Paper presented at Fourth International Workshop on Atmospheric Icing On Structures, September 4-7, 1988, Paris.

ASSESSMENT OF PROBABILISTIC CLIMATIC LOADINGS ON EXISTING 230 KV STEEL TRANSMISSION LINES

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To assess the reliability of existing or proposed lines, transmission line design engineers have always been challenged to establish appropriate climatological loadings on overhead line conductors. To evaluate the reliability of two existing parallel 230 kV steel transmission lines, a study was first conducted to assess the probabilistic climatic loadings on these lines from wind, ice, and combined wind and ice, using the meteorological data from seven weather stations operated by Atmospheric Environment Service (AES) in Newfoundland. A time dependent numerical ice accretion model was used to calculate the ice thickness for each storm. Results from the extreme value analyses are presented to predict the probabilistic occurrences of wind and ice loadings for both the weather stations and at selected elevations along the transmission line routes.

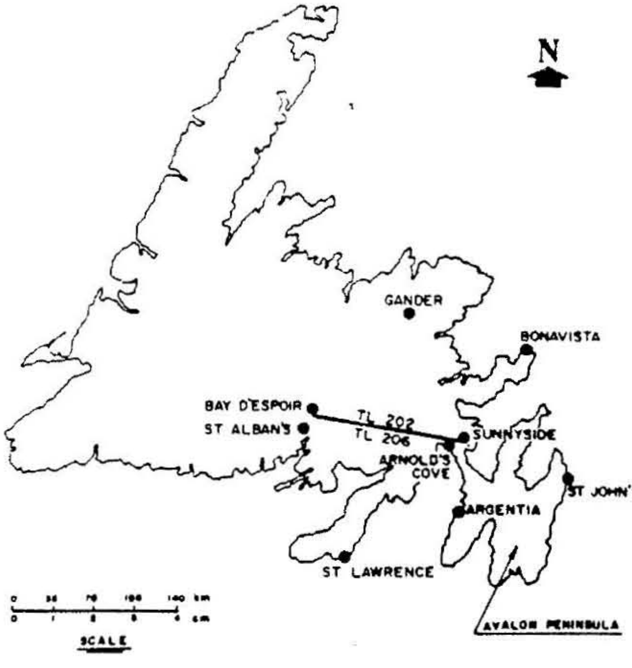
INTRODUCTION

During the construction of the Bay D'Espoir power development, Newfoundland and Labrador Hydro constructed several hundred miles of high voltage transmission lines which radiated out in single circuits north and west of Bay D'Espoir and eastward to St. John's. Since their commissioning in 1968, the eastern part of Newfoundland has experienced several ice storms, the most recent being the storm of April, 1984 on the Avalon Peninsula (Figure 1). The major cause of these storms is from freezing precipitation (rain and drizzle) which often produces heavy accumulation of glaze ice on the transmission lines.

In 1986, Newfoundland and Labrador Hydro decided to assess the reliabilities of two existing 230 kV steel transmission lines by conducting a study of the probabilistic climatic loadings on these lines from wind, ice, and combined wind and ice, based on the climatological records from nearby weather stations. This paper presents the results from this study including the predictions of the probabilistic occurrences of wind, and ice loadings for both the weather stations and at selected elevations along the line route. An icing model is used to theoretically simulate the amount of ice that will accrete on the conductor, based on the known weather conditions. The model also generates projected values of combined wind and ice loads for a large number of events based on the meteorological data obtained from the weather stations. Annual extremes are extracted from these events and an extreme value analysis is then carried out to determine the probable climatic loading parameters with selected return periods. Finally, extrapolation of these loading parameters to the line route is carried out taking into account the differences in elevation and exposure between the weather stations and the line route.

DESCRIPTION OF THE LINES

The 230 kV transmission lines TL 202 and TL 206 (approximate length of 140.0 km) run parallel between Bay D'Espoir and Sunnyside, Newfoundland. Figure 1 depicts the line route and the AES weather stations from which the data were extracted for this study. These two lines consist primarily of guyed v-tangent and small angle towers and self-supported heavy angle and dead-end towers.



