APPENDIX F

Overhead Line Construction

A. LINE CONSTRUCTION AND LOADING

Prevailing laws and practice in most states in the United States require overhead lines be designed, at the very minimum, to meet the National Electrical Safety Code (NESC).[1] New Hampshire Code of Administrative Rules Puc. 306.01 mandates that New Hampshire utilities must use the requirements of the NESC to construct their facilities in accordance with good utility practice. In addition, some states, such as California, have adopted by law their own codes which often refer to NESC requirements.[2] In the United States, most structures (other than transmission and distribution lines) are built according to the International Building Code (IBC), which often defaults to American Society of Civil Engineers (ASCE) standards on such issues as loading and methods. Current practice is to design structures using two well accepted design methods. The first and oldest is the "Allowable Stress Design" (ASD) method, and the second is "Load and Resistance Factor Design" (LRFD), which is the method most commonly taught in colleges and toward which the industry appears to be moving.

The NESC, however, uses neither of these commonly accepted methods. Instead, it historically has used an ultimate stress design method with overload factors used in the loading part of the design to provide the needed factors of safety. This method differs from all other commonly accepted design methods. Loading requirements contained in the NESC are different than those used in any other code. NESC rules for selection of design loads and for safety factors are largely based on successful experience, but have little basis in theory.[3] The more modern methods of design, such as LRFD, have been developed using successful experience as well as structural theory that has become accepted over the years. As a result, the 2007 edition of the NESC contains sections which have begun to include LRFD methodology such as is commonly accepted for other types of construction. It should be noted that the NESC still includes the older historical methods alongside the newer methods and appears to be in a process of transition. However, at this time the requirements of the NESC do not closely match the requirements that an engineer would be obliged to use when designing a habitable structure.

In many cases a power line design produced by strictly following the NESC loading and design criteria will deliver a less capable structure with lower factors of safety than would be produced

[1] Dagher, H.J. "Reliability of Poles in NESC Grade C Construction." *IEEE Rural Electric Power Conference 2001*, Pgs C4/1-C4/6. (10.1109/REPCON.2001.949521).
[2] State of California General Order 95. (January 2006). *Rules for Overhead Electric Line Construction*.
[3] Bingel, N., Dagher, H., et.al. (2003). "Structural Reliability-Based Design of Utility Poles and the National Electrical Safety Code." *Transmission and Distribution Conference and Exposition 2003*, Vol. 3.Pgs 1088-1093. (10.1109/TDC.2003.1335100).

if the structure were designed using methods required for other types of structures, such as the those required by the (IBC).[4] There is disparity between the results produced by building under the NESC instead of the IBC. The NESC tries to simplify things for the designer by specifying loading requirements that have been developed for average conditions over a large part of the country, while other codes use more exact data specific for small areas. Problems occur when local conditions vary from those considered average by the NESC. An area with high likelihood of large amounts of wind and ice, such as most of New Hampshire, will see more damage than average. Conversely, an area with lower expectations of wind and ice will see less than average damage on their system. Questions have also emerged as to the reliability of the NESC loading criteria with the development of joint use poles. Loading criteria and design methodology used in the NESC may not adequately anticipate the additional use of the utility's poles by a telephone or cable company.[5] For this reason, many utilities have developed their own standards which more closely match local conditions. In most cases, these standards produce a more robust and realistic design for an area than simply using the criteria in the NESC. In New Hampshire, all four major electric utilities use NESC loading. Only Public Service of New Hampshire uses an additional standard which exceeds NESC requirements for some transmission lines. It must be noted, however, that many utilities across the country have used NESC loading criteria exclusively over the years and have had good success. This is likely due to the fact that the average loading shown in NESC for their region closely matches or exceeds the actual conditions witnessed in their exact location.

The NESC recognizes three grades of construction which may be used in different areas: N, C, and B.[6] Grade N is the lowest strength, has the lightest loading requirements, and the smallest safety factors. Using Grade B construction results in the highest strength and largest safety factors. This results in the heaviest and most costly construction. Grade N may be used for emergency or temporary construction, on private right-of ways below 8.7kV, and for communication cables or cables below 750V. None of the four utilities in New Hampshire presently allow grade N construction on their systems. The NESC allows grade C construction in most other areas except at line, railroad. or limited access crossings where grade B is required. The grade of construction used is based upon the degree of importance and reliability level needed for the line.[7] Lines that are less important may be allowed to be constructed with a lower grade of construction, which has a lower factor of safety and may be expected to suffer more failures during an extreme weather event. For example, a rural single phase line crossing an

[4] Malmedal, K. and Sen, P.K. (2003)."Structural Loading Calculations of Wood Transmission Structures." *IEEE Rural Electric Power Conference 2003*.Pgs A3/1 – A3/8.
[5] Bingel, N., Dagher, H., et.al. (2003). "Structural Reliability-Based Design of Utility Poles and the National Electrical Safety Code." *Transmission and Distribution Conference and Exposition 2003*, Vol. 3.Pgs 1088-1093. (10.1109/TDC.2003.1335100).
[6] National Electrical Safety Code. (2007). ANSI/IEEE C2-2007.
[7] Bingel, N., Dagher, H., et.al. (2003). "Structural Reliability-Based Design of Utility Poles and the National Electrical Safety Code." *Transmission and Distribution Conference and Exposition 2003*, Vol. 3.Pgs 1088-1093. (10.1109/TDC.2003.1335100).

open pasture to a stock water tank may be constructed as grade N, especially if privately owned. The failure of this line during a storm might pose an inconvenience but would not normally pose a direct threat to human life. On the other hand, a line crossing an interstate highway or railroad could cause disastrous results if it failed and dropped onto an automobile or train. Additionally, the repair of this line without closing the highway or rail line would be very difficult. For this reason, a line of this type must be built to grade B construction, which has the highest factor of safety of all the grades of construction.

