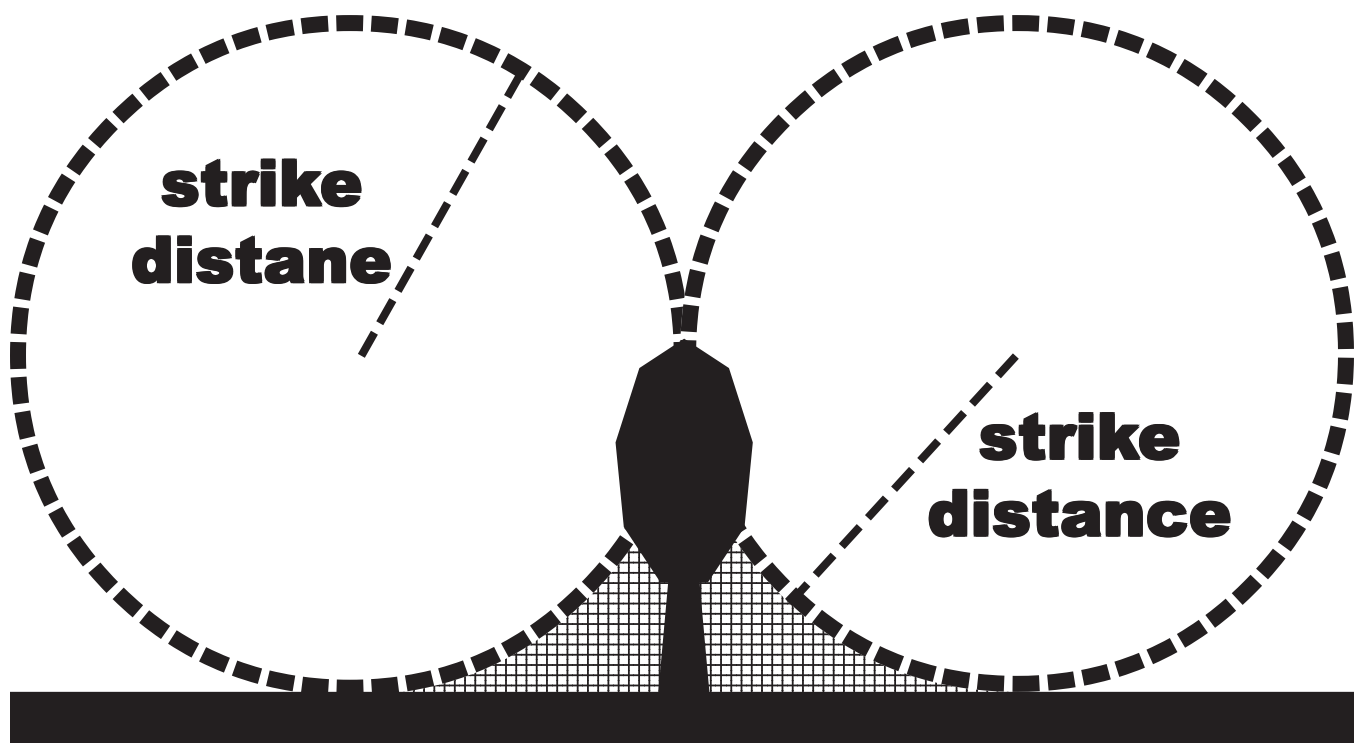# Trees & Lightning:
Principles For Controlling Damage

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University of Georgia   (9/2013)

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strike distane

strike distance

ROLLING SPHERE PROTECTION ZONE

This publication is an educational product designed for helping tree health care professionals appreciate and understand tree damage from lightning and tree protection systems / lightning conduction systems. This product is a synthesis and integration of current research and educational concepts regarding how trees are impacted by lightning, and how some tree damage can be mitigated by lightning conduction systems placed in a tree.