METHODOLOGY

In designing transmission lines, climatological loads which are of prime interest to the line designer are wind, ice, and combined wind and ice. In the northeastern and southeastern regions of the island of Newfoundland, freezing precipitation is by far the greatest problem related to ice accretion. This was evidenced by the damage caused by the previous storms in various regions of Newfoundland (Young and Schell, 1971) and again recently on the Avalon Peninsula (Hydro, 1984). The ability to account for realistic ice and combined ice and wind loads when evaluating the design of present and future transmission lines is currently hampered by the lack of site specific data and associated meteorological parameters. One alternative approach is to review the meteorological data from nearby weather stations and use a specific model to predict the wind and ice loads on the lines.

Advancement in the field of modelling ice accretion on circular cylinders has made it possible to simulate the conditions necessary to form ice on a transmission line conductor from the known weather data. In order to quantify accumulation of ice on a conductor, an updated version of the Makkonen (1984) icing model was first used to predict the maximum ice accretion resulting from the worst storm of each year for six (6) AES weather stations. Historical storm data from the six weather stations were then analyzed and extrapolated to the lines. Empirical methods were used to derive the input required by the icing model from the meteorological data. Model input parameters included wind speed, air temperature, liquid water content, median volume droplet diameter, and conductor diameter. The obvious advantage of using the Makkonen model is that this model accommodates the time dependencies, changes from wet to dry growth conditions (or vice versa) during the ice accretion process, and variations in the ice density and the relative angle between the wind direction and the conductor. Validation of the in-cloud ice model was originally done in icing wind tunnel experiments, where test results were close to the predicted values (Makkonen and Stallabrass, 1984).

The following section will briefly summarize the key features of the Makkonen model used in this study. This model was significantly updated prior to and during this study to accommodate freezing precipitation and wet snow conditions, to improve upon some empirical expressions and to input and process the data for large numbers of events with variable durations. Details of these developments have been presented elsewhere in a two-volume report (COMPUSULT, 1988) and by (Haldar, 1988).

Makkonen Model

Incremental deposition of ice on a circular cylinder over time can be computed in terms of the icing intensity, I, or growth rate of ice mass, dM_i, per unit area and given as

$$I = (dM_i/d\tau_i)/A \qquad \ldots\ldots (1)$$

where A is the surface area of the windward face.

The water mass flux, or the rate at which water droplets in the air are deposited on a collection surface, $dMw/d\tau_i$, depends on droplet speed, v_d, liquid water content, w, collection efficiency of the surface, E, (i.e., the ratio of the mass flow of the impinging water droplets to the mass flow that would be experienced by the collecting surface if the droplets were not deflected in the air stream), the diameter, D_c, and the length, L, of the cylindrical surface.

The freezing fraction, n, controls the dry and wet growth processes and is defined as the ratio of the icing intensity to the mass flow of the impinging droplets. Wet growth is considered when $n<1$, i.e., there is some water runoff from the ice deposit as a whole. Dry growth is said to occur when the freezing rate is greater than the impingement rate and there is no runoff. In this case, the value of n is equal to 1. Introducing the parameter, n, in Eqn. (2).

$$dM_i/d\tau_i = Env_d wD_c L \qquad \ldots\ldots (3)$$

The surface area of one half of a circular cylinder is given by

$$A = (1/2)\,\pi\, D_c L \qquad \ldots\ldots (4)$$

Combining Equations (1), (3) and (4), the following expression for icing intensity per unit length of conductor ($g/cm^2/h$) is obtained as

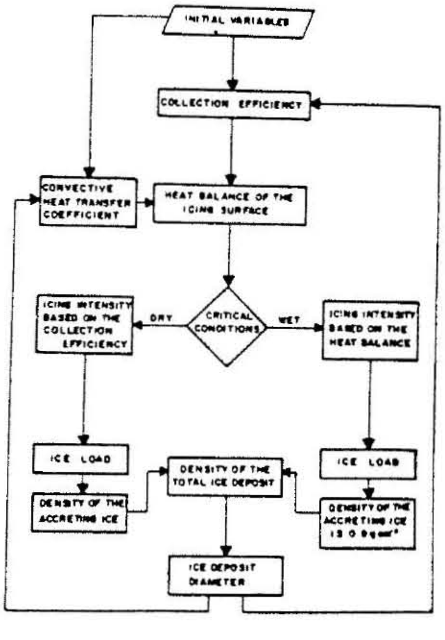
$$I = (2/\pi)\, Env_d w \qquad \ldots\ldots (5)$$

During the ice accretion process, the diameter of the conductor changes as the ice deposit increases. Therefore, the collection efficiency (for dry growth) and the freezing fraction (for wet growth), which are dependent upon conductor diameter, also change over time. Variations in meteorological conditions during an icing storm also affect these and other parameters associated with the ice accretion process.