Another design guide commonly used in the United States is the RUS Bulletin 1724E-200, Design Manual for High Voltage Transmission Lines. The specifications in this guide are required for all Rural Electric Co-ops (REC) which borrow funds from the Rural Utility Service (RUS, formerly known as REA). This manual requires Grade B construction for lines 35kV and over while accepting the NESC requirements for other voltage classes and definitions for construction grades. It also has more conservative loading requirement than the minimum required by the NESC. Following this guide will generally produce a more robust design with higher safety factors than those that will occur when using only the NESC.[8] RUS guidelines also recognize that NESC minimum construction may be inadequate for local conditions and that local requirements may supersede those contained on the NESC or RUS documents.[9]

There are other design manuals which are commonly used by designers when deciding how to determine loads and design criteria for overhead transmission and distribution lines. While not reaching the level of model codes or having the weight of either the NESC or RUS documents, they provide guidance that can be referred to and valuable information for the designer. The first is ASCE Manual and Report on Engineering Practice No. 74: Guidelines for Electrical Transmission Line Structural Loading. This manual supplies some of the theoretical basis for the methods suggested for determining wind, ice, and other types of loading. and provides examples that can be referred to in designing overhead line structures. It also provides suggestions for load and strength multiplying factors for various conditions and materials, and describes the probabilistic approach used to determine these factors. This manual is independent of the requirements in the NESC. It is based upon theory and loading data rather than using the legacy methods required by the NESC. This manual is presently being revised, as some of the information included in it is now considered outdated and is being replaced by the information contained in ASCE Standard 7-05.

ASCE Standard 7-05: Minimum Design Loads for Buildings and Other Structures is also of great value in determining loads to place on overhead lines. This manual contains the most up-to-date information available regarding maximum wind speeds and ice loads for each part of the

[8] U.S. Department of Agriculture, Rural Utility Service. (2004). *Design Manual for High Voltage Transmission Lines.* (RUS Bulletin 1724E0200)
[9] U.S. Department of Agriculture, Rural Electrification Administration. (1982). *Mechanical Design Manual for Overhead Distribution Lines*. (REA Bulletin 160-2).

country. It divides the country into much smaller areas than are shown in the NESC district loading maps. The provisions and methods included in ASCE 7-05 are also required when structures are designed using the International Building Code. The ice loading information contained in ASCE 7-05 is prepared, compiled, and updated by the U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory (CRREL) located in Hanover, NH. This manual contains historical maximum weather loading information compiled from data collected by the laboratory. It is more up-to-date and provides more realistic weather loading data than that contained in the NESC. It is interesting to note that the 2007 NESC has for the first time included extreme wind maps and concurrent wind and ice loading maps which are derived directly from ASCE 7-05, yet the NESC does not require using either extreme wind or extreme ice with concurrent wind until a structure is taller than 60 ft. This is in contrast to both the ASCE and RUS documents that suggest including these two loading cases in all designs. All structural codes presently used in the United States have either already adopted or are moving toward the loading and weather criteria contained in ASCE 7-05. This can be expected to continue into the future.

Another manual which explains the statistically derived loading and strength methods included in ASCE design manuals is ASCE Manuals and Reports on Engineering Practice No. 111: Reliability-Based Design of Utility Pole Structures. This manual explains and gives examples of the methods described in the ASCE codes use for determining load factors and strength factors.

Every line should be designed for reliability, security, and safety. Security is the ability of a design to prevent the propagation of an initial failure to additional failures; safety means protecting the public at all times and construction personnel during construction and maintenance; reliability is the ability of the line to resist without damage a climatic event with a certain return duration, such as designing a line with the ability to stand up to a storm without damage with a recurrence of 50 years, which is the most commonly used return period for overhead line construction.[10] These objectives are normally accomplished by assuming a design load equal to the maximum ice and wind load which can be expected to occur during the service life of the line. This value is then multiplied by a factor of safety to make sure that the weakest structure in the design can resist the expected loads even after some deterioration due to age and accounting for the variations in material tolerances, which can be large in the case of wood and somewhat less in designed materials such as steel and composites. The two most important climatic conditions of interest in New Hampshire are the amount of ice that can be expected to accumulate on a line, usually stated as radial thickness of ice, and the wind pressure on the line which is a function of wind speed, height, and terrain type. The line should be designed for three load types: The maximum wind pressure the line will be expected to see during its lifetime, the maximum ice load the line will be expected to see, and the combination of the maximum amount

[10]Peyrot, A., Maamouri, M., et al. (1991). "Reliability-Based Design of Transmission Lines: A Comparison of the ASCE and IEC Methods." *The International Conference on Probabilistic Methods Applied to Electric Power Systems, 1991*. Pgs 97-102.

of ice the line will see in combination with the amount of wind pressure that can be expected during this icing event. The way this information is derived varies depending upon the code the designer decides to use.

After deciding the level of loads to be placed on the line, the designer must next decide upon the safety factors which must be applied. These safety factors vary with types of material. Naturally occurring materials (such as wood) require larger safety factors than engineered materials (such as steel). This is due to the fact that there is a larger variation in strength based on the material. For example, tolerances between the strongest and weakest wood members will vary a much greater degree than those between the strongest and weakest steel or concrete members. The designer will design around some average value of strength of the material and the safety factors will account for the variations around these average values to try to ensure that even the weakest structures will not fail under the design conditions. The combination load and strength safety factors for steel structures may be up to 2.5, whereas the safety factors for wood could be as large as 4.0. Safety factors will also account for the unpredictability of characterizing the loads. Weather loads may be difficult to foresee and the safety factor accounts for this unpredictability. In the most modern method of design, load and resistance factor design, these factors of safety are added by multiplying the loads by a load factor to account for the uncertainty in the loading information, and then multiplying the strength of the material by a strength factor to account for the variation in material strengths. The latest version of the NESC has also begun to take this approach.

In order to optimize the design of an overhead line, loadings must be chosen correctly. This is not easy in practice, especially where ice loading is concerned. Several types of icing may occur on an overhead line depending upon the conditions occurring at the time. Some of these are:

- Glaze ice: Clear ice possibly with icicles, very dense
- Hard Rime Ice: Opaque milky to nearly transparent, may be alternate layers of clear and opaque ice, intermediate density to very dense
- Soft Rime Ice: White, granular, snow-like, weak and low density
- Hoar Frost: White snow-like, irregular crystalline deposits, very brittle and low density
- Snow and sleet: Can melt and re-freeze several times and attain large weights

Icing can occur in cloud during fog or during precipitation.[11] The type and amount of icing that may occur depends on air temperature, water droplet size, water content of the air, wind speed, and local topographic effects near the line. For this reason icing may be highly variable along the length of a line. Due to the high variability of icing, it is impractical to try to determine the exact type of ice that may occur along the entire length of a line. In the United States, the protocol is to design the line for an equivalent radial ice load. This load is normally found from

[11] Ervic, M., Fikke, S.M. (1982). "Development of a Mathematical Model to Estimate Ice Loading on Transmission Lines by Use of General Climatological Data." *IEEE Transactions of Power Apparatus and Systems, June 1982*. Pgs1497-1503. (10.1109/TPAS.1982.317197).

maps prepared by various groups using both actual historical measurements and theoretical statistical methods.[12] These maps are developed using algorithms developed from research done by groups such as CRREL.