This educational product is for awareness building and professional development of tree health care providers. This manual is NOT intended to be used, and should NOT be used, as a lightning system installation guide or design standard. At the time it was finished, this publication contained educational models concerning lightning and its impacts on trees thought by the author to provide the best means for considering fundamental issues of tree protection using lightning conduction systems.

Within this manual, the author and institution have in good faith examined and offered credible information within an educational framework for this subject area. The University of Georgia, the Warnell School of Forestry & Natural Resources, and the author are not responsible for any errors, omissions, misinterpretations, or misapplications from this educational product, or end-user use or mis-use, of these materials.

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Trees & Lightning: Principles For Controlling Damage
by Dr. Kim D. Coder, Professor of Tree Biology & Health Care

Most trees grow to a height and in locations where lightning is not a significant risk. As trees grow taller, their modification or enhancing the electrical ground effect becomes more important. Usually trees are struck by lightning within the top 5% of their height. But even a single tall tree in an isolated location can be struck in other locations. Figure 1 shows a single tall isolated tree is most likely (79%) to be struck at the top, 5% of the time struck along an area around three-quarters of its total height, and even with its modification of the ground electrical field, 16% of strikes attach at the ground around a tree. When trees are along the path of a cloud to ground current exchange, trees can be severely damaged.

Torn Apart!

Trees are damaged by several events during a lightning strike. (Uman 1969, 1971,1987; Taylor 1977) A direct strike can electrically disrupt the most vigorous areas of a tree. Heat generated from the strike (resistance heating), and associated steam expansion, can disrupt intercellular connections. The explosive shock wave radiating from the lightning core pounds against a tree stem, loosening bark and slabs of wood. The most common visible lightning injury is a limited longitudinal opening in the periderm (bark) of a tree. Unseen damage from disrupted cell connections lead to localized tissue death and compartmentalization.

Depending upon the state of a tree (active / dormant) and time of year (summer / winter), extensive damage can occur. Roots of a tree can sustain massive damage. Root periderm can be blown out of the ground. Lightning-caused root damage is one of the hardest types of mechanical disruption to diagnose in trees. Group death of trees can occur because of massive root damage from a single strike.

Massive!

Large sections of the periderm can be ripped away by a lightning strike. Periderm damage from lightning allows rapid water loss. Trees quickly react to damage but have few tools to effectively stop water loss along an extensive longitudinal injury. In addition, a lightning damaged tree is an open invitation to many pests, like bark beetles. Traditional treatments for lightning struck trees include watering and careful observations for pest problems.

Tree damage resulting from lightning strikes can take many forms and should be treated where possible. The most commonly encountered damage process is reviewed here. Because of the variability in lightning strike current, stroke number, residual current, polarity, and grounding conditions, each tree and each site will be affected differently by each lightning strike.

Visible Injury

The inner core of a lightning strike is thin, ranging from 1/5 to 1/2 inch in diameter, with a bright corona and charge sheath ranging from 1 to 5 feet across. Internal core temperatures can exceed 50,000°F for microseconds. A strong shock wave is generated which can exceed 40 atmospheres of pressure. The soil area below a tree grounds the energy, where roots can be damaged.

Most trees along a lightning discharge path are not killed. More than 20% of trees along a lightning path carry no visible external signs of past strikes. Trees presenting no visible sign of lightning damage can still be prone to decline and weakness leading to inadequate defenses from pest attacks. Most noticeable immediately after a strike and in the ensuing months, is some form of periderm damage along

