AmericanLifelinesAlliance

A public-private partnership to reduce risk to utility and transportation systems from natural hazards and manmade threats

Extreme Ice Thicknesses from Freezing Rain

September 2004

FEMA

National Institute of BUILDING SCIENCES

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This report was written under contract to the American Lifelines Alliance, a public-private partnership between the Federal Emergency Management Agency (FEMA) and the National Institute of Building Sciences (NIBS). This report was reviewed by a team representing practicing engineers, academics, and state climatologists.

Acknowledgements

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Advisory Committee:

A draft report was provided for review to the State Climatologists of the contiguous 48 states and Alaska, with the exception of states currently without climatologists (Montana, Rhode Island, and West Virginia) and State Climate Offices (SCOs) without current email addresses (Arkansas, Massachusetts, Nevada, and Virginia). Personnel at 27 of the remaining 42 SCOs provided reviews. The thoughtful and informative comments and suggestions from personnel associated with the SCOs from:

Alabama	Iowa	New Hampshire	Oklahoma
Colorado	Kansas	New Mexico	Oregon
Delaware	Michigan	New York	Pennsylvania
Florida	Minnesota	North Carolina	
Idaho	Mississippi	North Dakota	
Illinois	Nebraska	Ohio	

were used in preparing this final report.

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1.0 Introduction

The Federal Emergency Management Agency (FEMA) formed in 1998 the American Lifelines Alliance (ALA) as a public-private partnership. In 2002, FEMA contracted with NIBS through its Multihazard Mitigation Council (MMC) to, among other things, assist FEMA in continuing ALA earlier guideline development efforts. In 2003, ALA requested Kathleen F. Jones of the U.S. Army Corps of Engineers (USACE) Engineer Research and Development Center (ERDC) Cold Regions Research and Engineering Laboratory (CRREL) Snow and Ice Branch to provide maps of extreme equivalent radial ice thicknesses from freezing rain for mean recurrence intervals of 50, 100, 200 and 400 years for both English and metric units. This effort complements the map of 50-yr ice thicknesses in English units that is published in the ASCE 7 Standard *Minimum Design Loads for Buildings and Other Structures* (ASCE 2003). The latest revision is ASCE 7-2005 (ASCE in draft), which is expected to be published early in 2005. The 50-yr maps are also in the current draft for ASCE Manual 74 *Guidelines for Electrical Transmission Line Structural Loading* (the current revision is ASCE 1991) and are proposed to be included in the 2007 revision of the National Electrical Safety Code (the current revision is NESC 1997).

1.1 Project Objective

The purpose of this guide is to

- explain the concept of equivalent radial ice thicknesses
- provide references to background information
- describe how ice thicknesses are estimated for long mean recurrence intervals
- provide maps in English units for mean recurrence intervals of 100, 200 and 400 years to extend the 50-yr map in ASCE Standard 7
- provide maps in metric units for mean recurrence intervals from 50 to 400 years, for use in hard metric standards, codes, and guidelines

1.2 Project Scope

This guide addresses extremes of equivalent radial ice thicknesses from freezing rain with concurrent gust speeds.

This guide does not address accreted ice loads from in cloud icing or from sticky snow (see the various *Proceedings of the International Workshop on Atmospheric Icing of Structures*). These winter weather phenomena occur with different spatial distributions from freezing rain. It also does not address dynamic loads associated with icing, including galloping of conductors (e.g. Rawlins 1979), ground wires, and tower guys, which occurs with relatively small ice thicknesses in moderate to high winds and can cause significant damage, either in a single episode or over many winters through accumulated fatigue damage. Spatial factors, which quantify the increase in risk environmental loads to distributed structures, such as transmission lines and distribution line systems, are not discussed. The spatial effect for a variety of environmental loads is discussed in a number of papers, including Golikova (1983) on ice storms, Twisdale (1982) on tornadoes, and Vickery and Twisdale (1995) on hurricanes.