In some areas of the country, the loading described by the NESC and for which most overhead lines are designed (including those in New Hampshire) varies considerably from the loading described in other documents published by ASCE and other sources.[13] [14] The NESC should be considered the minimum mandatory requirement for loading and design. As utilities often recognize, the NESC merely describes conditions that can be expected to occur frequently rather than providing information about the maximum wind or ice that may be expected with a 50 year or 100 year recurrence.

Extreme weather events are described as random variables in probability distributions. The designer must decide on how rare of an event they are willing to design their systems to withstand. The designer of a building which may be expected to have a service life of 100 years or more might design for the largest weather event that may be expected to occur in 100 years. For the power line designer, the expected lifetime of their design is customarily 50 years. Therefore, the designer will design for the weather conditions that may be expected to occur only once every 50 years. The maps given in the NESC showing design loads typically show values of wind and ice which can be expected to occur once in any 50 year period.[15] The return period (RP) of the 2008 storm was 10 years, [12] which means that the magnitude of the storm was not highly unusual. Any lines designed for a storm of a 50 year return period should have weathered the impact of this storm.

In many areas the loading and safety factors in the NESC have produced reliable designs, while in others areas the loading conditions shown in the NESC have proven to be inadequate for local conditions. Because of this fact, utilities often require a stricter minimum loading condition than shown in the NESC, especially if local ice and wind loading data are available and conflict with those shown in the NESC.

Figure F-1 shows the loading criteria required by the NESC. There are only three loading conditions, or districts, defined: light, medium, and heavy loading.[16] These loading districts define both wind and ice loads to be used for structures below 60 ft. in height, and for these

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[12] Jones, K.F., Cold Regions Research and Engineering Laboratory (July 2009). The December 2008 Ice Strom in New Hampshire.
[13] Minimum Design Loads for Buildings and Other Structures. (2005). American Society of Civil Engineers 2005. (ASCE Standard 7-05).
[14] Guidelines for Electrical Transmission Line Structural Loading. (1991). American Society of Civil Engineers 1991. ASCE Manuals and Reports on Engineering Practice No. 74.
[15] Reliability-Based Design of Utility Pole Structures. (2006). American Society of Civil Engineers 2006. ASCE Manual and Reports on Engineering Practice No. 111.
[16] National Electrical Safety Code. (2007). ANSI/IEEE C2-2007.

structures, which would include most distribution lines, this is the only loading case required by the NESC. The loads defined for the three districts are:

- Heavy: 0.5 in. ice and 4 psf. of wind (equivalent to a 40 MPH wind)[17]
- Medium 0.25 in. of ice and 4 psf. of wind (equivalent to a 40MPH wind)[13]
- Light 0.0 in. of ice and 9 psf. of wind (equivalent to a 60 MPH wind)[13]

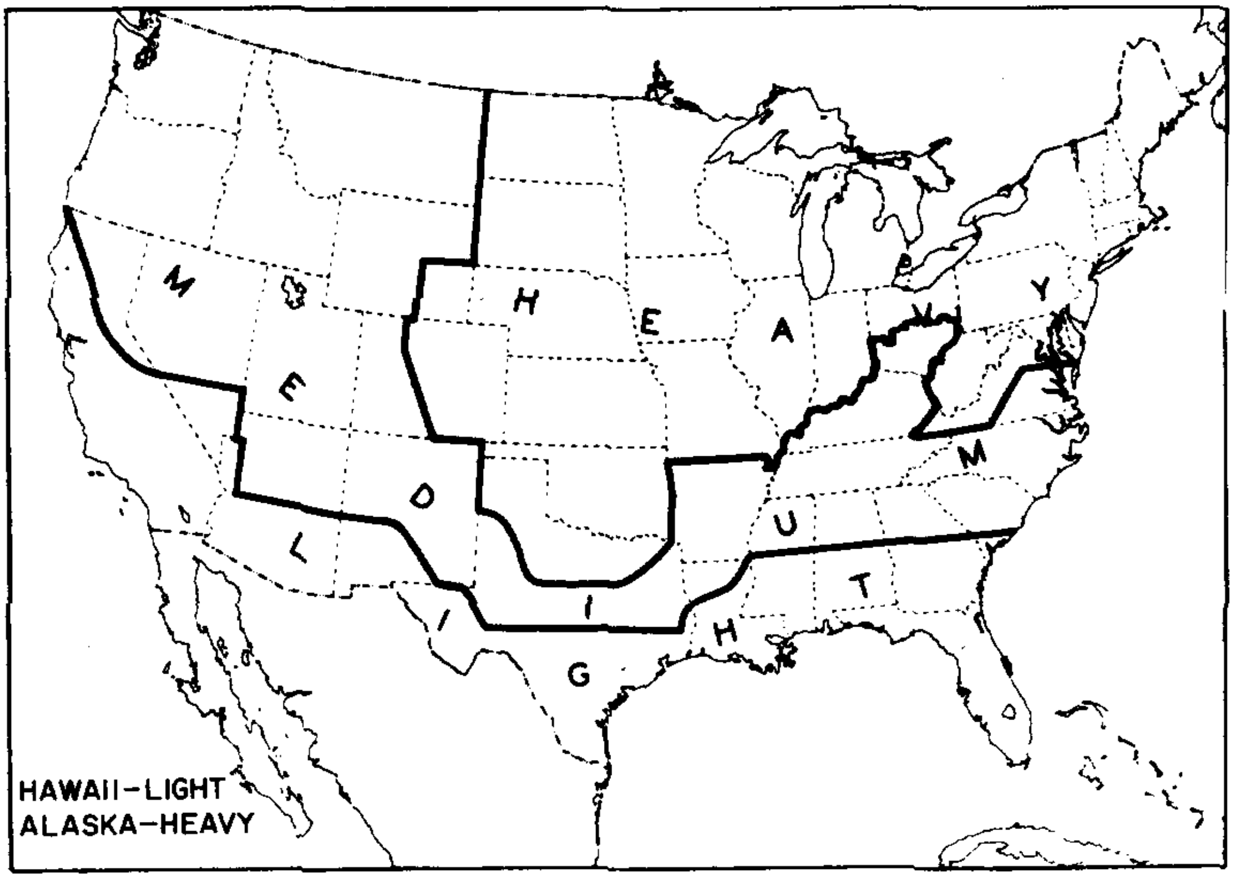

Figure F-1 - NESC loading map.