79%

side strike connection 45% - 90% of height

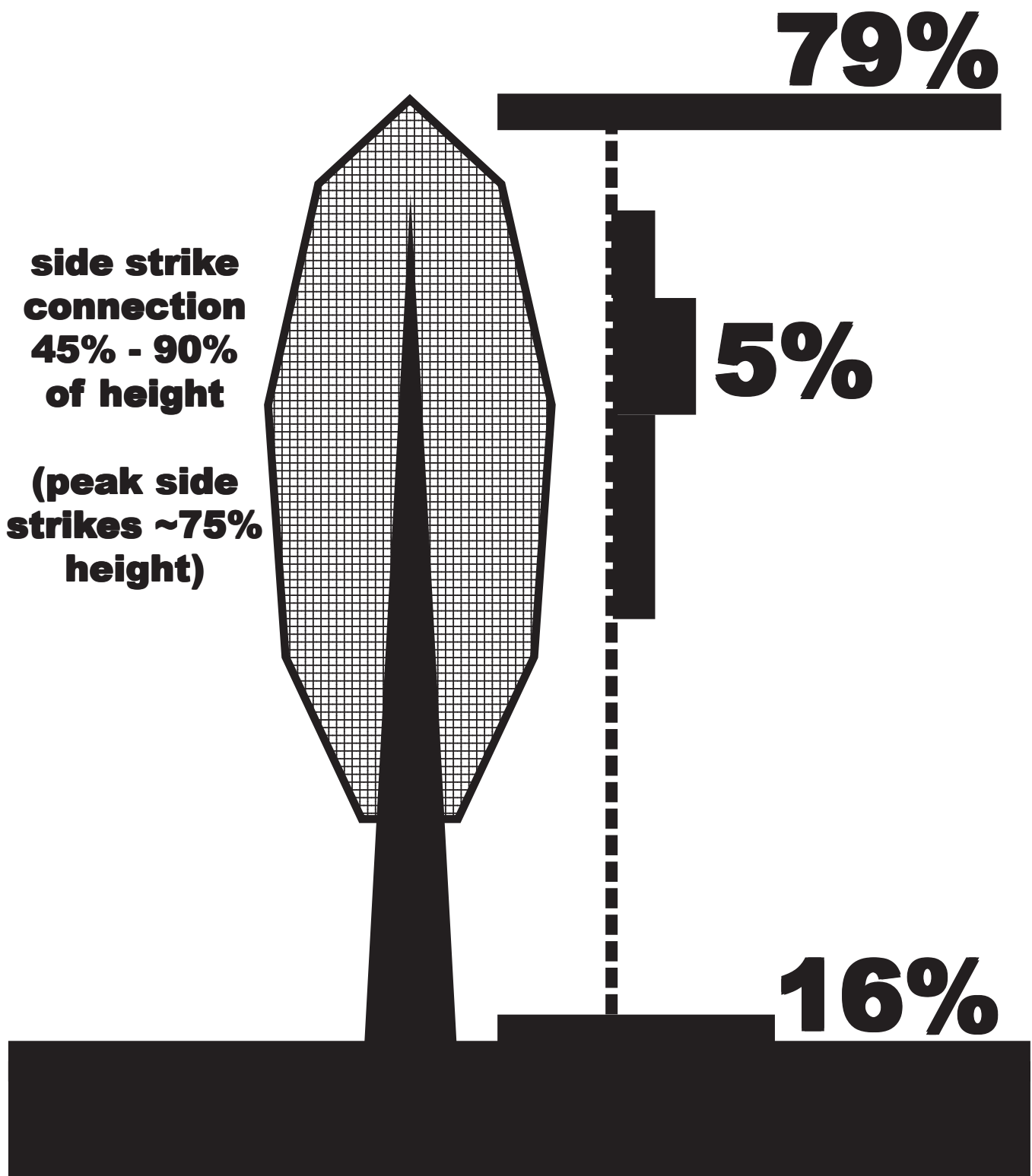**(peak side strikes ~75% height)**

5%

16%

Figure 1: Potential locations and numbers of lightning strikes on a single, isolated, tall (>100ft) tree.
(derived from Zhang et.al. 2009)

the longitudinal axis of a tree. In any woodland or park, a number of living trees may show scars of a lightning strike and survive. These scars in living trees suggest lightning damage does not always lead to immediate death. Tree damage mirrors the strength of the charge exchange and structural components of the tree. (Taylor 1977)

Observing Death

Over many years professional observers have examined lightning struck trees (most notably A. Taylor, 1977). Some of their key observations are critical in developing a better understanding of a tree damage process. Most tree lightning scars follow the longitudinal axis of the xylem. Because xylem grain orientation develops due to wind loading across the crown (bending & torque / twist), and many trees have lopsided crowns leading to unequal wind forces across their crowns, xylem grain is not always straight and can spiral down the stem. Most lightning scars follow xylem fiber orientation and follow the grain as it spirals down the stem. Electrical movement along the grain offers the least initial resistance within a tree.

