuckle Failure – Failure Event February 2021 in Labrador," Nalcor Energy, May 28, 2021, sec. 9, p. 13.

[18] "Failure Investigation Report – L3501/2 Pole Assembly Turnbuckle Failure – Failure Event February 2021 in Labrador," Nalcor Energy, May 28, 2021, sec. 10, p. 13.

[19] Material testing was completed on three turnbuckles in total (0.002%)—one turnbuckle from the December 2022 failures at Structure 1806, an intact turnbuckle that was replaced on Structure 1884 (near Structure 1872 failure), and a turnbuckle that had never been installed.

[20] In this case, indications refer to micro-cracks within the metal of the turnbuckle that could not be seen with the naked eye.

Failure Investigation, the most likely root cause of the failure of the turnbuckles was fatigue cracking due to reverse bending as a result of galloping. However, these findings suggest that the fatigue life of the turnbuckles had decreased as a result of the embrittlement. The life of the turnbuckles would likely be longer if no indications were present.

The consultant recommends ensuring galvanized replacement parts include the requirement to conform with ASTM A143[21] and the embrittlement test methods in ASTM F606[22] and to increase the cross-sectional thickness of the replacement parts.

11.0 Summary of Root Cause

The primary cause of the failure of the turnbuckles at Structures 1872, 1806, and 1014 is fatigue failure, with galloping believed to be the major contributing movement.[23] There are many similarities between the failures in December 2022 and those in February 2021. The conclusion of the February 2021 Failure Investigation, confirmed with testing at that time, was that galloping likely caused the turnbuckles to fail in fatigue under repeated reverse bending loads. It is logical to conclude that these most recent failures are due to the same issue.

Material testing of the turnbuckles from these most recent failures in December 2022 concluded the indications from manufacturing and fatigue contributed to the early failure; the most likely cause of the indication is hydrogen embrittlement. It is unlikely the turnbuckles would have failed six years into their service life if not subjected to reoccurring movement and bending in the form of galloping, causing fatigue, as evidenced by the failure rate of 0.4% of installed turnbuckles.

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[21] ASTM International. ASTM A143, *Standard Practice for Safeguarding Against Embrittlement of Hot-Dip Galvanized Structural Steel Products and Procedure for Detecting Embrittlement*.
[22] ASTM International. ASTM F606, *Standard Test Methods for Determining the Mechanical Properties of Externally and Internally Threaded Fasteners, Washers, Direct Tension Indicators, and Rivets*.
[23] It should also be noted that Aeolian vibration could contribute to the cause of the fatigue.

12.0 Recommendations

The recommendations to prevent further failures on the line due to failed turnbuckles include the following:

1) Install airflow spoilers;
2) Increased field monitoring and reporting;
3) Replace the turnbuckles; and
4) Install hardware as a short-term fix, if required.

The primary recommendation to prevent further failures is to control galloping using airflow spoilers. Galloping is a normal occurrence in transmission lines; it is not industry standard to design a transmission line that mitigates or controls galloping in all areas. Rather, galloping is addressed over time when observed in certain areas of the line that are identified as higher risk. It is recommended that airflow spoilers be installed at the location of the turnbuckle failures at Structure 1872 and 1806, as well as other areas that have experienced line damage and where galloping has been observed. These areas are in central Labrador from Structures 320 to 375 and Structures 500 to 530. Airflow spoilers are currently part of the maintenance spares; however, due to failures and galloping observations, it is recommended that the quantities be increased so they can be installed as required in a timely manner.

To determine other areas to install airflow spoilers, the results from the galloping study should be used as a guide for locations to monitor with line patrols. Increased field monitoring and a more detailed reporting process are recommended. A process to report galloping should be implemented so the extent of the galloping issues can be better understood. In addition, reports from tower inspections should note any signs of wear on tower hardware.

As previously stated, airflow spoilers will help control galloping but cannot be expected to stop galloping completely. All components of the line have been subjected to the forces from galloping but the component that has experienced failure at five different structures[24] is the turnbuckle of the dead-end assembly. Furthermore, material testing determined it is likely the turnbuckles have indications, likely from hydrogen embrittlement, which can act as the initiation point for cracking. Any repeated load

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[24] Two structures in the fall of 2021 and three structures in December 2022.

cycling can cause fatigue on the turnbuckles propagating the crack, resulting in failures. The turnbuckle is made of three separate pieces; the failures all occurred within the threaded portion of the eye piece, near where it fits into the body of the turnbuckle. The threaded piece, although secured with lock bolts, is still capable of slight movement during service. It is therefore recommended to replace the turnbuckle with hardware that will be less susceptible to fatigue failure in bending. The material testing report recommends ensuring that replacement galvanized hardware includes the requirement to conform with ASTM A143, the embrittlement test methods in ASTM F606, and increasing the cross-sectional thickness of the components.[25]

Several transmission line hardware suppliers were consulted to suggest alternatives to the turnbuckle. Given the requirements, the most appropriate option was determined to be an extension link with two shackles, as seen in Figure 19. The extension link is 102 mm x 38 mm.[26] The threaded portion of the turnbuckle has a diameter of 32 mm.[27] Therefore, the extension link has nearly 5 times the cross-sectional area of the turnbuckle and is 3.2 times the height in the direction of the most frequent bending. This is important, as it is the longest component in the assembly that will be subject to bending moments. The assembly will also have two points of articulation around the shackle bolt in the direction of most frequent movement and the manufacturing process for the extension link does not introduce the risk of hydrogen embrittlement.

As the procurement and installation of this alternative hardware will take several months, areas of higher priority should be addressed first. Areas of higher priority include those where galloping has been observed in the past, areas prone to icing, and remote areas. The two highest priority areas based on these factors are the Long Range Mountains and southern Labrador, which will be addressed in 2023.

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[25] These technical recommendations for the replacement material have been specified and included during the procurement process.

[26] Cross-sectional area equivalent to 3,876 mm^2.

[27] Cross-sectional area equivalent to 792 mm^2.

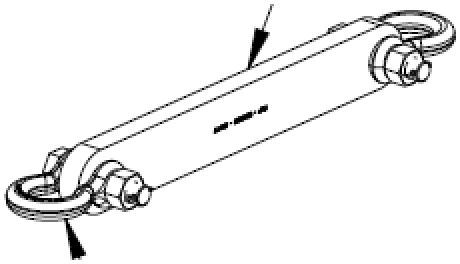

Figure 19: Extension Link Assembly - Alternative to the Turnbuckle

Depending on procurement timelines, safety locks and chains or additional turnbuckles were recommended for installation in the rigging holes of the tower plates and yoke plates as a temporary safety measure. However, the installation of these temporary hardware solutions would be equally as labour-intensive as the installation of the turnbuckle replacement. The installation would also require an outage, making the timing and logistics equally as complex as the turnbuckle replacement. Installing a temporary solution would add substantial cost to the line repairs, due to double the labour requirements in addition to extra materials, and is only recommended as a contingency plan if there are significant delays in the procurement of the extension straps for the turnbuckle replacement. At this time, there have been no delays in the procurement of the extension straps; therefore, no temporary hardware solutions are planned for installation.

13.0 Conclusions

Upon review of the suggested recommendations, Hydro has progressed with the following action items:

1) A capital program, which is currently underway, to complete the installation of airflow spoilers at the location of the turnbuckle failures at Structure 1872 and 1806 as well as other areas that have experienced line damage and where galloping has been observed.
2) The implementation of an increased field monitoring and reporting process, which is currently underway.
3) A capital project, which is currently underway, to replace turnbuckles with an extension link with two shackles; the installation is ongoing in areas of higher priority in the Long Range Mountains and southern Labrador for 2023. The capital project is expected to continue for four years to accommodate LIL outage requirements.

Summary of Findings from L3501/2 Failure Investigation

Optical Ground Wire Tower Peaks

Structures 1230 and 1231

October 4, 2023

A report to the Board of Commissioners of Public Utilities

Executive Summary

The Labrador-Island Link ("LIL") is a 900 MW, high-voltage direct current ("HVdc") transmission line that carries electricity from the Muskrat Falls Hydroelectric Generating Facility to the Soldiers Pond Terminal Station. Line L3501/2[1] is the 350 kV HVdc overland transmission line portion of the LIL. Construction of the 1,100 km LIL was completed in late 2017; power commenced flowing in 2018 and the asset was commissioned on April 14, 2023.

The LIL is comprised of 3,223 towers, stretching over 1,100 km, with an optical ground wire ("OPGW") connected to the top of each structure. During December 2022, failures occurred on transmission line L3501/2 on adjacent Structures 1230 and 1231. The failures of these structures were similar—the top peak of the tower where the OPGW was connected failed; however, the OPGW itself did not fail. The LIL tripped, likely as a result of contact between the OPGW and the pole conductor. The failure of an OPGW alone does not normally lead to an outage with customer impact, as it is a communications line and does not carry energy. The repairs for each structure and the surrounding areas were completed as recommended. The primary goal for the restoration work was to secure the OPGW to the pole without the risk of additional trips or structure failure.

A detailed failure investigation was completed to determine the root cause of the failures and to identify recommendations to mitigate against the reoccurrence of these failures. It was noted that the ice load at the time of the failure was less than the design load of the tower; therefore, it was concluded that the ice load alone did not cause the failure. The likely cause of the failures at Structures 1230 and 1231 was unbalanced ice loads due to ice shedding. Ice accumulation was observed on the line when the failure was located. As temperatures in the area had recently risen above zero, ice shedding likely occurred on the lines. Modelling confirmed that the suspected unbalanced ice-shedding loads could cause the failure of the OPGW peak. The OPGW tower peak failed as per the design under an unbalanced ice load.

Given the investigation findings, recommendations to mitigate against further failures on the LIL due to unbalanced ice load and ice shedding include the increased monitoring of ice conditions along the line and the strengthening of the towers to withstand higher unbalanced ice loads.

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[1] L3501 and L3502 are Pole 1 and Pole 2 of the line, respectively.

To date, Newfoundland and Labrador Hydro (“Hydro”) has progressed actions addressing these recommendations. These actions include increased real-time ice monitoring through the installation of a weather station in the Labrador Straits and the planned installation of an additional weather station in central Labrador in 2025. These weather stations will provide Hydro with real-time data to indicate whether inspections are needed. Hydro has also engaged an external consultant to further study the implications of unbalanced ice loads on the towers in 2024. This study will provide Hydro with the necessary information to mitigate the risk of further failures due to unbalanced ice load and ice shedding.

Contents

1.0 Introduction

During December 2022, there were failures on Structures 1230 and 1231 on transmission line L3501/2. The failures of these two structures were similar; the top peak of the tower where the OPGW connects, as shown in Figure 1, failed. The OPGW wire itself did not fail, nor did the rest of the tower.

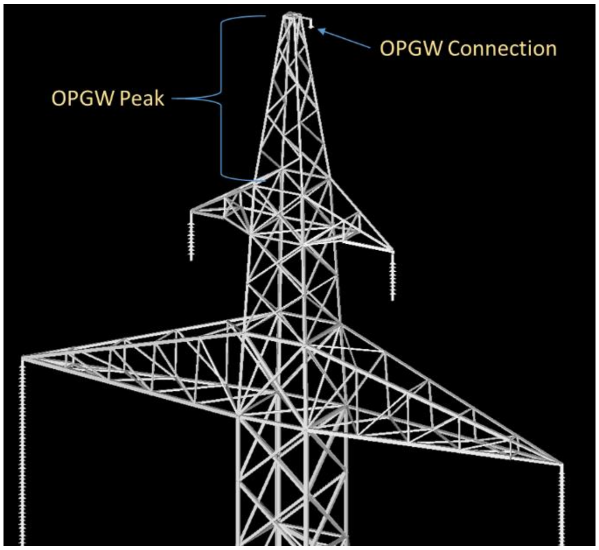

Figure 1: Tower Drawing showing OPGW Peak

2.0 Background

The LIL is an important transmission line for the provincial energy grid due to its power-carrying capacity, which will be used to deliver a large portion of the winter peak energy to meet demand on the Island Interconnected System. Line L3501/2 is the 350 kV HVdc overland transmission line portion of LIL, traversing a distance of approximately 1,100 km. As Figure 2 shows, the overland transmission line is a bipole line with a single conductor per pole, duel electrode conductors[2] for a portion of the line, and an OPGW communication cable. The lines are supported by galvanized steel lattice towers. The LIL was constructed in harsh terrain; it is subjected to heavy wind and ice loads and has experienced multiple winter seasons and weather events.

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[2] The electrode conductor is attached to the lattice towers until about 384 km southeast of Muskrat Falls (Structures 1 to 1229) where it diverts to a separate right-of-way on wood poles to an electrode site located in the L’Anse au Diable area. Sections of L3501/2 without the electrode on the towers do not have electrode crossarms.

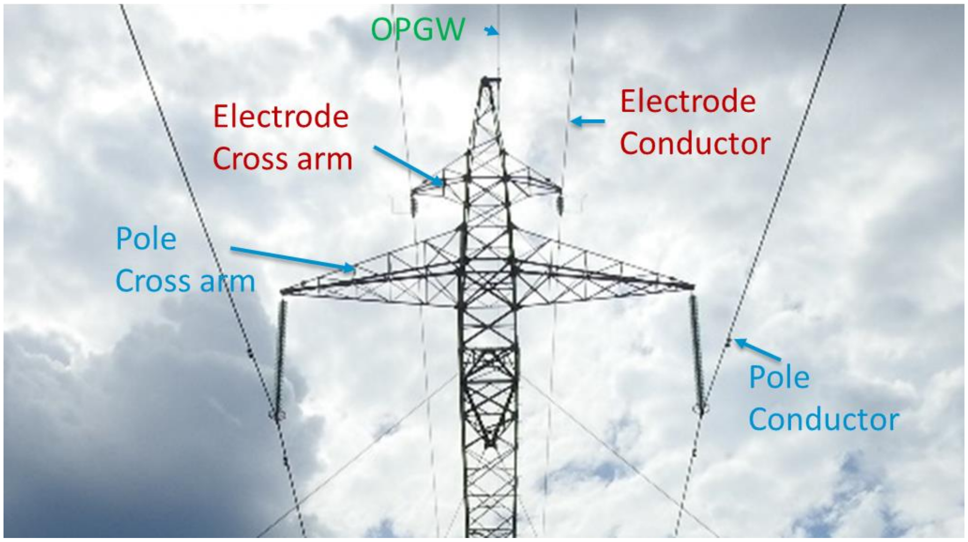

Figure 2: L3501/2 Structure Showing Wire Arrangement

The HVdc transmission line corridor has been divided into three major meteorological loading zones (average, alpine, and eastern) in combination with eight further subcategories related to meteorological loads, pollution levels (inland and coastal), and geographic location. The resulting combinations lead to the HVdc line consisting of 19 separate loading zones. There are 11 tower types (A1, A2, A3, A4, B1, B2, C1, C2, D1, D2, and E1) that were designed to meet the loading requirements applied to the line, which consist of a specified wind load, ice load, and combination of both. The tower types consist of both guyed towers and self-support towers. The tower types are summarized in Table 1.

Table 1: Tower Types

Tower Type	Structure Type	Insulator Assembly Type	Deflection Angle Limit (Degree)
A1, A2, A3, A4	Guyed	Suspension	0–1
B1	Guyed	Suspension	0–3
B2	Self Support	Suspension	0–3
C1, C2	Self Support	Dead End	0–30
D1, D2	Self Support	Dead End	0–45
E1	Self Support	Dead End	45–90

Structures 1230 and 1231 are both suspension tangent towers.[3] Structure 1230 and 1231 are both type A1, which represent 51% of towers and are used in various regions throughout the LIL's length and meteorological loading zones. Chart 1 breaks down the tower distribution on L3501/2.

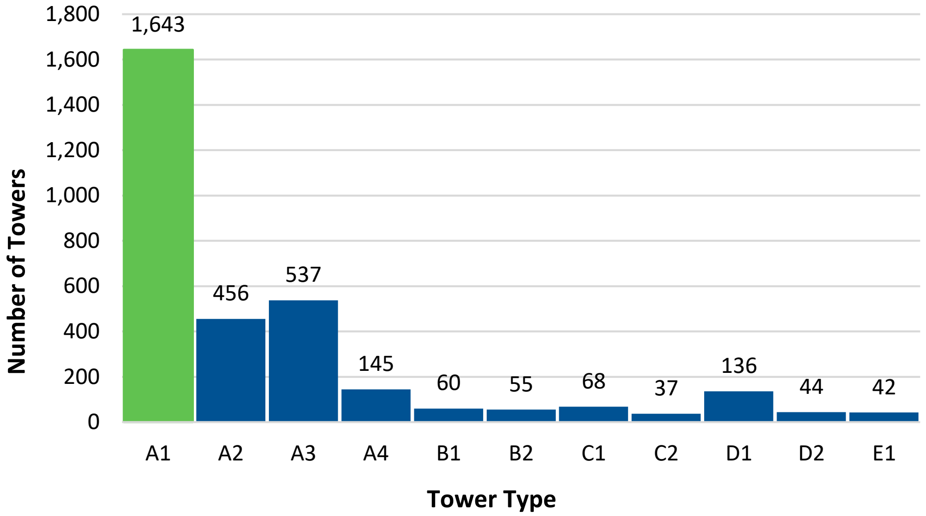

Chart 1: Distribution of Tower Types on L3501/2

3.0 Investigation Overview

To understand the line's performance in severe weather conditions, a detailed failure investigation was completed to determine the root cause of the failures and to conclude what actions can be taken to mitigate against further failures, including damage to the line, and provide appropriate remediation.

The investigation will be described in detail herein and includes the following components:

- Failure description;
- Weather information;
- Immediate repairs;
- Construction quality and maintenance review;

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[3] Suspension towers are categorized as tangent towers or turning towers. Tangent towers are used throughout the line on straight sections or sections with small angles. Tangent towers primarily carry the vertical load of the conductor. Turning towers are used to facilitate turns within the line.

- Analysis of loads causing failures;
- Galloping[4] and damper issues;
- Summary of root cause; and
- Recommendations.

4.0 Failure Description

At approximately 1000 hours on December 14, 2022, there was a line trip reported in the Labrador section of L3502. Later that same day, failures were identified at Structures 1230 and 1231. Both peaks had failed toward the Pole 2 side of the tower. The OPGW was still intact and connected to the towers; however, as Figure 3 and Figure 4 show, the steel had bent significantly. The line trip was likely a result of contact between the OPGW and the pole conductor during the failure of the peaks,[5] which resulted in minimal damage to the internal fibre optics but did not affect the overall performance of communications systems.

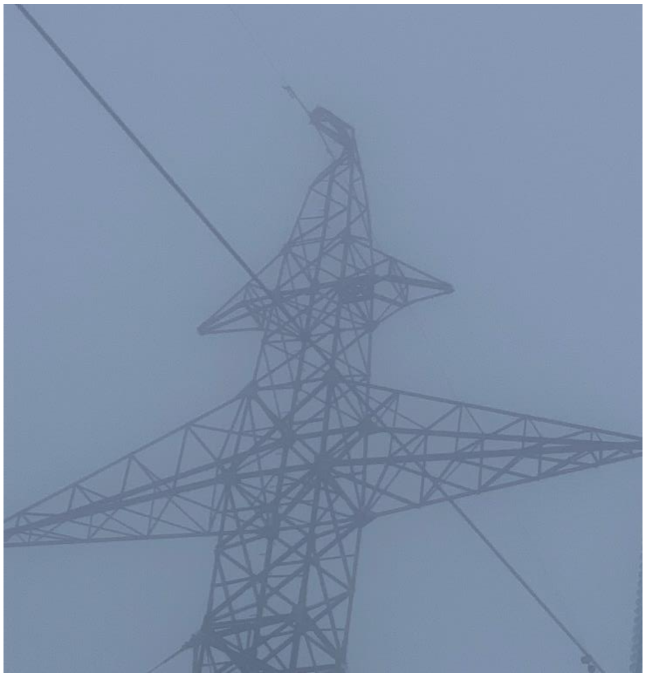

Figure 3: Failed OPGW Peak at Structure 1230

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[4] Galloping is a high-amplitude, low-frequency oscillation of overland power lines due to wind; it can be caused by specific wind conditions and is sometimes observed on lines with small amounts of icing.

[5] The bending of the tower peak reduced the clearance between the OPGW and pole conductor. Additionally, there was likely significant vertical movement of the OPGW during the failure, which could cause the wires to make contact.

Figure 4: Failed OPGW Peak at Structure 1231

4.1 Failure Location

Structures are numbered sequentially along the line, starting at Muskrat Falls. Figure 5 and Figure 6 show the location of Structures 1230 and 1231—near the southwest coast of Labrador, 11 km from the closest highway. Galloping has been observed in this section of the line. A study was completed to identify areas of the line that were susceptible to galloping based on factors including past observations and damage, ice accumulation, and wind direction; it was determined that this area was highly susceptible to galloping. A capital program is currently underway to complete the installation of airflow spoilers to mitigate galloping in this region as well as other areas that have experienced line damage and where galloping has been observed.

Figure 5: Map of Labrador Showing Location of OPGW Peak Failures

Figure 6: Location of Structures 1230 and 1231

4.1.1 Loading Zone

As discussed in Section 2.0, the LIL is divided into 19 loading zones. Structures 1230 and 1231 are located in Loading Zone 3a ("Average Loading Zone"). A summary of the wind and ice conditions for which Zone 3a is designed is provided in Table 2.

Table 2: Zones 3, 4, 6, and 8a Wind and Ice Design Loading

Load	Design Loading
Maximum Ice	50 mm radial glaze, 0.9 g/cm³ density
Maximum Wind	120 km/h (10-minute average wind speed at 10 m height above ground)
Combined Ice and Wind	25 mm radial glaze, 0.9 g/cm³ density 60 km/h (10-minute average wind speed at 10 m height above ground)

The OPGW at both structures is connected with a suspension assembly and is dead-ended at Structures 1229 and 1238. The line direction in this section is north-northeast to south-southwest.

5.0 Weather Information

There was snow on the ground and significant ice on the lines in the area of Structures 1230 and 1231 at the time of the failure. At the same time as the failures at Structures 1230 and 1231, a freezing rain event caused significant damage to a distribution line approximately 20 km away, in Red Bay on the south coast of Labrador. The event near Red Bay caused approximately 30 mm to 40 mm of radial glaze ice accumulation on the lines, as shown in Figure 7 and Figure 8. The ice accumulation led to the failure of more than 20 wooden distribution poles and multi-day customer outages.

