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Accumulation Of Ice On Trees

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Ice storms continue to damage trees and surrounding structures on an annual basis. The damaging features of an ice storm include: 1) thickness of ice accumulated on trees; 2) wind speed present during deposition and afterwards until any ice has melted; 3) duration of ice storm; and, 4) length of time ice encrusts trees. Ice, wind and time conspire to damage trees. (Jones et.al. 2002) Figure 1 demonstrates total ice accumulation in a storm is related to the amount of freezing rain falling per hour, and the ice storm duration. The amount of freezing rain falling, and associated ice accumulated, is a first key impact in appreciating tree damage.

Ice storms usually occurs when surface temperatures are between 32°F and 23°F. Freezing precipitation occurs when supercooled rain droplets or drizzle freeze on contact with tree surfaces. The increased weight of ice, and any wind loading, leads to physical bending and breakage of trees. Branches break and trees topple, damaging other trees, as well as surrounding structures and property. (Stuart & Isaac 1999)

Damage Scale

The largest ice loading event ever recorded occurred in Norway in 1961 with 205 pounds of ice per linear foot of utility line. (Fikke et.al. 2008) One of the thickest ice accumulations (i.e. radius) recorded was 3.5 inches in Iceland. (Fikke et.al. 2008) The radial thickness of damaging ice accumulations on wires was observed on 1689 sites in the United States where average thickness was >0.5 inch, with a maximum of >2 inches occurring in the South where ice storm durations are longer and moisture availability is greater than in the North. (Changnon 2003)

Relatively small ice accumulations can have large impacts. For example, ice thickness of ~0.6 inch can begin to generate flash overs on electrical insulators and can sometimes generate icicles long enough to bridge insulators. (Laflamme & Periad 1998) Ice thickness of ~0.2 inch can change how utility lines move in strong winds, causing line "galloping" – wide waves moving along lines. (Laflamme & Periad 1998) The faster the wind speed in an ice storm, the greater accumulation of ice on trees, covering all sides of stems and branches. (Houston & Changnon 2007) Ice accumulation and wind become a terrible combination for trees to resist.

Iced Trees

Ice accumulation is not uniform, consistent, and constant within one ice storm event. As liquid precipitation falls and is supercooled, collisions with below freezing branches or other tree surfaces can take several forms. The liquid which does not freeze on contact runs off to each side of (or along) a branch, and can form icicles. Figure 2. Icicles usually form directly beneath a branch and do not receive direct freezing rain impact under light winds.

As wind speeds increase, any runoff tends to be blown to the leeward side of a branch and is shielded from direct wind driven freezing rain, but does recieve indirect (i.e. eddy, vortext, turbulence, etc.) precipitation. Icicles freeze from the outside inward, with internal films of liquid water eventually freezing. (Jones 1996) Ice accumulation on a tree is determined by the portion of a supercooled water droplet which freezes onto a branch, and the rate of freezing, which determines the amount of ice accumulation and its shape on and around a tree branch. (Jones et.al. 2002)

Ice Capture

As liquid precipitation drops of various sizes fall, they impact horizontal surfaces on a tree. As wind increases, it imparts a horizontal movement to freezing rain and any drips from partial freezing. Winds push on droplets as they fall, generating swirling eddies and vortexes around branches, and move branches around. Wind provides dynamic deposition of ice on many, if not all, tree surfaces not just those horizontally orientated to freezing rain. As ice accumulates on a branch, branch diameter and surface area increase, providing a larger freezing rain interception area. (Jones 1996)

The ice capture area increases with ice accumulation. The formula for this ice capture area increase is:

branch surface area and diameter increase (in decimal percent)
with added surface ice accumulation =
[(branch diameter in inches + (2 * ice thickness in inches) * 37.7) /
(branch diameter in inches * 37.7)] - 1.

For example, if 0.5 inches of ice has accumulated around a branch per linear foot, derived from 1.4 inches of freezing rain, a 4 inch diameter branch would become a 5 inch diameter branch. The branch diameter and its surface area is increases by 25%. With this formula, the greatest percent change in surface area and diameter of a branch with ice accumulation are at the smallest branch sizes.

The fate of freezing rain striking tree structures, which have temperatures less than 32^{o}F include: (Makkonen 1998) (Jones 1996)

1. Completely freezes on contact into surface ice;
2. Almost complete freeze with some water sliding off the side expanding the area of surface ice;
3. A mix of contact freeze and liquid, with some water moving around sides to the underside and freezing.
4. A mix of contact freeze and more liquid, with water flowing around sides to underside and freezing into icicles;
5. Some water freezes as surface ice, some as icicles, and the rest drips off.

Icicles

At warmer temperatures, icicles hanging below a branch may account for the largest portion of ice accumulation. These icicles from warmer temperatures and slower freezing rates will be long and thin. At lower temperatures, impinging precipitation freezes where it strikes, causing a top surface ice layer or a cylindrical sleeve of ice around a branch. At intermediate temperatures, water flows slightly before freezing, causing thicker ice on sides and bottom of a branch. Any icicles formed from faster freezing rates will be short and thick. (Jones et.al. 2002) Figure 3.

Icicles form from freezing rain because not all the water completely freezes on surface contact. This is termed "wet" ice growth. As icicles grow, more surface area is available for more freezing rain capture and more associated icicle growth. A commonly observed icicle density on power lines is roughly 13 per foot of line before icicles begin to coalese. (Makkonen 1998) Ice accumulation cross-sectional shapes on a branch can range from: crescent shaped on one side; round enclosing; enclosing with a few icicles; heavy icicles; and, flattened, dangling ice sheath from fused icicles. (Jones 1996) Figure 4.

Wet or Dry?

As freezing rain impacts a surface with a temperature below freezing, ice can accumulate in a dry growth or accumulation form, which means all liquid freezes upon contact and no liquid remains. Figure 5. A wet growth or accumulation form, usually has >26% liquid remaining after initial impact with the branch, which allows water to flow away from the impact site, but be retained primarily by icicles. Wet growth ice accumulation has a lower density and is more spongy than dry growth form ice. Total ice loads formed near 32^{o}F are much greater than ice loads formed at lower temperatures. (Makkonen 1998)

At higher wind speeds, wet growth greatly increases ice loads on branches due to increasing surface capture area (radial ice on branch surface + icicle ice held below and leeward on branch). (Makkonen 1998) Whatever the shape and thickness of any tree accumulated ice, all ice on tree tissue will impact further ice accumulation. The shape of accumulated ice, and the amount of ice, will change branch drag coefficients (affecting both drag and lift), and the wind loading on any branch. (Jones et.al. 2002)

Layered

As freezing rain falls without wind to provide lateral movement, flat horizontal surfaces of equal dimensions open to falling precipitation will accumulate equal amounts of ice. Figure 6 presents a flat surface and a round surface under the same amount of freezing rain. If the width of the flat surface is equal to the diameter of the round surface, both will intercept equal amounts of ice. The round surface will have the same amount of ice spread over a larger surface area.

Figure 7 shows two flat surfaces (below freezing), one horizontal and one vertical. Both are in freezing rain which is falling at a rate of 1.0 inch per hour. The amount of ice accumulated per hour on both surfaces are shown. Remember ice is less dense and takes up more space than liquid water. Without any lateral force (i.e. wind) acting on falling freezing rain, only the horizontal surface accumulates ice.

Figure 8 presents the same set of flat surfaces (below freezing) in a 4.5mph wind. The wind provides a lateral force on falling freezing rain. The freezing rain in the figure is again falling at 1.0 inch per hour. Ice accumulation on both surfaces are shown. In this case (with this wind speed) the vertical surface accumulates the same amount of ice as the horizontal surface.

Icy!

If two flat surfaced 1 X 4s (below freezing) are placed separatly in freezing rain, which is falling at 1 inch per hour, each will accumulate ice. Figure 9. If one is in wind, all surfaces will tend to be coated in ice, due to lateral force on falling freezing rain droplets and turbulence. For the object not in wind, it is subject to ice accumulation only on its upper surface. Under the same freezing rain amount falling, each object will have different amounts of ice thicknesses accumulated.

If one 1 X 4 object and one circular object (diameter = 4) are placed seperately in freezing rain falling at 1 inch per hour with wind, each (below freezing object) will accumulate different ice thicknesses. Figure 10. The rectangular object will accumulate ice around its perimeter of 0.44 inches, while the circular object, of the same interception width, will accumulate ice of 0.35 inches. The circular object has a greater surface area than the rectangular object, and will have the same amount of freezing rain spread around its larger surface leaving a thinner ice layer.

Figure 11 shows two circular objects (below freezing) under a freezing rain fall of 1 inch. One is under no wind and one is under wind. Falling percipitation without lateral wind forces, freezes to the top of the object. Ice accumulates to a layer thickness of 0.71 inch. The object in wind has an ice layer all the way around due to lateral force of the wind. This object accumulates an ice layer of 0.35 inches. Note, little wind is required to begin spreading ice accumulation around an object.

Flats

Ice accumulation from freezing rain striking a flat horizontal surface is proportional to the hourly freezing precipitation rate in inches per hour. Ice accumulation from freezing rain on a flat vertical surface is proportional to the precipitation rate in inches per hour and wind speed in miles per hour. The formulae are given below: (Yip 1995)

ice accumulation on horizontal flat surface in inches =
precipitation rate in inches per hour

ice accumulation on vertical flat surface in inches =
0.078 * (hourly wind speed in miles per hour) *
(precipitation rate in inches per hour) $^{0.88}$

In The Wind

Without wind, only the top half of a branch is open to falling freezing rain, and so, accumulates ice. In most storms, there is usually some level of wind providing a lateral motion to falling freezing rain. Figure 12 shows the faster wind velocity, the greater ice accumulation. In addition, any wind load will cause an osillation in twig and branch motion, which also causes a wider spreading ice accumulation layer. Using the formula above for ice accumulation on a vertical flat surface, several consequences of ice on branches are revealed. (Yip 1995)

Without wind, ice can not accumulate around a branch, just on the top side open to falling freezing rain. With a 4.5 mph wind speed, horizontal and vertical forces controlling ice accumulation become equal. Above a 4.5 mph wind speed, lateral forces of wind are greater than simple gravity fall for accumulating ice on a branch. At a 2.25 mph wind speed, lateral force on ice accumulation is 50% of gravity fall. At a 0.2 mph wind speed, lateral force is just 5% of gravity fall impact on freezing rain. (Yip 1995)

Changing States

Any ice accumulated will be ~1.1 times thicker in inches than liquid water in inches deposition rate, because water is less dense and expands, as it changes states from liquid to solid. Ice accumulation will be at least 10% less dense than the freezing rain source. (Yip 1995) Water density is 1 g/cc and ice density is 0.9 g/cc. (Yip 1995) (Jones et.al. 2002) A 0.39 inch freezing rainfall will result in a uniform 0.43 inch ice layer. (Jones 1998)

For example, a 1 inch diameter branch intercepts and holds the same depth of ice as a 1 inch wide flat surface. The ice accumulation for a round cross-section branch is 35% of the freezing rain volume falling. If 1 inch of freezing rain falls, a 1 inch diameter branch would accumulate roughly a 0.35 inch ice layer around a branch. The amount of freezing rain falling can be multiplied by 1.1 for its volume converted to an ice state, divided by 3.14 (pi) for conforming to a round branch surface area (or the freezing rain amount in inches multiplied by 0.35). (Jones 1996)

Determining Thickness

To determine ice accumulation on a tree branch, ice accumulation on a horizontal flat surface and a vertical flat surface can be combined to generate an uniform radial thickness. (Yip 1995) Note, the correction factor for small diameter branches has been ignored.