Most (80%) lightning scars on trees are shallow and continuous between a point at least 80% of the tree height above the ground to within several feet of the tree base, unless lightning jumped (side-flash) to another object. Of trees with lightning scars, about 10% have more than one scar. In approximately 9% of lightning struck trees, various portions of the tree crown are killed or blown apart. In 1% of tree lightning strikes, large areas of the above ground portion of a tree are severely deconstructed and torn apart.

Damage!

There exists a trend toward different damage forms occurring with different periderm and annual xylem increment structures. Ring-porous and thick-barked trees tend toward narrow injuries, while diffuse-porous and thin-barked trees tend toward ragged, wide spread damage. (Taylor 1977)

The cause of tree structural damage is derived primarily from a short distance, short duration, intense, strong shock wave radiating from the lightning core. Additional structural damage is caused by green tissues being superheated and steam venting, which is a significant cause of root damage. An interesting observation from tree lightning strikes was the presence of a thin, narrow line of collapsed phloem tissue remaining attached at the center of a strike wound even beneath unbroken bark. This "line" of tissue is generated by pressure-caused adhesion from an external explosive force directed inward. (Taylor 1977)

Lightning Pathway

Tree tissues all have highly variable electrical resistances to charge movement. Unfortunately, tissue resistance is only important in the first few moments (1-4 micro-seconds) of a charge exchange until the massive current blasts through. These first few moments of pathway development set the stage for establishing the pathway of any stroke.

In outer twigs and branches of a tree, which have a high percent of sapwood and thin periderm, the charge path moves internally. As current quickly builds, internal pathways cannot sustain current load and a "flash over" to the surface begins. The flash-over point is usually around 80% of the tree height. Branches and twigs above this point in a tree, if along the charge exchange path, will have electrical disruption of cells, heating, burning, and structural disruption which can lead to severe damage and death. Branch and twig death around the outside of a crown (stag-heading) is a direct result of an internal current flow. Alternatively, the lightning exchange path can occur over the exterior of the tree crown leaving few injures. (Taylor 1977)

Tree Resistance

Precipitation and tree surface moisture changes have little effect on the electrical resistance of tree surface tissues, although surface water can provide a current conduit. The charge exchange path develops along the internal grain pattern of a tree. The periderm has a high resistance to charge exchange compared with internal living tissue. Leaf surfaces and buds have extremely large electrical resistances. Figure 2.

Generally tree tissues have relatively large resistances to electric current movement. Measures of tissue resistance include a perimeter of leaves which can have as much as a 25,000 ohm resistance. As tree tissues are measured farther down a tree, large resistances of the crown edge quickly diminish. On average, tree electrical resistance is reduced 15 ohms for every foot of branches and stem pathway, as the ground is approached.

Pirouette

The least resistant of the tree tissues are the phloem and cambial xylem-initial cells just below the periderm. As current quickly builds in a strike, the internal electrical pathway reaches capacity and a surface flash-over occurs through to the periderm surface. Because the initial pathway is imbedded within xylem initials and phloem, the charge exchange path follows the grain of xylem. If the wood grain does not proceed perfectly along the longitudinal axis of a tree, a portion of the primary charge exchange will follow this spiral grain path.