It may be seen that each of the three loading areas shown in Figure F-1 are quite large. Small variations due to terrain and even geographic location do not affect the loading levels shown in this map. The ice and wind load for New Hampshire, for example, is shown to be exactly the same as that for eastern Colorado, when in reality both icing and wind conditions for New Hampshire are far more severe than they are for eastern Colorado.

If a structure is taller than 60 ft. (which would primarily include transmission structures), the NESC requires that two other loading conditions be examined: extreme wind and extreme ice

[17] Bingel, N., Dagher, H., et.al. (2003). "Structural Reliability-Based Design of Utility Poles and the National Electrical Safety Code." *Transmission and Distribution Conference and Exposition 2003*, Vol. 3.Pgs 1088-1093. (10.1109/TDC.2003.1335100).

with concurrent wind. Figure F-2 shows the NESC map for extreme wind contained in the NESC.[18] It may be seen that a wind speed of 90 to 100 MPH is given for New Hampshire with a special wind area for the mountainous area along the New Hampshire and Vermont border. A special wind area means that local wind information must be found and the speeds shown on the map cannot show adequate information for these areas. The wind values for these locations are usually determined from local building departments in cities within the special areas. Officials in these cities have usually determined from experience the wind speeds required for safe design of buildings in their areas. The basic wind speeds shown in Figure F-2 are substantially higher than those required by NESC heavy loading for New Hampshire, which would be the equivalent of a 40 MPH wind. The map in Figure F-2 is taken from the latest data included in ASCE standard 7-05 while the loading in Figure F-1 has been included in the NESC without change for many years.

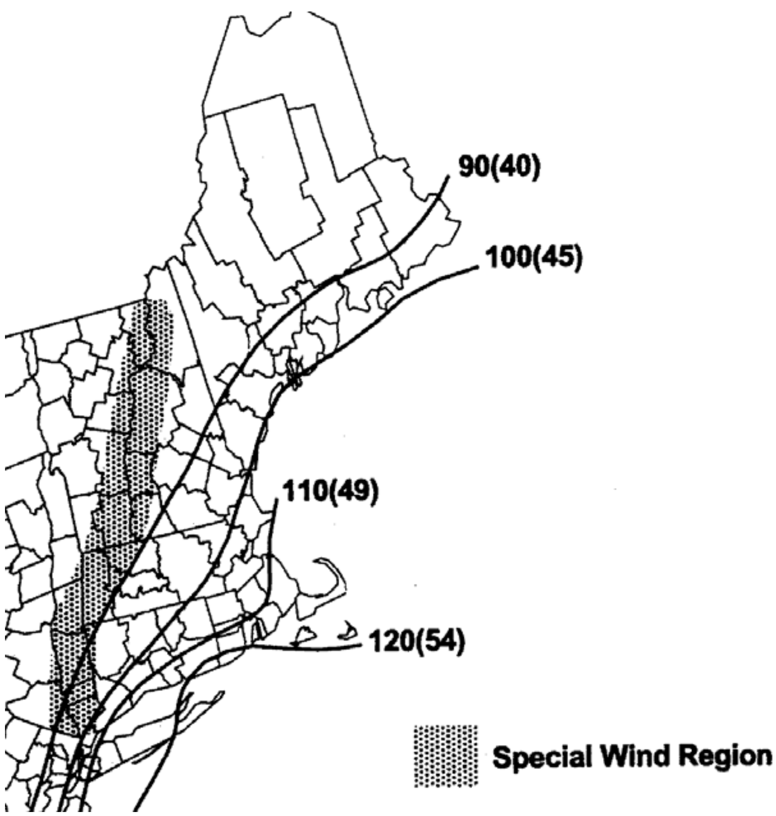

Figure F-2 - Basic wind speed for extreme wind design.

The third loading condition, extreme ice with concurrent wind, is considered by taking information from the map in Figure F-3. This map shows the 50-year return period levels for

[18] National Electrical Safety Code. (2007). ANSI/IEEE C2-2007.

wind and ice for New Hampshire. It is also taken from the latest version of ASCE 7-05.[19] [20] As may be seen in Figure F-3, the ice loading for New Hampshire varies from 0.75 in. with 40 MPH wind, to 1.0 in. with 40 MPH wind, and although not shown in the NESC map, the ASCE map shows a special wind area shown along the Vermont-New Hampshire border. This wind and ice loading shown in Figure F-3 is greater than is required using only the district loading from Figure F-1. For all structures designed using ASCE standards or the International Building Code, the loading shown in both Figure F-2 and Figure F-3 would have to be considered, but the NESC only requires these loads for structures above 60 ft. in height, which would not include most distribution lines that only need to be designed for the loads shown in Figure F-1.

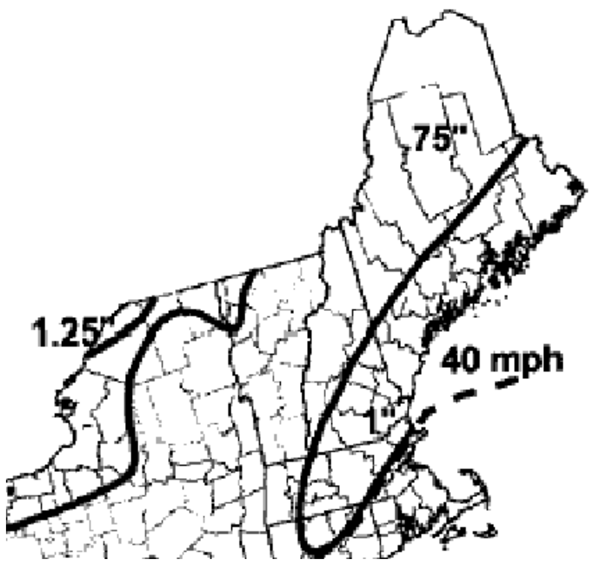

Figure F-3 - Ice and concurrent wind for line design.