Figure 7: Distribution Line Failure from Freezing Rain in Red Bay

Figure 8: Ice Sample from the Distribution Line in Red Bay

Before the failure, a line patrol was initiated to evaluate the effect of the ice storm on the LIL's electrode wood pole line and steel tower line in the Labrador Straits. During this patrol, significant icing was observed on L3501/2; however, the ice thickness appeared to be less than the design thickness of 50 radial mm. Figure 9 and Figure 10 show ice accumulation on the OPGW at Structures 1230 and 1231 before the failures. From the available pictures, the ice thickness on the OPGW at Structures 1230 and 1231 is estimated to be approximately 20 mm to 30 mm of radial glaze ice. After the failure, there was no ice on the OPGW; this could be due to ice shedding before the failure or the ice could have shed due to the dynamic forces that occurred during the failure.

Figure 9: Ice on OPGW at Structure 1230 before Failure

Figure 10: Ice on OPGW at Structure 1231 before Failure

The weather station with hourly data nearest to Structures 1230 and 1231 is located approximately 23 km away in Blanc-Sablon, Quebec.

The wind speed in Blanc-Sablon on the day of the failure, December 14, 2022, ranged from 40 km/h to 70 km/h with an average speed of 55 km/h. Winds on the day of the failure were not extreme or above design loads, which is indicative of fatigue failure due to movement over the life of the line. The wind direction varied from east to northeast, as shown in Chart 2.

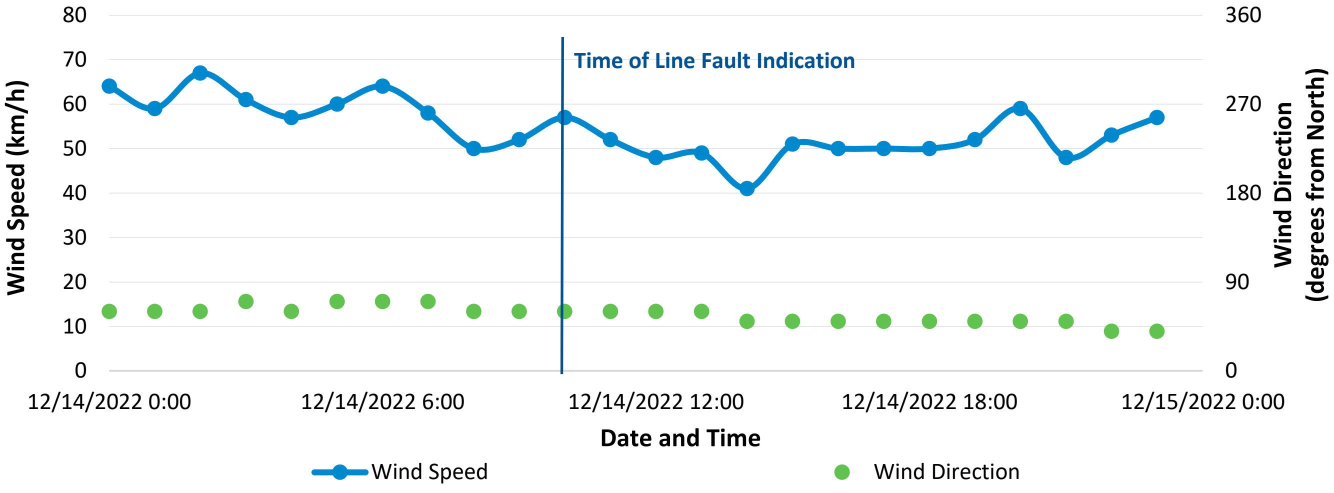

Chart 2: Blanc-Sablon Wind Data for December 14, 2022

As shown in Chart 3, over the course of December 12 to 14, 2022, the temperature at Blanc-Sablon rose from -15°C to +3°C. This rise in temperatures could cause ice to melt and shed from the transmission lines.

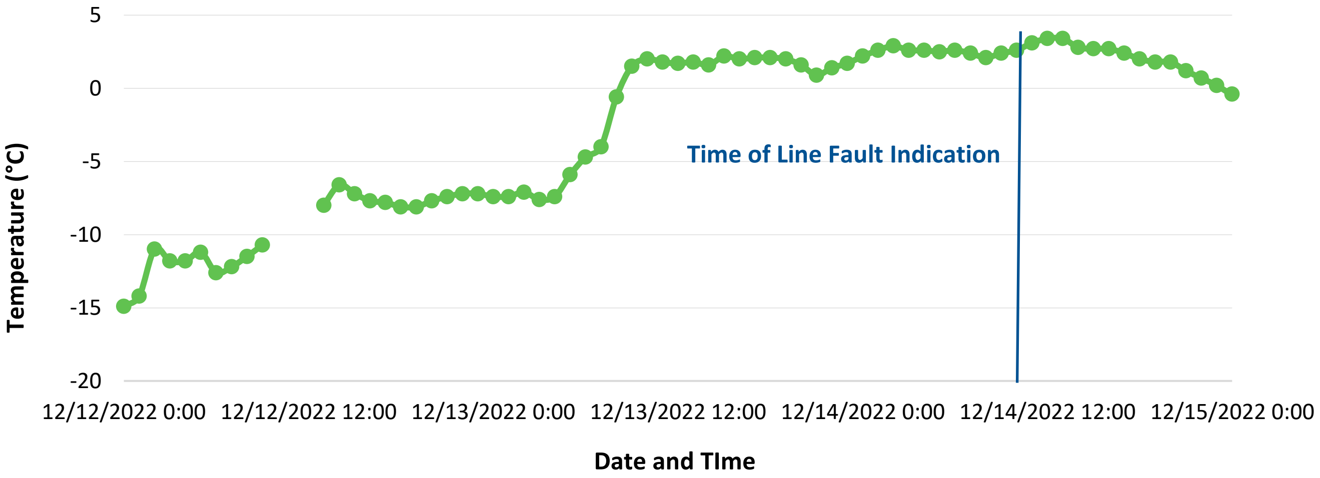

Chart 3: Blanc-Sablon Temperature Data from December 12 to December 15, 2022

6.0 Immediate Repairs

6.1 Engineering Recommendations

The primary goal for the restoration work at the time was to secure the OPGW and ensure that power was safely restored to the pole without the risk of additional trips or tower failure. The recommendation from engineering was to replace the tower peaks with new tower steel and reconnect the OPGW. If this work could not be completed immediately due to issues such as adverse weather, the recommendation was to secure the OPGW to the electrode crossarm.[6]

6.2 Restoration Summary

The OPGW tower peaks were replaced at Structures 1230 and 1231 and the existing OPGW wire was reconnected to the towers. Crews later returned to this area to further troubleshoot the damaged fibre signal and verify if a section of OPGW should be replaced when the weather is more favourable. Pictures of the repairs are provided as Figure 11 and Figure 12.

Figure 11: Repair work to OPGW Peak

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[6] The electrode line moves from the towers to a wood pole line at Structure 1229; however, the first 16 tangent towers after this point still have an electrode crossarm installed.

Figure 12: New OPGW Tower Peak Installed

7.0 Construction Quality and Maintenance Review

Construction quality reports were reviewed to determine if there were any issues present that may have contributed to the failure. No non-conformance reports were submitted on the tower steel for Structures 1230 or 1231 during construction that would indicate any known construction quality issues at the location during that time.

On June 7, 2022, there was a corrective work order entered for Structure 1230 that indicated the OPGW pulled through the suspension assembly. The corrective work was completed on November 21, 2022.

There were three corrective work orders entered for Structure 1231 on June 7, 2022, all related to the OPGW. The noted issues were that the OPGW pulled through the suspension assembly, the OPGW damper slid out from its required location, and the grounding strap on the OPGW assembly broke. The pulled OPGW and the broken ground strap were corrected on November 21, 2022; due to the priority and division of work scopes, the slide damper was corrected on February 16, 2023.

8.0 Analysis of Loads Causing Failures

A complete as-built finite element model of L3501/2 in PLS-CADD,[7] including the existing terrain and as-built tower locations and heights, was undertaken to enable the investigation and assist with recommendations.

8.1 Ice Loading

As discussed in Section 5.0, pictures from the site show the ice thickness at the failure locations to be approximately 20 mm to 30 mm of radial glaze ice, which is less than the design ice load of 50 mm of radial glaze ice. Therefore, it is unlikely that the forces due to ice alone were the cause of the failures.

8.2 Wind and Ice Combined Loading

As noted in Section 4.1, the combined wind and ice design load case uses 25 mm of radial glaze ice and a 60 km/h, 10-minute average wind speed. The failed structures would experience loading conditions near these values on the day of the failures, as the maximum wind speed on that day was 67 km/h[8] and the maximum ice load was approximately 30 mm of radial glaze ice. This section of the line was modelled to determine if these loads would cause failures to any components of the towers, specifically the OPGW peaks. The model was run with 70 km/h wind and ice thicknesses of 25 mm, 26 mm, 27 mm, 28 mm, 29 mm, and 30 mm of radial ice on all wires.[9]

The results indicated that Structures 1230 and 1231 would not fail under these conditions.[10] The maximum utilization[11] of Structures 1230 and 1231 under the described wind and ice combinations is 52% and 54%, respectively. In addition, as Chart 4 shows, no towers in Zone 3a from Structures 1209 to 1246 would fail under these loading conditions.

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[7] PLS-CADD is a transmission line design program that allows the user to enter different loading conditions to analyze how they will affect the line and structures under the as-built conditions and ultimately how the towers will fail under extreme loading conditions. The program allows the user to complete detailed analysis of how loads on the lines will affect the towers.

[8] The weather data was taken from the Government of Canada Climate website that states the data at a station could be averaged at one-minute, two-minute, or ten-minute periods. Therefore, equivalent ten-minute average wind speed could range from 58 km/h to 67 km/h.

[9] Although these load cases are above the wind and ice combination used for the line design, there were other load cases that governed the design; therefore, the towers can withstand a higher wind and ice combination.

[10] Tower failure is defined in the analysis as any component of the tower exceeding its maximum damage limit.

[11] The reaction of the tower to the load cases can be quantified by the maximum utilization, which is the ratio of the force applied to any member from the specified loads, divided by the damage limit capacity, expressed as a percentage. Any value greater than 100% is considered failure of a tower component.

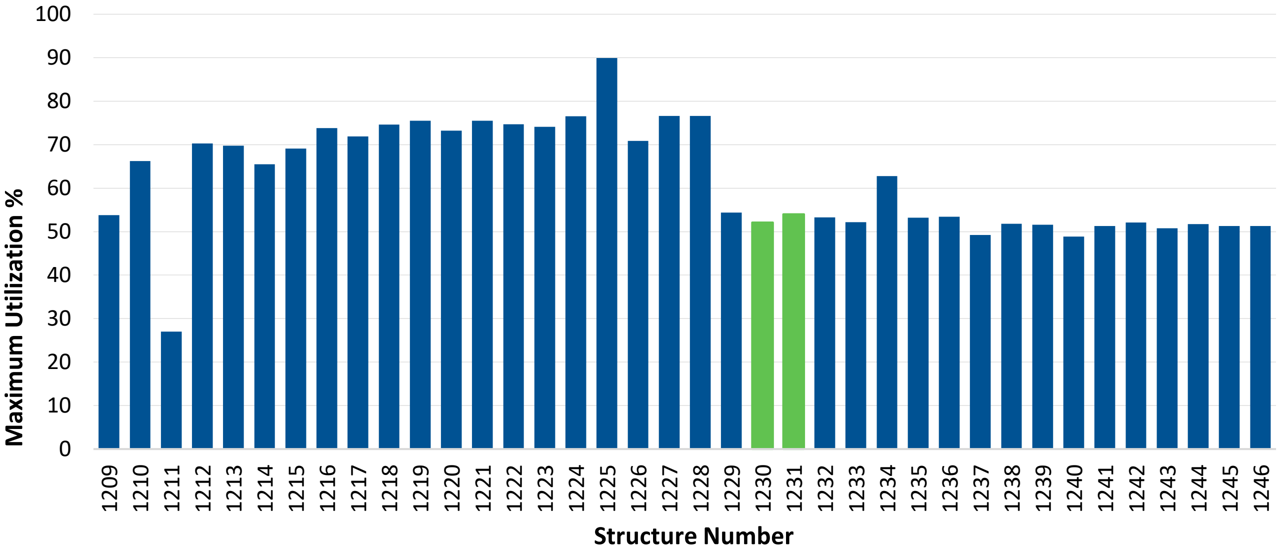

Chart 4: Utilization of Structure under Wind and Ice Load Cases

8.3 Unbalanced Icing

Unbalanced icing is a loading case that considers the loads on a structure when there are different amounts of ice on the front span and back span of the structure, as well as on the different wires—Pole 1, Pole 2, and OPGW.[12] Unbalanced icing can occur due to variations in ice accretion or due to ice shedding. The design load cases for unbalanced ice for tangent towers is 100% of the maximum design ice thickness on one side and 70% of ice thickness on the other side, one conductor at a time. For loading Zone 3a and Structures 1230 and 1231, the 100% maximum ice is 50 mm and 70% of the maximum ice is 35 mm. The three design load cases for unbalanced ice are:

- Pole 1 100/70% of 50 mm maximum ice;
- Pole 2 100/70% of 50 mm maximum ice; and
- OPGW 100/70% of 50 mm maximum ice.

To evaluate the possible conditions at Structures 1230 and 1231 that caused the failures, the unbalanced load combinations of 100/70%, 100/50%, 100/30%, and 100/0% were analyzed for 15 mm, 20 mm, 25 mm, 30 mm, and 35 mm of radial glaze ice. This results in 200 load case combinations, when considering each combination on the structure, both front/back and back/front.

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[12] Electrode cables are not considered here; the electrode cables move from the steel towers of the LIL at Structure 1229 to wood pole structures.

The unbalanced ice combinations shown in Table 3 caused failures when applied to the OPGW wire but not when applied to Pole 1 or Pole 2. This is also true of the condition that caused the failures.

Table 3: Unbalanced Ice Load Combinations Causing Failures[13]

Load Cases	Maximum Utilization in Structure 1230	Maximum Utilization in Structure 1231
100/0% of 30 mm of ice	116%	116%
100/30% of 35 mm of ice	112%	112%
100/0% of 35 mm of ice	141%	141%

In addition, the way in which the structures failed in the model is similar to the failures experienced in the field. As seen in Figure 13, Figure 14, and Figure 15, the failed members are contained to the OPGW peak while the crossarms and tower body members have lower utilization. The failed members are also located on the side of the tower, which would lead to the peak crumbling to the side, as seen in the pictures of the failed structures in Figure 3 and Figure 4.

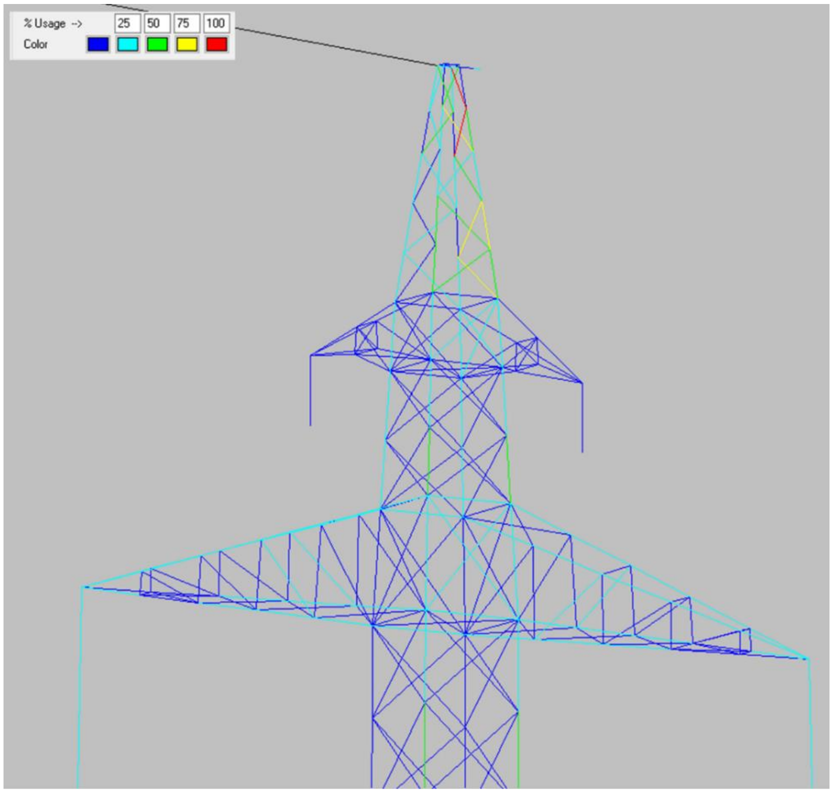

Figure 13: Model of Structure 1230 Failure under OPGW 100/0% of 30 mm Load Case

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[13] Any maximum utilization value greater than 100% is considered failure of a tower component.

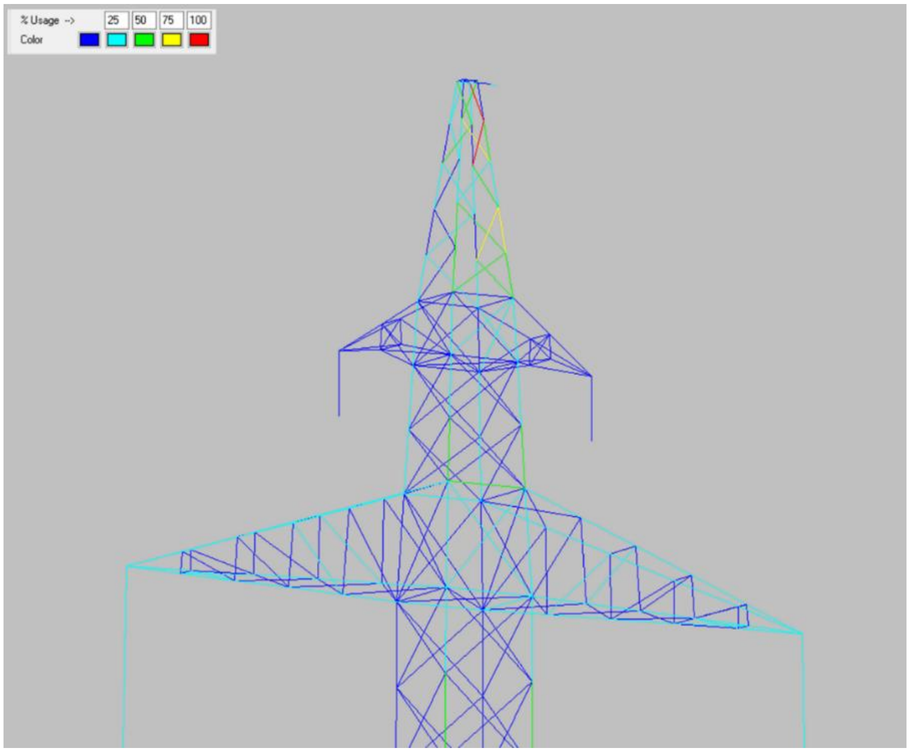

Figure 14: Model of Structure 1230 Failure under OPGW 100/30% of 35 mm Load Case

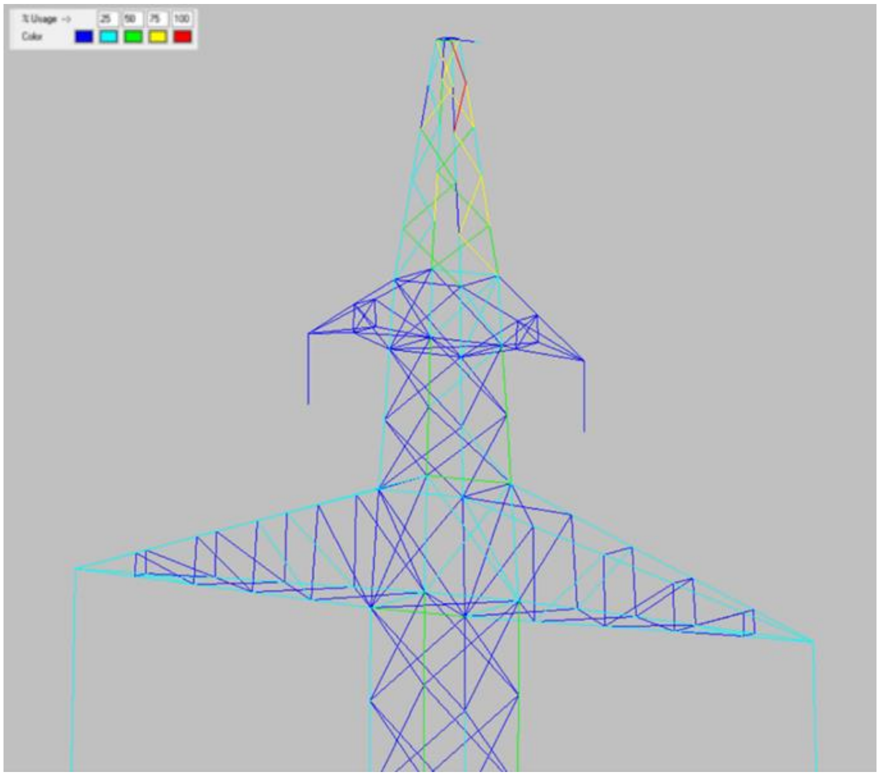

Figure 15: Model of Structure 1230 Failure under OPGW 100/0% of 35 mm Load Case

A similar analysis was completed using the same unbalanced ice load cases but adding a 60 km/h wind perpendicular to the line. As shown in Table 4, the unbalanced ice combinations that caused failures when applied to the OPGW wire but not when applied to Pole 1 or Pole 2 were similar to those in Table 3 but included the OPGW 100/0% of 25 mm load case and had higher utilization.

Table 4: Unbalanced Ice with Perpendicular Wind Load Combinations Causing Failures[14]

Load Cases	Maximum Utilization in Structure 1230	Maximum Utilization in Structure 1231
100/0% of 25 mm of ice	100.2%	100.3%
100/0% of 30 mm of ice	124%	124%
100/30% of 35 mm of ice	113%	113%
100/0% of 35 mm of ice	149%	149%

The modelling described in this section only considers the static loads caused by unbalanced icing and wind; however, when unbalanced icing is due to ice shedding, there would also be a dynamic component to the loads on the tower. This could result in failure of the OPGW peak at lower ice loads and loads that are less unbalanced between front and back spans. Dynamic loads can also lead to an increase in the unbalanced longitudinal load of 30%.[15]

The analysis was repeated using the same unbalanced ice loads with wind and a dynamic factor of 1.3 on the longitudinal load. With this load criterion, several load cases caused failure when the unbalanced loads were applied to the pole conductor, as well as the OPGW. These load cases include:

- 100/0% of 25 mm of ice;
- 100/0% of 30 mm of ice;
- 100/30% of 30 mm of ice;
- 100/0% of 35 mm of ice;
- 100/30% of 35 mm of ice; and
- 100/50% of 35 mm of ice.

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[14] Any maximum utilization value greater than 100% is considered failure of a tower component.