1.3 Notation

d = **wire, branch diameter**

L = **sample length**

m = **ice mass**

P = **depth of freezing rain**

t = **equivalent radial ice thickness**

V = **average wind speed**

V_o = **10 knots or 5 m/s**

π = **3.14**

ρ = **density of ice = 0.9 g/cm^3**

2.0 Determining extreme ice thicknesses from freezing rain

2.1 Ice accretion models

The CRREL model for the accretion of ice on cylinders (e.g. wires and branches) from freezing rain is described in Jones (1996). This model determines the amount of ice that freezes both directly to the wire and as icicles, as any initially unfrozen water starts to drip off the wire. The Simple model is also introduced in the above report, but is described in more detail in Jones (1998).

In both models the severity of icing is quantified in terms of the equivalent radial ice thickness *t*. A back-of-the envelope formulation of the Simple model that can be used, for example, to estimate the potential damage to trees and overhead wires in forecasted freezing-rain storms is:

$$t = 0.35P\sqrt{1+\left(\frac{V}{V_0}\right)^2} \tag{2-1}$$

where P is the total depth of freezing rain expected and V is the average wind speed accompanying the freezing rain. The equivalent radial ice thickness t is in the same units as P, and V_0 is 10 for V in mph (or knots) and 5 for V in m/s. Note that t is independent of the wire diameter. Based on our measurements and observations in the field in freezing rain storms, we expect significant tree damage when $t \geq 0.25$ in.

The mass m of ice with density ρ_i on a wire with diameter d and length L is calculated from the equivalent radial ice thickness t:

$$m = \rho_i \pi L\left(dt + t^2\right) \tag{2-2}$$

The ice mass increases with wire diameter for a given t.

2.2 Equivalent radial ice thickness

The equivalent radial ice thickness that describes the mass or weight of ice on a wire (or other cylinder) is different from the maximum dimension of the ice accretion provided in Bennett (1959) and Changnon (2003) and used in various papers by Hay (e.g. Hay 1957). These authors use the measurements made by the American Railroad Association (ARA) during a 9 year period in the 1920s and 1930s. According to Stanley Changnon (personal communication, August 2004) he and William W. Hay were contemporaries at the University of Illinois. Hay had gotten the ARA to provide him with all the data from the 9 year study. At one point, Hay gave Changnon a summary list he had compiled from the original data of all the measurements of ice that were associated with damage. This list is the 1689 point measurements that Changnon refers to in his 2003 paper. The summary (which is not publicly available) lists the location, date, and total ice thickness, but with no description of how the thickness was measured. Changnon believes the measurements were made by someone at the depot by climbing up the signal mast ladder with a

ruler to measure the maximum dimension of the ice on the wires where they entered the depot above the double window, 8 to 10 ft above ground.
The CRREL Ice Storm Team has deployed in a number of freezing rain storms beginning in the mid 1990s to measure equivalent radial ice thicknesses and document the distribution and severity of icing on trees and wires. The photographs in Figure 2.2-1 were taken in those storms and are chosen to illustrate some of the variety of ice accretion shapes that occur. This figure shows that because of the great variety of ice accretion shapes, the maximum dimension of the accretion that is reported in papers that use ARA data is not a good measure of the load of ice on the wire. The determination of the equivalent radial ice thickness t from field measurements of ice samples in freezing rain storms is presented in Figure 2.2-2.

2.3 Application to weather data

The approach used to apply the CRREL and Simple ice accretion models to U.S. and Canadian hourly weather data to determine equivalent radial ice thicknesses in past freezing rain storms is described in Jones et al. (2002). A map of the weather stations used in this analysis in the lower 48 states and neighboring portions of Canada is shown in Figure 2.3-1. Stations in Alaska and portions of northwest Canada are shown on the extreme ice maps for Alaska in the Appendix. As is mentioned in the 2002 paper, we obtained damage information from *Storm Data* (NOAA 1959-present), *Climatological Data: National Summary* (NOAA 1950-1958), and newspaper reports on freezing rain storms for which the modeled ice thicknesses were significant. From the model results and this qualitative damage information we mapped the region of each storm in which there was enough ice to damage trees, overhead wires (telegraph, phone, power, cable TV, etc.), and communication towers. A map of the compiled damaging ice storm footprints is in Figure 2.3-2.