It is generally recognized that the loading required in Figure F-1 has produced an adequate design on average when coupled with the safety factors (overload factors) contained in the NESC. For some areas with higher than average icing loads or higher than average wind loads, both of which would be true of New Hampshire, these levels of loading have produced designs with higher than average failure rates. In areas of lower than average wind and ice loads these levels of loading have produced a more robust than necessary design.[21] No design approach is inherently more reliable than another; all design methods make assumptions about loading and

[19] National Electrical Safety Code. (2007). ANSI/IEEE C2-2007.
[20] Minimum Design Loads for Buildings and Other Structures. (2005). American Society of Civil Engineers 2005. (ASCE Standard 7-05)
[21] Bingel, N., Dagher, H., et.al. (2003). “Structural Reliability-Based Design of Utility Poles and the National Electrical Safety Code.” *Transmission and Distribution Conference and Exposition 2003, Vol. 3,* Pgs 1088-1093. (10.1109/TDC.2003.1335100).

accept some probability of failure. The art of good design is to reduce the probability of failure while at the same time minimizing the total lifetime cost.[22] If specific and accurate design criteria is available for a region it becomes easier to produce a reliable design without spending too much on overdesign. Overdesigning can occur when an engineer has insufficient loading data available making it impossible to accurately characterize the actual loads that will occur in a certain location. As a result the designer must compensate by using larger safety factors. In the attempt to make sure the structures are adequate the designer will likely produce an overly stout design.

The latest version of the NESC has endeavored to begin addressing the differences in reliabilities that can be seen in lines built according the NESC district loading values from Figure F-1. It has addressed the differences apparent in various parts of the country, by revising the overload factors it uses. The overload factors used for overhead line design before the 2007 version of the NESC were historically derived and often based on subjective criteria including engineering judgment and experience.[18] While the loading and methods historically used in the NESC have proven successful over the years for most of the country, questions have arisen as to their validity due to new methods and materials being used for line construction, including the use of extensive numbers of shared-use poles by electric utilities and communications companies. There is some evidence that as communication under build (as used in the New Hampshire system) has become common, the loading criteria shown in the NESC has become less reliable over the years.

The load and strength factors used in the 2007 version of the NESC are designed for use with both NESC district loading and 50 year repeat period loading as shown in ASCE maps. Even though only NESC district loading cases are required for structures less than 60 ft., it is recommended that the higher wind and ice loading cases required by ASCE data also be taken into account for the design of all structures no matter their height. This should produce a more realistic design for the conditions that can be expected in New Hampshire. Since the system would be designed for loads that can be expected to occur only once every 50 years, it should be easily robust enough to sustain the loads imposed by a storm which can be expected to be repeated every 10 years, such as the one seen in 2008. This would include determining from local sources the actual wind and ice loads which can be expected in the special wind areas shown on ASCE maps rather than relying on loading data from NESC maps.

The question arises as to how the storm of December 2008 compares with the design criteria contained in the NESC and in ASCE standards under which the lines in New Hampshire were designed. The first thing that must be understood is the levels of ice which occurred. The design values of ice and the values contained in the NESC tables are “equivalent radial glaze ice” values. These are not the same values as typically reported in the media or measured by weather

[22] Sayer, B. (2000). “What of the Weather? Wood Pole Line Design & Weather Loadings.” *IEE Seminar on Improved Reliability of Woodpole Overhead Line, (March 8).* Pgs. 1/1-1/8.

stations. Forecasters and weather observers usually report ice accretion on a horizontal surface or on the ground. This might include the thickness of ice pellets and snow in addition to freezing rain. Occasionally the amounts of ice reported include icicles and the ice located on top of branches or wires. To determine the equivalent radial ice it would be necessary to take the average thickness of the same amount of moisture if it were spread evenly over the surface of a conductor. There is no method by which the ice accretions reported by weather stations can be accurately converted to equivalent radial ice as needed for design and analysis of utility structures.[23]

To produce the maps contained in ASCE 7, and to determine equivalent radial ice for this storm, hourly weather data from weather stations is needed. This data must include wind, temperature, dew point, precipitation rate and type among other factors which are used in an ice accretion model developed by the New Hampshire Cold Regions Research and Engineering Laboratory (CREEL) to determine equivalent radial glaze ice values. These values may also be directly measured with freezing rain sensors if a weather station is so equipped. The exact methods used are more completely explained in the CREEL report on this storm contained in Appendix D. Figure F-4 shows the amount of precipitation that occurred in New Hampshire during the storm.

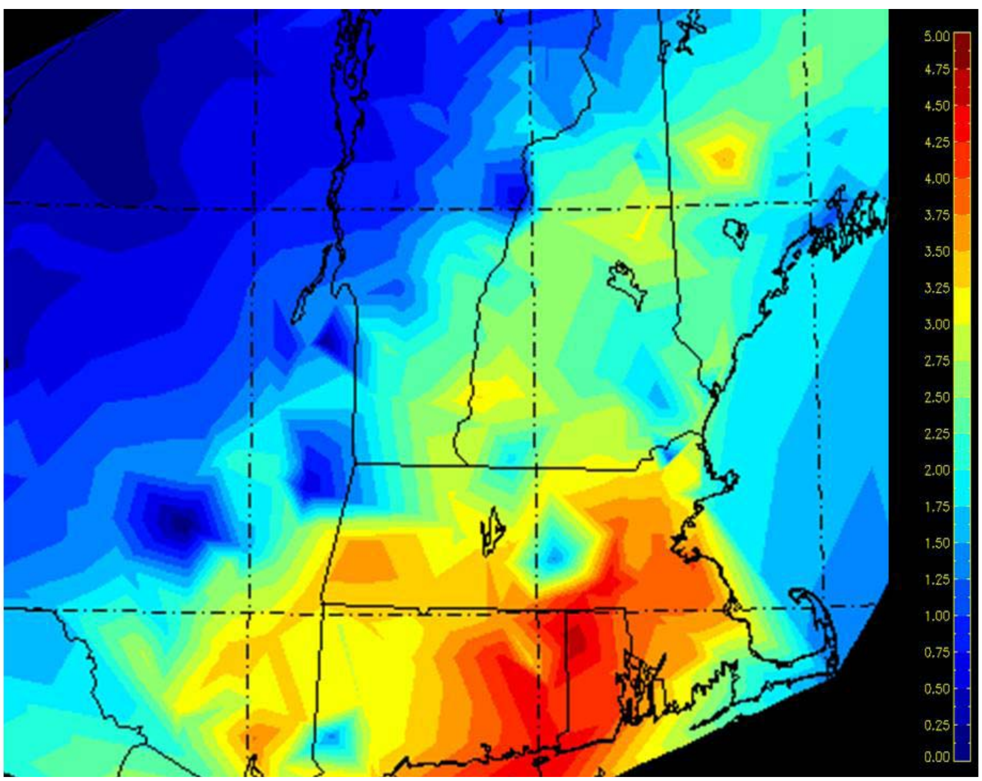

Figure F-4-Precipitation levels as reported by CREEL.