[15] Forti, Tiago. "Numerical Simulation of Transmission Line Vibration Caused by Ice Shedding," CEATI Report T163700-33/109, Centre for Energy Advancement through Technological Innovation, June 2020.

The unbalanced ice combinations that caused failures when applied to the OPGW wire but not when applied to Pole 1 or Pole 2 are summarized in Table 5. While this analysis shows the increase in structure utilization when considering higher loads using a dynamic factor, it is difficult to compare static and dynamic loads and their effect on a transmission line.

Table 5: Unbalanced Ice with Perpendicular Wind and Dynamic Factor Load Combinations Causing Failures to OPGW Peak[16]

Load Cases	Maximum Utilization in Structure 1230	Maximum Utilization in Structure 1231
100/0% of 20 mm of ice	116%	116%
100/30% of 25 mm of ice	122%	122%
100/50% of 25 mm of ice	103%	103%
100/50% of 30 mm of ice	124%	124%

8.4 Galloping Forces

The dynamic forces associated with galloping can be up to 2 times the static vertical load and 2.9 times the static longitudinal load.[17] While it's difficult to quantify the exact loads that galloping could cause on this line in these conditions, using dynamic factors in this range on the ice loads found at the site does not cause failures to the tangent tower when modelled.

9.0 Galloping and Damper Issues

Galloping has been observed on the line since construction, causing extreme movement of the conductor—often vertically but occasionally horizontally. The area near the south coast of Labrador where these peak failures occurred has been confirmed through observation to be prone to galloping. A study completed using serval indicators to identify galloping-prone areas also confirmed this area of the line, from Structure 1000 to 1250, has a higher likelihood of galloping. Galloping was observed in the area during the repairs of Structures 1230 and 1231.

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[16] Any maximum utilization value greater than 100% is considered failure of a tower component.

[17] D.G. Harvard, "Dynamic Loads on Transmission Line Structures During Galloping – Field Data and Elastic Analysis," paper presented at the Fifth International Symposium on Cable Dynamics, Santa Margherita, Italy, September 15 to 18, 2003. <https://www.researchgate.net/publication/319532962_Dynamic_Loads_On_Transmission_Line_Structures_During_Galloping_-_Field_Data_and_Elastic_Analysis_by_D_G_Havard_Fifth_International_Symposium_on_Cable_Dynamics_Santa_Margherita_Italy_15-18_Sept_2003>.

The towers on L3501/02 have been designed so the wires can gallop without flashover[18] between them. Galloping can also cause increased loads on the tower, as discussed in Section 0, and will also cause fatigue and wear on hardware and conductors over time.

Galloping has been studied in the transmission industry since the early 1900s;[19] however, while there have been advances in the understanding and controlling of galloping, there is no industry standard to design a line that will not experience galloping.

The line has also experienced issues with the Stockbridge damper, as shown in Figure 16, which is installed on the line to control Aeolian vibration.[20] Damper failures, which do not cause an outage to the line, could be caused by inadequate damping, ice loads, or galloping and have been identified throughout the line during routine inspections. Through testing of the dampers and vibration monitoring of the line, it was determined the dampers currently installed on the electrode conductors and OPGW are not adequately controlling the vibration. There is a capital project proposed for 2024 to specify new damper requirements and purchase new dampers for the line. Damper failures were found near the failed Structures 1230 and 1231, exhibiting significant damage to the clamp of the damper and bending in the messenger wire as shown in Figure 17 and Figure 18.

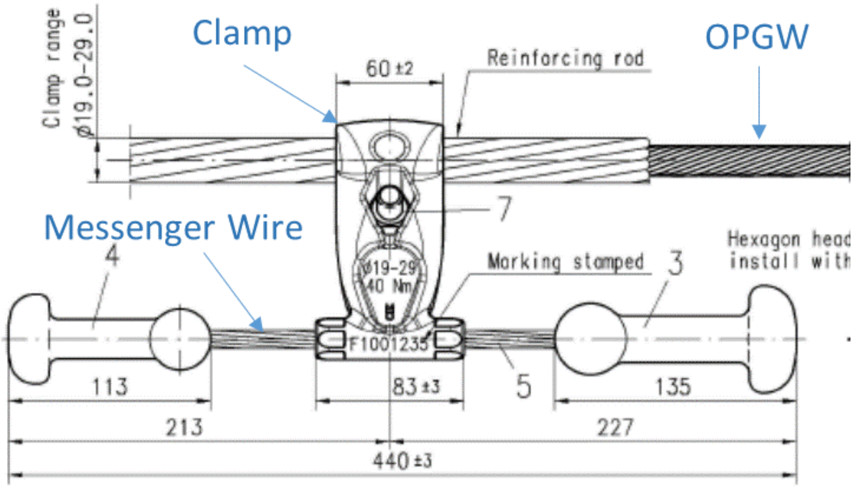

Figure 16: OPGW Stockbridge Damper

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[18] Flashovers between phases are the most immediate and frequently damaging effect of galloping.
[19] "State of the art of conductor Galloping," *Cigré-Brochure* 322, 2007.
[20] Aeolian vibration is a high frequency, low-amplitude oscillation of the overhead power lines caused by low-velocity, steady wind.

Figure 17: OPGW Stockbridge Damper Failure

Figure 18: OPGW Stockbridge Damper Failure

10.0 Summary of Root Cause

Several conclusions arose from the failure analysis of Structures 1230 and 1231:

- Failure at both structures occurred as per the design under an unbalanced ice load and was contained to the OPGW peak;

- Ice loads in the area ranged in radial thickness from 20 mm to 30 mm; the maximum design ice load for this zone is 50 mm of radial ice. The assumed ice loads of 20 mm to 30 mm alone would not cause failure to the OPGW peaks.
- Wind speed averaged 55 km/h on the day of failure;
- Temperatures rose from -15°C to above freezing on the day of the failure;
- There were corrective work orders related to the OPGW at Structures 1230 and 1231, including issues with OPGW slipping through the clamp, bonding strap breaking, and damper failures, all of which are indications that these structures may have experienced unbalanced icing in the past.
- Modelling of the line with the wind and balanced ice loads observed at the site will not cause the modelled towers to fail;
- Modelling of the line with unbalanced ice loads and considering dynamic impact loads from ice shedding will cause the modelled towers to fail at the OPGW peak;
- Modelling of the line with ice loads and considering dynamic impact loads from galloping will not cause the modelled towers to fail;
- Galloping has been observed at this line location in the past and during repairs; and
- Damper failures have been observed at this line location in the past and during repair. Dampers could fail due to ice shedding or galloping and are a further indication that the line has experienced these loads in the past.

Failure at both structures was contained to the OPGW tower peak, which is preferable to failure lower in the tower body, as that could result in more significant damage and/or operational impacts. The OPGW cable did not break and there was no damage to the pole crossarm or the body of the tower. Therefore, the loads that caused the failures were loads that would cause the peak to fail but not the pole crossarms[21] or they were contained to the OPGW.[22] The wind in the area at the time of the failures ranged from 40 km/h to 70 km/h with an average wind speed of 55 km/h. The design load case for combined wind and ice is 60 km/h and 25 mm of radial glaze ice. Although these loads were higher than

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[21] For example, an unbalanced ice load of 100/0% of 30 mm of ice on the OPGW would cause the OPGW peak to fail; however, the same load on Pole 1 would not cause the crossarm to fail.

[22] An ice-shedding event that would cause failure could be contained to the OPGW if only that wire experiences ice shedding.

the design loads for this combination, modelling confirmed that this load case did not govern the design and the towers would not fail under these loads.

Temperatures rose from -15°C to 3°C over the two days leading up to the date of the failure; this could cause ice to shed from the lines. Unbalanced ice loads can result from ice shedding if the ice sheds unevenly from the front and back spans of a tower. Ice shedding can also cause dynamic impact loads on the line. Modelling confirmed that unbalanced ice loads and dynamic loads from ice shedding could cause failures to the OPGW tower peaks of Structures 1230 and 1231 under the icing conditions observed at the site.

As highlighted herein, the modelling confirmed that the wind and ice loads observed at the site alone would not cause the towers to fail; however, the unbalanced ice load and dynamic impact loads from ice shedding will cause the tower peaks to fail. In addition, the modelling confirmed that dynamic impact loads from galloping would likely not cause the towers to fail. Based on the modelling, it is unlikely galloping was the cause of the failures. Galloping dynamic loads are proportional to the static vertical and tension loads; therefore, the dynamic galloping loads are greater when the line is loaded with ice.

Based on this information, the likely cause of the failures at Structures 1230 and 1231 was unbalanced ice loads due to ice shedding. The ice accumulation was in the range of 20 mm to 30 mm, temperatures rose to 3°C in the days leading up to the failure, and modelling confirmed that these unbalanced and ice-shedding loads could cause failure to the OPGW tower peak. The towers are designed for specific unbalanced ice loads of 100/70% of 50 mm of radial glaze ice; however, less ice with a higher differential in the unbalanced loads could cause failure. Furthermore, modelling also confirmed that there are unbalanced ice and ice shedding load combinations that would cause failure to the OPGW tower peak alone and not other components of the tower.

11.0 Recommendations

Recommendations to prevent further failures on the LIL due to unbalanced ice and ice shedding include the following:

1) Increased monitoring of ice conditions along the line; and
2) Strengthening of the towers to withstand higher unbalanced ice loads.

To better understand the ice loads experienced by the line, monitoring of the line is occurring and required. Currently, a test span is installed near Structure 1225 with plans to install more test spans in 2024.[23] The test span consists of one span of conductor between two wood poles with a load cell to monitor ice load and equipment to monitor wind and temperature.

Monitoring of ice conditions can also be accomplished by line patrols, estimation of the amount of ice on the lines from pictures, and weighing and measuring ice that has fallen from the lines. It is recommended that crews collect this information whenever possible during routine line patrols and maintenance. If ice accumulation on the lines were found to be approaching the maximum design loads, ice removal protocols would be initiated.

The tangent towers on the line are designed for unbalanced ice loads of 70% on one wire and 100% of the maximum design ice thickness on the other. If the differential in ice thickness is higher, there is a chance that the tower components will fail. It is recommended that the towers be analyzed for more conservative unbalanced ice loads. Gathering more information on ice loads experienced by the line through monitoring will be beneficial to this analysis. Any recommended changes to the towers would have to consider the slip strength of the clamps, the redistribution of loads within the towers, and constructability considering the line is built and in service. Currently, the OPGW peak is designed for a longitudinal force of 32 kN[24] and the slip strength of the OPGW clamps is 35 kN. If the towers were modified to increase the longitudinal capacity, the slip capacity of the clamps should also be increased. Consideration must also be given to minimize the level of effort and outage time required to complete the work on existing in-service towers.

12.0 Conclusions

Upon review of the suggested recommendations, Hydro has progressed with the following action items:

1) Monitoring of ice has been increased through the installation of a weather station in Labrador Straits, increased monitoring by field personnel around weather events, and continued helicopter patrols. An additional weather station is planned for installation in central Labrador in 2025. Ice can be removed from the lines through existing ice removal protocols, if necessary.

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[23] The icing in the area of Structure 1225 at the time of the failures also caused damage to the solar panel powering the test span; as such, there is no data from that site at this time.
[24] Kilonewton ("kN").

2) An external consultant has been engaged to further study the implications of unbalanced ice loads on the towers, and potential options for mitigation of the issue.

Summary of Findings from L3501/2 Failure Investigation

Optical Ground Wire Top Plates

Structures 2135 and 2136

October 4, 2023

A report to the Board of Commissioners of Public Utilities

Executive Summary

The Labrador-Island Link ("LIL") is a 900 MW high-voltage direct current ("HVdc") transmission line that carries electricity from the Muskrat Falls Hydroelectric Generating Facility to the Soldiers Pond Terminal Station. Line L3501/2[1] is the 350 kV HVdc overland transmission line portion of the LIL. Construction of the 1,100 km LIL was completed in late 2017; power commenced flowing in 2018 and the asset was commissioned on April 14, 2023.

The LIL is comprised of 3,223 towers, stretching over 1,100 km, of which 90% are suspension towers. During December 2022, failures occurred on transmission line L3501/2 on adjacent Structures 2135 and 2136. The failures of these structures were similar—the double angle member at the top of the tower, which connects to the top plate and the optical ground wire ("OPGW") suspension assembly, detached from the tower and fell into the pole crossarm. There was no customer impact associated with the incident and it did not cause an outage from a power perspective, as the damage was isolated to the OPGW that carries fibre optics to facilitate system communications. This system is redundant and communications can continue, even when out of service. The OPGW itself remained intact; however, the internal fibres suffered damage, resulting in the loss of communication signal. The repairs for each structure and the surrounding areas were completed as recommended. The primary goal for the restoration work was to repair the OPGW by splicing a new section, repairing the towers, and reconnecting the OPGW.

A detailed failure investigation was completed to determine the root cause of the failures and to identify recommendations to mitigate against the reoccurrence of these failures in the future. The primary cause of the failures at Structures 2135 and 2136 was the overload failure of the top plate connection. This overload failure was likely due to an error in the design of the top plate connection on tower type A3, which failed once it was subjected to an ice load that was less than the vertical design load[2] for the OPGW plate connection. The vertical load that caused the failures was likely due to ice, which was observed on the line and the towers when the failure was located. As temperatures in the area had

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[1] L3501 and L3502 are Pole 1 and Pole 2 of the line, respectively.

[2] Vertical design load refers to the force or weight that acts in a downward direction on a structure or structural component. It is a critical consideration in engineering design and construction, as it helps determine the load-bearing capacity and stability of a structure or structural element.

recently risen above zero, ice shedding likely occurred on the lines, which could contribute to the vertical load that caused the failure.

Given the investigation findings, recommendations to mitigate against further failures on the line resulting from the issue with the design of the OPGW top plate connection include consulting a tower designer on correcting the connection detail, checking the bolted connection design of all tangent tower types, and implementing corrections, as required, starting in the most critical locations. At this time, Newfoundland and Labrador Hydro ("Hydro") has engaged an external consultant to assist in redesigning the plate and connection detail for the A3 towers and in an assessment of the bolted top plate connection design of all other tower types. This will provide Hydro with the necessary information to form a plan in the fourth quarter of 2023 for the implementation of corrections to mitigate further communication outages. Corrections will be implemented, as required, starting with areas of high priority.

Contents

1.0 Introduction

During December 2022, there were failures on Structures 2135 and 2136 of Hydro's transmission line L3501/2. The failures of these structures were similar—the double angle member at the top of the tower that connects to the top plate and the OPGW suspension assembly connection, as seen in Figure 1, detached from the tower, falling into the pole crossarm, resulting in a communication system outage. The OPGW cable itself experienced some damage but remained attached to the assembly and double angle.

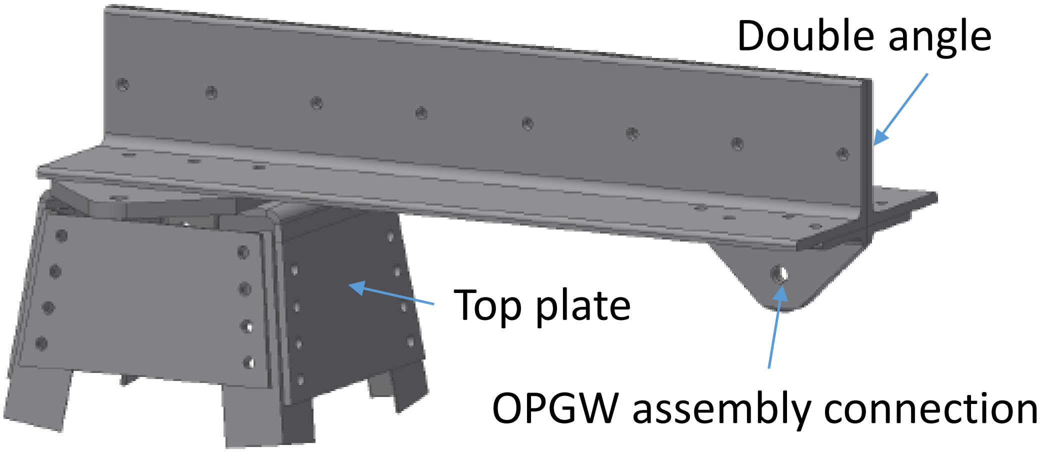

Figure 1: Top of Tower

2.0 Background

The LIL is an important transmission line for the provincial energy grid due to its power-carrying capacity, which will be used to deliver a large portion of the winter peak energy and demand on the Island Interconnected System. Line L3501/2 is the 350 kV HVdc overland transmission line portion of LIL, traversing a distance of approximately 1,100 km. As shown in Figure 2, the overland transmission line is a bipole line with a single conductor per pole, duel electrode conductors[3] for a portion of the line, and an OPGW communication cable. The lines are supported by galvanized steel lattice towers. The LIL was constructed in harsh terrain; it is subjected to heavy wind and ice loads and has experienced multiple winter seasons and weather events.

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[3] The electrode conductor is attached to the lattice towers until about 384 km southeast of Muskrat Falls (Structures 1 to 1229) where it diverts to a separate right-of-way on wood poles to an electrode site located in the L'Anse au Diable area. Sections of L3501/2 without the electrode on the towers do not have electrode crossarms.

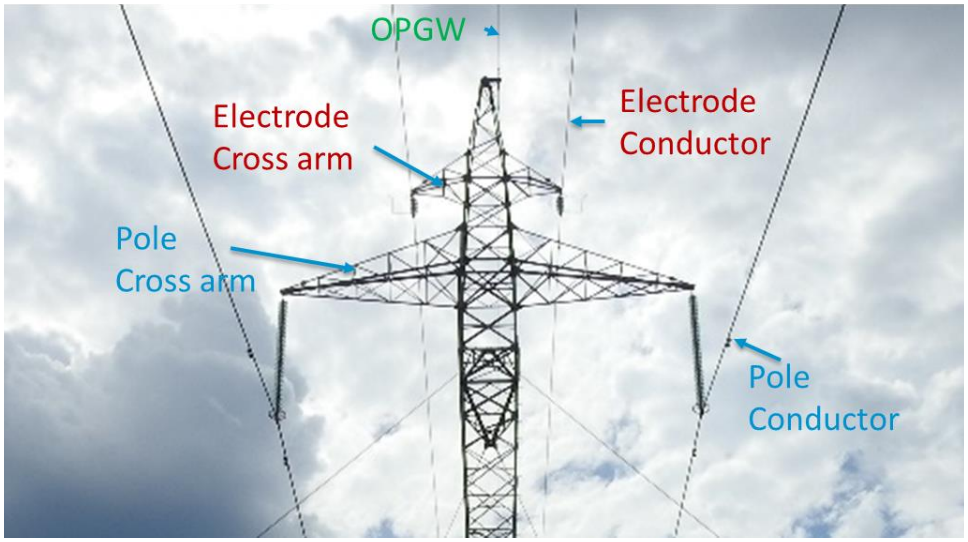

Figure 2: L3501/2 Structure Showing Wire Arrangement

The HVdc transmission line corridor has been divided into three major meteorological loading zones (average, alpine, and eastern) in combination with eight further subcategories related to meteorological loads, pollution levels (inland and coastal), and geographic location. The resulting combinations lead to the HVdc line consisting of 19 separate loading zones. There are 11 tower types (A1, A2, A3, A4, B1, B2, C1, C2, D1, D2, and E1) that were designed to meet the loading requirements applied to the line, which consist of a specified wind load, ice load, and combination of both. The tower types consist of both guyed towers and self-support towers. The tower types are summarized in Table 1.

Table 1: Tower Types

Tower Type	Structure Type	Insulator Assembly Type	Deflection Angle Limit (Degree)
A1, A2, A3, A4	Guyed	Suspension	0–1
B1	Guyed	Suspension	0–3
B2	Self Support	Suspension	0–3
C1, C2	Self Support	Dead End	0–30
D1, D2	Self Support	Dead End	0–45
E1	Self Support	Dead End	45–90

Structures 2135 and 2136 are both type A3 tangent towers. Of all the towers on the L3501/2, 90% are suspension towers[4] (types A1, A2, A3, A4, B1, and B2). There are 537 type A3 towers; Chart 1 breaks down the tower distribution on L3501/2.

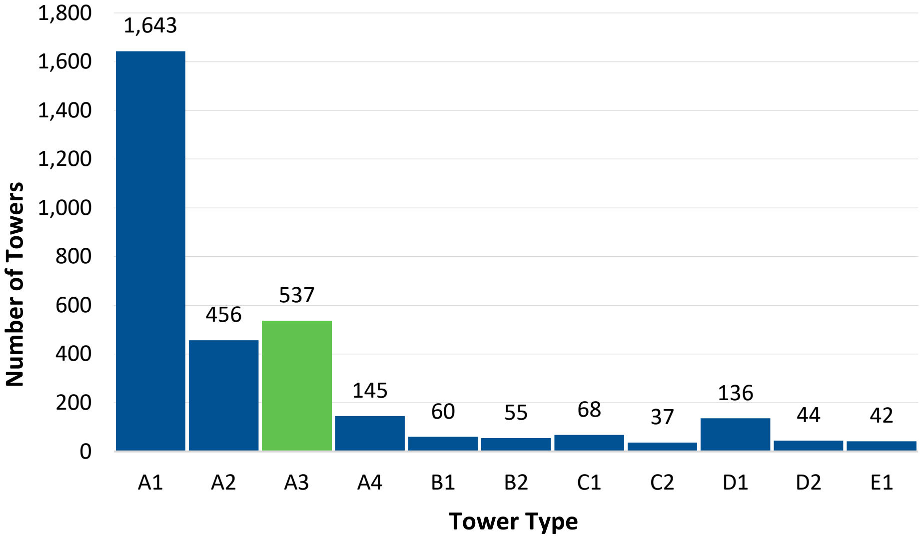

Chart 1: Distribution of Tower Types on L3501/2

3.0 Investigation Overview

To understand the line's performance in severe weather conditions, a detailed failure investigation was completed to determine the root cause of the failures and to conclude what actions can be taken to mitigate against further failures, including damage to the line, and to provide appropriate remediation.

The investigation is described in detail herein and includes the following components:

- Failure description;
- Weather information;
- Immediate repairs
- Design and manufacturing review;

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[4] Suspension towers are categorized as tangent towers or turning towers. Tangent towers are used throughout the line on straight sections or sections with small angles. Tangent towers primarily carry the vertical load of the conductor. Turning towers are used to facilitate turns within the line.

- Construction quality and maintenance review;
- Finite element analysis;
- Material testing;
- Analysis of loads causing failures;
- Summary of root cause; and
- Recommendations.