Assuming the atmospheric conditions remain unchanged, the ice load M_i per unit length of the conductor at time τ_i is obtained from Eqn. (5) as

$$M_i = v_d w_o \int^{\tau_i} E(\tau_i)\, n(\tau_i)\, D_c(\tau_i)\, d\tau \qquad \ldots\ldots (6)$$

Model calculations are performed in a step-wise manner to reflect the changes in geometry and environmental conditions. The model uses the hourly meteorological records of wind speed, air temperature, relative humidity, precipitation rate, and visibility for each hour of an icing event to calculate the collection efficiency, freezing fraction, effective wind speed, and liquid water content using empirical and/or theoretical relationships between the above parameters. Figure 2 illustrates the flow diagram of the Makkonen model.



RESULTS

Probabilistic Wind Loading

In this study, the annual maximum hourly wind speeds for each of the seven AES weather stations were used to develop the probabilistic wind speed values. These data were then extrapolated to the line route taking into account the effects of line location, exposure, and elevation. Analysis included the ranking of all yearly extreme wind speeds for the stations, in ascending order, along with the associated plotting positions and probabilities calculated in terms of return periods. Table 1 provides a summary of the annual maximum wind speeds (in order of year) for each station. Gust wind speeds are also computed for selected return period values following either Boyd (1965) for hourly wind speed under 120 km/h or Sissenwine et al (1973) for wind speed above 120 km/h. The 10, 25 and 50-year return period values were then generated along with the confidence limits for these stations.

Year	St. John's (1953-86)	Gander (1953-86)	Argentia (1953-85)	Bonavista (1959-86)	St. Lawrence (1966-1986)	St. Alban's (1968-1983)	Arnold's Cove (1971-1986)
1953	84	89	87	-	-	-	-
1954	97	80	76	-	-	-	-
1955	105	77	84	-	-	-	-
1956	121	80	72	-	-	-	-
1957	93	92	84	-	-	-	-
1958	80	92	77	-	-	-	-
1959	137	87	98	Too Few Data	-	-	-
1960	93	84	79	89	-	-	-
1961	89	89	64	97	-	-	-
1962	80	90	58	87	-	-	-
1963	90	93	61	105	-	-	-
1964	121	89	72	113	-	-	-
1965	80	77	109	97	-	-	-
1966	97	105	105	84	90	-	-
1967	105	105	90	97	145	-	-
1968	80	71	84	97	145	Too Few Data	-
1969	89	72	100	72	116	64	-
1970	80	64	111	97	113	55	-
1971	92	76	89	84	103	58	Too Few Data
1972	80	80	89	113	90	58	87
1973	80	72	72	89	84	51	60
1974	97	77	77	116	90	48	87
1975	101	66	72	105	74	58	69
1976	93	84	Too Few Data	127	111	76	82
1977	120	74	107	111	102	65	92
1978	83	70	83	93	83	98	85
1979	89	107	102	102	83	70	80
1980	78	74	93	102	83	61	74
1981	76	74	93	89	89	56	80
1982	89	117	93	124	93	76	Too Few Data
1983	93	78	93	102	Too Few Data	Too Few Data	93
1984	85	87	83	89	Too Few Data	-	76
1985	85	70	102	89	Too Few Data	-	72
1986	83	93	-	89	Too Few Data	-	Too Few Data

Table 1 Annual Extreme Wind Speeds (km/h) for each Weather Station

Table 2 summarizes the wind speeds for selected return period values for all seven stations. Figure 3 depicts the plot for the extreme value analysis carried out on the annual maximum hourly wind speed for St. John's data (1953-1986). For all other stations, the data appear to be well-fitted by a Gumbel distribution.

Stations	Return Periods 10-yr	25-yr	50-yr	Maximum Hourly Wind (km/h)	99.9% Confidence Limit on 50-yr. Values (km/h)	Max. Gust for 50-yr. Return Period (km/h)
St. John's	110	122	130	136	±31	160
Gander	99	108	116	117	±26	157
Argentia	104	114	122	111	±31	152
Bonavista	115	124	131	126	±31	162
St. Lawrence	126	141	152	144	±67	184
St. Alban's	80	90	96	98	±48	135
Arnold's Cove	91	99	104	93	±39	142

Table 2 Maximum Wind Speed (km/h) for Selected Return Period Values

A gradient wind model which essentially uses uniform wind speed over large areas, typically within a radius of 160 to 240 kilometers, from a weather station was used to extrapolate the annual maximum wind speed value to a selected conductor height, Z_c.