uniform radial ice accumulation thickness = (modified from Yip 1995)
$$\left[\left((\text{horizontal surface accumulation in inches})^2 + (\text{vertical surface accumulation in inches})^2 \right)^{0.5} + (0.5 * \text{branch diameter in inches})^2 \right]^{0.5} - (0.5 * \text{branch diameter in inches}).$$

Another estimate of ice accumulation (IA) using precipitation in inches and wind speed in miles per hour is: (Jones et.al. 2004)

ice accumulation in inches = IA in inches =
$$0.35 * (\text{amount of freezing rain expected in inches}) * \left[1 + (\text{wind velocity in mph} / 10)^2 \right]^{0.5}.$$

As ice accumulation (IA) values reach and exceed 0.25 inches of depth, tree damage can be significant. (Jones et.al. 2004)

Simple Ice

A uniform radial ice thickness on a branch is a combination of falling precipitation plus wind driven precipitation. A model has been developed for ice accumulation termed the “simple” model. This model is termed simple because it does not use complex heat flow components. (Jones 1998)

The simple model of ice accumulation per hour is given as: (Jones 1998) (Jones et.al. 2002)

uniform radial ice thickness in mm =
$$(\text{hours of storm} / 2.8) * \left[(\text{precipitation rate per hour in mm})^2 + \left[3.6 * (\text{wind velocity in m/s}) * (0.067 * (\text{precipitation rate per hour in mm})^{0.846} \right]^2 \right]^{0.5}.$$

This formula estimates total ice accumulated for an entire ice storm, using hourly precipitation rates and ice storm duration. Figure 13 presents a graphical representation of the simple model. This figure shows ice accumulation under various wind speeds and precipitation rates.

Ice Weight

The weight of any ice accumulated on a branch can be determined by: (Jones et.al. 2004)

ice weight on branch in pounds per cubic inch =
$$0.1 * (\text{branch length in inches}) * \left(\left((\text{branch diameter in inches}) * (\text{ice accumulation in inches}) \right) + (\text{ice accumulation in inches})^2 \right).$$

The associated ice accumulation formula for a tree branch, using ice weight as determined above, and assuming no taper for a measured branch length, is: (Jones et.al. 2004)

ice accumulation in inches =
(-branch diameter in inches / 2) + [((branch diameter in inches) ^{2} / 4) +
(ice weight in pounds per cubic inch) / (0.1 * branch length in inches))] $^{0.5}$.

Summarizing Ice Thickness

Ice accumulation amounts on a branch is dependent upon the surface area of a branch. Branch surface area can be considered the maximum ice capture area of a branch under dry ice growth. Figure 14. Branch surface area per linear foot of branch (assuming no taper) can be estimated by:

branch surface area (BSA) in square feet =
maximum ice capture surface area in square feet =

branch diameter in inches * 37.7.

The thickness of ice accumulated, in an uniform sheath around a branch (assuming a circular cross-sectional shape), can be estimated by: Figure 15.

uniform radial ice accumulation thickness (RIAT) in inches =
freezing rain precipitation in inches * 0.354. (under windy conditions)

OR

uniform radial ice accumulation thickness (RIAT) in inches =
freezing rain precipitation in inches * 0.707. (under no wind – dead calm conditions)

A formula for estimating ice mass accumulated per linear foot of branch is given as:

ice weight per linear foot of branch =
branch surface area (BSA) in square inches *
uniform radial ice accumulation thickness (RIAT) in inches *
0.0325 pounds per cubic inch.

OR, in a more simplified form:

ice weight per linear foot of branch =
freezing rain precipitation in inches * branch diameter in inches * 0.434.

Note, ice density used here is 0.0325 pounds per cubic inch (or 56.2 pounds per cubic foot), which is equivalent to metric ice density of 0.9 g/cc. Figure 16.

The Problem !

Most models of ice accumulation must assume a uniform layer around a branch or over a surface. Under the dynamic and variable (i.e. chaotic) nature in and around a tree crown, actual ice accumulation amounts and layer shapes are not uniform. Ideal ice accumulation shapes range from a thin crescent on one side of the branch to heavy icicle shapes. (Jones 1998) Actual ice shapes and thickness are as variable as tree crown shape, size, and periderm texture.

Windy Ice

Because of dynamic wind loading throughout a tree crown – freezing rain falling from above and freezing rain being blown in from the side – coupled with twig and branch movement and structural issues of supporting additional weight -- ice accumulation in trees presents complex mechanisms.

For example, wind impacts alone can be confusing. Wind has been shown to equal ice accumulation impacts of falling freezing rain with wind speeds of 4.5 mph or greater. (Yip 1995) In another study, falling freezing rain and lateral wind force were found to be equal in accumulating ice on tree branches at wind speeds around 11 mph. (Jones 1998) (Jones et.al. 2002)

Never Alone

No component which impacts freezing rain delivery and deposition onto a branch acts alone and independently. Ice accumulation and wind, around a moving tree crown, generate highly variable ice related tree damage. Moderate ice accumulations with strong winds generates similar damage in trees as do heavy ice accumulations with gentle winds. (Lemon 1961)

Wind speed is critical in freezing rain events because it provides for lateral ice accumulation loads, and accentuates tree failures. Average wind speed during ice storms was recorded in one review as ~11mph, with maximum wind speed measured at ~27 mph. (Rauber et.al. 2001) Measured single wind gusts have ranged from 30-60 mph. Precipitation rates will remain the same onto a horizontal surface, but increasing wind speed (and turbulence) will increase ice accumulation onto vertical surfaces, thus increasing radial ice accumulation around a branch. (Yip 1995)

Icy Wind

One method for appreciating the combination of ice accumulation and wind speed on ice storm severity is through using the Sperry-Piltz Ice Damage Index. Figure 17. This index has been found to work well, especially for utility applications. The Sperry-Piltz Index demonstrates an increasing severity rating (from 0-5 -- 5 is the most severe) with both increasing ice accumulations and faster wind velocity. (NOAA 2009) Figure 18 is an image of the Sperry-Piltz Index.

Ice accumulation increases with tree height due to both increased precipitation capture (no self blocking), and increasing wind speed above the ground surface. (Yip 1995) (Jones et.al. 2002) Figure 19. In general, for every 33 feet increase in height above a 33 feet tall tree, ice accumulation increases by roughly 5% up to 98 feet in tree height, and roughly 3% beyond 99 feet. (Yip 1995)

Breaking Down

Tree branch breakage is a major cause of downed power lines, structure damage, and injury to other landscape features. When ice thickness reach 0.25 to 0.5 inches, there is significant twisting, bending, and breakage of tree tissues. Catastrophic tree damage occurs when ice accumulations reach 0.5 to 1.0 inches of ice. (Lemon 1961)

The amount of ice deposited on a tree is proportional to the surface area of twigs and branches under dormant Winter conditions. Deciduous trees carry less surface area than do evergreen trees. Evergreens trees are at a disadvantage in dealing with freezing precipitation due to increased ice deposition surface area, much of which is concentrated near the end of branches. (Lemon 1961)

Branch Geometry

The first tree components to break are twigs and branchlets with preformed abscission layers which shear off. The next tree tissues to fall away are structurally compromised branches (in the process of natural pruning or previously damaged). As a general rule, medium sized (diameter and length) tree branches have more resistance to twisting, bending, and breakage under ice loads than do extremely large or extremely small branches. (Lemon 1961) Tree tissues are resistant to breakage. Many twigs can accumulate more than 30 times their own weight and become more than 10 times their normal diameter under ice loads. (Lemon 1961)

A tree branch covered with ice becomes stiff, and continually changes where stress and strain concentration points are located, as wind velocity increases. (Jones et.al. 2002) Small amounts of ice accumulation on longer branches in moderate to high winds significantly change the pattern of branch movement. (Jones et.al. 2004) Ice covered branches continue to be impacted by wind throughout the time of ice deposition, and well after until the ice melts off. (Jones et.al. 2002) Figure 20.

Reorientated

Within tree crowns, twigs, branchlets and branches fall back against increasing ice and wind loads. This falling back against the wind, may lead to some breakage at faster wind speeds. Reorientating crowns with periferal and flexible components helps maintain more stable drag and prevents more catastrophic damage. Figure 21 shows the Coder Index of Tree Crown Reconfiguration for increasing wind loads. (Coder 2014) By the time a tree is under wind loads of 8 pounds per square foot of crown frontal surface area (~55mph wind), it has reorietated all it can.

The combination of wind and ice generates great changes in how tree fall back against the wind. As ice accumulates, it takes less wind to reach maximum crown reconfiguration. For example, with a significant ice accumulation, tree crown components becomes more stiff and less flexible, reaching a 100% reorientated stage at roughly one-half the wind speed and one-quarter the wind pressure per square foot. Figure 22 demonstrates the difference ice accumulation on tree crown parts has on the amount (i.e. reconfiguration class) of tree bending and flexing against the wind.

Conclusions

It should be noted that single features of ice storms like ice accumulation loads, ice storm duration, wind speeds, and variability of ice deposition across different topographic features and elevational differences do not individually determine potential for tree damage. Figure 23. It is the interaction of all these features which impact trees, in chaotic and dynamic applications, causing tree damage and failures. Ice storms crush and push trees to their structural limits.

Selected Literature

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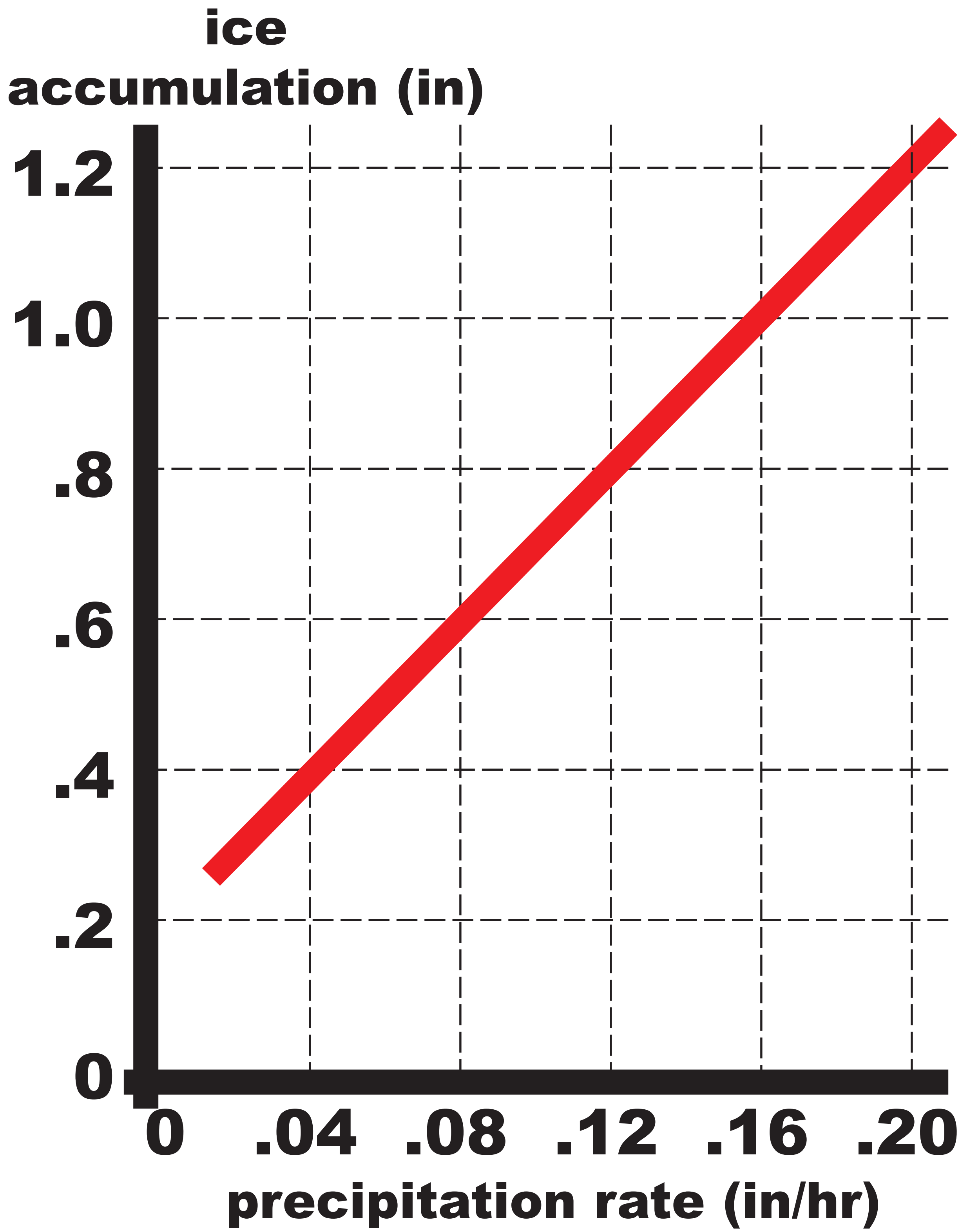