[23] Jones, K.F., Cold Regions Research and Engineering Laboratory. Phone Interview by Malmedal, K. August 5, 2009.

Figure F-5 shows the locations of the weather stations in New Hampshire and nearby. All the stations shown below are automated and all are able to record precipitation levels. However not all the stations shown are capable of recording all of the types of data needed to compute equivalent radial glaze ice using the CREEL model. Only those stations which are labeled in Figure F-5 record all the parameters needed for this computation. There are six labeled stations shown in New Hampshire, one in Maine, two in Massachusetts, and one in Vermont. The values below these stations are the equivalent radial glaze ice in inches as reported in the CREEL report.[24] Not all the stations shown reported complete data. Some data was missing for Fitchburg, MA, Lawrence, MA, and Jaffrey, NH and the values shown should be considered lower limits of ice. Only the station at Manchester has automated data augmented with human observations. Figure F-6 shows the footprint of the area where damage was reported due to ice. Both maps below were developed by CREEL.

[24] Jones, K.F., Cold Regions Research and Engineering Laboratory (July 2009). The December 2008 Ice Strom in New Hampshire.

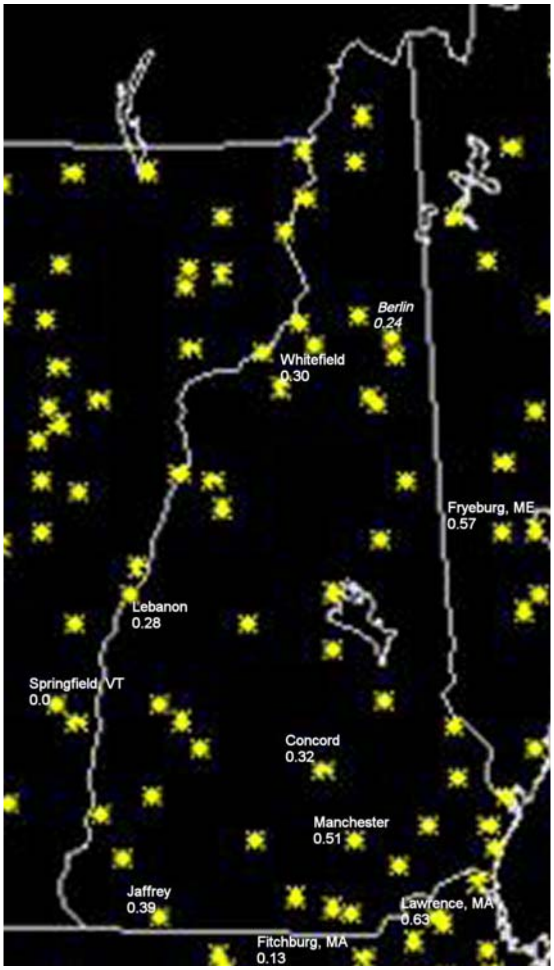

Figure F-5-Weather stations in New Hampshire and the surrounding area and equivalent radial glaze ice in inches.

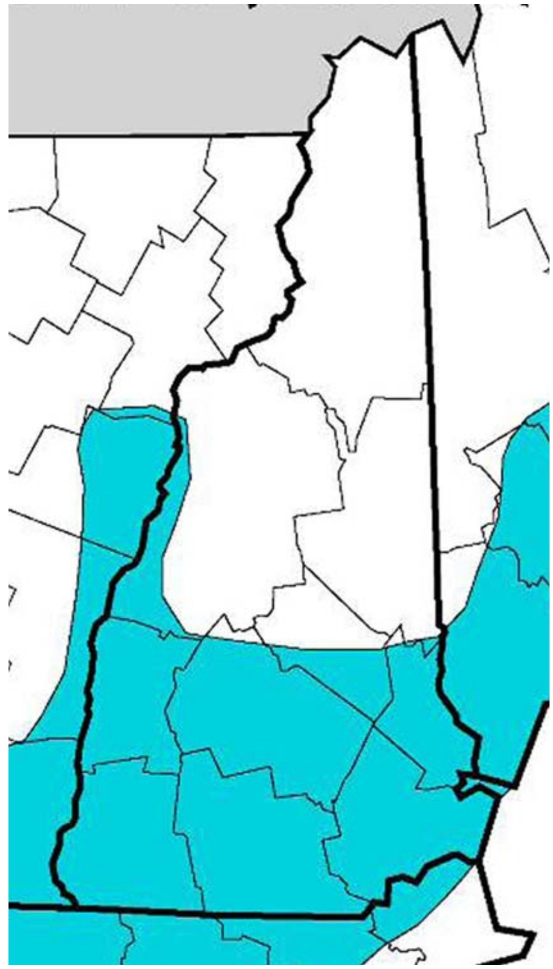

Figure F-6-Ice storm footprint showing area where damage to trees, power lines, and communications towers was reported.

It may be seen in Figure F-5 that the largest equivalent radial ice which occurred at any station in New Hampshire was 0.51 inches. It was also reported by CREEL that winds during the storm were light to moderate and wind on ice should not have been a significant factor in causing damage. The largest wind speed reported was approximately 9 MPH. The largest values for radial ice reported during this storm were reported in Maine with 0.9 inches, and New York where 0.8 inches was recorded. It appears that New Hampshire missed the worst effects of this storm in terms of the amounts of radial ice deposited.