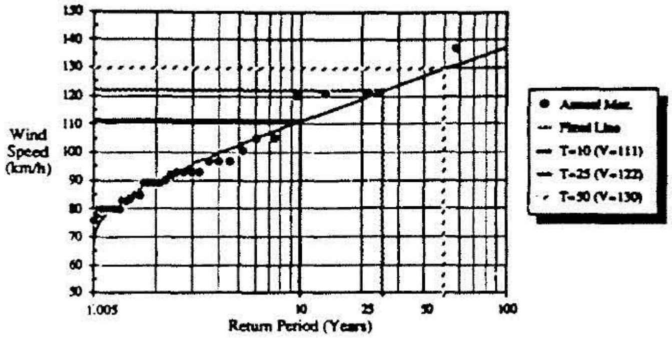


Fig. 3 Plot for Extreme Value Analysis of Wind Speed Data for St. John's

$$V_c = V_g\,(Z_c/Z_g)^{\alpha} \quad \ldots\ldots (7)$$

where V_c = wind speed at the conductor attachment point,

V_g = gradient wind speed, obtained from the weather station,

Z_c = conductor attachment point,

Z_g = gradient height,

and α = the appropriate terrain roughness factor (COMPUSULT, 1988)

The gradient wind model was also applied to the Gander and St. John's data as a check on the gradient wind speed values, since annual maximum upper air wind speeds were available only for the period of 1961 to 1986 and appeared to increase noticeably after the upper air station was relocated from Argentia to St. John's in 1971 (that is, the data for the annual maximum gradient wind speed do not show good stationarity). Table 3 shows the wind speed derived from gradient wind model for the TL 202/TL 206 routes for selected return period values.

	Return Period (Years) 10	25	50
Annual Max. Gradient Wind (1961-1986)	168	184	197
Wind at 28 m Derived from Gradient Wind	107	117	125
Wind at 28 m Derived from St. John's Data	109	120	128
Wind at 28 m Derived from Gander Data	98	108	114

Table 3 Summary of Wind Speed (km/h) at Conductor Height Derived from Gradient Wind Model

Probabilistic Ice Loading

Probabilistic ice loading on TL 202 and TL 206 was determined using the Makkonen ice accretion model. Annual maximum radial ice thicknesses were computed at six weather stations based on the reported meteorological conditions conducive to icing. Extreme value analysis was then applied to annual maxima to yield return period values of ice thicknesses at each of the six weather stations. By applying extrapolation techniques to the relevant input parameters for the most severe annual icing storms, probable annual maximum ice thicknesses for each type of accretion were simulated for the entire transmission line route for various elevations. These data were then used to produce 10, 25, and 50 year return period values for glaze and rime icing for vertical load and combined wind and ice for transverse load. Because of the space limitation, results for the glaze ice at the stations and along the line routes will only be presented here.

Glaze Ice Thickness at the Weather Stations

For each of the six weather stations, the hourly freezing precipitation data were input to the model. Icing events were defined as any group of freezing precipitation observations of at least 3 hours in duration with no more than 12 hours separating subsequent observations of freezing precipitation. The latter figure was arbitrary, but succeeded in correctly isolating all icing events as might be done manually. For extreme events, each case was checked to ensure that the choice of time separation was appropriate, based on numbers of observations and changes, most importantly increases, in air temperature during the event. The hourly changes in wind speed, wind direction, air temperature, relative humidity, and precipitation were also used to identify the specific icing process.

Table 4 presents the annual maximum glaze ice thickness for each station, in order of year. Table 5 summarizes the results obtained from the extreme value analysis performed on the annual maximum glaze ice thicknesses for each station.