Pressure Wave

As surface flash-over of current builds, any cellular spaces near xylem initials and phloem cells are subjected to great forces of heating and cellular disruption. The surface flash-over remains connected through the periderm to the under-bark portion of the charge exchange. Surface flash-over generates a strong shock wave from atmospheric heating that pounds against the periderm surface. This strong shock wave is a focused compression onto periderm and into wood, followed by a tension wave rebounding from the tree center and moving around its perimeter. Resistive heating forces in internal tissues are pushed slightly to either side beneath the focused shock wave center.

Blown Out

Mythology suggested resistance heated water turned to steam was a primary force in damaging trees. In living tree tissues, water contents are large. Super heating water instantaneously (<5 micro-seconds) causes steam explosions in intercellular spaces and moist tissues. The surrounding water jacket in tissues shield and rapidly dissipates any heat load.

The energy of steam explosions and super heated air in open intercellular spaces does not generate enough force to present the damage seen in most lightning struck trees. If damage from this source does occur, it is very narrowly confined in tree tissues. Large circumferential damage of periderm, and extent and pattern of the debris field after a lightning strike is difficult to explain if steam alone was the sole mechanical damaging agent.

Shocking

The shock wave generated along the thin core of a charge exchange path produces hundreds of pounds of force per square inch over a short distance (1/5 inch). The range of energy expended can be greater than 600 pounds of force per square inch or greater than 40 atmospheres of pressure. Not all of this force is focused on a tree, but a significant portion impacts the tree stem. The reflection (rebound) of this compression wave impacting the stem is a tension wave which tears tissues apart. The moving wave around the stem surface first compresses and then pulls upon periderm, potentially shearing off periderm connections from the rest of a tree.
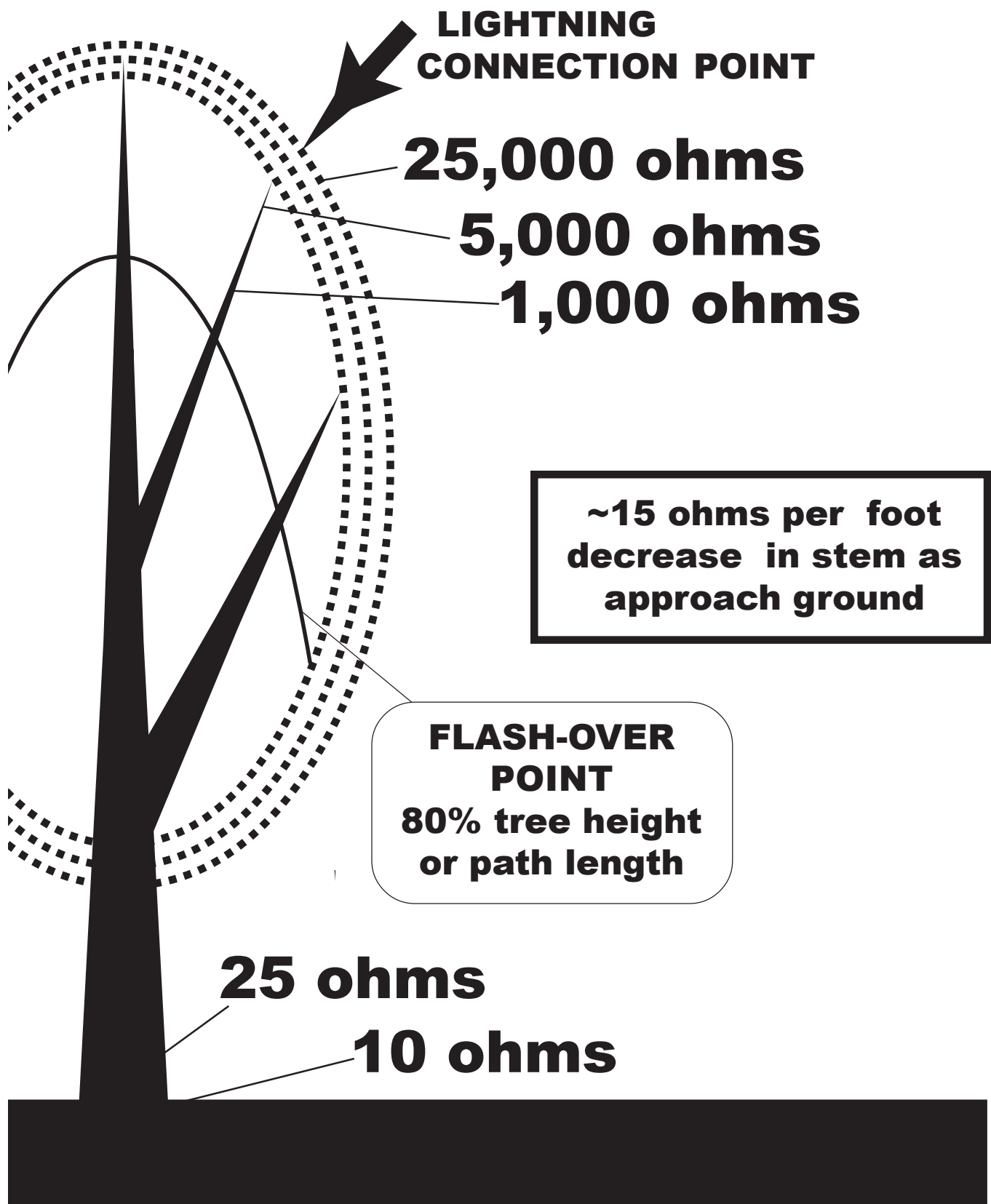
Figure 2: Model-based tree resistance value estimates from leaf surface to the ground. (Defandorf 1956)