4.0 Failure Description

At approximately 0400 hours on December 20, 2022, there was a loss of communication signal detected on the OPGW. On December 21, 2022, the failure was identified at Structures 2135 and 2136. As seen in Figure 3 and Figure 4, the double angle at the top of the structure that connects to the OPGW assembly detached from the tower and fell into the pole crossarm while still attached to the OPGW assembly and cable. While the OPGW cable did not physically break, there was damage caused to the internal communication fibres.

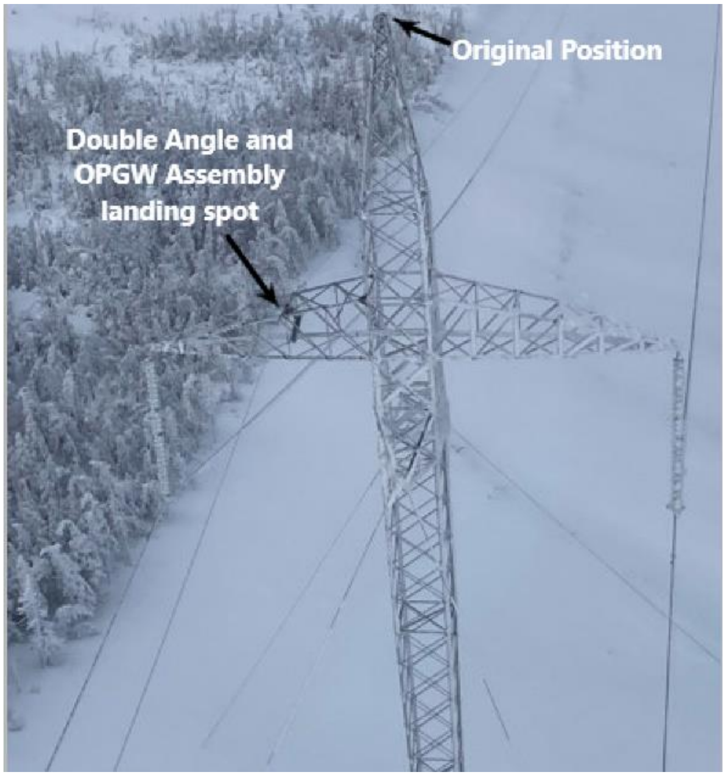

Figure 3: Structure 2135 OPGW Connection Failure

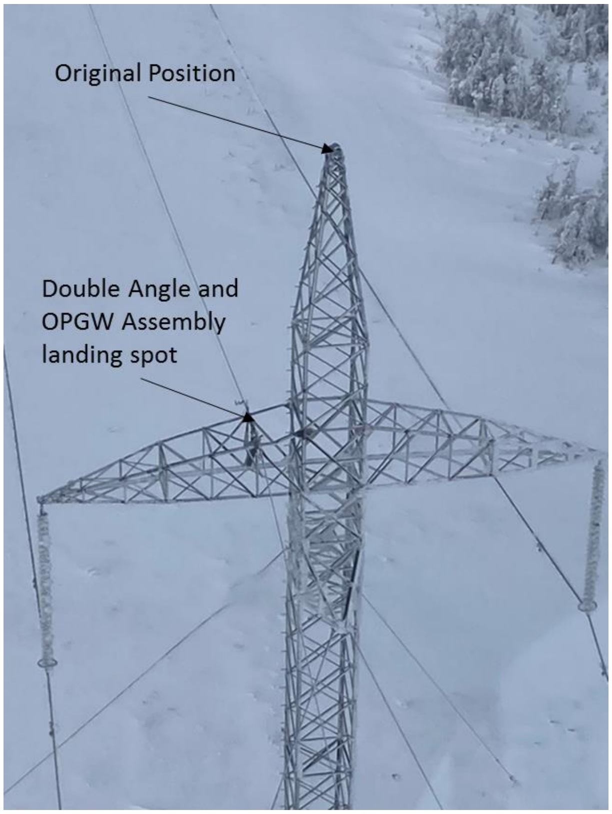

Figure 4: Structure 2136 OPGW Top Plate Failure

As shown in Figure 5, the top plate of the tower was bent significantly during the failure and there were no longer any bolts connecting the top plate to the double angles. The bolts connecting the top plate to the double angles were lost during the failure and not recovered. There was no apparent damage to the double angles during the failure.

Figure 5: Bent Top Plate after Removal from Tower

4.1 Failure Location

Structures are numbered sequentially along the line, starting at Muskrat Falls. As shown in Figure 6, Structures 2135 and 2136 are located in the central-western region of the island portion of the province.

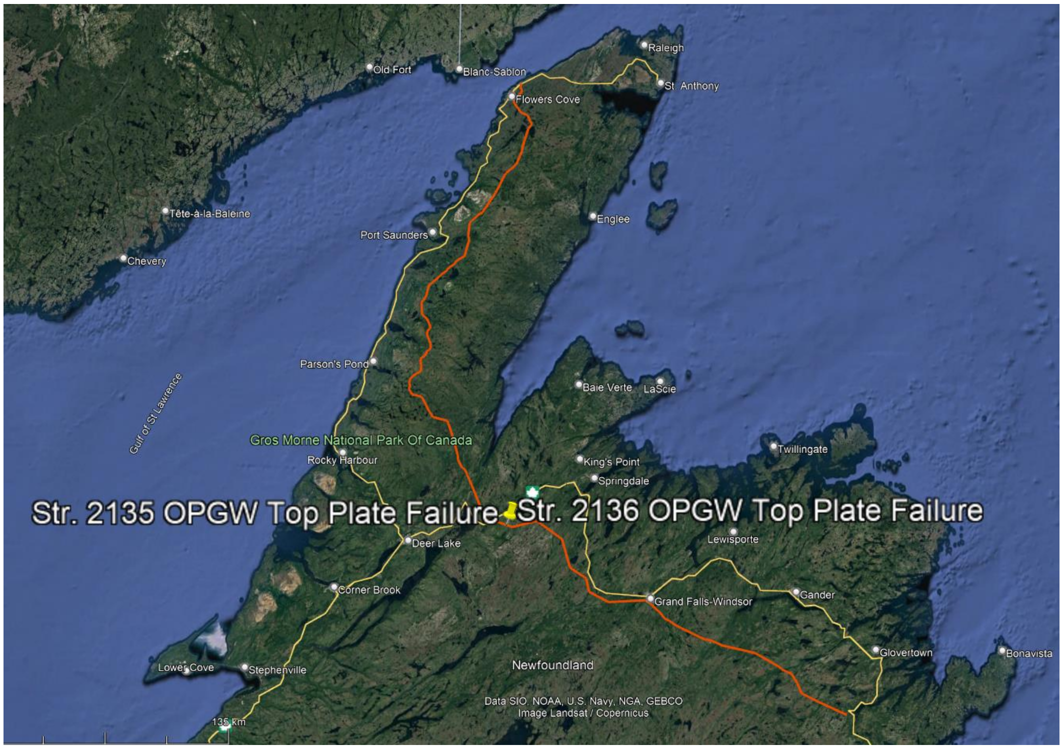

Figure 6: Map of Newfoundland with Failure Locations

4.1.1 Loading Zone

As discussed in Section 2.0, the LIL is divided into 19 loading zones. Structures 2135 and 2136 are located in Zone 9 ("Birchy Narrows Alpine Loading Zone"). Structures 2135 and 2136 are at an elevation of 490 m and 494 m above sea level, respectively, as seen in Figure 7. These are the highest elevations of structures in Zone 9 and are some of the highest on the Island outside of the Long Range Mountains.[5] Due to the elevation change between Structures 2135 and 2136 and the adjacent structures, Structures 2135 and 2136 have the highest weight spans[6] of any structures in this section of the line.

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[5] Elevation is important to note, as it is an indication of possible rime or in cloud icing locations throughout the LIL corridor.

[6] The weight span is the horizontal distance between the low point of sag in the back span and the low point of sag in the ahead span; it is used in calculating the vertical load that the conductor imposes on the supporting structure.

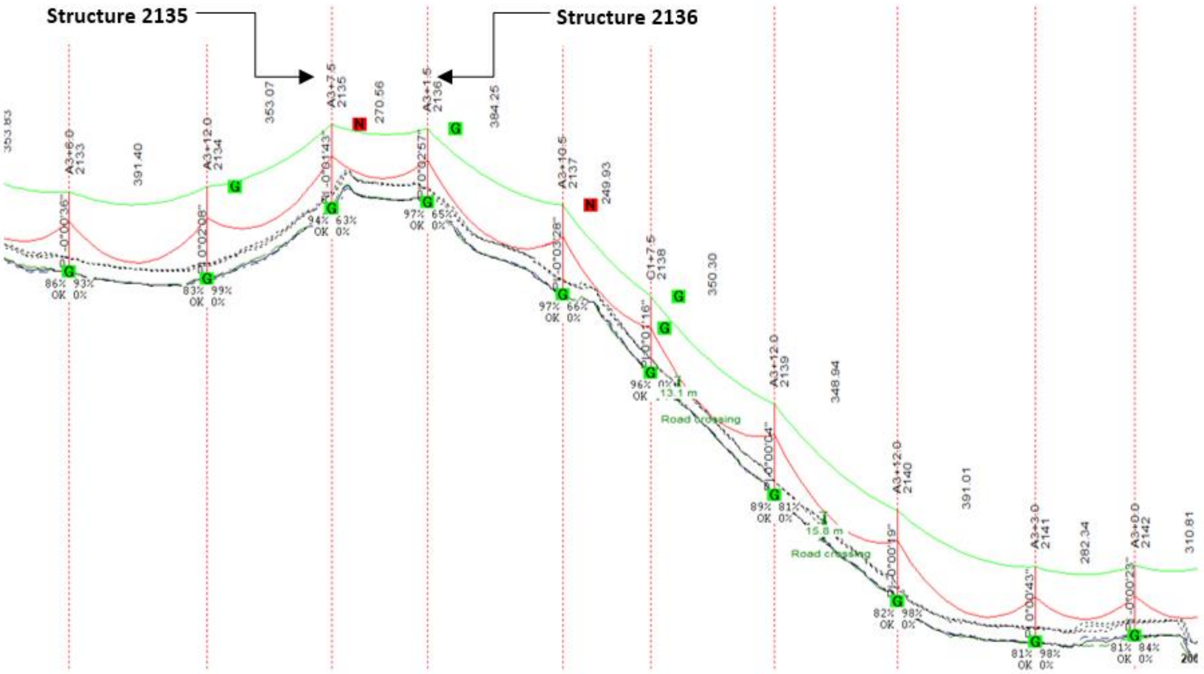

Figure 7: Profile View of Zone 9 Showing Relative Elevation of Structures 2135 and 2136

5.0 Weather Information

There was snow on the ground and ice on both the lines and towers in the area of Structures 2135 and 2136 when the failures were discovered. During the repairs, the crews at the site observed that these structures had a significant amount of ice accretion, as Figure 8 shows, which changed daily due to the local topography and weather systems at the time of the repair.

Figure 8: Ice on Structure 2135

The weather stations with hourly data nearest to Structures 2135 and 2136 are located in Deer Lake and Millertown. These stations are approximately 52 km and 51 km from the structures, respectively. Localized weather is heavily impacted by the hilly landscape and high elevation of Structures 2135 and 2136. Reports from site noted there was a significant change in the weather from the highway to the peak elevation in the location of Structures 2135 and 2136, a distance of approximately 9 km. This suggests that the ridge where the structures are located could be a microclimate.[7]

The wind speed in Deer Lake on the day of the failure, December 20, 2022, ranged from 7 km/h to 36 km/h. The wind speed in Millertown on the day of the failure was less than 15 km/h. Winds on the day of the failure were not extreme or above design loads, which is indicative of fatigue failure due to movement over the life of the line. The wind direction varied from east to south, as shown in Chart 2.

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[7] A microclimate is the climate of a very small or restricted area, especially when this differs from the climate of the surrounding area.

These winds are much lower than the design load case winds and are not considered a factor in the failure.

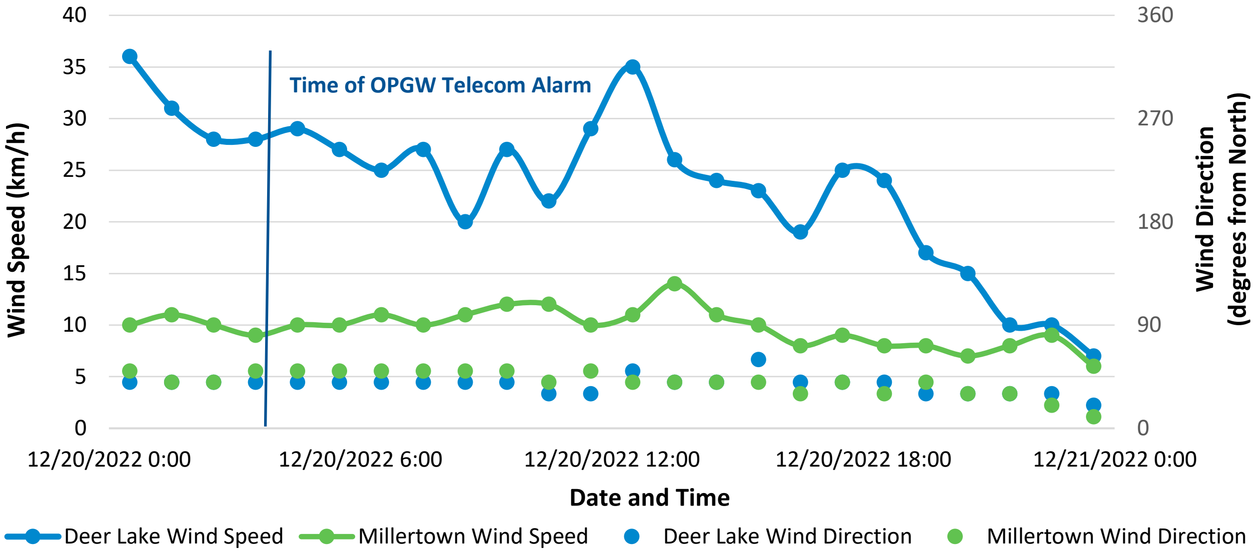

Chart 2: Deer Lake and Millertown Wind Data for December 20, 2022

The temperature on the day of the failure ranged from -2°C to 2°C in Deer Lake and -2°C to 1°C in Millertown. Chart 3 shows the temperatures in Deer Lake and Millertown from December 17, 2022 to December 20, 2022. The temperatures rose to above freezing on December 18, 2022. The fluctuations in temperature around and on the day of the failure could cause ice shedding and unbalanced icing on the structures, which could be a significant factor contributing to the failure.

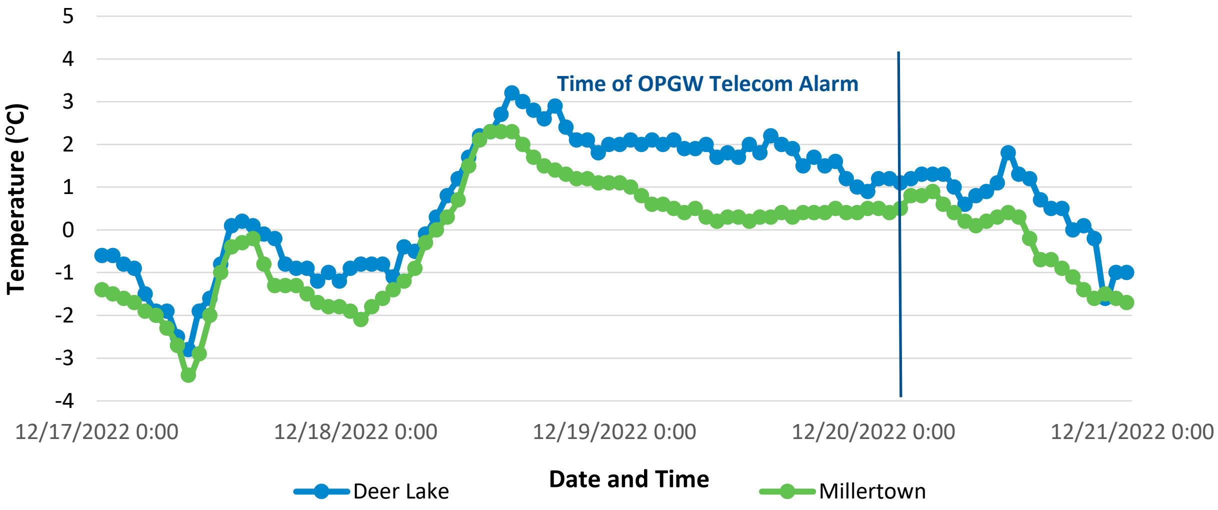

Chart 3: Deer Lake and Millertown Temperature Data, December 20, 2022

6.0 Immediate Repairs

6.1 Engineering Recommendations for Repairs

The primary goal for the restoration work was to repair the OPGW by splicing a new section, repairing the towers, and reconnecting the OPGW. It was decided that dead-ending the OPGW to the towers was preferable to replacing the suspension assemblies.

6.2 Restoration Summary

On December 23, 2023, the OPGW was secured to Structure 2136 using straps to avoid further damage to the structures. It was not possible to secure Structure 2135 in this way, as ice falling from the structure made it unsafe to do so. This work was completed as a temporary solution while materials and equipment were mobilized for permanent repairs.

As a permanent solution, a new section of OPGW was spliced in the line between Structures 2134 and 2137, with splice boxes added to both structures. The OPGW top plates were replaced at Structures 2135 and 2136. The OPGW was connected to all towers from Structures 2134 to 2137 with a dead-end assembly instead of a suspension assembly connected to the double angle.[8] In addition, repairs were completed to crossarm steel, which was damaged due to the impact of the OPGW assembly and double angles, as well as the tower steel on the OPGW peak at Structure 2137. The failure did not cause an outage on the line; however, a bipole outage was taken to complete the repair work. Pictures of the repairs are provided in Figure 9 and Figure 10.

Figure 9: Repair Work to OPGW Peak

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[8] All tangent towers are designed to accommodate either a suspension or dead-end connection for the OPGW; dead-end OPGW assemblies are installed on many tangent towers throughout the LIL.

Figure 10: Repair Work

7.0 Design and Manufacturing Review

For the failure investigation, a review of the revision history of drawings for both the tower and the hardware assemblies was compared to the model and calculation submitted by the Engineer of Record. All of the drawings, calculations, and models from the design of the type A3 tower were reviewed in detail and a discrepancy was found between the length of the connection plate in the model and the length on the drawings, as shown in Figure 11. This resulted in the structure being only able to withstand roughly 30% of the force of its design load before the bending of the top plate occurred, as shown in Figure 12.

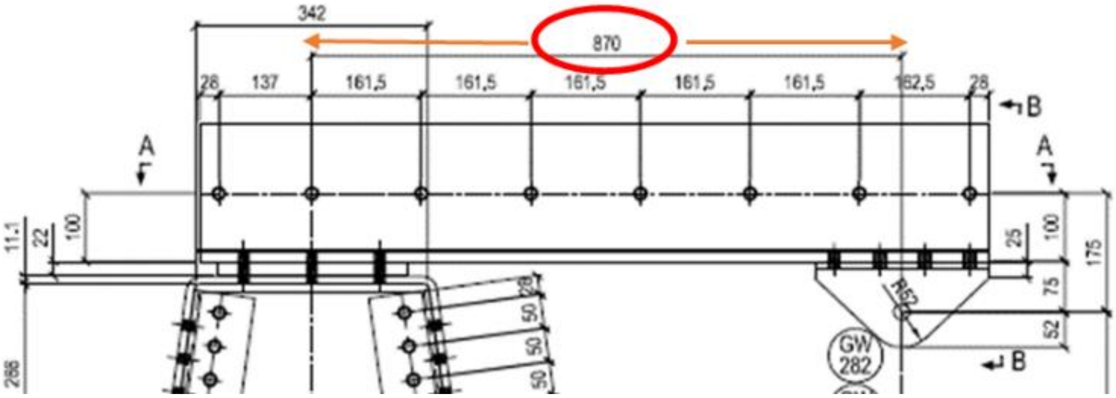

Figure 11: Distance from Tower Center to OPGW Connection

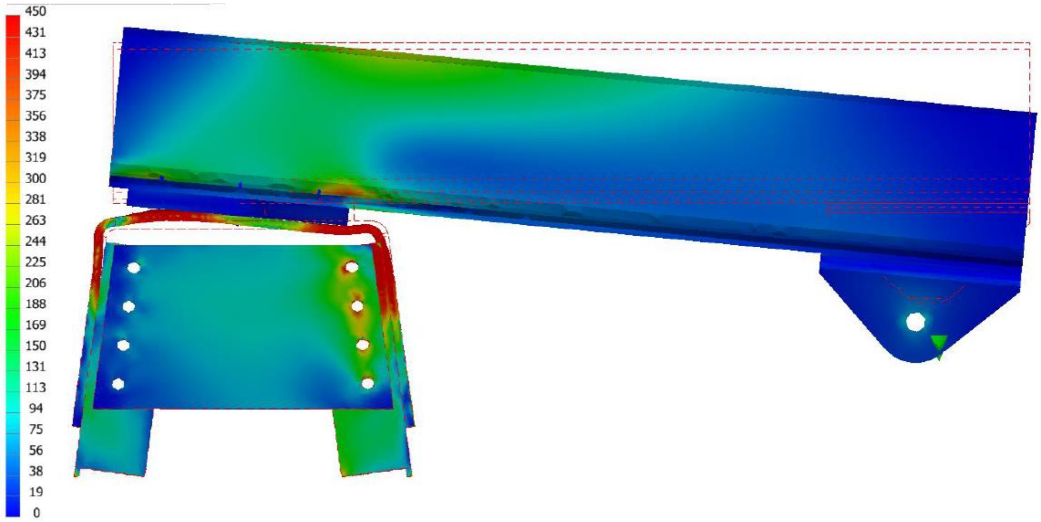

Figure 12: Model of Top Plate Bending

Based on the issues found in the review of the type A3 tower, the top plate connections of the other tangent towers were reviewed. Further analysis is required to review the top plate design of the remaining tower types; however, based on a preliminary review of the designs, Hydro believes it is unlikely that this same design error is present in other tower types; no other similar failures have occurred to date.

8.0 Construction Quality and Maintenance Review

The construction quality reports were reviewed to determine if any issues were present that may have contributed to the failure. No non-conformance reports were submitted on the tower steel for Structures 2135 and 2136 during construction.

On July 6, 2021, there were two corrective work orders related to top plates entered on Structure 2135 and Structure 2136, respectively. The damage was discovered during a routine inspection; work orders were entered to replace the top plate of each structure due to bending. As seen in Figure 13, the top plate at Structure 2136 is bent; however, the bolted connections between the top plate and double angle remained intact. Similar damage was incurred on the top plate of Structure 2135. As this had not been observed anywhere else on the line and no significant icing events had been recorded, the bent plates were assumed a manufacturer or construction quality defect and were replaced. The work orders both noted completion as September 7, 2021.