The ice and wind loads recorded during this storm should not have resulted in stresses to the structures in excess of those required for design by the NESC for New Hampshire. It is interesting to note that the stations in the northern part of the state, outside the damage area, recorded nearly the same amount of ice as some of the stations in the area recording damage in the south. Even the relatively low values used for distribution structures below 60ft in height, as shown in Figure F-1, were not exceeded by this storm and the amount of ice and wind seen were far below the 50 year return period values shown in Figure F-3, 0.75-1.0 inch and 40 MPH winds. It can be concluded, therefore, that simple ice and wind loading on the transmission and distribution system should not have caused widespread structural failures in New Hampshire during this storm since the structures should have been designed to handle higher stresses than were seen during this weather event. Since all four New Hampshire utilities are designing their systems to meet the NESC, and the conditions during this storm did not exceed those stated in the NESC, the reasons for the widespread damage during this event do not include deficiencies in design. The reasons for the widespread damage witnessed in New Hampshire during this storm must reside elsewhere.

According to the CREEL report, the return period for equivalent radial glaze ice for storms in New Hampshire is shown in Table F-1. It may be seen that the return period of this storm is approximately 10 years. A storm of this magnitude should be relatively common and the distribution and transmission systems should be expected to experience an event of this magnitude many times during their lifetimes.

Table F-1-Return periods of ice.

Equivalent Radial Ice (inches)	Return Period (years)
0.5	10
0.7	25
0.9	80

Even though this storm did not produce loads exceeding the design loads, it is clear that 50 year levels of ice and wind would exceed the design loads of structures less that 60 ft in height which used only NESC district loading. It is recommended that all structures, regardless of height, be designed for not only district loading but also extreme wind and extreme ice with concurrent wind as is now required in the NESC for structures exceeding 60 ft. in height. This should prevent widespread damage to the distribution system during a weather event with a 50 year return period which the distribution system would be expected to experience at least once during its design lifetime.

Another weather related phenomena which can cause damage to overhead power lines is galloping. Galloping of conductors is a low frequency high-amplitude wind induced vibration that happens in the presence of glaze ice or rime ice deposits, which changes the cross sectional profile of the conductor from circular to some shape that is modified in aerodynamic characteristics.[25] Damage caused by galloping is not primarily due to ice loading itself, but due to the aerodynamic forces imposed on the structures and cables due to the wind acting on the

[25] Electric Power Research Institute, (n.d.) *Transmission Line Reference Book, Wind-induced Conductor Motion*.

deformed shape of the conductor. This causes lift on the conductor which is sufficient to cause large conductor motions. Galloping occurs most commonly with moderately strong steady crosswinds acting on asymmetrically-iced conductors.[26] There is some evidence that some of the damage which occurred on the transmission system during this storm may have been caused by this phenomenon.

Figure F-7 shows the conditions than cause galloping.[25] Ice forms on one side of the conductor, then wind crossing the conductor causes lift that causes the conductor to move up or down. This lift along the entire conductor causes it to move in a vertical direction either up or down, and variations in wind velocity may result in cyclical repetitive conductor oscillation.

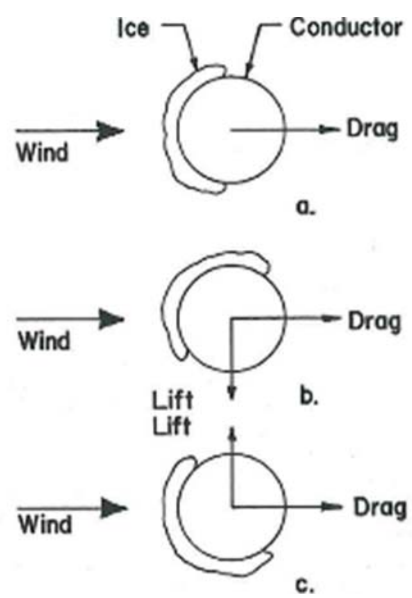

Figure F-7-Conditions causing galloping.[25]

The vertical motion of a conductor between supports that may result from these forces is shown in Figure F-8. Illustrated in this figure is a single mode of motion between supports which is the type that will produce the largest amplitude of motion between the normal location of the conductor and the farthest excursions of conductor location.[27] The conductor movement due to galloping has been known to cause contact between phase conductors and between phase conductors and overhead ground wires resulting in electrical outages and conductor burning and failure. While relatively less common in the United States due to types of construction used, it has been estimated that in England and Wales up to 20% of all line-line or line-ground faults on

[26] Wang, J. (2008). "Overhead Transmission Line Vibration and Galloping." *2008 International Conference on High Voltage Engineering and Applications, Chongqing China, November 9-13, 2008.*
[27] Ratowski, J.J. (1968). "Factors Relative to High-Amplitude Galloping." *IEEE Transactions on Power Apparatus and Systems, Vol 6*. June, Pg. 87.

275 to 400kV transmission lines were caused by line contacts due to galloping[28] and one of the main causes of failure to large extremely high voltage transmission line in China. Galloping has also been known to cause failure of hardware and supporting structures due to the large dynamic forces imposed upon them during galloping, and excessive conductor sag due to stressing the conductors beyond their elastic limits.[29]

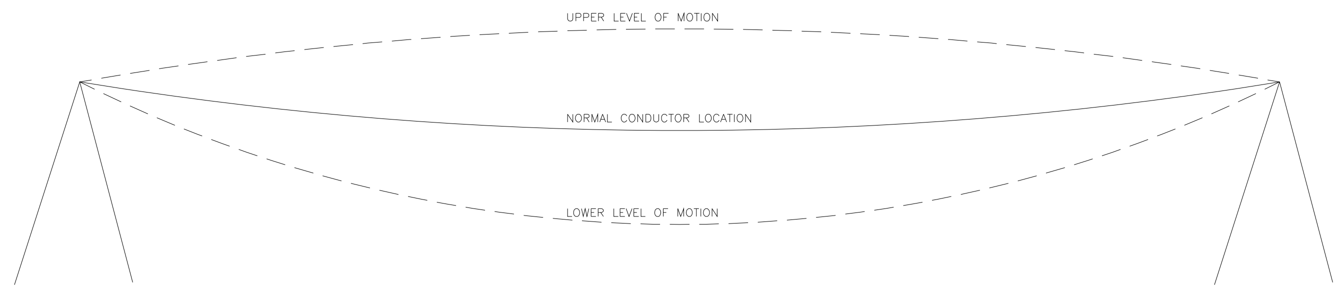

Figure F-8-Conductor motion during galloping, single mode galloping.