Figure 1: Impacts of precipitation rates (in/hour) on total ice accumulation (in.) in ice storms. (derived from Yip 1995)

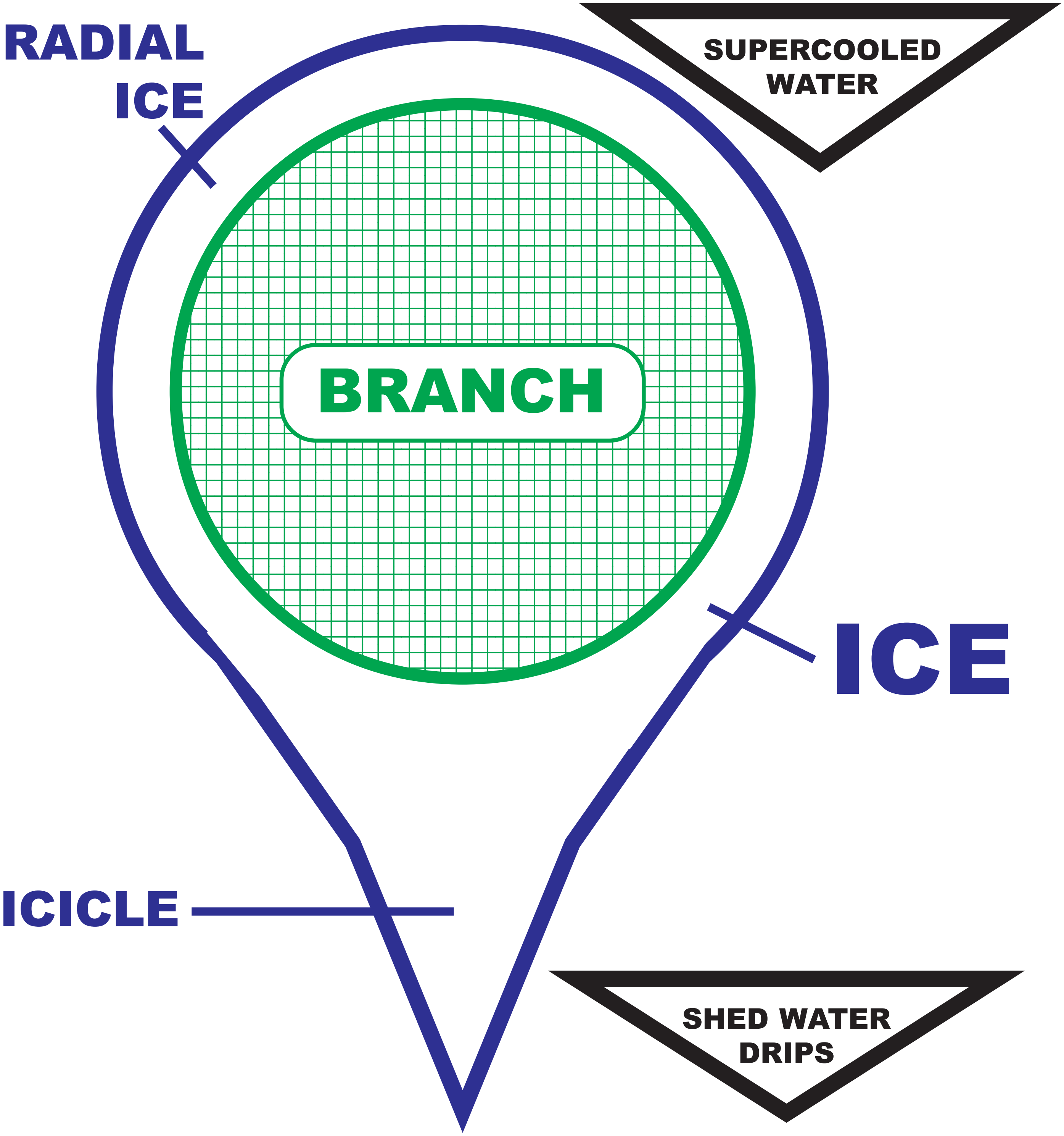


Figure 2: Glaze ice on tree branch cross-section (with a surface below freezing) in freezing rain.
(after Makkonen 1998)

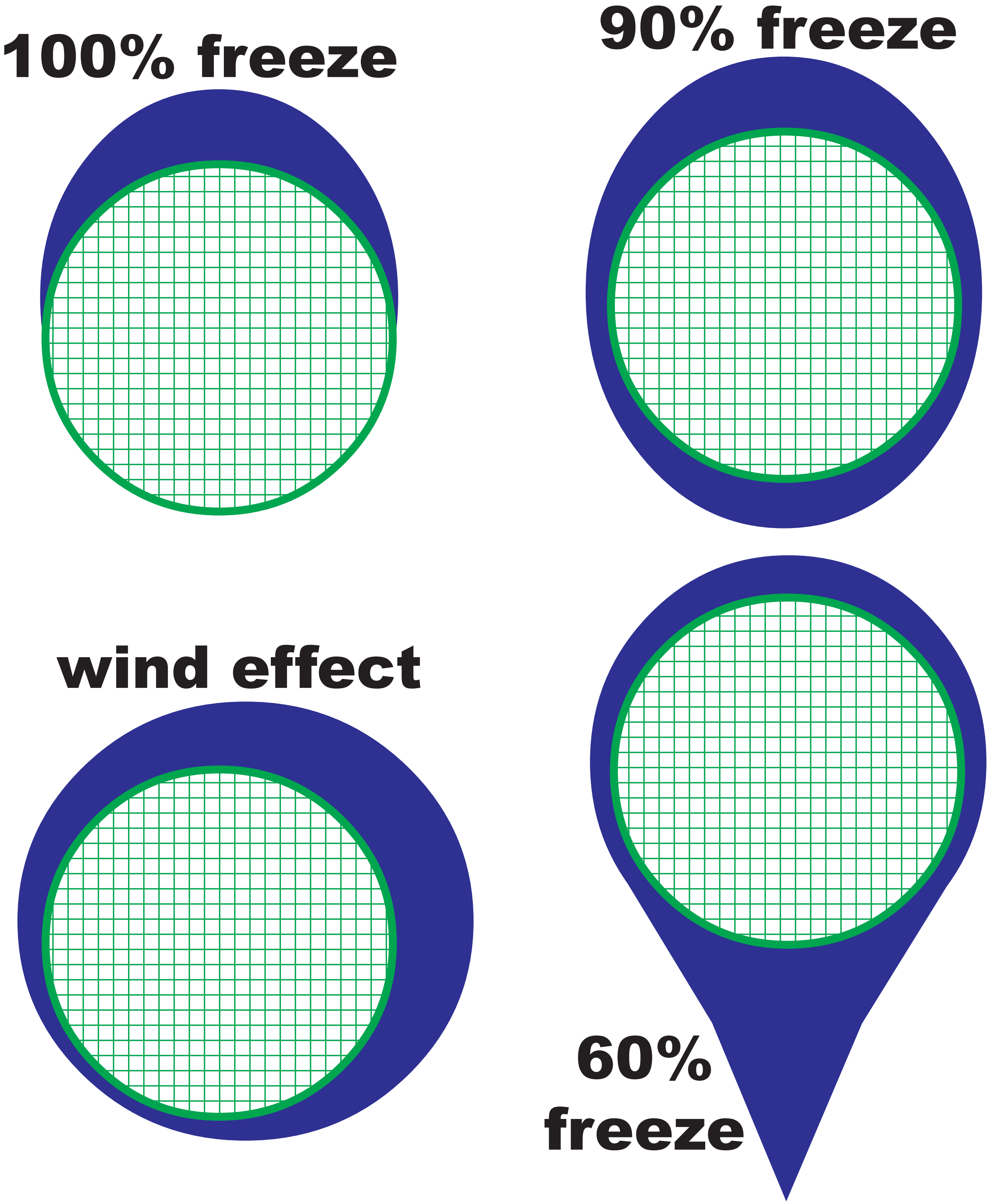


Figure 3: Extent of contact freeze for supercooled precipitation.

GENERAL ICE ACCUMULATION SHAPES ON BRANCHES

upper side crescent (dry)

round enclosing (dry)

round enclosing (wet) w/ small icicles

round enclosing (wet) w/ heavy icicles

elongated accretion (wet) [fused icicles]

Figure 4: Ice accumulation shapes from freezing rain impacts under no wind for dry ice growth (complete freeze on contact) and wet ice growth (partial freeze on contact).
(after Jones 1996)