The weather conditions during ice storms are not extraordinary. Winds are typically light to moderate, precipitation rates are relatively low, and temperatures are at or below freezing but not bitterly cold. Thus, extraordinary ice storms typically occur when conditions favorable for freezing rain or drizzle persist for many days. This also means there is no natural maximum equivalent radial ice thickness. Weather conditions that produce 1 in. of ice in two days will produce 2 in. after four days, or 4 in. after eight days, with the same freezing rain rate and wind speed.

2.4 Extreme value analysis

A discussion of extreme events and various approaches for the calculation of extreme values is in Jones and White (2002). The maps of equivalent radial ice thickness (henceforth shortened to "ice thickness") from freezing rain with concurrent gust speeds are organized by mean recurrence interval (50, 100, 200 and 400 years) in the Appendix. For each recurrence interval, there is a map of the lower 48 states, a map of Alaska, and detail maps of Lake Superior, the Columbia River Gorge, and the Fraser Valley. For 50 and 100-yr mean recurrence intervals, ice thicknesses are mapped in 0.25 in. increments. Each ice thickness zone includes values from 70% below the nominal value to 30% above. For example, the 0-in. zone includes ice thicknesses up to 0.075 in.; the 1-in. zone includes ice thicknesses from 0.825 in. to 1.075 in. On the 200 and 400-yr maps, ice thickness zones are 0 in., 0.25 in., 0.5 in., 1 in., and continue in 0.5-in., rather than 0.25-in. increments, reflecting the greater uncertainty in the values for these long mean recurrence intervals. Similarly, the corresponding metric maps use 5-mm increments for the 50 and 100-yr maps, and 10-mm increments for the 200 and 400-yr maps. Major terrain features were used in defining some of the ice zones on the maps. For comparison, a color relief map of the United States is available at http://fermi.jhuapl.edu/states/us/big_us_color.gif .

As is described in Jones et al. (2002), the 50-yr ice thicknesses are calculated by grouping the ~500 weather stations into superstations to generate longer periods of record for the extreme value analysis. By doing this, the 50-yr values are within the sample of extremes rather than far out in the tail of the distribution. However, the 100-yr to 400-yr extremes are farther out in the tail and thus may still be significantly affected by the tail shape parameter, which in turn is affected by the random occurrence, or not, of storms with long mean recurrence intervals (e.g. the January 1998 storm in the northeast) in the period of record. To decrease this variation between superstations, 100-, 200- and 400-yr values are calculated for each superstation using an average multiplier on the 50-yr value for each mean recurrence interval. The same multipliers are used for all superstations in zones with 50-yr ice thicknesses of 0.5 in. or more. Separate multipliers are used for stations in the 0.25-in. and 0-in. zones. These factors are calculated as the average of the ratios of ice thickness (e.g. the 100-yr value divided by the 50-yr value) weighted by the number of years in the period of record for each superstation. The factors are shown in Table 2-1.

	Factor to multiply 50-yr value		
	100-yr	200-yr	400-yr
Superstations in 50-yr 0.5” zone and greater	1.25	1.55	1.91
Superstations in 50-yr 0.25” zone	1.34	1.76	2.31
Superstations in 50-yr 0” zone	1.62	2.42	3.49