Year	St. John's (1953-86)	Gander (1953-86)	Argentia (1953-85)	Bonavista (1959-86)	St. Lawrence (1966-1986)	St. Alban's (1968-1983)
1953	9.4	4.6	4.1	-	-	-
1954	19.8	9.3	13.1	-	-	-
1955	20.6	12.4	9.2	-	-	-
1956	21.9	6.9	0.7	-	-	-
1957	16.8	16.4	6.9	-	-	-
1958	58.9	14.6	18.8	-	-	-
1959	17.8	26.8	10.0	4.3	-	-
1960	10.8	16.7	4.2	14.7	-	-
1961	10.8	9.4	Too Few Data	7.4	-	-
1962	12.7	5.7	4.4	9.4	-	-
1963	7.3	2.8	1.9	5.7	-	-
1964	9.8	5.3	10.8	11.9	-	-
1965	10.5	3.4	8.9	6.2	-	-
1966	1.2	7.9	4.9	9.2	3.2	-
1967	18.4	9.3	7.2	5.9	10.4	-
1968	5.1	3.0	Too Few Data	16.8	5.4	4.5
1969	16.0	3.2	Too Few Data	2.3	Too Few Data	Too Few Data
1970	14.3	10.7	Too Few Data	27.8	2.8	6.8
1971	12.2	8.1	0.8	4.4	9.0	Too Few Data
1972	13.6	11.2	10.3	11.8	3.6	5.6
1973	7.8	6.0	16.8	8.6	13.5	2.5
1974	8.9	12.1	9.2	6.9	4.7	0.5
1975	20.5	21.7	6.6	4.9	18.3	1.5
1976	6.1	1.8	Too Few Data	2.5	1.3	Too Few Data
1977	10.0	10.8	Too Few Data	9.9	4.0	Too Few Data
1978	4.0	14.9	Too Few Data	8.5	10.6	3.0
1979	15.7	7.1	1.5	8.6	7.2	2.6
1980	14.9	2.6	4.4	9.1	8.8	3.4
1981	11.0	8.6	1.3	7.3	2.0	2.0
1982	30.3	11.5	4.5	19.6	13.6	4.6
1983	20.9	7.3	2.7	13.8	3.1	-
1984	12.3	10.7	11.7	19.4	2.4	-
1985	12.5	9.7	7.1	7.4	2.6	-
1986	22.8	3.9	20.9	13.1	0.8	-

Table 4 Annual Extreme Glaze Ice Thicknesses (mm) for

Figure 4 and Figure 5 depict the typical plot for St. John's data over 34 years and the graphical representation on an extreme value paper. With the exception of St. John's, the 50-year return period value for radial glaze ice thickness is less than or equal to 25 mm.

A ten-year return period value of just over 25 mm thickness is projected for St. John's, with a 50-year thickness of 41 mm. The large variance in data for all stations results in wide confidence limits, especially at the 50-year level.

Stations	Return Periods 10-yr	25-yr	50-yr	99.9 % Confidence Limit on 50-yr. Values (mm)	Max. Glaze Ice Thickness (mm)
St. John's	28	35	41	±21	59
Bonavista	18	22	25	±12	28
Gander	16	21	24	±13	27
Argentia	15	19	22	±14	21
St. Lawrence	13	16	19	±14	18
St. Alban's	6	7	8	± 9	7