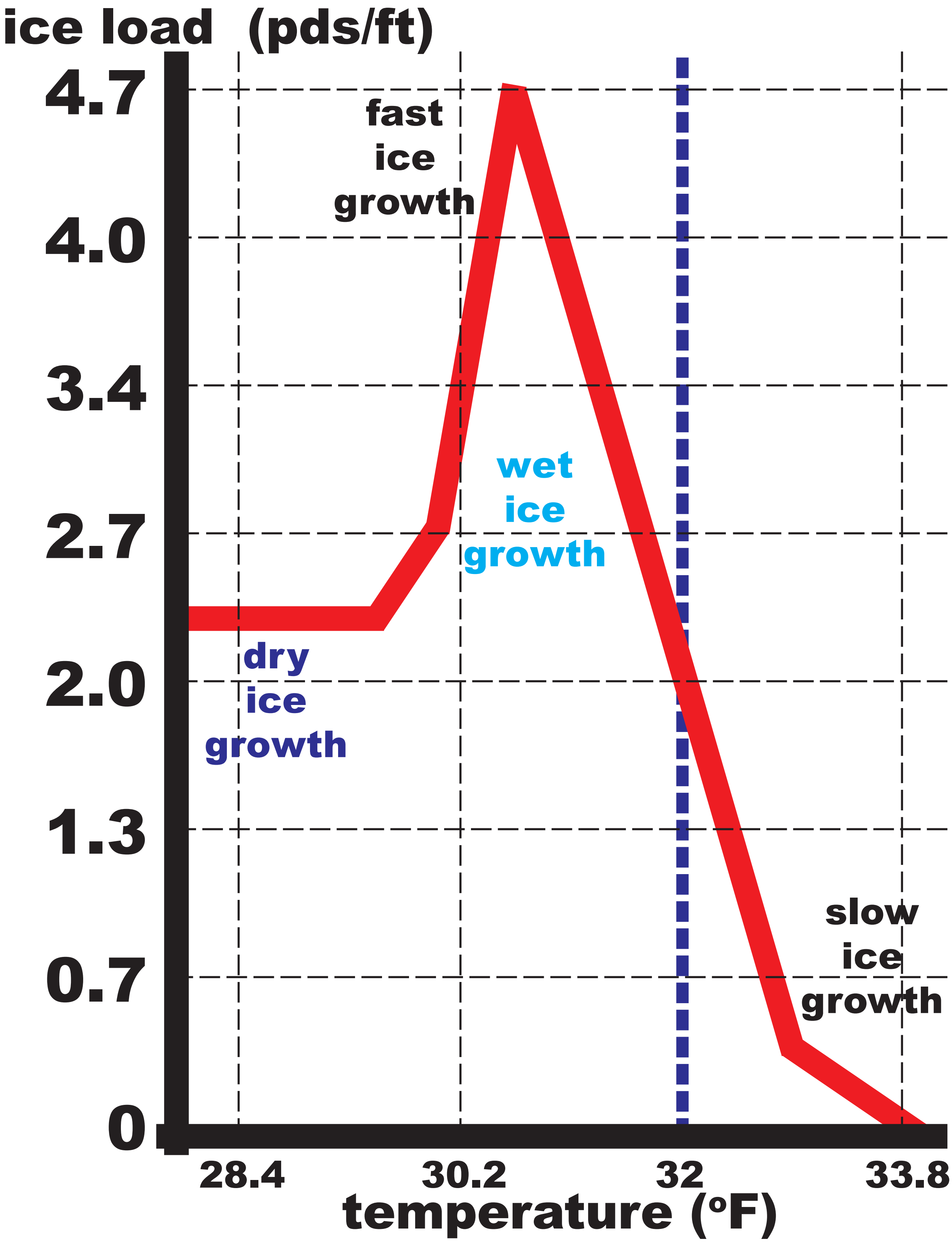


Figure 5: Temperature impacts on branch ice loads.
(derived from Makkonen 1998)

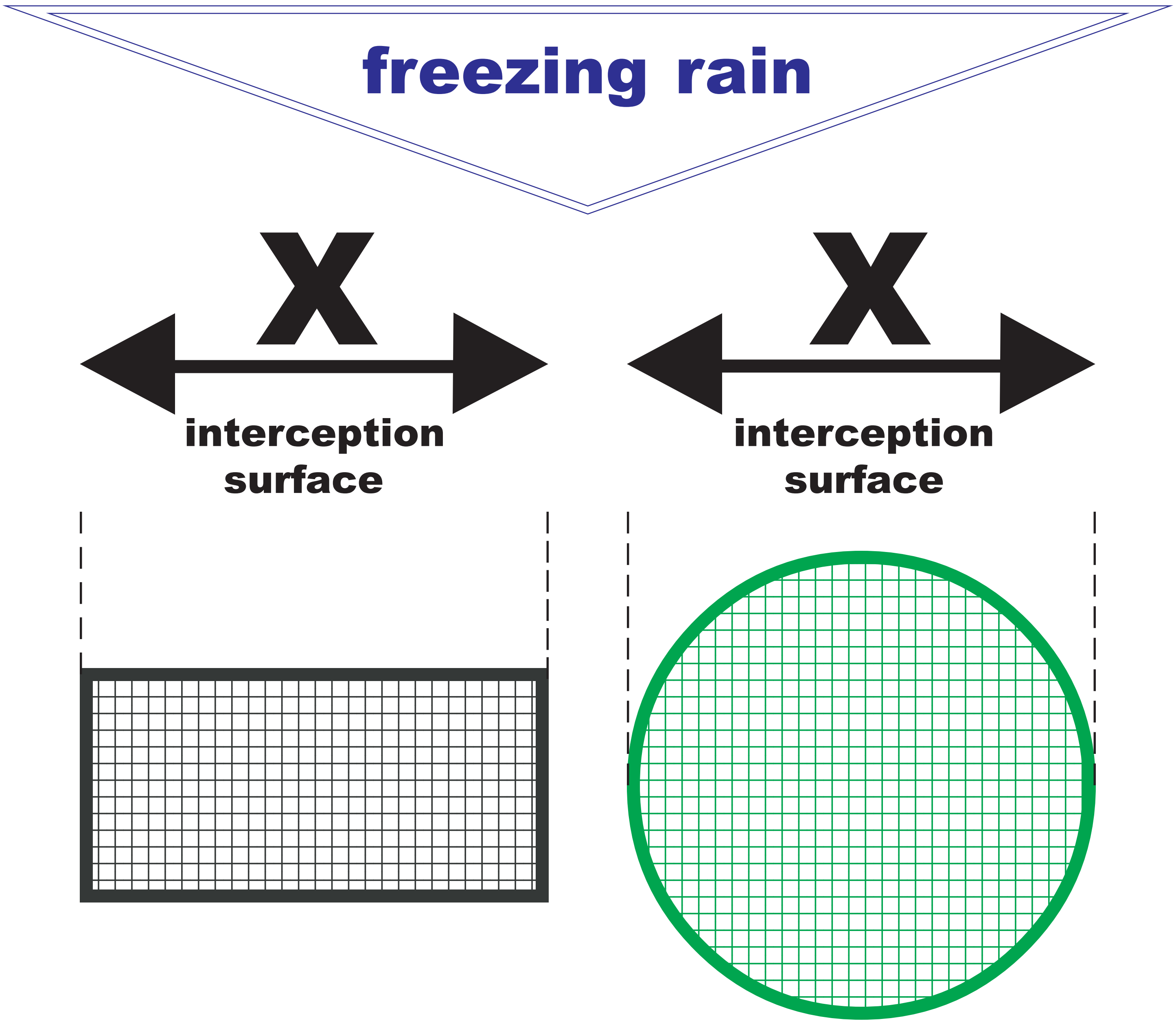


Figure 6: Freezing precipitation interception area on a round and flat surface are the same, if diameter and length dimensions are the same and no wind.
(derived from Jones 1996)

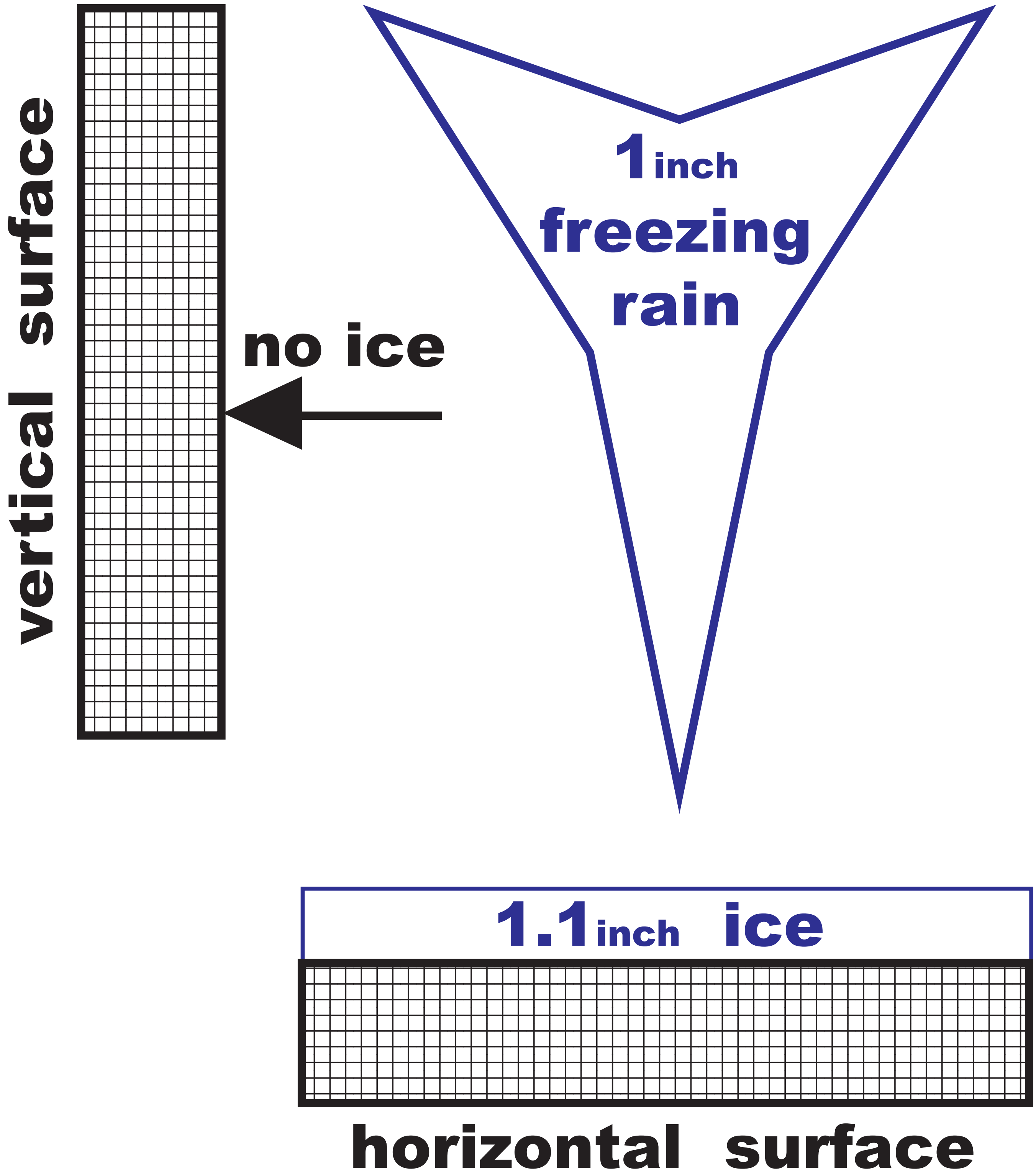


Figure 7: Freezing precipitation interception and ice accumulation on horizontal and vertical surfaces with no wind.
(uniform dry growth form of ice accumulation) (Jones 1996) (Yip 1995)