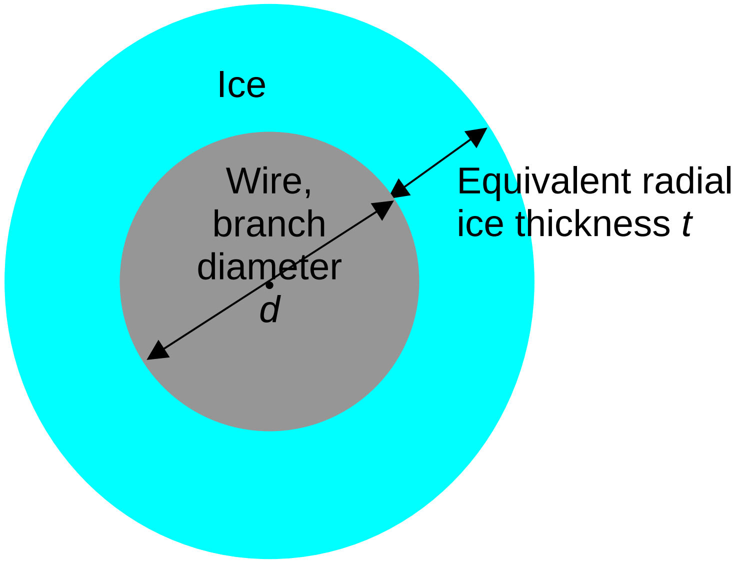
Table 2-1. Factors on 50-yr thicknesses

The 50-yr map was developed over the past 8 years as CRREL, utility organizations (e.g. EPRI, CEA), individual utilities (e.g. VELCO, NYPA, BPA), and FEMA funded the mapping of various regions of the country. Partial maps were included in ASCE Standard 7 Minimum Design Loads for Buildings and Other Structures, initially in the 1995 revision, and then in the 1998 and 2002 revisions as additional regions were analyzed. The map in this document is in the draft for ASCE 7-2005. There are discrepancies between this 50-yr map and the maps for the longer recurrence intervals. On the 50-yr map, zones in southern Minnesota-northern Iowa and eastern Pennsylvania-northern New Jersey are shown with ice thicknesses greater than the surrounding area, but these zones are not delineated on the 100-, 200-, and 400-yr maps. Those are only two of the many relatively small areas across the country with significant local variations in the severity of icing associated with variations in terrain and thus, should not be delineated. A list of examples for ASCE Standard 7 of areas where extreme ice thicknesses are expected to be greater than in the surrounding terrain include: Signal and Lookout Mountains in Tennessee; Ponatock Ridge and the edge of Yazoo Basin in Mississippi; Shenandoah Valley and Poor Mountain in Virginia; and Mt. Washington in New Hampshire. As a result of the State Climatologist review, Buffalo Ridge in southwest Minnesota is being added to this list.

The maps of extreme ice thicknesses should not be interpreted as predictions of the future. They are simply an evaluation of the risk based on current information. Rare ice storms can and do occur now. Because structures are designed for specified risk levels that correspond to relatively long return periods, we need to evaluate the severity of ice storms with large equivalent radial ice thicknesses based on the information now available. For example, the 1998 ice storm in the northeast appears to be consistent with a mean recurrence interval of about 250 years in the Montreal area. As time goes by, and no other extraordinary ice storms occur, then the estimate of that mean recurrence interval will increase. Or, on the other hand, if another storm as severe as the 1998 storm occurs 20 years from now, a reanalysis of the data will indicate a shorter mean recurrence interval. Any nonstationarity in the climate, whether natural or anthropogenic, can certainly further affect the estimates of extremes as well.

Figure 2.2-1 Some shapes of ice accreted from freezing rain on cylinders

Definition:



Determining t from measurements in the field:

Measure:

sample ice mass m
branch or wire diameter d
sample length L

Calculate equivalent radial ice thickness t:

$$t = -\frac{d}{2} + \sqrt{\frac{d^2}{4} + \frac{m}{\pi \rho_i L}}$$

where

$\pi = 3.14$
ρ_i = density of ice = 0.9 g/cm^3

Figure 2.2-2 Equivalent radial ice thickness

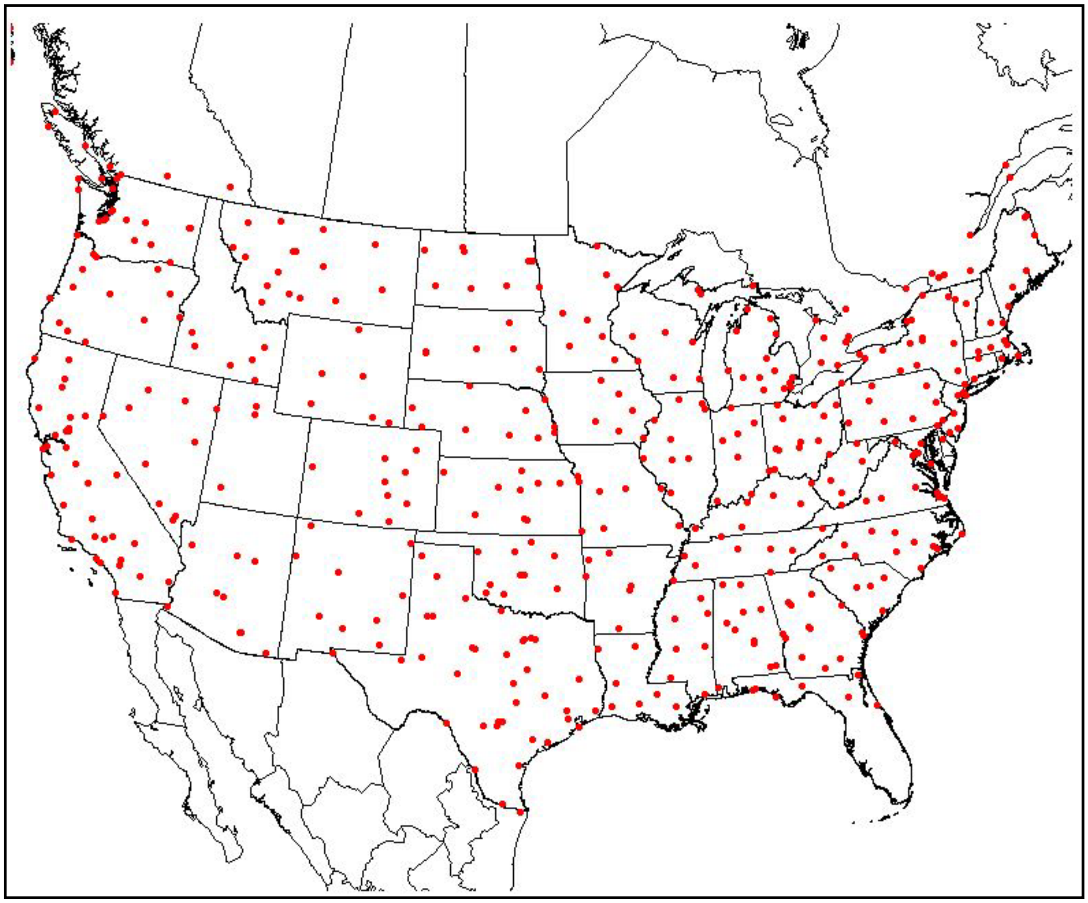


Figure 2.3-1 Weather stations in contiguous 48 states

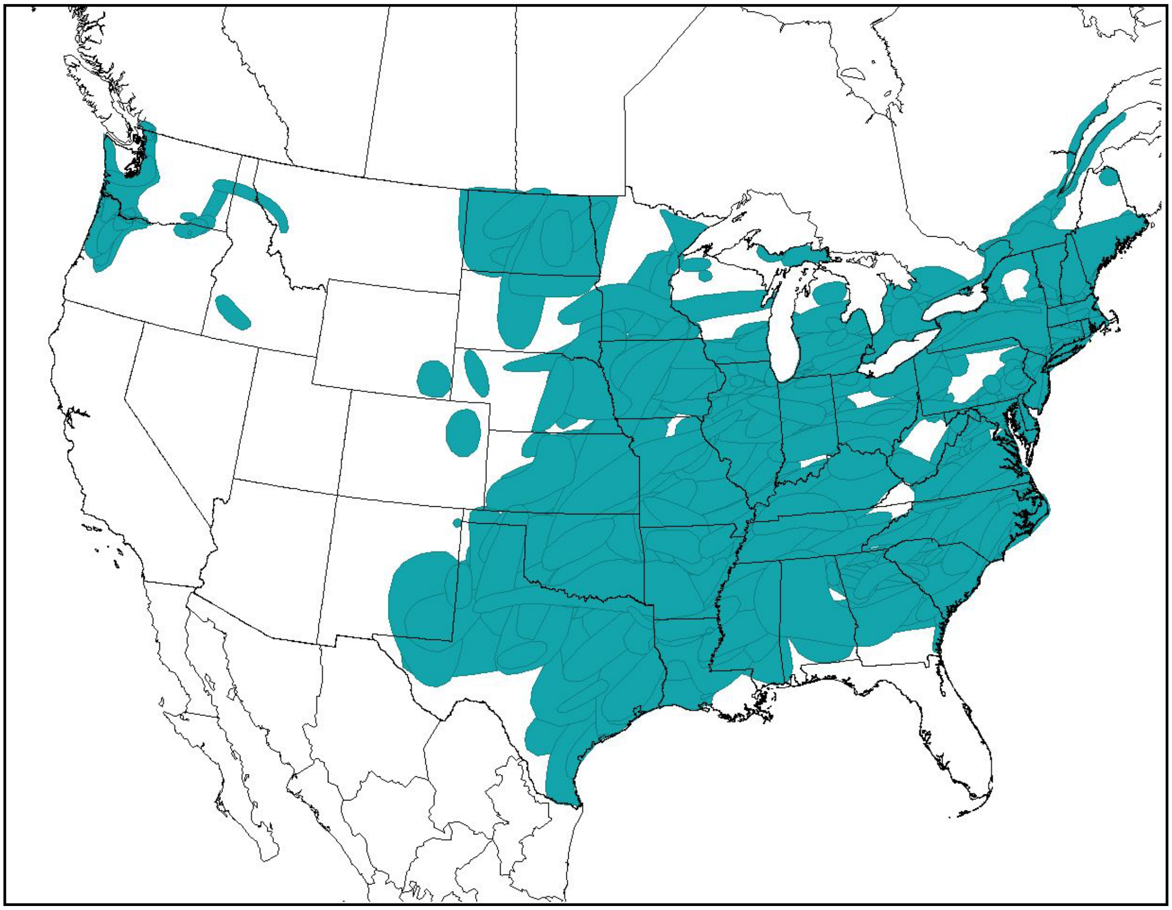


Figure 2.3-2 Footprints of damaging ice storms 1948-2002

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Acronym List

ALA	American Lifelines Alliance
ARA	American Railroad Association
ASCE	American Society of Civil Engineers
BPA	Bonneville Power Administration
CEA	Canadian Electricity Association
CRREL	Cold Regions Research and Engineering Laboratory
EPRI	Electrical Power Research Institute
ERDC	Engineer Research and Development Center
MMC	Multihazard Mitigation Council
NIBS	National Institute of Building Science
NOAA	National Oceanic and Atmospheric Administration
NYPA	New York Power Authority
VELCO	Vermont Electric Company

Terms and Definitions

equivalent radial ice thickness: The uniform radial thickness of ice on a cylinder; describes the ice load.

galloping. Large amplitude, low frequency vibration, typically of overhead wires and guys for tall towers.

mean recurrence interval. The inverse of the annual exceedance probability. For example, the ice thickness with an annual exceedance probability of 0.02 has a 50-yr mean recurrence interval.

superstation. A grouping of weather stations with similar climatology for the environmental load under consideration for the purpose of generating a longer period of record for an extreme value analysis.

Appendix. Maps for mean recurrence intervals of 50, 100, 200, and 400 years

Maps with English units (ice thicknesses in inches, wind speeds in miles per hour) are in Appendix A. Maps with metric units (ice thicknesses in millimeters, wind speeds in meters per second) are in Appendix B. For each mean recurrence interval, the map of the 48 contiguous states is followed by the Alaska map and then the three detail maps for Lake Superior, the Columbia River Gorge, and the Fraser Valley. The maps are arranged in order of increasing mean recurrence interval.