Table 5 Glaze Ice Thicknesses (in mm) For Selected Return Period Values

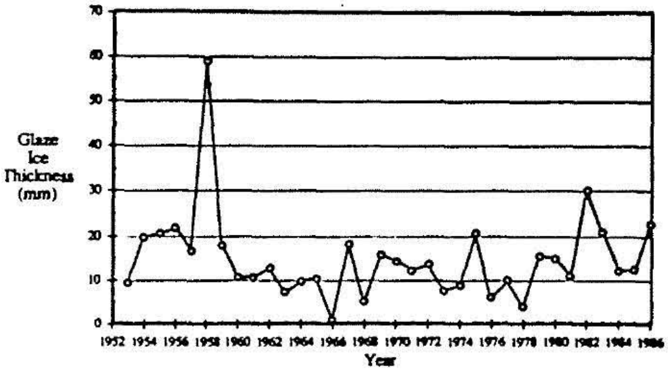


Fig. 4 Annual Maximum Glaze Ice Thickness for St. John's Data

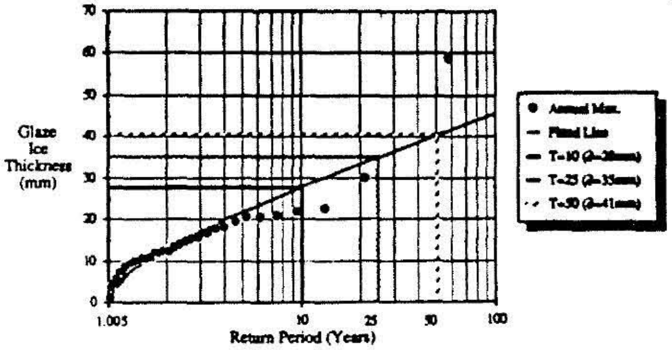


Fig. 5 Plot of Extreme Value Analysis for St. John's Data

Glaze Ice Thickness at the Line Route

The worst glaze storms identified for St. John's, Gander, and Bonavista were selected to extrapolate icing conditions to the transmission line route. In each case the input parameters such as wind speed and air temperature were adjusted to reflect the terrain. The icing model was applied to all of these storms using four different elevations; that is, 30 metres, 91 metres, 183 metres, and 274 metres. These are representative of the minimum, mid-range, mean and maximum elevations along the transmission line route. The maximum predicted radial ice thicknesses at the line route for selected return period values and elevations were then extracted from the model results.

Table 6 presents the glaze ice thicknesses computed for 10, 25 and 50-year return period values for four elevations. At 30 metres, the return period values of glaze ice thickness are similar to those for most of the weather stations. At 183 metres and 274 metres elevations, these values approach those for St. John's. For an elevation of 274 metres along the route, the 50-year return period value is about 46 mm. Figure 6 depicts the plot of 50-year glaze ice thickness along the line route.

	Elevation (metres)			
Return Period (Years)	30	91	183	274
T = 10	20.6	25.4	31.0	32.0
T = 25	25.7	32.0	39.1	40.1
T = 50	29.2	36.6	45.0	46.2

Table 6 Glaze Ice Thickness (mm) for Selected Return Period Values Along the Line Route

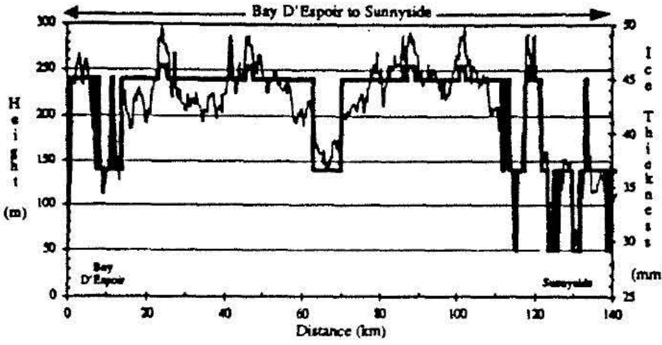


Fig. 6 Plot of 50-year Glaze Ice Thickness Along the Route

The greater ice accretion thicknesses at the maximum route elevation must be considered in terms of the meteorological conditions. Since freezing precipitation often occurs when a layer of cold air resides below a warm layer, there may be a maximum vertical extent to which this situation might occur. However, as the lapse rate varies widely, the air temperatures may either decrease or increase with elevation, depending upon the specific event.

Of the weather stations reviewed, the maximum elevation was 151 metres for Gander. Occurrence of glaze icing at the Oxen Pond terminal station (elevation 183 metres) near St. John's has also been documented (Newfoundland and Labrador Hydro, 1984). No other data are available for the eastern part of Newfoundland to indicate that severe glaze icing occurs at higher elevations (e.g., 274 metres to 305 metres). Therefore, 50-year return period values derived for a conductor at 275 metres elevation along the TL 202 and TL 206 routes should be approached with some bias, especially given the degree of variation in the data and the relatively wide

CONCLUSIONS

The long term climatological records from seven (7) weather stations were used to project probabilistic climatic loadings from wind speed, ice accretion, and combined wind and ice, both at the weather stations and at the line routes for TL 202 and TL 206. Wind speeds for selected return period values at the weather stations were higher than 120 km/h, with associated gust speeds ranging between 135 km/h and 184 km/h. At the line route, a 50-year return period wind speed of 128 km/h is obtained for a conductor height of 28 metres.

Maximum glaze ice thicknesses were predicted for St. John's, Gander, and Bonavista, with 50-year return period values of 41 mm radial ice thickness for St. John's, and 25 mm for the other two stations. Along the TL 202 and TL 206 routes, at higher elevations, a design load value of 46 mm was determined: however, this should be considered with some bias, given lack of sufficient information on temperature variation with elevation during freezing precipitation as well as the vertical extent of the freezing precipitation condition in the Eastern part of Newfoundland.

ACKNOWLEDGEMENT

The authors would like to thank Dr. Samy Krishnasamy, of Ontario Hydro Research for reviewing the final report prepared by COMPUSULT Limited, 1988. Finally, appreciation is also expressed to Ms. Paula English for her typing of the manuscript.

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