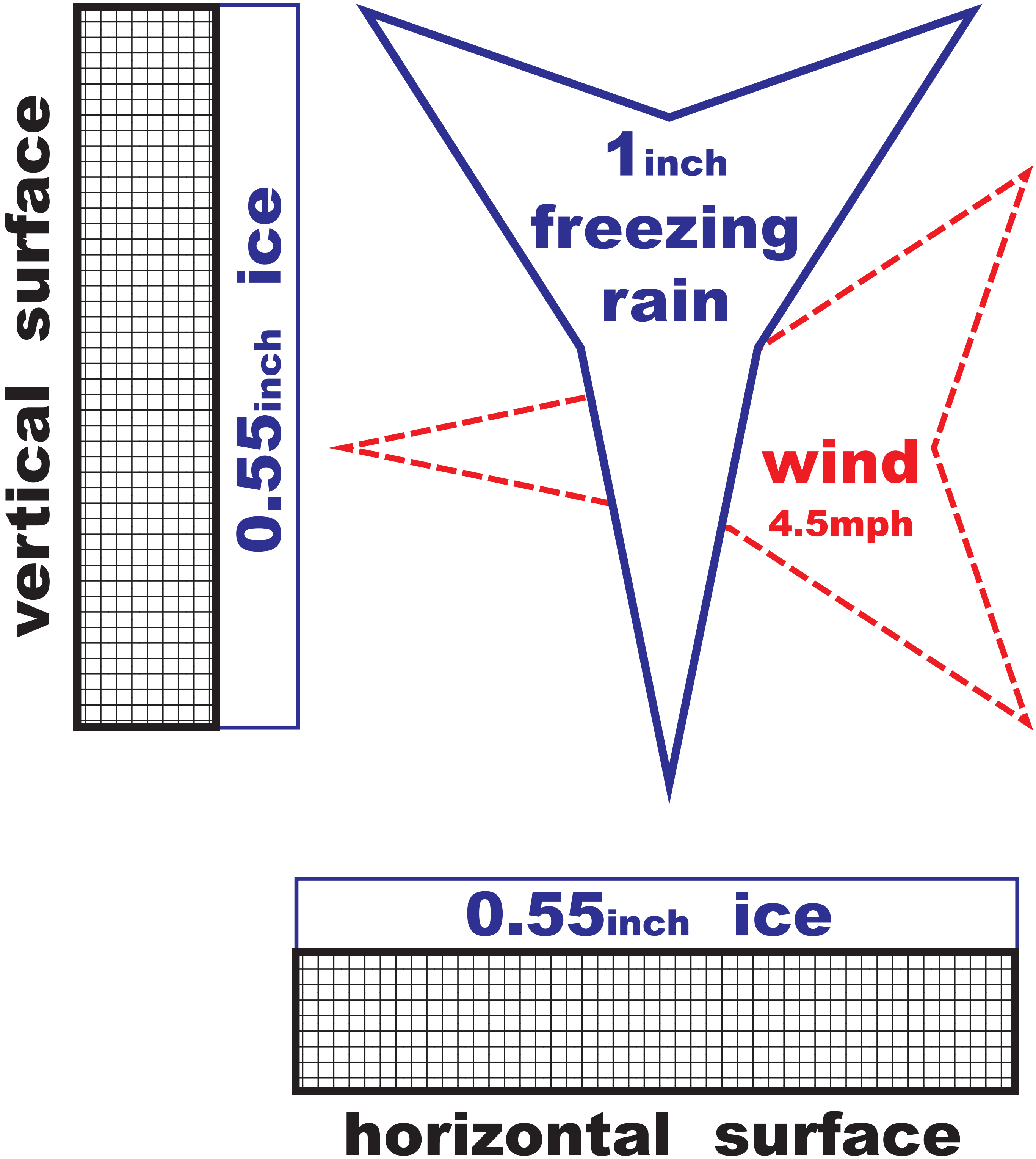


Figure 8: Freezing precipitation interception and ice accumulation on horizontal and vertical surfaces in wind.
(uniform dry growth form of ice accumulation) (Jones 1996) (Yip 1995)

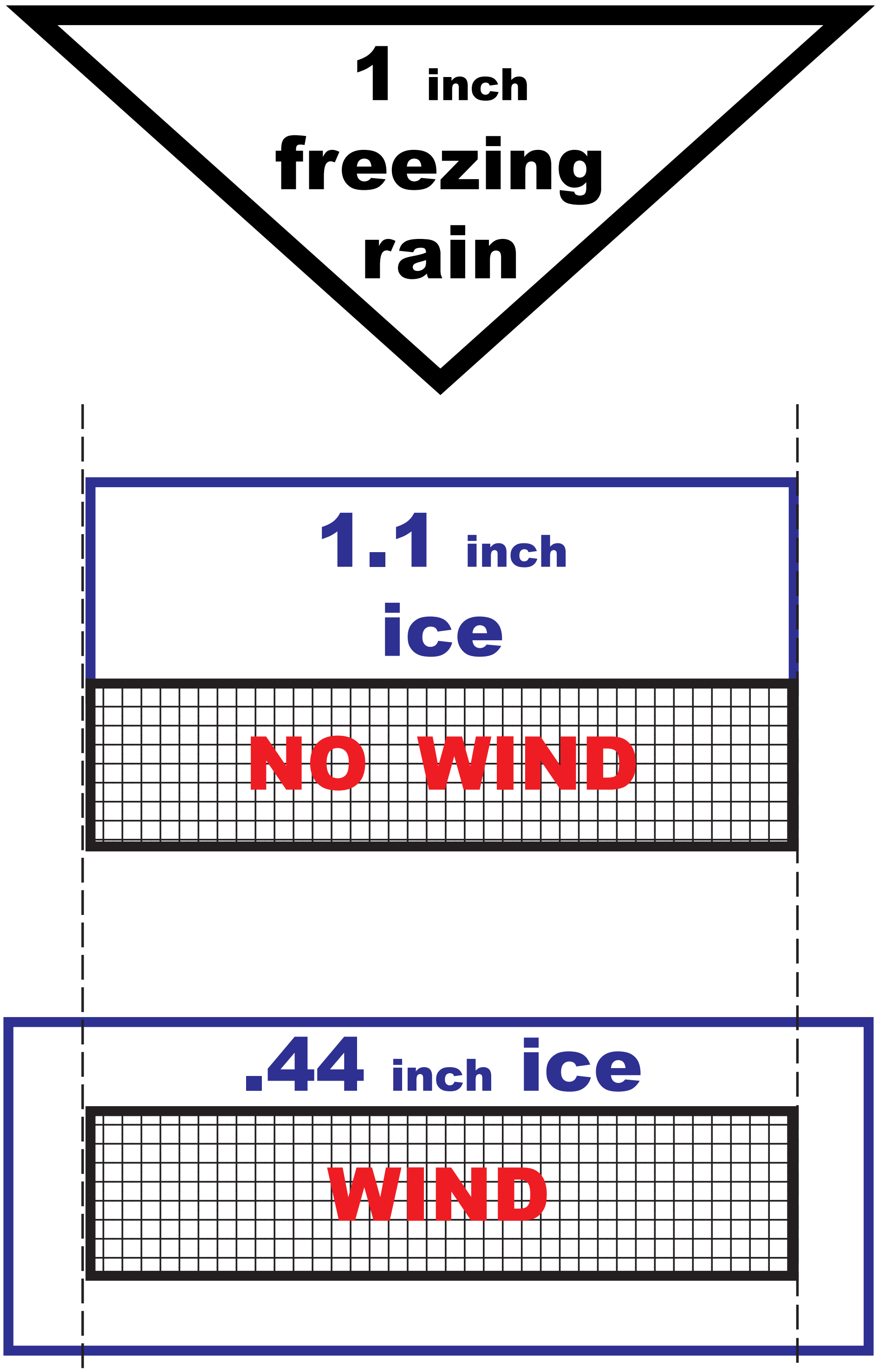


Figure 9: Freezing rain striking flat plates of equal size, and ice accumulation with and without wind.
(same depth freezing rain intercepted & uniform dry growth form of ice)
(Jones 1996) (Yip 1995)

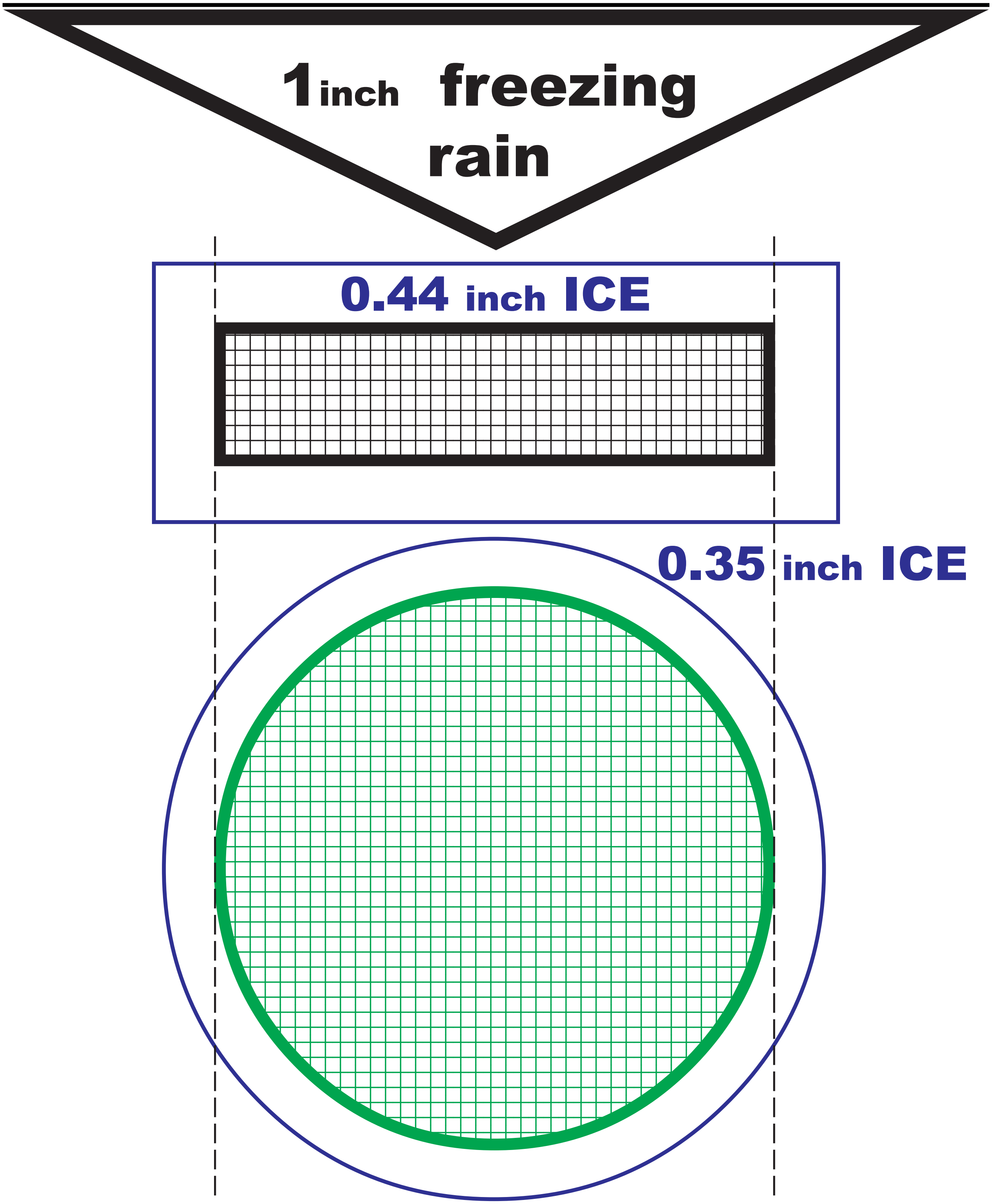


Figure 10: Freezing rain impacting a 1 X 4 inch flat surface, and a 4 inch diameter branch under wind. (Jones 1996) (Yip 1995)