Figure 13: Bent Plate at Structure 2136 in 2021

9.0 Finite Element Analysis

An external consultant was engaged to complete a finite element model ("FEM") of the tower peak, to better understand the forces that caused the failure at the top plate. The focus of this FEM is the behaviour of the bent plate and the bolted connection under vertical load, as it was determined that this is the most likely mode of failure.

The results of the analysis are summarized in Figure 14, which shows the vertical load on the OPGW connection versus the displacement of the connection. The vertical design load for the OPGW connection is 95 kN.[9] The yield point of the connection is calculated at 36 kN, which is approximately one-third of the design load and is considered low for yielding of the plate. Based on the model, the outmost bolts break at 70 kN (or 74% of the design load) and the 5% strain of the top plate is reached at 120 kN.

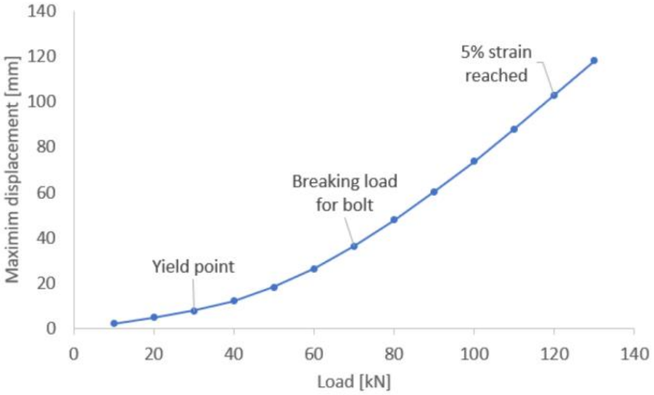

Figure 14: Vertical Load versus Displacement

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[9] Kilonewton ("kN").

The report concludes the outmost bolts failed at 70 kN, causing a progressive failure of all bolts. Plastic deformation calculations indicated the bolts should be sufficiently robust; however, elastic calculations determined the bolts were not strong enough for the 94.7 kN design load.[10] The calculations also determined the top plate was too thin for the design load.

It was estimated that the bending of the plates on Structures 2135 and 2136 in 2021, as discussed in Section 8.0, occurred under a vertical load of 50 kN to 60 kN and the failure of the plates on these structures in December 2022 occurred under a vertical load of greater than 80 kN.

10.0 Material Testing

Another external consultant was engaged to complete material testing on the top plate to determine the mechanism of failure. The top plates and double-angle assemblies from Structures 2135 and 2136 were shipped to the consultant's facility for testing. Testing concluded the bending moment from a vertical load on the OPGW connection caused plastic deformation of the top plate. There was no evidence that the bolts pulled through; therefore, they must have failed. This failure may have been due to fatigue, overload, or a combination of factors. The way in which the top plates are bent suggests the bolts furthest from the OPGW connection failed first. Chemical analysis, microstructural analysis, hardness test results, and impact test results of the top plate material indicated that the material conformed to a CSA G40.21 350WT[11] material.

11.0 Analysis of Loads Causing Failures

The results of both the FEM and material testing concluded that the deformation of the top plate and failure were due to a downward vertical force on the OPGW connection. A summary of the FEM failure loads (yield and bolt failure), the estimated load-causing damage, and the estimated load-causing failure is provided in Table 2.

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[10] Plastic deformation occurs when material deforms and it remains changed; elastic deformation occurs when material deforms, then returns to its original form.

[11] CSA G40.21 350WT is a high-strength, low-alloy steel plate grade specified within Canadian Standards Association (2013). CSA Standard G40.21, *General requirements for rolled or welded structural quality steel/Structural quality steel*.

Table 2: Summary of FEM results

Failure Description	Vertical OPGW Load (kN)
Yield of plate	30
Bolt Failure	70
Estimated March 2021 Damage	55
Estimated Dec 2022 Failure	80

A complete as-built FEM of L3501/2 in PLS-CADD[12] includes the existing terrain as well as as-built tower locations and heights. Since the load that caused the failure was determined to be vertical, the analysis focused on load cases that would cause vertical loads.

11.1 Ice Loading

To understand what amount of ice would cause the vertical load on the OPGW connection shown in Table 2, PLS-CADD was used to analyze uniform radial ice thickness of 30 mm, 40 mm, 50 mm, 60 mm, 70 mm, and 75 mm.[13] The results for all tangent structures in Zone 9 are shown in Figure 14. Figure 14 shows that of all the structures in the zone, the ice load puts the greatest vertical load on the OPGW connection of Structure 2135 and 2136. With 75 mm (the maximum ice design load) of ice on the lines, the vertical loads on the OPGW of Structures 2135 and 2136 are 90 kN and 92 kN, respectively, while all other structures range from 56 kN to 88 kN.

Chart 4 demonstrates the loads corresponding to bolt failure, the estimated load at which the failure occurred in December 2022, and the design load of the OPGW connection. From Chart 4 it can be concluded that between 60 mm to 70 mm of radial glaze ice (or 87 mm to 101 mm of radial rime ice) would cause a load on Structures 2135 and 2136 that would result in bolt failures and that 70 mm of radial glaze ice (or 101 mm of radial rime ice) would cause a load that is estimated to cause the failures experienced in December 2022.

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[12] PLS-CADD is a transmission line design program that allows the user to enter different loading conditions to analyze how they will affect the line and structures under the as-built conditions and ultimately how the towers will fail under extreme loading conditions. The program allows the user to complete a detailed analysis of how loads on the lines will affect the towers.

[13] Due to the error in the model of the OPGW top plate connection, the program will not accurately determine the failure of the structures; however, it will accurately calculate the vertical force on the OGPW connection.

Observations from the site during the repair indicated that, overall, there was more rime ice and less glaze ice; as such, determining the exact thickness of the ice during the event is difficult.

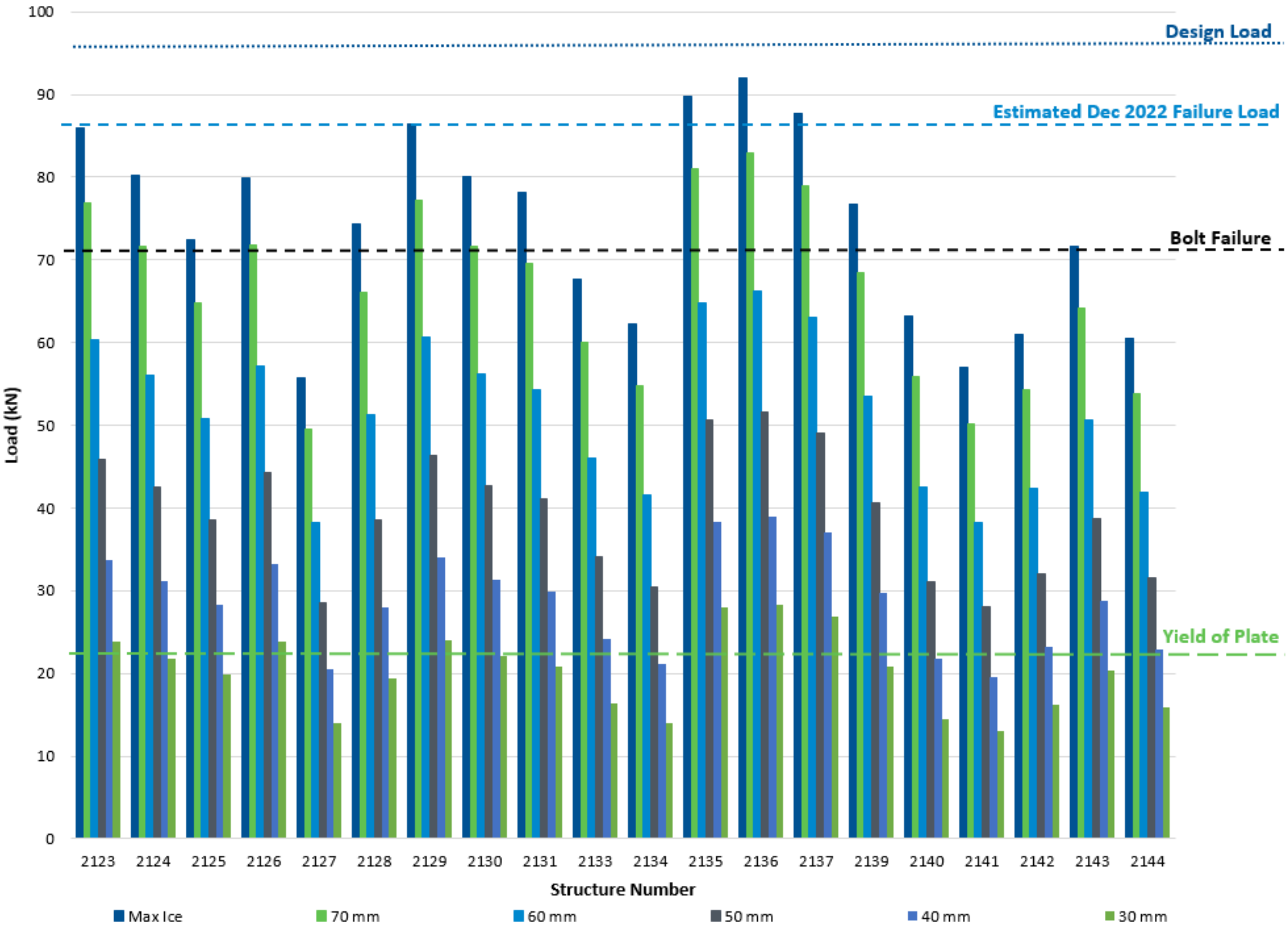

Chart 4: Vertical Load on OPGW Connection by Str. for Various Ice Thickness

11.2 Ice Shedding

When ice sheds from the line there is a dynamic, and likely vertical, component to loads on the tower. The dynamic loads can lead to an increase in cable tension of 13%.[14] Considering the increase in vertical loads because of ice shedding, it is possible this action could cause the vertical loads required for failure at a lower ice thickness than discussed in Section 11.1.

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[14] Forti, Tiago. “Numerical Simulation of Transmission Line Vibration Caused by Ice Shedding,” CEATI Report T163700-33/109, Centre for Energy Advancement through Technological Innovation, June 2020.

12.0 Summary of Root Cause

The primary cause of the failures at Structures 2135 and 2136 was overload failure, likely due to an error in the original design of the top plate connection. Some points to consider are:

- This error caused the connection to fail at a load less than the vertical design load requirements for the OPGW connection;
- It is theorized that the lever arm of the double angle was changed during the design process and the associated connection was not checked or updated; and
- While the vertical design load of the OPGW connection is 95 kN, a FEM analysis determined the bolts of the connection can fail at 70 kN. Material testing confirmed a bending moment from a vertical load at the OPGW connection caused plastic deformation of the top plate and a failure of the bolt; it was also confirmed that the steel conformed to the specification of a CSA G40.21 350WT material.

The vertical load that caused the failures was likely due to ice, which was observed on the line and the towers when the failure was located. As the temperatures in the area had recently risen above zero, ice shedding likely occurred on the lines due to rising temperatures, which could contribute to the vertical load that caused the failure. The FEM estimates that approximately 80 kN of vertical load on the OPGW connection would cause the failures at Structures 2135 and 2136. Modelling suggests this would be equivalent to a uniform radial glaze ice thickness of 70 mm for these structures; however, if a dynamic factor from ice shedding is considered, this thickness could be less.

13.0 Recommendations

The recommendations to mitigate against further failures on the line due to the issue with the design of the OPGW top plate connection include the following:

1) Consult a tower designer for recommendations on correcting the connection detail;

2) Check the bolted connection design of all tangent tower types;

3) Implement fixes as required, starting in the most critical locations; and

4) In the interim, repair any additional issues to the top plates found during inspections by dead-ending the OPGW to the structure, as completed for Structures 2135 and 2136.

It was determined that the current design of the top plate and the connection to the double angle on the type A3 tower design do not meet the design load requirements; therefore, the plate and connection must be redesigned. The redesign should consider the fact that the towers are already erected and the line is in service.

14.0 Conclusions

Upon review of the suggested recommendations, Hydro has progressed with the following action items:

1) An external consultant has been engaged to assist in redesigning the plate and connection detail, reviewing all tangent tower types, and understanding the extent of the risk. A primary review of the other top plate connection designs in Section 8.0 has been completed; however, further analysis is required to determine if there is any issue with these other tangent tower types.

2) Hydro will formulate a repair plan in the fourth quarter of 2023 to mitigate the risk of further communication failure, which would be implemented based on priority. There are 537 type A3 towers on the line, 502 of which contain OPGW suspension assemblies. Of the 502 towers containing OPGW suspension assemblies, 437 are in Zone 11 on the Avalon Peninsula and 20 are in Zone 9, the location where the failures occurred on Structures 2135 and 2136.[15] Zone 9 would be the highest priority for replacement, as it is remote and has had more ice observed in recent years than in Zone 11; therefore, in the event of future failures would likely require longer outages to complete repairs.

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[15] The 45 remaining towers are in Zones 3 and 4, which have a maximum radial ice design thickness of 50 mm; these are likely the lowest priority and fixing may not be required.

Summary of Findings from L3501/2 Failure Investigation

Electrode Conductor Failure

Structures 514 to 517

October 4, 2023

A report to the Board of Commissioners of Public Utilities

Executive Summary

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The LIL is comprised of 3,223 towers, stretching over 1,100 km, with electrode conductor systems in Labrador and on the Island connecting the converter stations to the grounding sites. The electrode conductor system in Labrador is a redundant system[2] consisting of two conductors supported on 1,229 transmission line steel towers of the LIL and provides a connection between the converter station in Muskrat Falls to the grounding site in L'Anse au Diable.[3] During December 2022, it was observed that the electrode cable on Electrode Line 2 ("EL2") had been damaged in Segment 1[4] of the LIL at three locations between Structures 514 and 517, with a full break at Structure 515. During this event, there was no specific damage to the towers themselves. The damage was limited to the EL2 cable only, with aluminum strands bird caging[5] at the suspension clamp of Structure 514, full mechanical failure of the steel and aluminum cable strands of Structure 515, and full mechanical failure of the aluminum cable strands of Structure 517. As a result of system redundancy, the LIL was able to operate following the failures, aside from a brief outage[6] while all damages to EL2 were repaired and the cable was restored to its original condition.

A detailed failure investigation was completed to determine the root cause of the failure and to identify recommendations to mitigate against the reoccurrence of these failures. The primary cause of the failure was tensile overloading of the cable as a result of ice accumulation and unbalanced load due to ice shedding. It is suspected that the cable structure was compromised, resulting in reduced tensile capacity. A similar failure previously occurred in 2021, wherein a similar weather event caused extensive

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[1] L3501 and L3502 are Pole 1 and Pole 2 of the line, respectively.
[2] The redundant system is in place to allow the operation of the LIL while outages are taken to facilitate repairs on either line.
[3] In addition to the 1,229 towers in Labrador, there is a second set of towers carrying two electrode lines between the converter station in Soldiers Pond and the grounding site in L'Anse au Diable.
[4] Segment 1 includes Structures 1 to 687.
[5] Bird-caging is a form of wire rope distortion.
[6] A bipole outage was required daily for the repair work due to safety and clearance issues; however, the line was able to return to service in the evenings, as required.

damage to both the electrode cable and the tower crossarm in multiple locations throughout Segment 1 of the transmission line.

Given the investigation findings, recommendations to mitigate against further failures on the electrode line due to unbalanced ice load and ice shedding include increased monitoring of ice conditions along the transmission line, including real-time monitoring; ensuring adequate information is collected following a failure event; and engaging an external consultant to study unbalanced ice loads, changes in weather patterns, and potential design changes to facilitate informed decision-making regarding corrective action, where required.

To date, Newfoundland and Labrador Hydro ("Hydro") has progressed the actions addressing these recommendations. These actions include the installation of a weather station in the Labrador Straits and the planned installation of an additional weather station in central Labrador in 2025, ensuring that adequate information is collected by personnel following a failure event, and increased real-time ice monitoring through increased monitoring by field personnel around weather events and continued helicopter patrols. In addition, an external consultant has been engaged to identify an alternate electrode suspension assembly design that could aid in mitigating cable stress for the transmission line locations that have seen this ice loading throughout the icing events. Hydro, in conjunction with external consultants, will complete a detailed engineering study within Labrador to analyze tower performance with respect to unbalanced loading in 2024. This study will help determine if any structural enhancements for specific areas are deemed necessary and develop a plan to upgrade the section of the line that is impacted.

Contents

1.0 Introduction

At 1435 hours on December 31, 2022, the Energy Control Centre recorded an electrical fault on the LIL. As a result of the fault, the high-voltage line tripped, resulting in a loss of power on the LIL and a reduction of power on the Maritime Link, to ensure the Island frequency remained stable. The LIL was in monopole mode at the time of the event. From an Island Interconnected System perspective, there was no major impact or customer outage.

After the initial event and upon inspection, it was observed that the electrode cable[7] had been damaged in Segment 1 of the line between Structures 514 and 517, with a full break at Structure 515. These structures are located in the southeastern portion of Labrador, where the line runs from Muskrat Falls to Forteau Point.

2.0 Background

The LIL is an important transmission line for the provincial energy grid due to its power-carrying capacity, which will be used to deliver a large portion of the winter peak energy and demand on the Island Interconnected System. Line L3501/2 is the 350 kV HVdc overland transmission line portion of LIL, traversing a distance of approximately 1,100 km. As Figure 1 shows, the overland transmission line is a bipole line with a single conductor per pole, duel electrode conductors[8] for a portion of the line, and an optical ground wire ("OPGW") communication cable. The lines are supported by galvanized steel lattice towers. The LIL was constructed in harsh terrain; it is subjected to heavy wind and ice loads and has experienced multiple winter seasons and weather events.

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[7] The electrode cables installed on the LIL are 1192.5 million cubic metres ("MCM) aluminum conductor steel-reinforced ("ACSR") conductor "Grackle" 54/19 with a diameter of 33.94 mm and a rated tensile strength of 194,000 Newtons ("N").

[8] The electrode conductor is attached to the lattice towers until about 384 km southeast of Muskrat Falls (Structures 1 to 1229), where it diverts to a separate right-of-way on wood poles to an electrode site located in the L'Anse au Diable area. Sections of L3501/2 without the electrode on the towers do not have electrode crossarms.

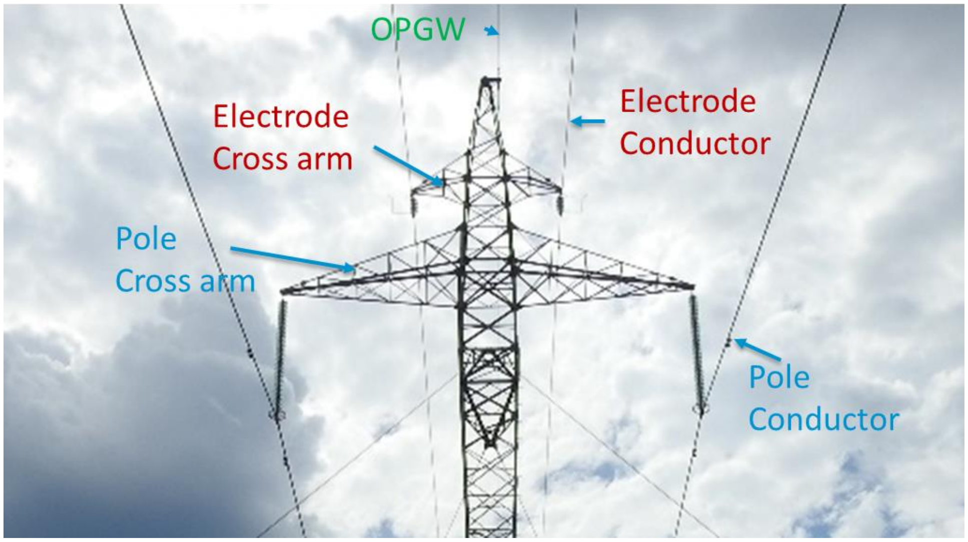

Figure 1: L3501/2 Structure Showing Wire Arrangement

The HVdc transmission line corridor has been divided into three major meteorological loading zones (average, alpine, and eastern) in combination with eight further subcategories related to meteorological loads, pollution levels (inland and coastal), and geographic location. The resulting combinations lead to the HVdc line consisting of 19 separate loading zones. There are 11 tower types (A1, A2, A3, A4, B1, B2, C1, C2, D1, D2, and E1) that were designed to meet the loading requirements applied to the line, which consist of a specified wind load, ice load, and combination of both. The tower types consist of both guyed towers and self-support towers. The tower types are summarized in Table 1.

Table 1: Tower Types

Tower Type	Structure Type	Insulator Assembly Type	Deflection Angle Limit (Degree)
A1, A2, A3, A4	Guyed	Suspension	0–1
B1	Guyed	Suspension	0–3
B2	Self Support	Suspension	0–3
C1, C2	Self Support	Dead End	0–30
D1, D2	Self Support	Dead End	0–45
E1	Self Support	Dead End	45–90

Both suspension and dead-end towers contain electrode connections; 1,229[9] of these structures in Labrador connect to electrode cables. Chart 1 details the tower distribution on L3501/2.

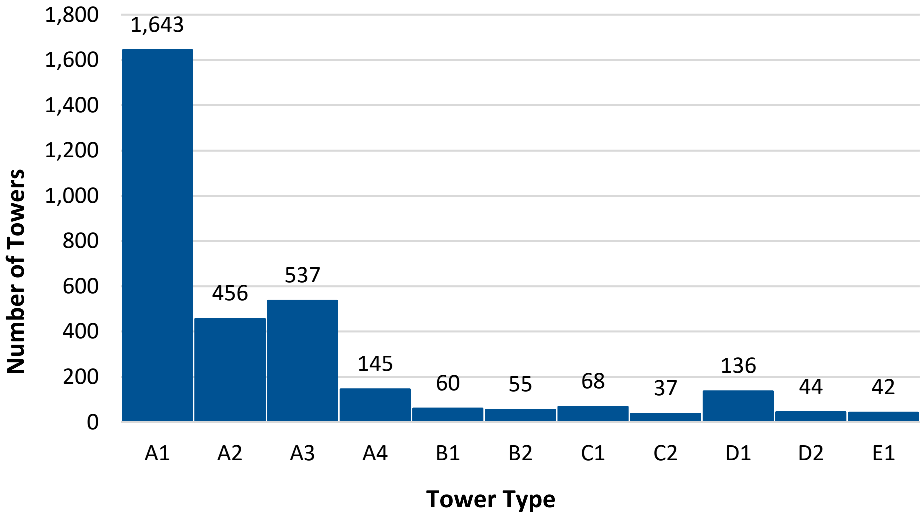

Chart 1: Distribution of Tower Types on L3501/2

3.0 Investigation Overview

To understand the line's performance in severe weather conditions, a detailed failure investigation was completed to determine the root cause of the failures and to conclude what actions can be taken to mitigate against further failures, including damage to the line, and provide appropriate remediation.