The results of a galloping line which caused enough stress in the conductors to greatly increase the conductor sag are shown in Figure F-9. The large amplitudes produced by galloping are usually vertical and may typically range from 0.1 to 1.0 times the sag of the span.[30] Frequencies will vary with the types of construction and are typically between 0.15 Hz and 1.0 Hz.

[28] Rowbottom, M.D. (1981). "Method of Calculating the Vulnerability of an Overhead Transmission Line to Faults Caused by Galloping." IEE Proceedings, Vol. 6, November, 128 Pt. C.
[29] U.S. Department of Agriculture, Rural Utility Service. (2004). D*esign Manual for High Voltage Transmission Lines*. (RUS Bulletin 1724E0200)
[30] Wang, J. (2008). "Overhead Transmission Line Vibration and Galloping." *2008 International Conference on High Voltage Engineering and Applications, Chongqing China, November 9-13, 2008.*

Figure F-9-Excessive sag as a result of galloping. (Photo courtesy of CIGRE)

It is difficult to predict which spans or lines might be susceptible to galloping. The phenomenon has been difficult to study due to the sporadic nature of when and where it might occur.[31] While the precise meteorological conditions that cause galloping are not known, it is thought that in addition to some ice being present, wind speeds greater than15 mph at a minimum angle of 45° to the line direction are needed to produce galloping.[32] It is also thought that spans in excess of 800 feet on structures using suspension insulators with conductors exceeding 1-inch in diameter using older conductors with relatively high tension are most susceptible to galloping. However, under proper conditions, galloping may occur in nearly any span. Galloping with amplitudes of 10 feet has been reported on spans of 300 feet.[33] Anything that produces mechanical dampening such as newer conductor[34] or stiffer mounting methods will tend to minimize galloping.

In the parts of the United States where galloping is expected or historically known to exist, design methods are used to try to minimize the possibility of galloping causing conductors coming into contact with each other. The main method is to increase line-line spacing of conductors.[35] To determine the distances needed to minimize contact due to galloping, research performed by A.E. Davison during the 1930s is used. Davison determined that galloping

[31] Electric Power Research Institute, (n.d.) *Transmission Line Reference Book, Wind-induced Conductor Motion*.
[32] Rowbottom, M.D. (1981). "Method of Calculating the Vulnerability of an Overhead Transmission Line to Faults Caused by Galloping." *IEE Proceedings*, Vol. 6, November, 128 Pt. C.
[33] McDaniel, W. N. (1960). "An Analysis of Galloping Electric Transmission Lines." *Power Apparatus and Systems Part III Transactions of the American Institute of Electrical Engineers, Volume 79,* April, pgs 406-412. (10.1109/AIEEPAS.1960.4500782).
[34] Rawlins, C.B. (1988). "Research on Vibration of Overhead Ground Wires." *IEEE Transactions on Power Delivery*, *Vol 3*, No. 2, April.
[35] Rawlins, C. B. (1981). "Analysis of Conductor Galloping Field Observations-Single Conductors." *IEEE Transactions on Power Apparatus and Systems, Vol.* 8, August, Pg. 100.

conductor loops appeared to remain within an elliptical region and he suggested the dimensions these ellipses would attain. Further research modified the dimension of these ellipses, but the basic method is still the one designers use as one determining factors controlling the minimum distances required between conductors. A typical example of these ellipses is shown in Figure F-10. If the structure is designed so these ellipses do not touch each other, theory states that the probability of contact between either the conductors or the phase conductors and overhead ground wires should be minimized.

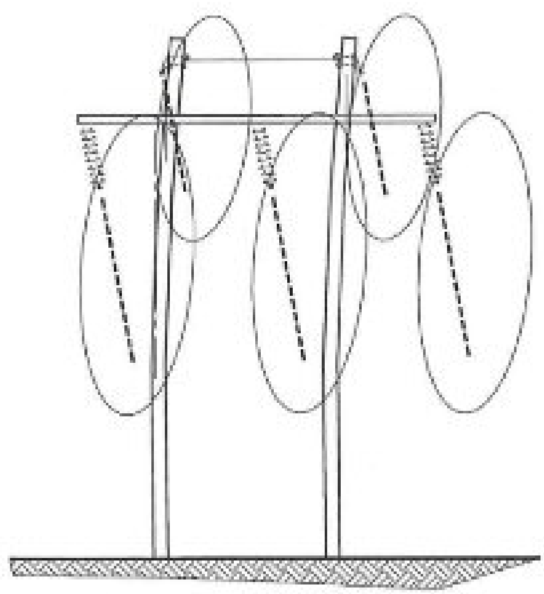

Figure F-10-Galloping ellipses. [36]

When galloping occurs there are mitigating measures which can be added. If a galloping problem is predicted or seen, there are a number of different line dampening technologies that can be included in design or added after a line is completed. There are also types of conductors that can be used which are designed to minimize vibrations including galloping. These conductors are more costly than standard conductors and are usually used only in areas where galloping has been seen historically.

Since predicting which spans will experience the proper conditions to produce galloping is difficult, susceptible spans may only be identifiable after a line is constructed. One method which may be used to identify these troublesome spans is using fault location, which is a feature of many newer protective relays.[37] This can help determine where faults on the system are

[36] U.S. Department of Agriculture, Rural Utility Service. (2004). *Design Manual for High Voltage Transmission Lines*. (RUS Bulletin 1724E0200).
[37] Rowbottom, M.D. (1981). "Method of Calculating the Vulnerability of an Overhead Transmission Line to Faults Caused by Galloping." *IEE Proceedings*, Vol. 6, November, 128 Pt. C.

occurring and whether any spans are experiencing frequent unexplained faults during icing conditions. After these susceptible spans or lines are identified, it may be possible to retrofit them with vibration dampers or other galloping prevention hardware to reduce the possibility of galloping on these spans in the future.

All four utilities are using proper design methods to minimize the possibility of damage and flashover due to galloping. However, there was one shield (overhead ground) wire failure on the transmission system that was unexplained, and two faults whose cause was not determined. Galloping is a possible cause of both of these conditions. No changes in design or overhead line construction are recommended at this time, but the utilities should monitor these locations in the future to determine if repeated failures are occurring which may be attributable to galloping. If these problems become frequent enough, it may be necessary to add vibration dampeners to the spans in question to eliminate galloping damage in the future.