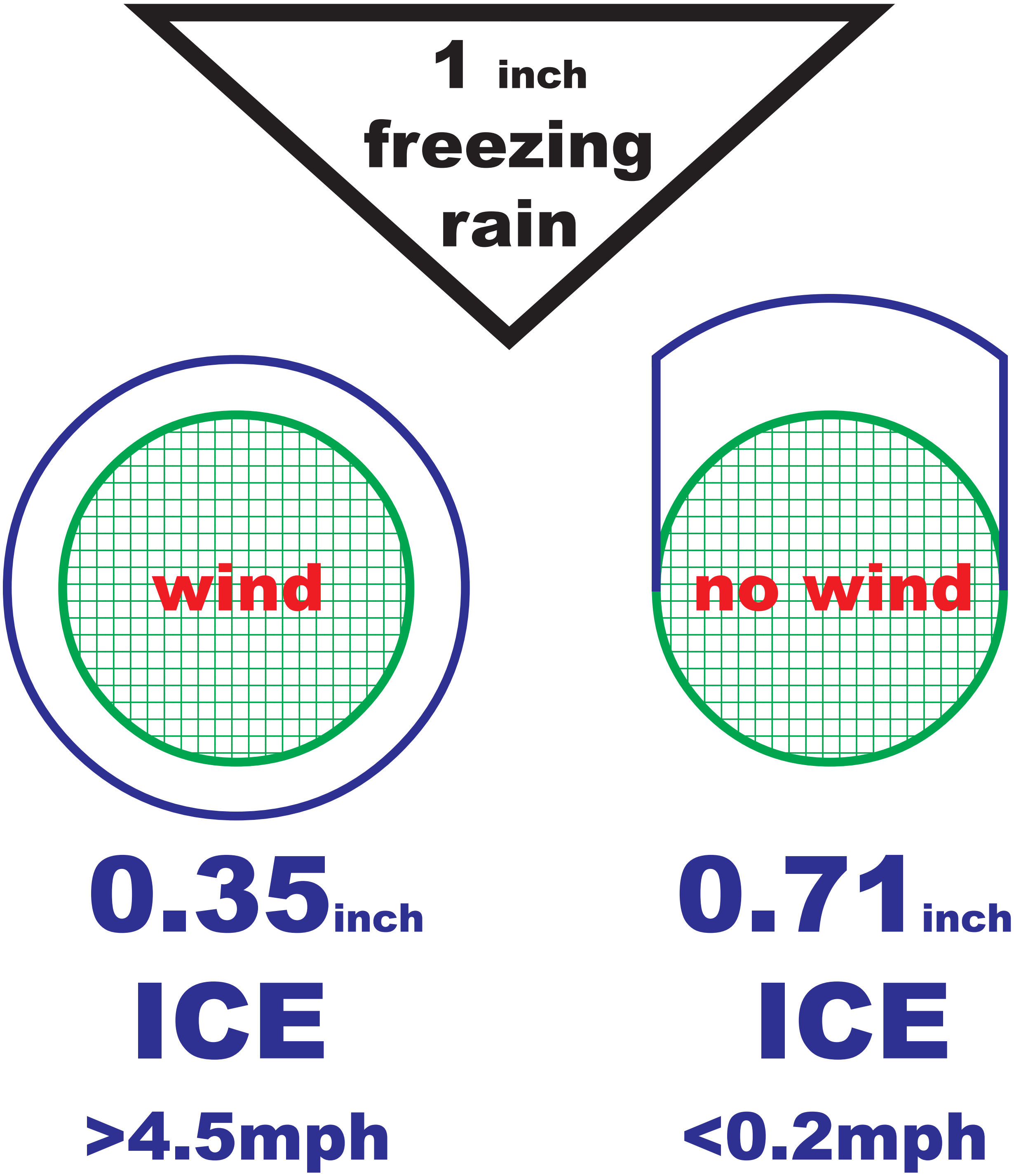


Figure 11: Ice accumulation on branches
with wind and no wind.
(same depth of freezing rain intercepted & uniform
dry growth form of ice accumulation)
(Jones 1996) (Yip 1995)

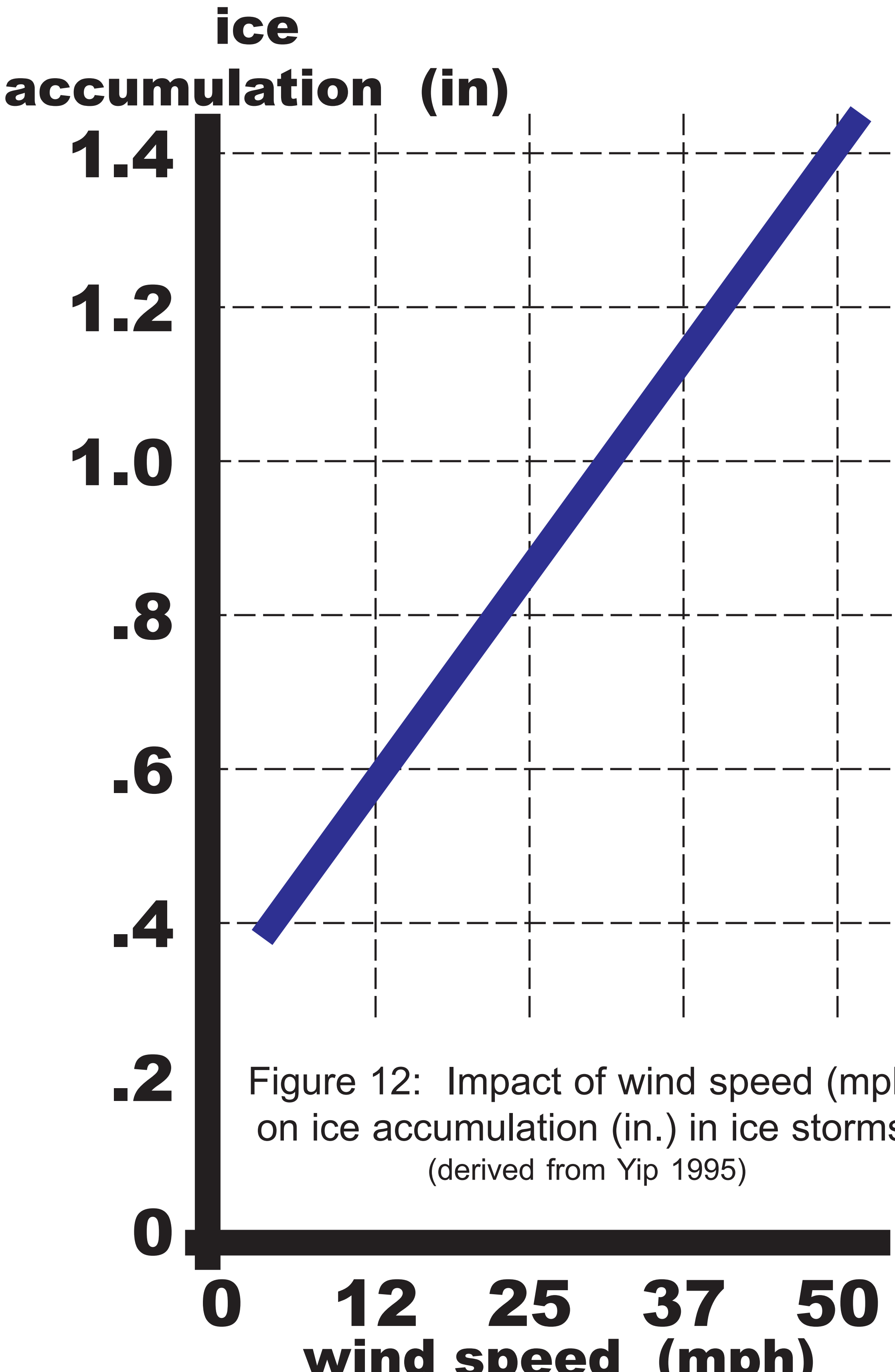


Figure 12: Impact of wind speed (mph) on ice accumulation (in.) in ice storms.
(derived from Yip 1995)

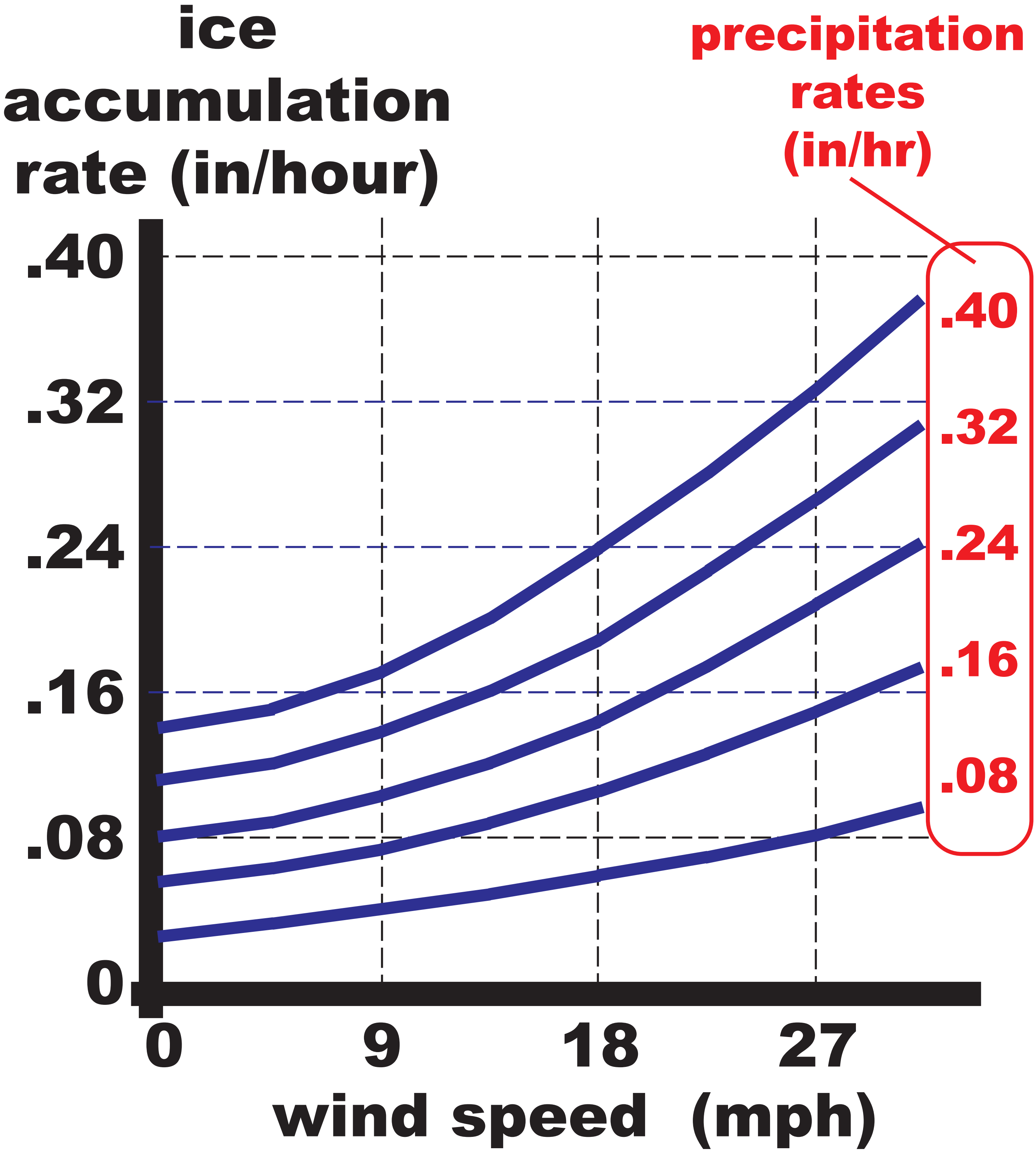


Figure 13: Uniform radial ice accumulation rate ("simple" model) under various wind and precipitation conditions.
(derived from Jones 1998)

branch diameter (inches)	surface area per linear foot (square inches)
1 in	38 in^2
2	75
3	113
4	151
5	189
6	226
7	264
8	302
9	339
10	377
12	452
14	528
16	603
18	679
20	754