The investigation will be described in detail herein and includes the following components:

- Failure description;
- Weather information;
- Material testing;
- Failure analysis and discussion of findings;
- Summary of root cause; and
- Recommendations.

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[9] There are 2,458 electrode/tower connections, 2,240 of which connect the electrode cables to the tower by suspension clamp. At the remaining 218 locations, the electrode cables are connected to the tower by a dead-end terminal.

4.0 Failure Description

During December 2022, it was observed that the electrode cable on EL2 had been damaged at three locations between Structures 514 and 517, with a full break at Structure 515. As identified during the investigation through visual inspection, there was no specific damage to the towers themselves During this event; damage was limited to the electrode cable on EL2 in three locations. Damages experienced during the event are listed in Table 2; no damage was observed on EL1 despite being co-located on the three towers that experienced the failures.

Table 2: LIL Towers Damaged during the 2022 Weather Event

Structure Number	Conductor EL1	Conductor EL2	Comments
513			
514		X	Aluminum strands bird caged at the suspension clamp.
515		X	Full mechanical failure of the steel and aluminum cable strands.
516			
517		X	Full mechanical failure of the aluminum cable strands.
518			

A full mechanical break of both the conductive aluminum and steel-reinforcement strands occurred at Structure 515, as shown in Figure 2 and Figure 3, resulting in the electrode cable dropping to the ground on the western side between Structures 514 and 515. As a result of the cable break at Structure 515, the cable experienced western longitudinal loading, resulting in severe bird caging of the aluminum strands at the clamp on the adjacent Structure 514, as shown in Figure 4 and Figure 5.

Electrode damage at Structure 517 (Figure 6) was isolated but appeared to be similar to Structure 515 damage; all of the aluminum strands were broken but the steel strands were still intact, as shown in Figure 7. All damages to EL2 were repaired, and the cable was restored to its original condition.

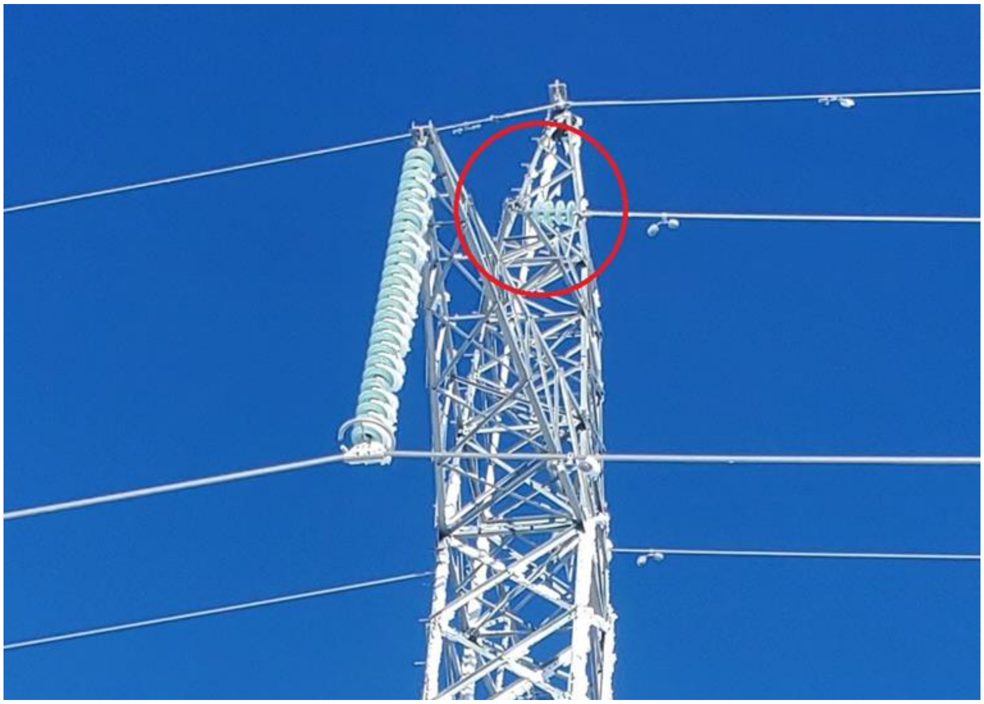


Figure 2: Structure 515

Figure 3: Broken EL2 at Structure 515

Figure 4: Structure 514

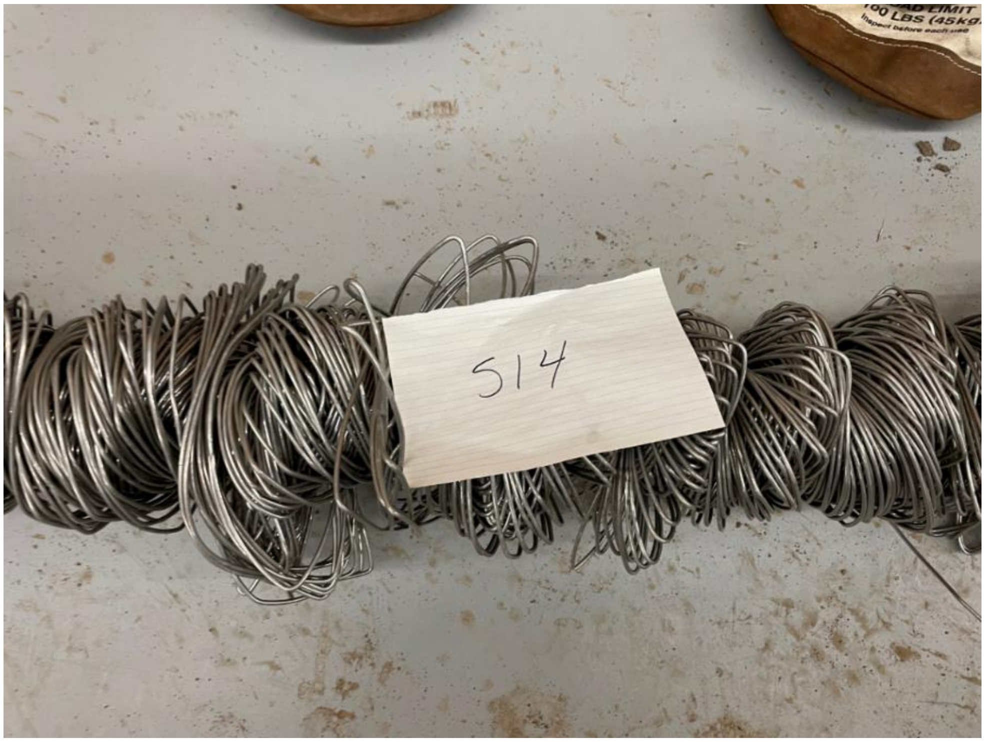


Figure 5: Electrode Cable Bird Caged at Structure 514

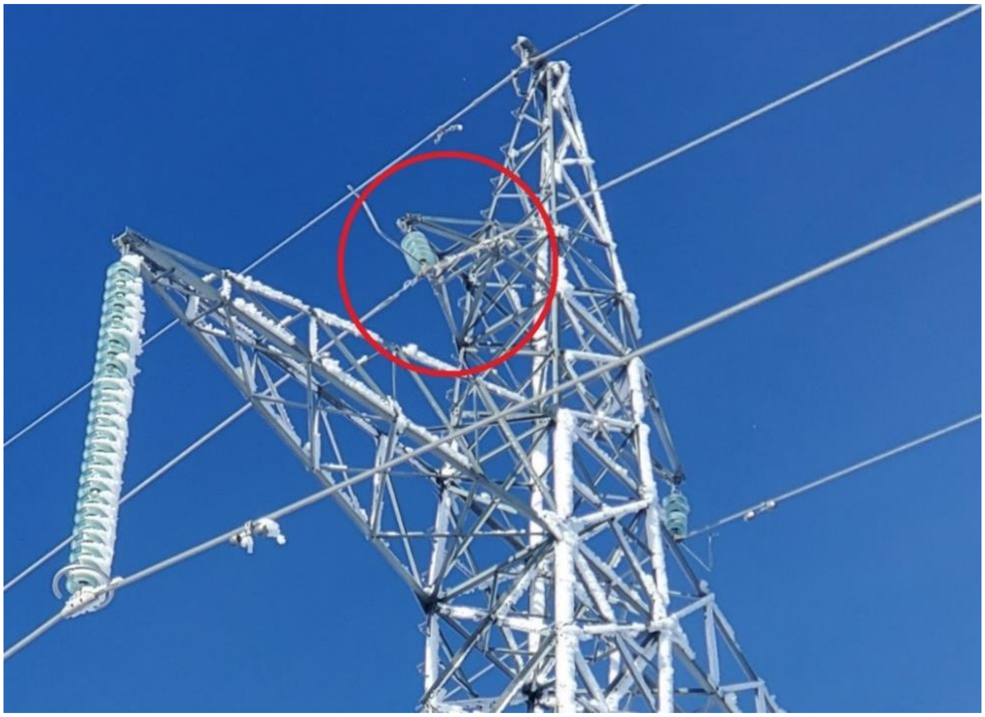


Figure 6: Structure 517

Figure 7: Structure 517 Broken Aluminum Strands

4.1 Failure Location

The failures described herein all occurred within Segment 1 of the LIL, shown in Figure 8 and Figure 9. Within Segment 1, there are 750 towers, primarily consisting of type A1 guyed suspension structures.

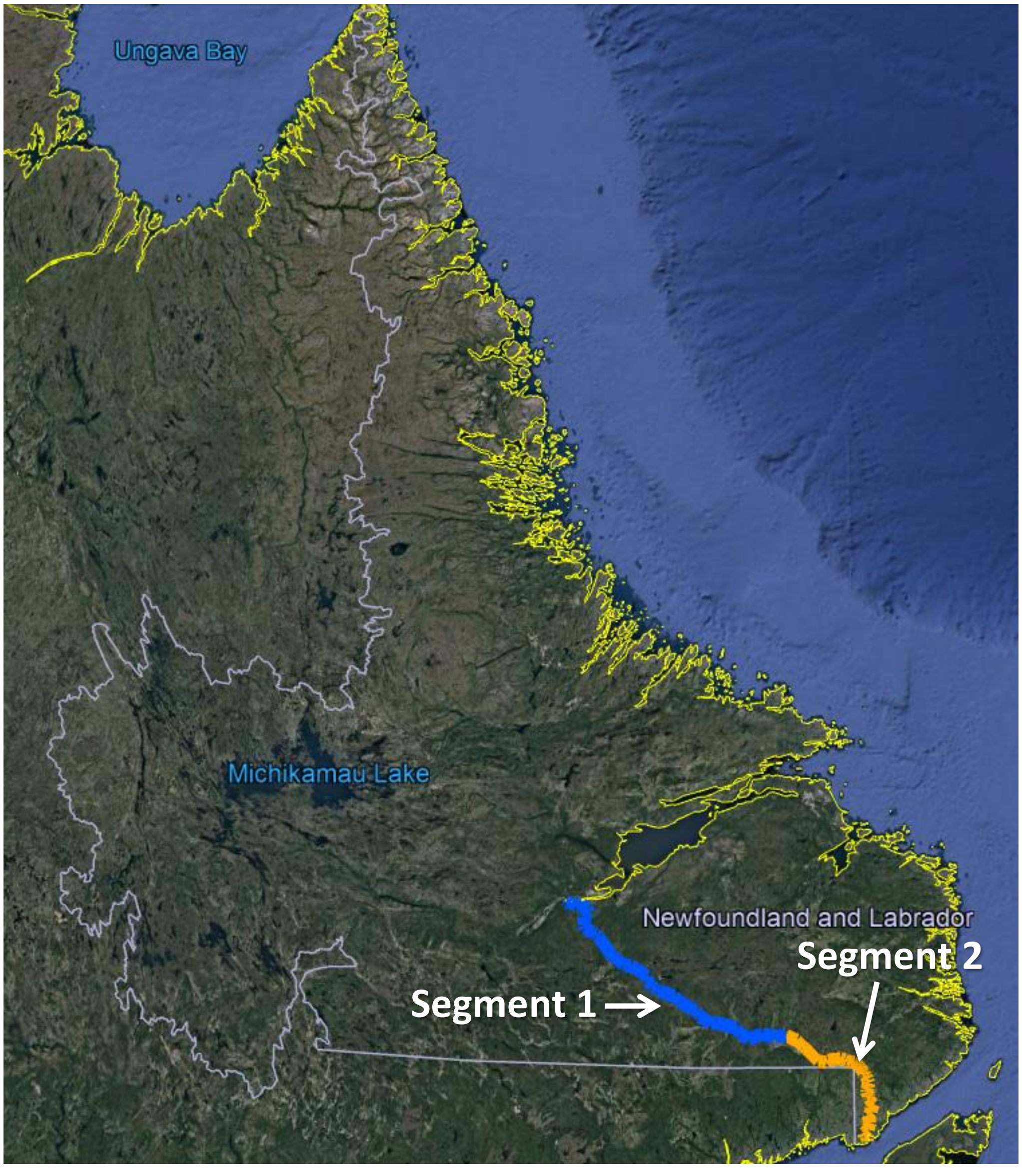
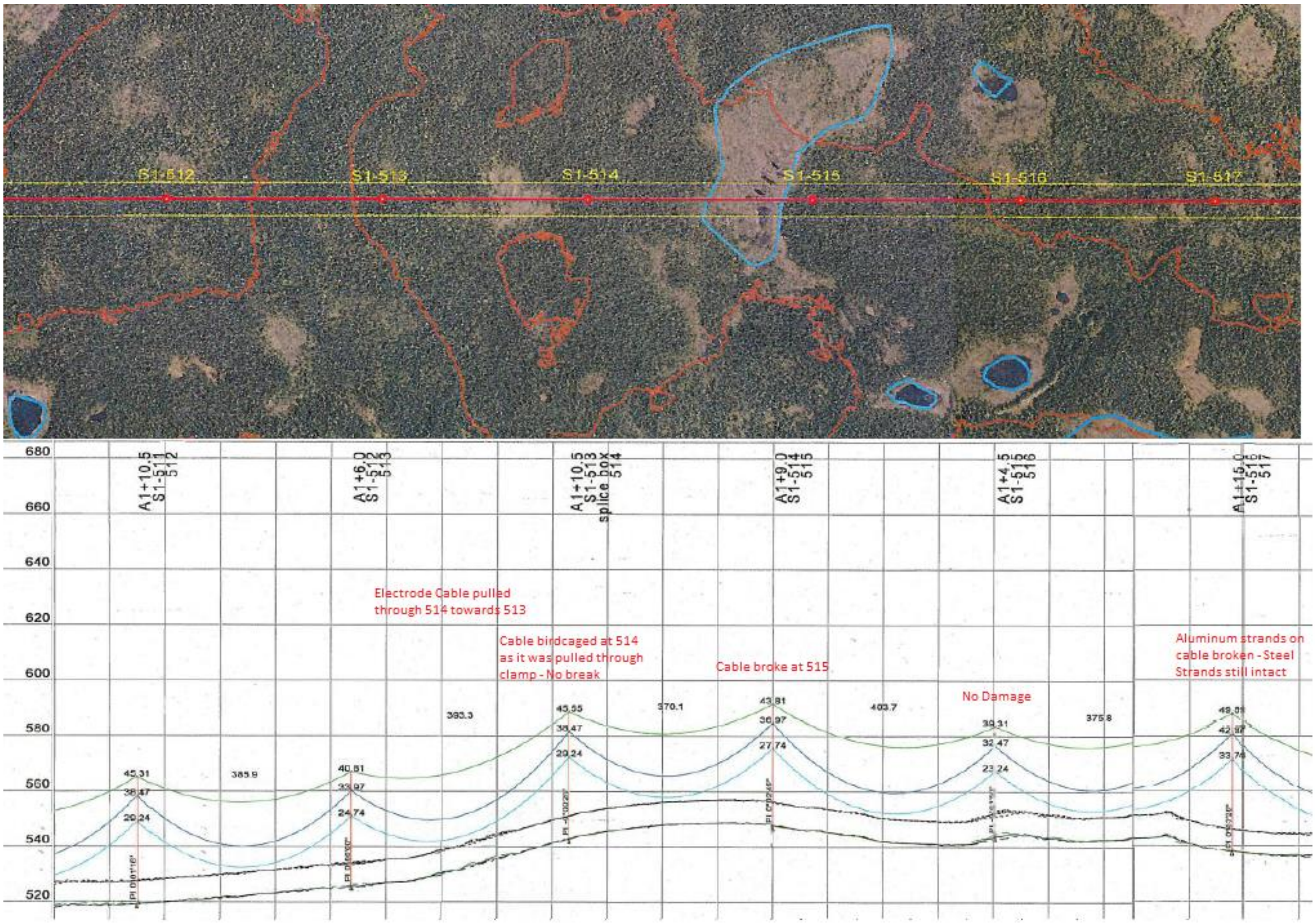


Figure 8: Segments 1 and 2 of the LIL in Labrador

Figure 9: Location of Electrode Damage



Electrode Cable pulled through 514 towards 513

Cable birdcaged at 514 as it was pulled through clamp - No break

Cable broke at 515

No Damage

Aluminum strands on cable broken - Steel Strands still intact

Figure 10: Plan and Profile View

As can be seen in Figure 10, there is no significant increase in the relative elevation between the structures. However, the overall elevation is over 500 m, which is typically conducive to conditions that support the formation of wet snow/rime ice[10] in the atmosphere. This aligns with the type of ice accumulation observed during this event and prior events experienced in this area.

The electrode damage associated with this failure is very similar to the event experienced in 2021; however, during the 2021 storm, significant damage was caused to both the electrode cable and the tower crossarm. This indicates that the weather events responsible for the 2022 failure were not as extreme as the ones experienced in 2021.

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[10] Rime ice is an opaque, less dense ice that occurs as a result of in-cloud icing or freezing fog. The density of rime ice is approximately 500 kg/m^3.

4.1.1 Loading Zone

As discussed in Section 2.0, the LIL is divided into 19 different zones. All damage that occurred during this icing event was in loading Zone 1 ("Average Loading Zone"), which stretches from Structures 1 to 750 for a distance of approximately 273 km, starting at Muskrat Falls. A summary of the ice and wind conditions for which Zone 1 is designed is provided in Table 3.

Table 3: Zones 1, 8b, and 10 Ice and Wind Design Loading[11]

Load	Design Loading
Maximum Ice	50 mm radial glaze, 0.9 g/cm³ density
Maximum Wind	105 km/h (10-minute average wind speed at 10 m height above ground)
Combined Ice and Wind	25 mm radial glaze, 0.9 g/cm³ density 60 km/h (10-minute average wind speed at 10 m height above ground)

4.2 Benchmarking Considerations in Design Load Selection

Zone 1 is located in central Labrador, which has been historically understood as a location that experiences less ice accumulation and freezing rain events in comparison to other zones throughout the province, as winter temperatures are generally well below temperatures for freezing rain. Existing transmission experience within similar regions (735 kV lines from Churchill Falls to Quebec and L1301 from Happy Valley-Goose Bay to Churchill Falls) have a maximum ice design of 12.7 mm to 25 mm of radial glaze ice,[12] with limited experience of freezing rain outages, historically. These lines are located in central Labrador but not in parallel corridors to Segment 1 of the LIL. Furthermore, one study determined a maximum value of 11 mm of radial glaze ice accumulation was predicted as a 1:50-year maximum freezing rain value for Zone 1.[13] The equivalent CSA ice thickness for the section for a 50-year, 150-year, and 500-year return period would be 37 mm, 45 mm, and 53 mm of radial glaze ice,

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[11] Maximum wind and combined wind values assume Terrain Type C as per CSA Group. CSA C22.3 No. 60826-10 *Overhead transmission lines - Design criteria*. Any deviation from this terrain type for select locations along the corridor must be included in the HVdc tower design criteria.

[12] Glaze ice is clear, dense ice that occurs as a result of freezing rain. The density of glaze ice is approximately 900 kg/m³.

[13] Jones, Kathleen F., "Evaluation of extreme ice loads from freezing," Terrestrial and Cryosphere Science Branch of the Cold Regions Research and Engineering Laboratory (CRREL), January 11, 2010.

respectively.[14] Based on this information, a design ice load of 50 mm of radial glaze ice[15] was selected for this zone.

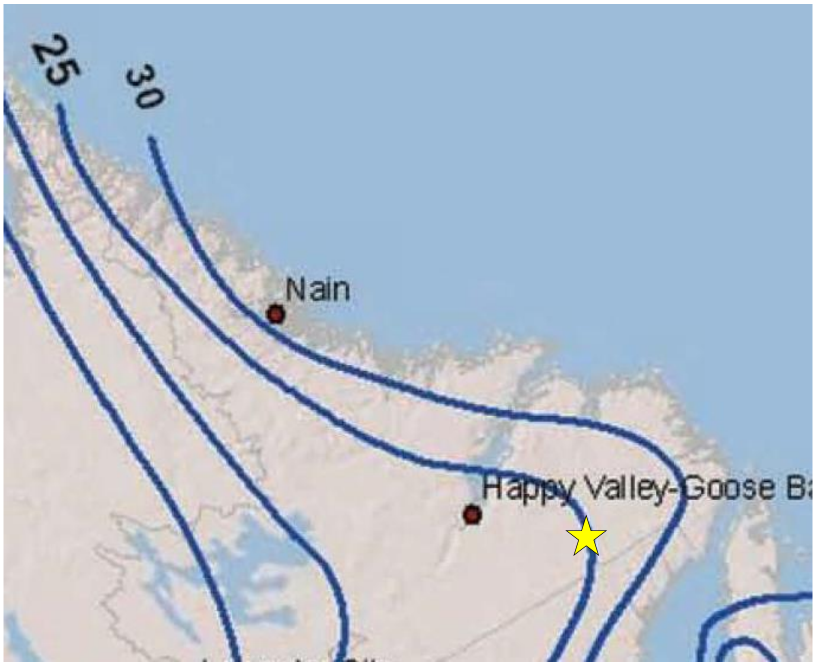

Figure 11: CSA Recommended Ice Loading Map

5.0 Weather Information

5.1 Tower and Line Icing Photos

The pictures included in Figure 12 to Figure 16 were taken during a snowmobile patrol, which was completed by Hydro's Operations team upon receiving notification of the fault. It is evident from the photos that significant icing had accumulated over time on the cables. Figure 13 and Figure 15 show ice accumulation on the towers; it is assumed that when ice is not present on the lines but is present on the towers ice shedding has occurred.