Figure 14: Branch surface area (BSA) in square inches, or maximum ice capture area per linear foot of branch length (assuming no taper).
(Multiply BSA value by branch length (in feet) for total surface area.)

freezing rain (inches)	with wind	no wind
0.10	0.04in	0.07in
0.25	0.09	0.18
0.50	0.18	0.35
0.75	0.27	0.53
1.00	0.35	0.71
1.50	0.53	1.1
2.00	0.71	1.4
2.50	0.88	1.8

Figure 15: Uniform radial ice accumulation thickness (RIAT value) in inches, under both wind and no wind conditions, for various freezing rain amounts in inches.

branch diameter (inch)	uniform radial ice accumulation thickness (in)						
	0.1	0.2	0.3	0.4	0.5	0.6	0.7
1	.12 pds	.25	.37	.49	.62	.74	.86
2	.24	.49	.73	.98	1.2	1.5	1.7
3	.37	.74	1.1	1.5	1.8	2.2	2.6
4	.49	.98	1.5	2.0	2.5	3.0	3.4
5	.61	1.2	1.8	2.5	3.1	3.7	4.3
6	.74	1.5	2.2	2.9	3.7	4.4	5.1
7	.86	1.7	2.5	3.4	4.3	5.2	6.0
8	.98	2.0	3.0	3.9	4.9	5.9	6.9
9	1.1	2.2	3.3	4.4	5.5	6.6	7.7
10	1.2	2.5	3.7	4.9	6.1	7.4	8.6
12	1.5	2.9	4.4	5.9	7.4	8.8	10.3
14	1.7	3.4	5.2	6.9	8.6	10.3	12.0
16	2.0	3.9	5.9	7.8	9.8	11.8	13.7
18	2.2	4.4	6.6	8.8	11.0	13.2	15.5
20	2.4	4.9	7.4	9.8	12.3	14.7	17.2

Figure 16: Weight of accumulated ice in pounds per linear foot of branch for a given branch diameter and for various uniform radial ice accumulation thicknesses.
(assuming no branch taper and freezing rain deposition with wind)

catagory	severity description (wind mph & ice inches)
0	**= minimum risk - <0.25 ice & <15 mph**
1	**= local short term outages (1-2 hours) -**
	1a = low wind <15 mph & 0.25 - 0.5"
	1b = high wind 15-25 mph & 0.10 - 0.25"
2	**= scattered outages (8-12 hours) -**
	2a = low wind <15 mph & 0.5-.75"
	2b = medium wind 15-25 mph & 0.25-0.50"
	2c = high wind 25-35 mph & 0.1-0.25"
3	**= numerous outages (1-3 days) -**
	3a = low wind <15 mph & 0.75-1.0"
	3b = medium wind 15-25 mph & 0.50-0.75"
	3c = high wind 25-35 mph & 0.25-0.50"
	3d = severe wind >35 mph & 0.10-0.25"
4	**= prolonged & widespread outages (3-5 days) -**
	4a = low wind <15 mph & 1.0-1.5"
	4b = medium wind 15-25 mph & 0.75-1.0"
	4c = high wind 25-35 mph & 0.5-0.75"
	4d = severe wind >35 mph & 0.25-0.50"
5	**= catastrophic damage (>1 week) -**
	5a = any low wind mph & >1.5"
	5b = medium wind 15-25 mph & 1.0-1.5"
	5c = high wind 25-35 mph & 1.0-0.75"
	5d = severe wind >35 mph & 0.5-0.75"

Figure 17: Sperry-Piltz utility ice damage index (SPIA Index) uses radial ice accumulation and wind speed to set severity categories 0-5. (NOAA 2009)

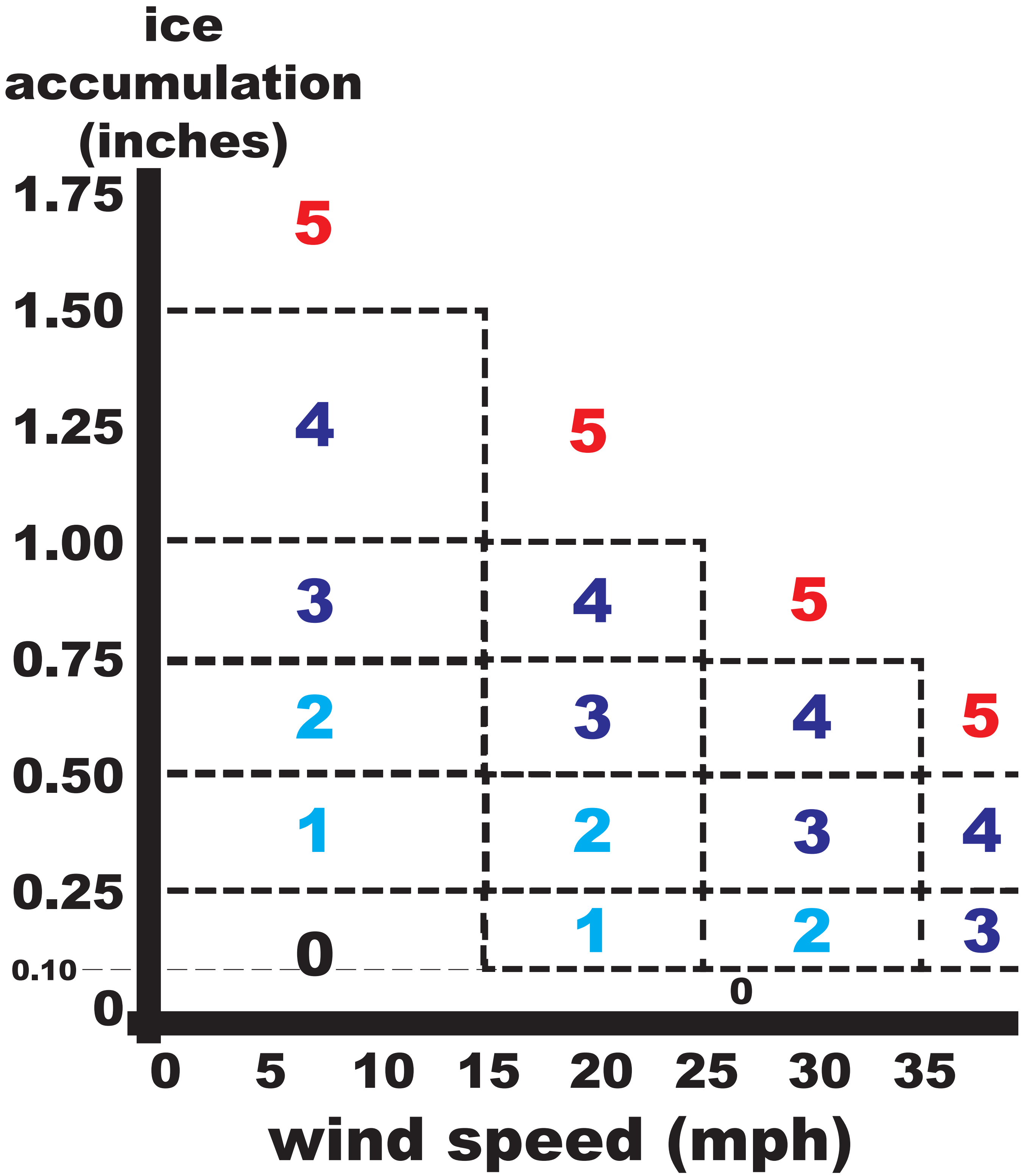


Figure 18: Determining SPIA Index severity catagories using ice accumulation (inches) and wind speed (mph).
(derived from NOAA 2009)

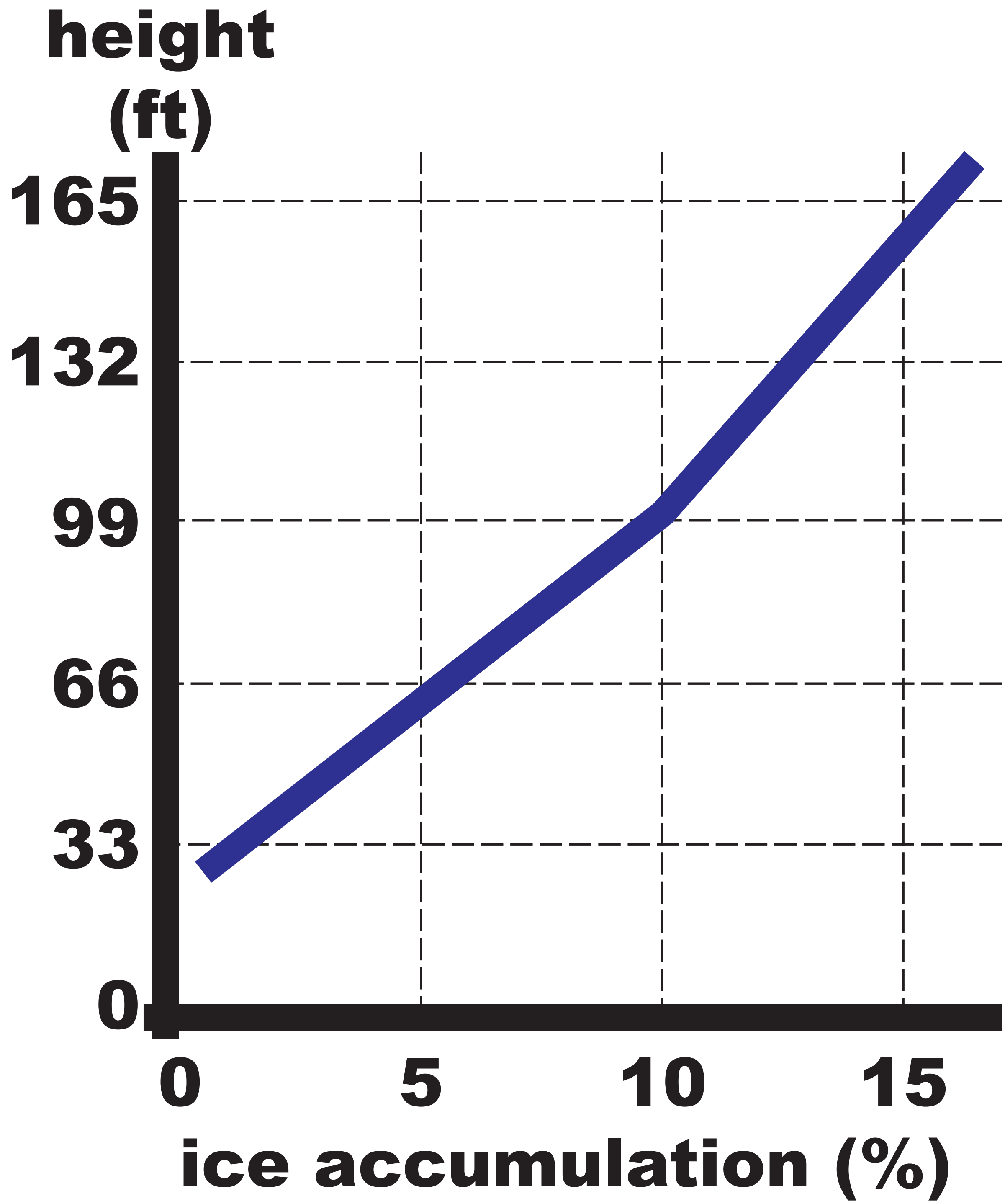
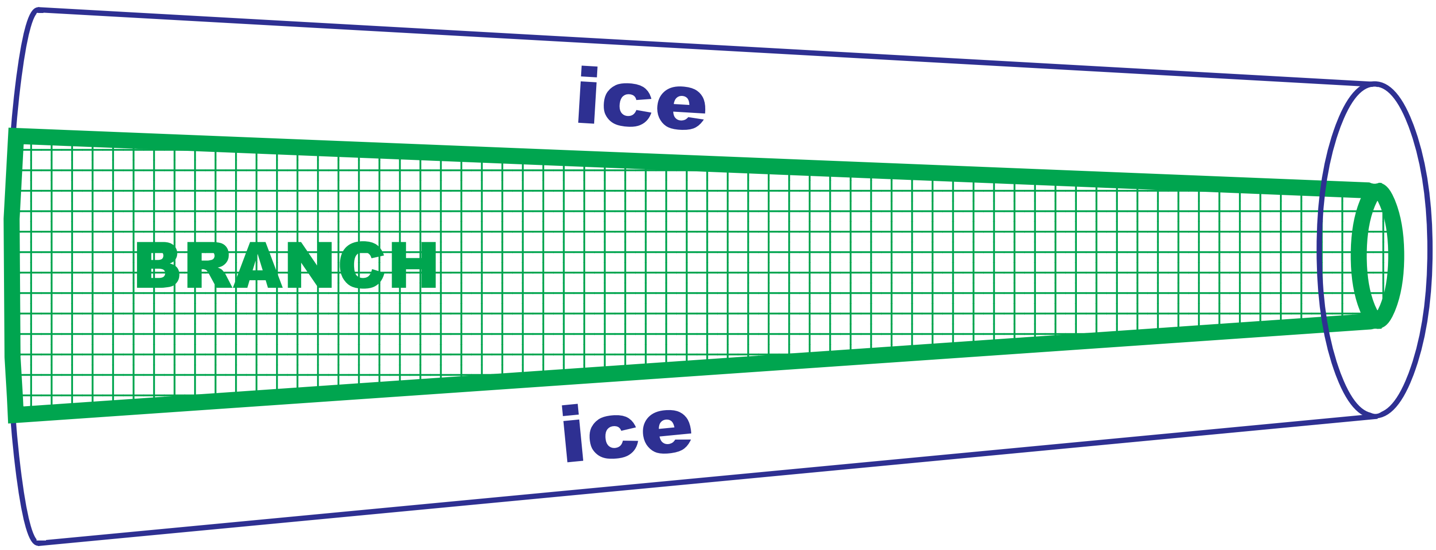