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[14] CSA C22.3 No. 60826-10 recommended reference loading for the region ranges from 25 mm to 30 mm for a 1:50-year return period, as seen in Figure 11. This reference load must be multiplied by a spatial factor of 1.3 and a height factor of 1.15 for a comparison to the 50 mm design load.

[15] This design ice load was the highest used throughout all Labrador loading zones.

Figure 12: Ice Accumulation on Cables Immediately After Failure

Figure 13: Ice Accumulation on Towers/Insulators (Mixture of Snow/Ice)

Figure 14: Cables with Partial Ice Accumulation (Indication of Ice Shedding)

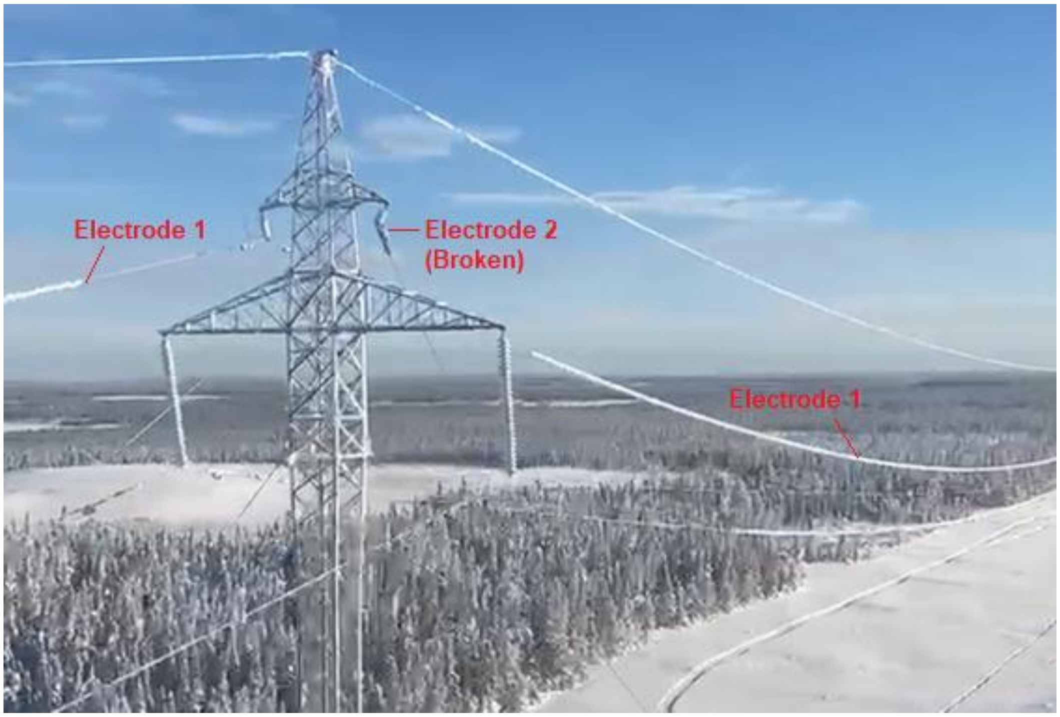

Figure 15: Structure 515 with Ice Accumulation on the Intact Electrode Cable

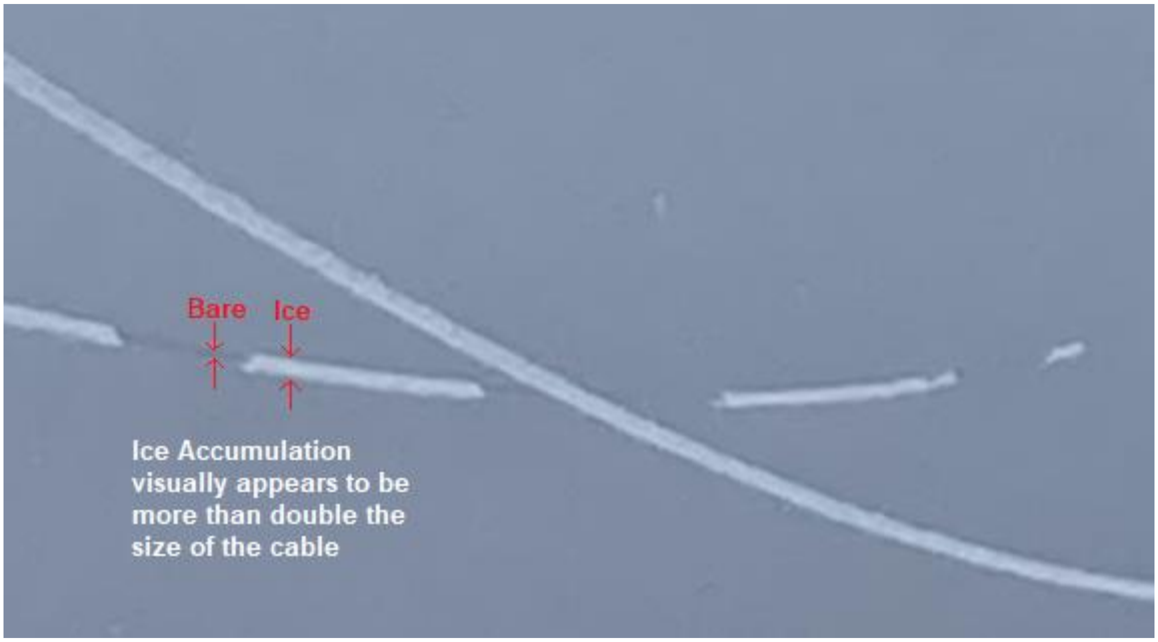

Figure 16: Ice Accumulation/Partial Shedding on Cables

There are two types of ice considered for transmission line design—glaze ice and rime ice. The icing accumulation experienced during this event was a mixture of glaze and rime icing. Figure 16 shows that a significant amount of ice had accumulated on the cables prior to the failure event experienced on December 31, 2022. The formation appears to be a mixture of glaze and rime ice, similar to what was experienced during the 2021 failure event.

As a result of the remoteness of the failure location and the ongoing repair initiatives resulting from failure events on the LIL, limited data-based evidence was collected during this failure. As a result, this investigation is primarily based on a qualitative assessment of the limited pictures received from field crews at the time of discovery. Other pictures of the event were taken during a helicopter patrol on January 2, 2023, two days after the event occurred. This lapse in time could have resulted in changes in the site conditions as a result of varying temperatures and weather conditions, as well as ice removal protocols that were initiated.

As seen in Figure 16, it was qualitatively deduced from photos that the ice accumulation was more than double the diameter of the pole conductor. As the electrode conductor has a smaller diameter at a higher elevation than the pole conductor, it is possible that the electrode cable was exposed to an even higher amount of ice. Based on the information collected, it is estimated that between 14 kg/m to

15 kg/m[16] of ice was present at the time of failure, which suggests that the icing experienced was very close to or slightly above the original design value of the electrode cable.

5.2 Weather Data from Nearby Weather Stations

There are currently no weather stations located in direct proximity to Segment 1 of the LIL; however, there are several weather stations within the general geographic area from which information has been collected for this investigation and upon which the design was informed. These weather station locations include Happy Valley-Goose Bay (northwest of the LIL failure area), Mary's Harbour (southeast of the LIL failure area) and L'Anse-au-Loup–Blanc-Sablon (southeast of the LIL failure area), as shown in Figure 17.

As transmission lines traverse many different geographical regions and landscapes, they are exposed to various changes in weather parameters. As a result, weather conditions at the failure location could be quite different than those experienced at the established weather monitoring station locations. The information presented herein is meant to provide a general overview of the conditions experienced in the central Labrador region at the time of the failure event and not the actual conditions experienced at the site.

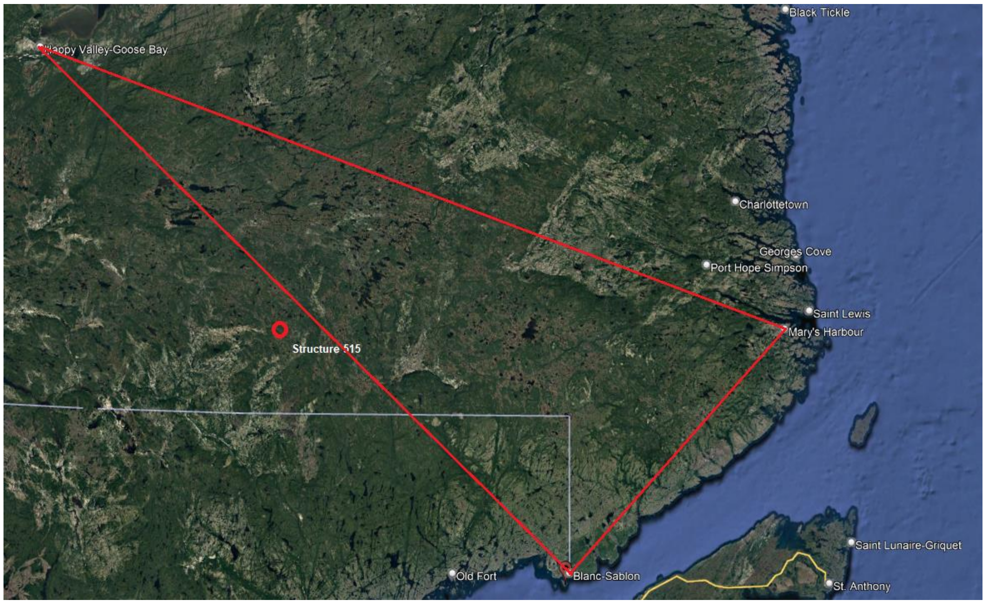

Figure 17: Location of Weather Stations in Relation to Failure Location

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[16] Equivalent to 55 mm to 58 mm of radial glaze ice.

In the days prior to the failure event, the temperature ranged from 2°C to -18°C, as shown in Figure 18. The wide range in temperatures created conditions that were conducive to the accumulation of an ice mixture on the cables that consisted of both glaze and rime ice. On December 30, 2022, the temperature again rose above the 0°C mark, which could have caused ice softening and shedding, resulting in unbalanced longitudinal loading on the cables.

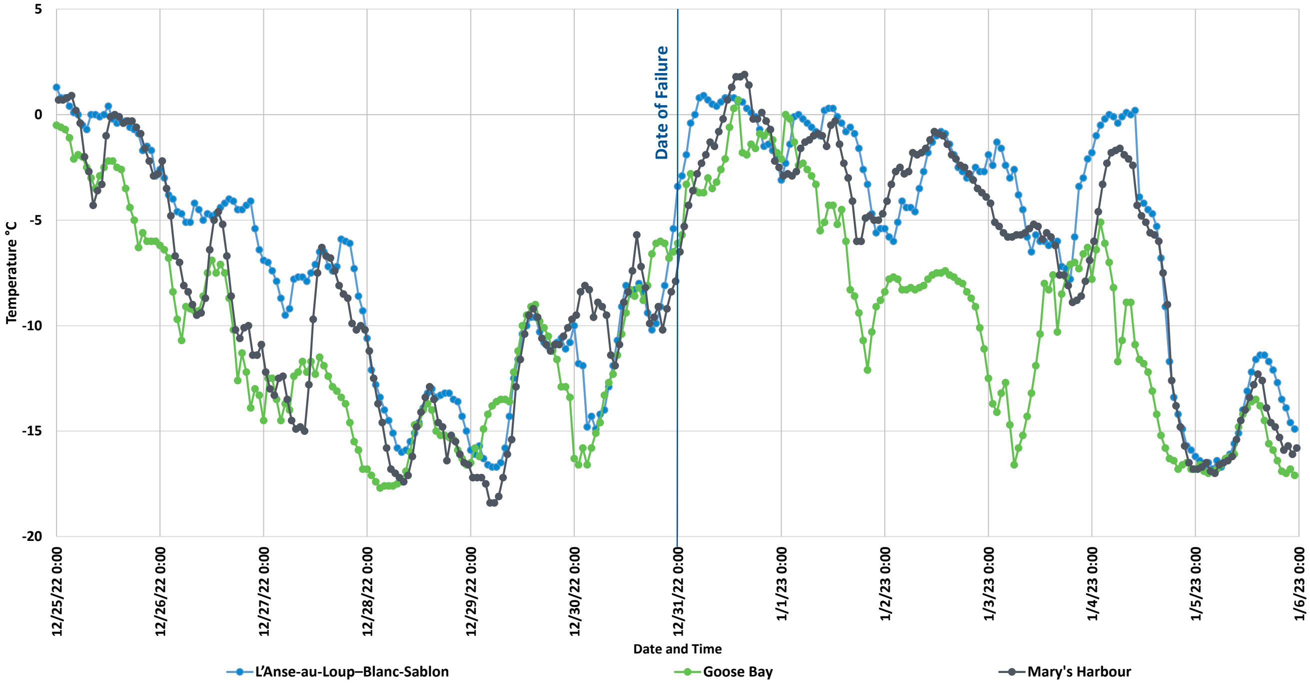

Figure 18: Weather Station Temperature Data

Figure 19 provides information on the wind speeds recorded at the three existing stations within the geographic region. Winds during the event varied considerably throughout the regions but for the most part were considered to be lower in magnitude, which is indicative of fatigue failure due to movement over the life of the line. For the purpose of the investigation and analysis, the average wind speed was approximated as 22 km/hr; however, since there is a broad spatial arrangement between these stations, this value may be conservative when compared to winds at the actual failure site.

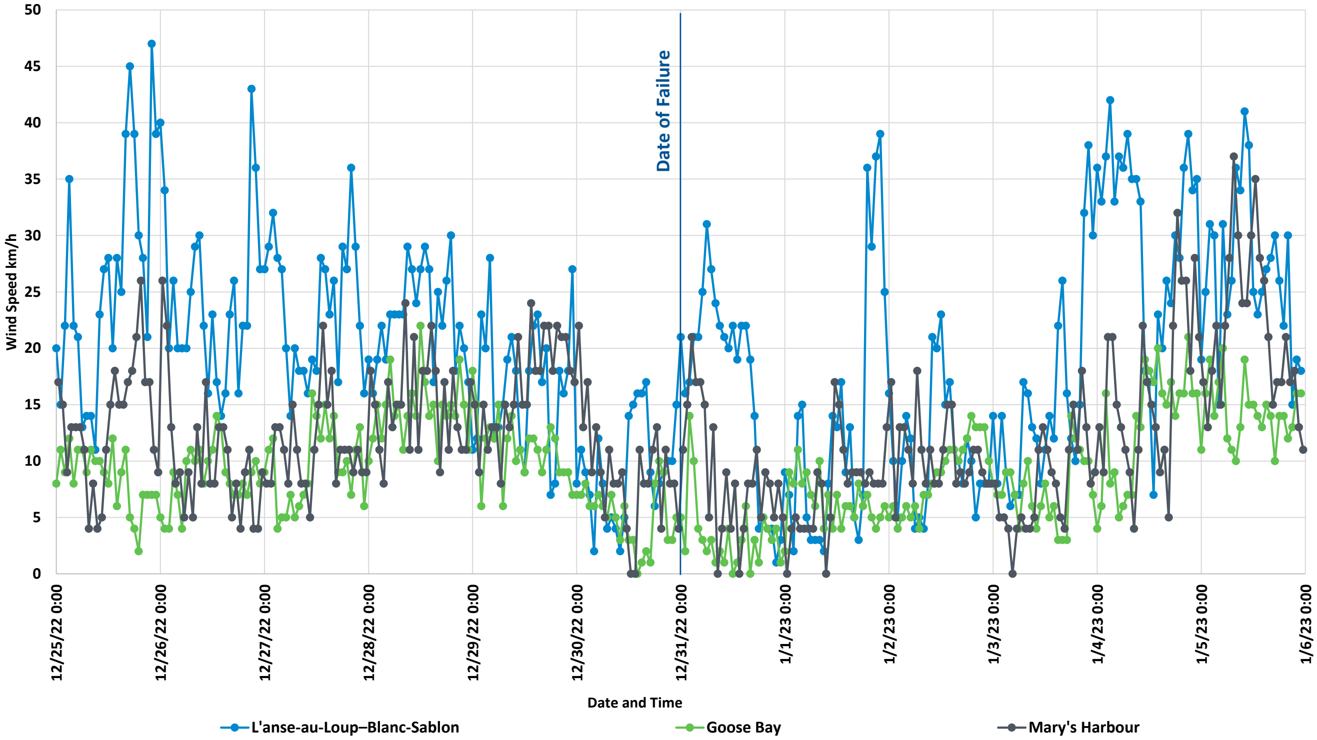

Figure 19: Weather Stations Wind Data

Figure 20 identifies precipitation events within the region between mid-November 2022, and the end of December 2022, just before the failure event. No significant precipitation was recorded directly before the failure event at any of the weather stations in the geographic area, which indicates that the ice accumulation shown in the pictures may have developed over a longer period before the failure. Multiple light precipitation events over an extended period of cold temperatures, as is typical in Labrador, have the potential to result in a buildup of ice over time.

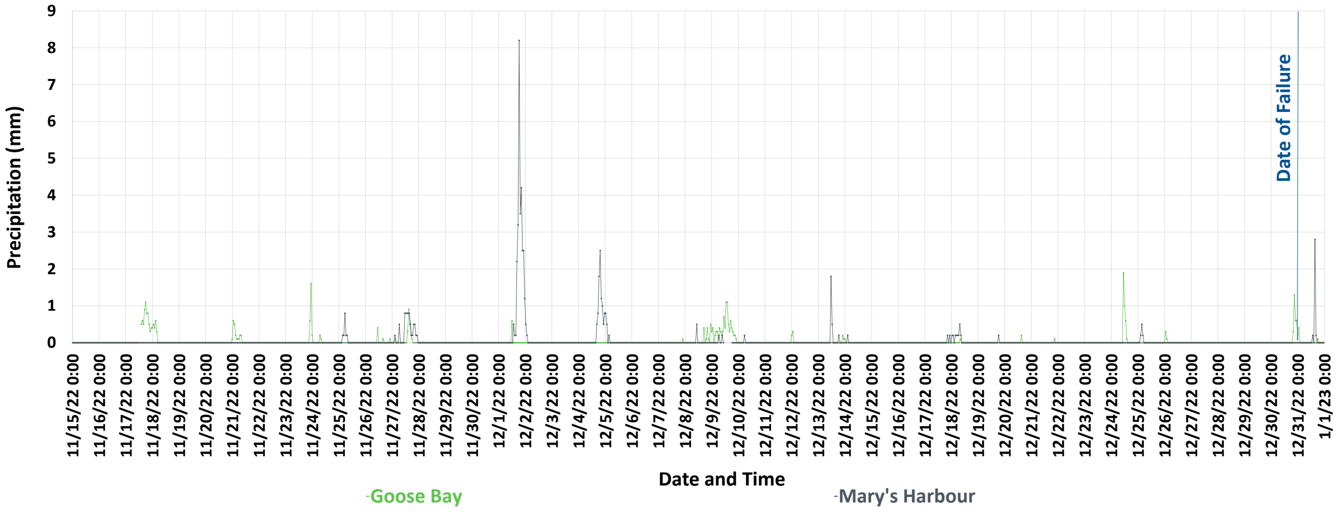

Figure 20: Weather Stations Precipitation Data

6.0 Material Testing

Cable sections removed from Structures 515 and 517 were sent to an external consultant to complete material testing on the damaged components. Material testing included visual examination of the damaged cable, examination of the failure surface with a scanning electron microscope, and tension testing. The purpose of this testing is to verify the conductor meets the original specification and to determine the mechanism of failure.

Tensile testing for individual strands of the damaged cable will occur to confirm whether or not the original strength of the cable was reduced due to external factors after it was originally installed.[17] Based on the data currently available, it is not suspected that any deficiency will be identified. This cable was replaced after the 2021 failure event using critical spare inventory; at that time, material testing was completed on the cable to ensure it met the original specification requirements.

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[17] Hydro is still awaiting the laboratory results for this test.

7.0 Failure Analysis and Discussion of Findings

7.1 Conductor Failure

The consultant also completed a visual assessment and analyzed the failed samples pertaining to the conductor breakage at Structures 515 and 517. Based on a holistic examination of the conductor assembly, the following failure scenario has been hypothesized:

- Based on strength and toughness, it is likely that the aluminum strands initiated cracks and failed before the high-strength steel strands.
- The failure was initiated near the top of the conductor due to excessive uniaxial tension, which is consistent with the necking and ductile tensile overload fracture surfaces from both the aluminum and steel strands.
- As the tensile load was shed to the remaining aluminum and steel strands connected to the assembly, each remaining strand experienced a localized increase in tensile stress until they were overloaded. This sequential failure of the aluminum strands resulted in the conductor experiencing a gradual increase in nominal tensile and bending loads, with the highest levels of stress observed near the bottom of the conductor assembly.
- An increase in bending loads led to an increase in the shear stress on the surfaces of the strands at the bottom of the conductor assembly, which aligns with the slanted fracture surfaces at the bottom strands of the conductor. In the absence of excessive wear at the base of the suspension clamp where the shear strands are present, it is very unlikely that the failure initiated at the bottom of the conductor and then failed via uniaxial tension near the top of the conductor.
- Four aluminum strands failed via ductile tensile overload at the top of the conductor near the bolt holes on the clamp, which was unique compared to the majority of the aluminum strands. Limited evidence of rub damage was observed on the surface of the clamp or the surface of the specific aluminum strands. It cannot be proven or refuted whether the failure was initiated at this location.
- The arcing damage observed on the steel wire was likely post-failure damage, introduced to the conductor as it gradually unwound and shed load to other wires.

Testing completed by the external consultant determined that the conductor met the required specification and CSA standard. It also determined that the failure was due to axial overloading of the conductor; this was primarily supported by the necking of the strands at the fracture.

The laboratory testing also indicated that there is no validation that the clamp did or did not impact the integrity of the cable. If premature failure occurred on any of the individual strands as a result of damage caused by the conductor clamp, there would have been a reduction in tensile capacity. Figure 21 shows how the strength of the cable decreases with the presence of the damaged strands. As the cable capacity lowered and the load continued to increase due to extreme ice accumulation, other strands would have experienced a localized load increase, causing them to eventually fail and ultimately resulting in a catastrophic failure of the cable. Four aluminum strands that are broken in a different location than others are shown in Figure 22; this location is near the top of the clamp. It is hypothesized that this is the location where the failure was initiated.

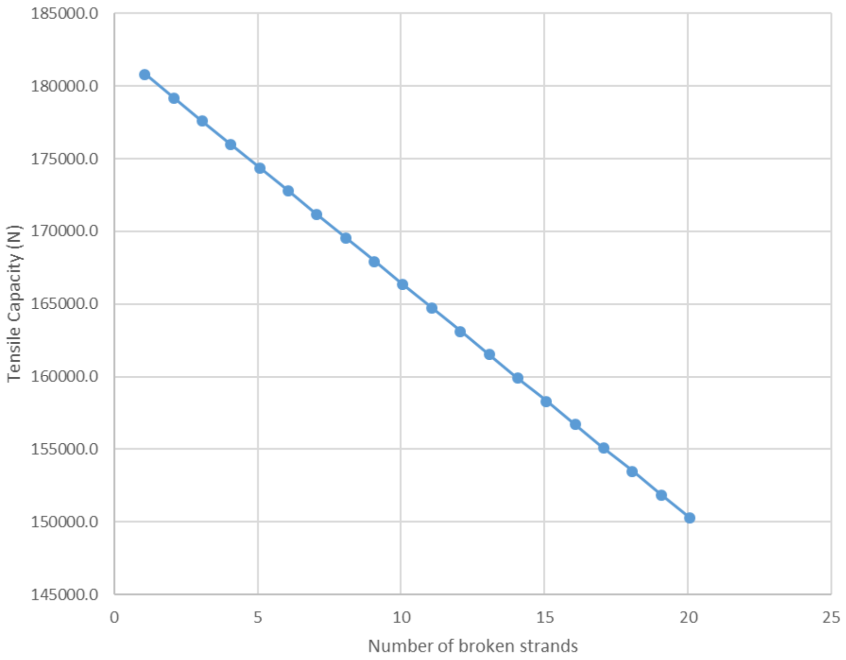

Figure 21: Electrode Conductor Strength Reduction with Damaged Strands

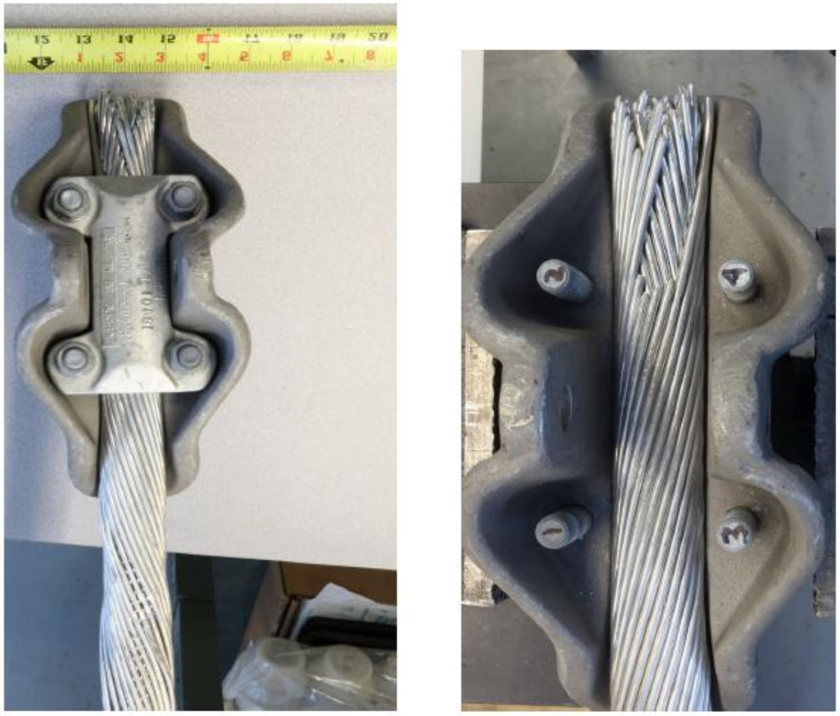

Figure 22: Cable Damage at Clamp at Structure 515

An external consultant responsible for reviewing the investigation report identified a possibility that the electrode conductor may have been weakened by an extreme heat event that resulted in the annealing[18] of the aluminum strands. If this occurred, the cable's strength may have been lowered, resulting in a premature failure of the cable. Based on operational data collected between February 2021 (the date at which this cable was previously replaced during a prior failure) and December 31, 2022, there is no evidence to suggest that the static operating temperature of the electrode cables elevated to levels that were capable of causing annealing.

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[18] During the annealing process, the wire is heated to a temperature that releases stresses, making the wire more ductile. Annealing of the aluminum material in ACSR cables would not typically occur until the temperature reaches 100°C or higher.

7.2 Line Modeling of Observed Conditions

During the investigation into the 2021 failure event ("February 2021 Failure Investigation"),[19] the section affected at that time between Structure 497 and 596 was modelled using PLS-CADD[20] to check the line's performance under the ice and wind loading experienced during the event. Since the failure event in 2022 was located within this same section, this data was used in this analysis as well. The results of the analysis following the 2021 event indicated that with 60 mm of radial ice thickness and above, there are failures in the unbalanced ice load cases. With 70 mm of radial ice thickness or more, there are some failures in the ice load case and the combined ice and wind load case, with many more failures in the unbalanced ice load cases.

For that analysis, the following load conditions were considered using an ice density of 0.75 g/cm^3:

- Ice only;
- Ice with a low wind of 22 km/h;
- Unbalanced ice load of 70/100% ice thickness on the electrode cable; and
- Unbalanced ice load of 28/100% ice thickness on the electrode cable.

The findings suggest that the ice load is equivalent to a radial thickness somewhere in the range of 65 mm to 70 mm.[21] As the exact amount of ice on the line in any given span can vary, the following radial thicknesses of 65 mm, 70 mm, and 75 mm were modelled, all with a density of 0.75 g/cm^3. As there is no way to know how much ice will shed from adjacent spans, the unbalanced ice percentages are based on the design loads (70/100%) and CSA C22.3 No. 60826-10 recommendations (28/70%).

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[19] The "Failure Investigation Report – L3501/2 Pole Assembly Turnbuckle Failure – Failure Event February 2021 in Labrador," Nalcor Energy, May 28, 2021 was filed as an attachment to the "*Reliability and Resource Adequacy Study Review* – Labrador-Island Link Failure Investigation Reports," Newfoundland and Labrador Hydro, May 31, 2023. <http://www.pub.nl.ca/applications/NLH2018ReliabilityAdequacy/correspondence/From%20NLH%20-%20Labrador-Island%20Link%20Failure%20Investigation%20Reports%20-%20January%20and%20February%202021%20-%202021-05-31.PDF>.

[20] PLS-CADD is a transmission line design program that allows the user to enter different loading conditions to analyze how they will affect the line and structures under the as-built conditions and ultimately how the towers will fail under extreme loading conditions.

[21] Under this range, we are less likely to see failures; over this range, we are likely to see more failures due to ice only.

Table 4 identifies load cases that would result in towers becoming overloaded and potentially experiencing a structural failure. All of the loads identified in Table 4 are in excess of the original design loads.[22] From the modelling, it appears that if fully intact, the electrode cable will only break at approximately 80 mm of ice. The cross arm should fail before this level of loading; however, since the cross arm did not fail during this event, it is suspected that the capacity of the electrode cable was reduced due to broken individual strands.

Table 4: Towers Exceeding Maximum Capacity[23]

		Utilization %		
Load Case		**Structure 514**	**Structure 515**	**Structure 517**
Unbalanced Loading	UBI[24] (70/100%) – 65 mm	103.07%	100.38%	100.71%
	UBI (28/70%) – 65 mm	106.59%	104.03%	104.10%
	UBI (70/100%) – 70 mm	114.06%	111.20%	111.33%
	UBI (28/70%) – 70 mm	117.80%	115.84%	114.92%
	UBI (70/100%) – 75 mm	125.72%	122.69%	122.59%
	UBI (28/70%) – 75 mm	129.95%	128.12%	126.52%
Max Ice	70 mm	104.28%	101.72%	101.97%
	75 mm	115.05%	112.38%	112.41%
Combined Ice and Wind	70 mm + 22 km/hr	104.95%	102.40%	102.62%
	75 mm + 22 km/hr	115.76%	113.12%	113.11%

If an ice loading value remains consistent (i.e., assume 70 mm), the unbalanced load cases are more critical than just ice or combined ice and wind, as can be seen by the increasing loads in Table 5. In this particular case, the 70 mm interval is used as an example to show that the load distribution varies throughout the different scenarios identified herein.

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[22] Unbalanced Loading: UBI (100/70) - 50 mm, one wire at a time; Maximum Ice: 50 mm; Combined Ice and Wind: 25 mm + 60 km/h.

[23] Utilization at a value greater than 100% indicates tower failure.

[24] Unbalanced ice ("UBI").

Table 5: Structure 515, 70 mm Ice Interval Example[25]

Load Case	Description	Utilization (%)
Max Ice	70 mm	101.72%
Combined Ice and Wind	70 mm + 22 km/hr	102.40%
Unbalanced Loading	UBI (70/100%) – 70 mm	111.20%
	UBI (28/70%) – 70 mm	115.84%

The consultant that reviewed the investigation report identified a possibility that if the tower steel had a higher yield stress than the specification required, the tower could accommodate a higher loading before failing, which could ultimately result in the electrode cable failing before the tower. As a result, an additional analysis was completed by increasing the strength of the steel incrementally (110%, 120%, 125%, and 130%). It was determined that the steel would need to be approximately 25% over the nominal specified strength for this to occur. The steel manufacturer identified that the yield strength ranged from 109% to 140% of the original specified strength. The specific test results are not linked to specific towers; therefore, it would not be possible to determine if increased steel strength was the main contributing factor to the electrode cable failing before the tower.

7.3 Conductor Slippage

Based on observations made by the consultant, there does not appear to be any signs of slippage on the clamps at Structure 515, indicating that the clamps performed as per the design. However, the type of clamp utilized on the LIL is conducive to a combination of increased stresses induced on the cable as a result of the suspension clamp. This increase of maximum stress at the top of the clamp may have resulted in localized bending forces, which could have the potential to initiate failure at the top of the clamp. This may have resulted in the four aluminum strands failing first near the top of the clamp, as shown in Figure 23. As a result of this concern, the external consultant will complete performance testing on alternative styles of clamps to eliminate the potential for damage to the suspension clamp.

This differs from the investigation findings from the February 2021 Failure Investigation, where the slipping of the cable through the clamp directly contributed to cable failure. Signs of conductor slippage

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[25] Utilization at a value greater than 100% indicates tower failure.

were observed on the clamp in that investigation, which has the potential to cause damage to individual strands, thereby reducing the capacity of the cable.

7.4 Comparison to 2021 Failure Event

In 2021, the LIL experienced a similar weather event that resulted in mechanical failures of the electrode cable in multiple locations throughout Segment 1. During this event, extensive damage was caused to both the electrode cable and the tower crossarm, which supports the electrode cable. During the 2022 event, no damage was sustained to the crossarm, which indicates that although the phenomena were similar, the severity was not as high during the 2022 event. Although icing was present during the 2022 event and was suspected to cause unbalanced loading as a result of ice shedding, the amount was below the threshold to cause a crossarm failure.

Based on load condition modelling, it is suspected that the tower cross arms would fail before the electrode conductor, as was observed during the 2021 failure. During the event in 2022, the cross arm did not fail, suggesting that the ice load was lower than what was experienced in 2021. However, the cable did break, therefore it is hypothesized that damage to the individual strands at the clamp resulted in a reduction to the cable's rated tension strength, ultimately leading to failure under axial load.

7.5 Hardware Performance

Due to the short length of the electrode insulator assembly and the large insulator swing due to unbalanced ice, it was observed that the insulator can contact the electrode cable.[26] As a result, there have been dents observed in the conductor near the insulator assembly, likely due to insulator contact, as the hardness of the glass insulator is greater than that of the conductor. This occurrence could be a contributing factor to the premature failure of individual strands, as the damage has the potential to reduce the capacity of the top strands. Once these strands start to break, the applied load will start to increase on the remaining intact strands, with the potential to over-stress the strands. In this particular case, the failure was at the edge of the clamp and not at the location where the insulator makes contact with the cable.

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[26] During past modelling, it was calculated that this occurrence can be created by a difference of approximately a 4.5 kg/m ice load on adjacent spans.

Figure 23: Dent in the Conductor near the Tangent Assembly from Structure 515

This occurrence presents another possible theory—as the insulator gets pulled out due to unbalanced ice loading, the glass portion of the insulator pushes downward on the aluminum portion of the cable, resulting in the wearing and denting of the individual cable strands. In turn, this downward thrust causes an upward motion on the clamp, pinching the cable between the downward force due to the insulator on one side and the weight of the cable on the other (see Figure 24). As this cycles back and forth with imbalance, it has the potential to result in increased localized stress at both the edge of the saddle and the clamp. If an alternate style of clamp was utilized that allowed the cable to slide, the cable may not become pinched. While it may still result in slippage through the clamp, armour rods would provide additional protection for the cable in this scenario, as any direct force from the clamp or insulator would be induced on the armour rod first, instead of the cable. As a result of this concern, the consultant will complete performance testing on alternative styles of clamps to eliminate the potential for damage to the suspension clamp.[27]

During the material testing, it was noted by the consultant that four of the strands in proximity to the top keeper of the clamp were broken uniquely compared to the other strands. It is possible that these were the first individual strands broken as a result of wear at this location. As the individual strands

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[27] The suspension clamp and additional conductor analysis will further refine engineering knowledge but are not required to finalize the root cause of the failure.

failed, the capacity of the cable would have been reduced, making it more susceptible to applied loading and premature failure.

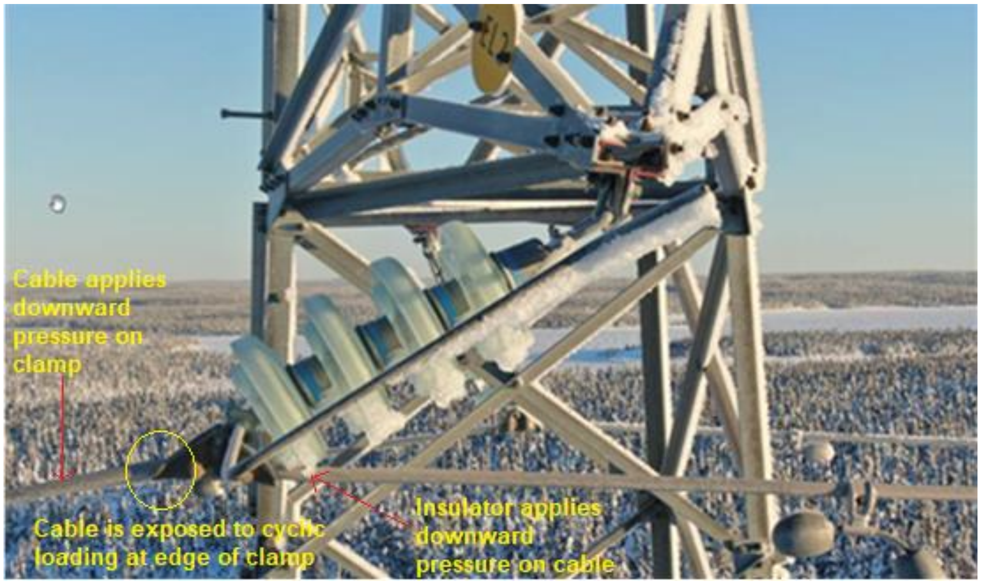

Figure 24: Longitudinal Pull on Insulator

7.6 Galloping and Aeolian Vibration

The material testing completed by the consultant indicated that none of the samples tested showed obvious signs of high- or low-cycle fatigue, as would result from galloping[28] and Aeolian vibration.[29] However, galloping and Aeolian vibration do have the potential to impose undue stress on the cable and should be mitigated to avoid premature failure due to cyclic loading in known areas of occurrence.

Galloping has been observed on the line since construction; causing extreme movement of the conductor, often vertically, but occasionally horizontally. The area near the south coast of Labrador, where this failure occurred, has been confirmed through observation to be prone to galloping. Galloping will cause fatigue on hardware and conductors over time; this type of movement has the potential to result in low-cycle fatigue.

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[28] Galloping is a high-amplitude, low-frequency oscillation of overland power lines due to wind; it can be caused by specific wind conditions and is sometimes observed on lines with small amounts of icing.
[29] Aeolian vibration is a high-frequency, low-amplitude oscillation of the overhead power lines, caused by low-velocity, steady wind.

In contrast to galloping, Aeolian vibration protection is designed into the line using Stockbridge dampers; this type of movement has the potential to result in high-cycle fatigue.

8.0 Summary of Root Cause

Based on the material testing completed as a part of this investigation, it is known that the root cause of the failure is tensile overloading of the cable as a result of ice accumulation. It is unclear at this time whether the integrity of the cable was compromised as a result of additional stresses imposed on the cable at the location of the clamp. Typically, a cable will not fail before the tower crossarm; therefore, it is suspected that the cable structure was compromised in some way, resulting in reduced structural capacity. However, adequate evidence is not available to equivocally confirm that the cable was compromised.

The main observations drawn from this investigation included the following:

- Icing accumulation was suspected to be close to or slightly above the original design criteria.
- The cable broke before the tower crossarm, which could indicate either of the following scenarios:
  - The tower steel was stronger than originally specified when provided by the manufacturer; or
  - The rated cable tensile strength was reduced over time post-installation.
- Damage to the cable originated at or near the top of the suspension clamp, which is suspected to have caused a reduction in the tensile capacity of the cable making it susceptible to breakage under at-design weather conditions.
- The conductor met the original technical specifications when originally installed; its failure was determined to be a tensile failure due to overloading as a result of ice accumulation.
- The clamp type is suspected to induce a combination of stresses at the keeper location, resulting in increased bending forces in the location where failure is suspected to have initiated.
- Based on visual analysis, engineering modelling, and the fact that the crossarm did not fail, the ice load at the time of the event is not suspected to have been high enough to break the fully

intact cable. Evidence does not support the annealing of the cable due to a high heat event from line operations. It is estimated that between 14 kg/m and 15 kg/m of ice was present at the time of failure.

- The Ice loading experienced was suspected to be unbalanced as a result of ice shedding due to the following:
    - Pictures taken directly after the event show significant ice accumulation and ice shedding on the various cables;
    - Denting on the outer strands of the aluminum cable indicates a high longitudinal load on the cable caused by unbalanced loading;
    - Immediately before the failure, there was an increase in temperatures (-18°C to 2°C) within the geographic region, which may have contributed to the accumulated ice becoming softer and potentially shedding off the cables. As there was significant ice accumulation on the cables, any shedding would have resulted in longitudinal loading; and
    - PLS-CADD tower modelling indicates that ice shedding causing unbalanced loading would create the type of failures experienced.

9.0 Recommendations

The recommended mitigations to address the failure event detailed herein include the following:

1) Ice monitoring and the removal of ice, as required, through both real-time monitoring and line patrols.

  a. A study should be completed to assess the rate at which ice accumulates in the area, considering the impacts of climate change; this information should then be used to optimize the frequency of inspections. Without this information, and based on the uncertainty of the impacts of climate change in the area and the importance of this line, it is suggested that helicopter patrols be increased in frequency, especially during critical icing periods[30] and in known areas of past storm damage.

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[30] Annual critical icing periods for this line are considered to be from November to March.

  - **b.** Icing thresholds should be strictly followed to trigger the implementation of ice removal procedures following inspections. This threshold should be based on engineering design and information collected from past failure events and may vary between regions depending on the types of towers utilized. For the area in question, it has been shown during multiple events that an ice load of approximately 13 kg/m to 16 kg/m (53 mm to 60 mm of radial glaze ice) has resulted in failure. In addition, there is a risk of inducing an unbalanced load scenario through the completion of ice removal techniques; this should also be acknowledged when establishing an appropriate trigger point for removal.
  - **c.** Long-term forecasts could also be used to aid in identifying a trigger point for ice removal. Labrador is prone to continuous colder temperatures during the winter, which promotes the continued buildup of ice on the lines between weather events. If the temperature is forecasted to warm, there is an increased risk that the formation will begin to melt and potentially shed off the lines. Operators should monitor this parameter closely and, in conjunction with recent visual inspections, areas of concern could be identified.

2) Established protocols for evidence collection should be strictly followed to ensure that adequate information is collected following a failure event to assist with the best possible investigation.

  - **a.** Regularly review collection protocols and requirements with Operations personnel who are responsible for troubleshooting and inspecting the infrastructure;
  - **b.** Assign a representative, who is not involved in the emergency response/repair, to be directly accountable for the collection of evidence from the site; and
  - **c.** Develop a detailed list of evidence to collect during a failure to ensure that the correct information is collected.

3) Incorporate the inspection of critical areas[31] and equipment into Operations inspection protocols.

4) Engage an external consultant to identify an alternate electrode suspension clamp design to reduce/eliminate increased stress on the cable for consideration of installation in future.

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[31] Critical areas to be identified through past failure events and the aforementioned reliability assessment.

   - **a.** Utilization of armour grip[32] style clamps will help reduce strain by using a neoprene protection layer and armour rod, which will eliminate aluminum-to-aluminum contact.

   - **b.** Other alternatives include a cushion grip clamp or a regular suspension clamp with an armour rod. This will still result in aluminum-to-aluminum contact but it will provide additional protective barriers and a larger bending radius at the clamp, which will help to spread any induced load as a result of unbalanced loading.

5) Investigate the ability to increase the distance between the insulator and conductor in the electrode conductor.

   - **a.** Investigate the ability to install longer hardware between the bottom insulator and clamp, which will provide adequate clearance to prevent the insulator from coming into contact with the cable. This may not fully eliminate the concentrated effect on the cable at the clamp location; however, it should be successful in reducing the impact. A finite element analysis may be required to assess the impact on the cable.

6) Ice accumulation in excess of the original design loads has now been experienced on multiple occasions in this geographic region. A detailed engineering study, which considers the effects of climate change, should be completed to analyze the towers in these areas and develop options to upgrade, as appropriate and as justified, the section of the line that is impacted. This could include options such as:

   - **a.** Relocating electrodes from towers to independent pole structures adjacent to the right-of-way to reduce load on the towers; and

   - **b.** Installing mid-span structures to reduce the impact of unbalanced loading. This would reduce the load experienced but may not eliminate the imbalance fully. As a result, this approach may have to be coupled with the installation of alternative clamps and hardware to mitigate any damage to the cables.

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[32] Armour grip was originally used on the OPGW and there have been no mechanical failures of the OPGW cable to-date, despite occurrences of the OPGW slipping through the clamps.

10.0 Conclusions

Upon review of the suggested recommendations, Hydro has progressed, or is in the process of advancing, the following action items:

1. The monitoring of ice has been increased through the installation of a weather station in the Labrador Straits, increased monitoring by field personnel around weather events, and continued helicopter patrols. An additional weather station is planned for installation in central Labrador in 2025.
2. A consultant has been engaged to identify an alternate electrode suspension clamp or hardware assembly design to reduce/eliminate increased stress on the cable, with planned upcoming laboratory and field testing for the equipment.
3. The completion of an engineering design study in 2024 to evaluate the performance of the transmission line under unbalanced icing conditions and high ice loading in the central Labrador region.
4. The review of collection protocols and requirements with Operations personnel is ongoing to ensure that adequate information is collected following a failure event.