Figure 19: Amount of ice accumulation (percent increase) with added tree height.
(derived from Yip 1995)



BRANCH CHANGES:

increase branch diameter

increase volume / surface area

increase stiffness

decrease flexibility

increase weight

increase drag coefficient

Figure 20: Addition of ice on a branch can greatly disrupt structural / mechanical properties, especially under wind loads.

index value	wind speed (mph)	wind pressure (lbs/ft2)	tree crown reconfiguration descriptor	tree crown reconfiguration value (%) wind	tree crown reconfiguration value (%) wind+ice
C0	0	0	gravity impacts only	0%	[10%]
CI	10	0.3	petiole & blade deforming, & twig sway	5%	[30%]
CII	19	1.0	leaves rolled back & large peripheral twigs sway	10%	[60%]
CIII	28	2.0	twigs pulled back & peripheral branches sway	25%	[100%]
CIV	37	3.6	branches pulled back & stem sway	45%	–
CV	46	5.6	twig breakage, stem pushed / held downwind	70%	–
CVI	55mph	8.0lbs/ft2	twig & branch breakage (~ T1 threshold)	100%	–

Figure 21: Coder Index of Tree Crown Reconfiguration under wind load (drag coefficient = 1.0), and under wind + ice load. (Coder 2014)

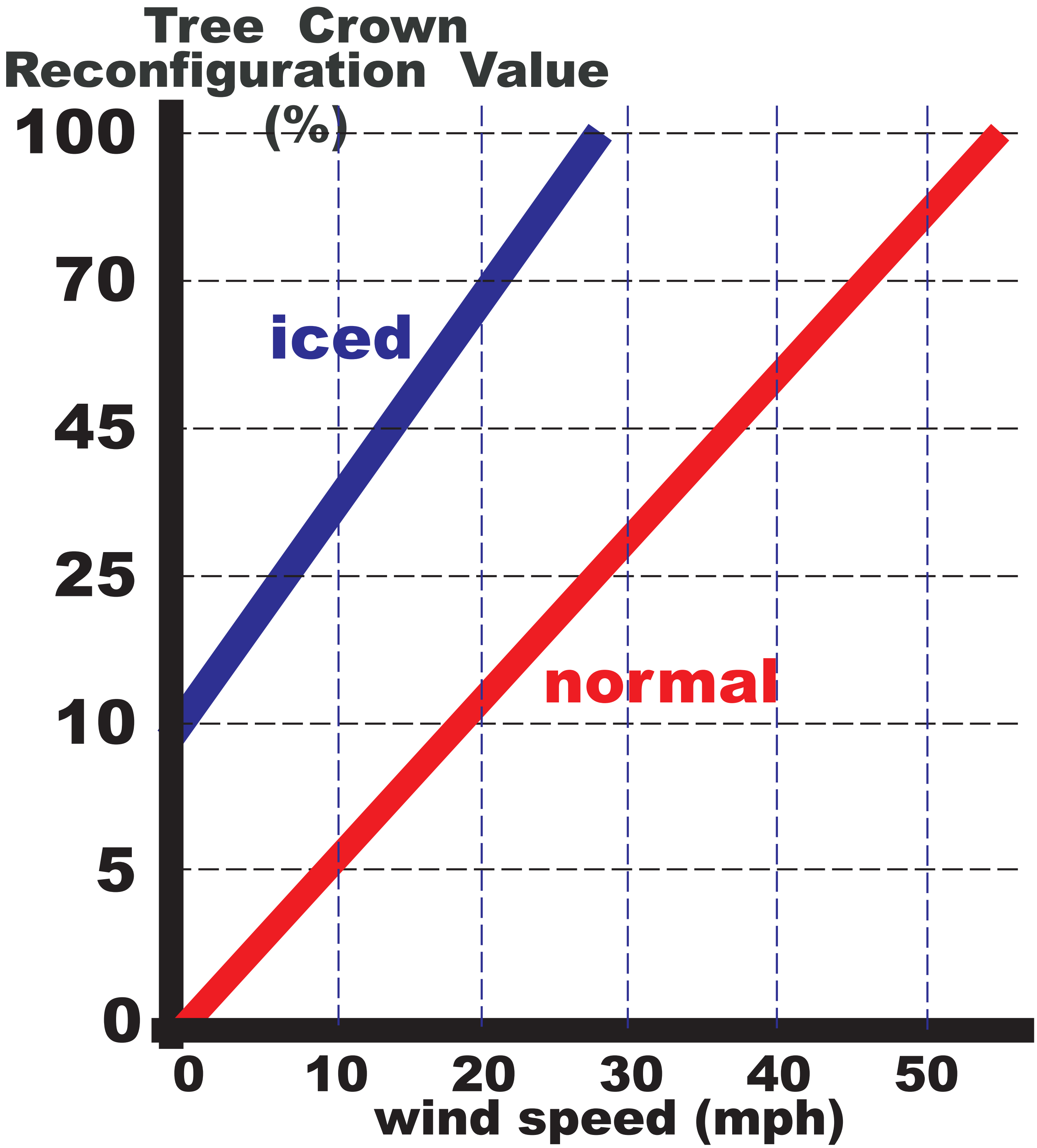


Figure 22: Ice accumulation prevents tree crown components from falling back against the wind individually, and places more stress and strain on all tree structural components.
(Coder 2014)

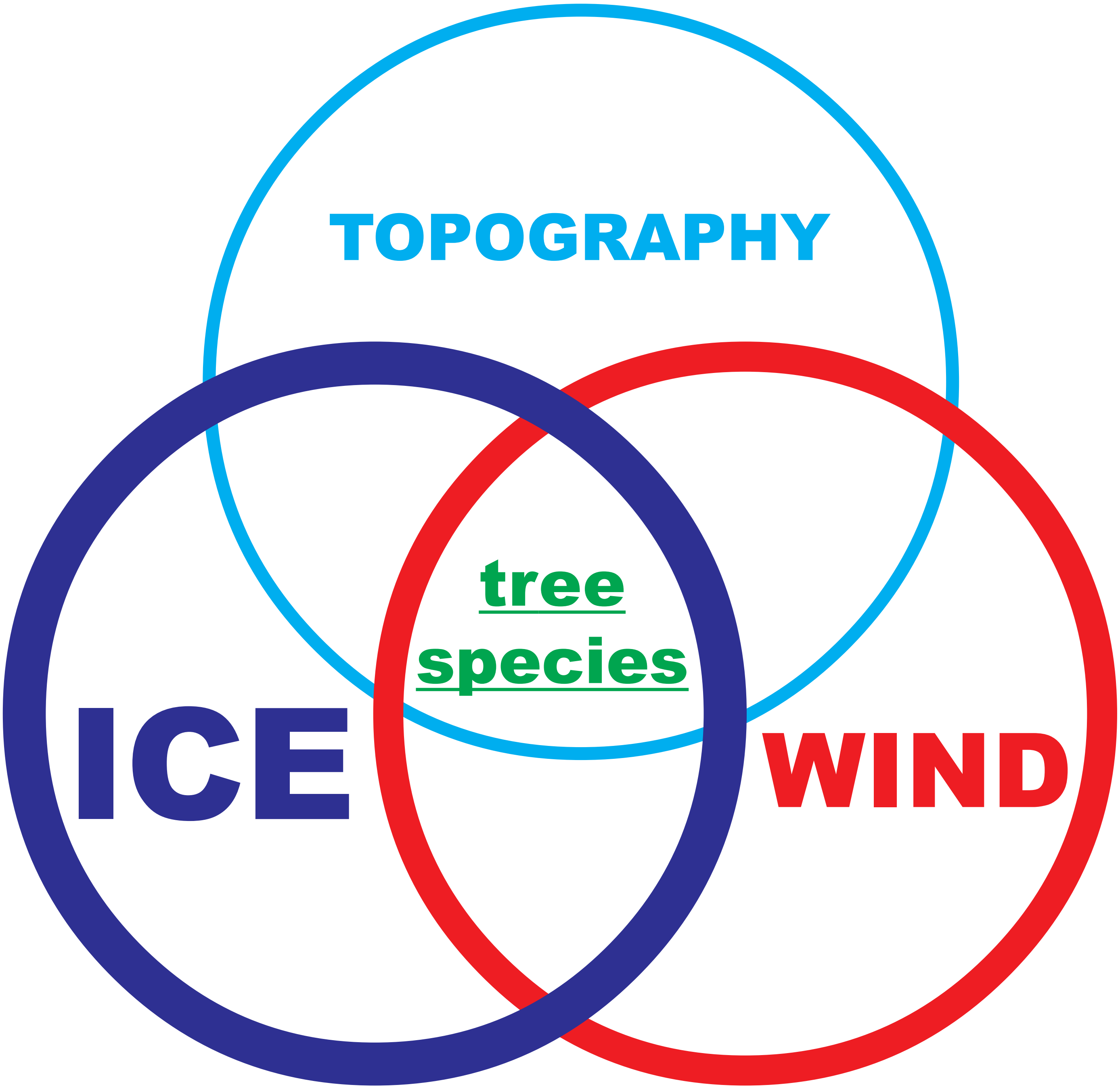


Figure 23: Characteristics of ice storm events interacting to damage trees.

Citation:

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