The most visible result of the strong shock wave is splitting of the periderm and wood along ray cells directly beneath the charge exchange path. There follows an energetic rebound of woody material leading to periderm and wood loosening or loss. The shock wave shears-off cellular connections, pulls fibers apart, and loosens periderm-phloem, phloem-cambial, cambial-xylem, and xylem growth increment connections. Multiple strokes in a single lightning strike generate multiple shock waves. (Taylor 1977)

Waves

The strong shock waves bounce off the inside of a tree, moves through a tree, and moves around the circumference of a tree. Because of the high moisture content inside trees, the shock wave can be thought of as similar to slapping a watermelon and feeling reverberations within. The time pulse for this shock wave is extremely short given its intensity.

Old-knotty heartwood cores, cavities, longitudinal faults, and well-developed compartments lead to internalization and concentration of current flow. These internal concentrations of energy can represent an explosive force.

Damage Pattern

A lightning strike and associated damage to a tree usually follows a specific pattern. Figure 3. First, the current exchange front begins to build in the phloem and xylem cambium-initials, with some tissue heating and disruption of intercellular connections. Second, most of the current flow breaks out to the periderm surface (termed a surface flash-over). Third, an intense explosive pressure wave is generated from the lightning core focused on a narrow portion of the bark and wood, pounding against the branches and stem. Figure 4.

Fourth, the high intensity shockwave first compresses the bark and wood toward the center of the tree with a surface compression wave moving around tree circumference. Fifth, tree tissues are subjected to tension forces as the shockwave rebounds within a tree. The sixth step because of shockwave impacts, includes cell and tissue separations and loss of interconnections. Wood and periderm split, and tissues are shattered, leading to internal and external injuries. Figure 5.

The seventh step is compression and tension portions of the shockwave tearing through a tree leading to annual ring separations, breakage along old compartment lines, loosening of periderm and wood pieces, and propelling of loose tissue pieces away from a tree. Eighth step is mechanical stress and strain are focused on existing structural faults, injury-modified wood, open spaces, gaps, cavities, drill holes, imbedded metal objects, and insect galleries. The stress and strain of the shockwave concentrates force along the edges of faults leading to additional fiber separations. Trees are torn apart along natural compartmentalization boundaries and opened to the environment. Figure 6. The pattern of lightning damage is summarized in Figure 7.

Tree Differences

Key observations of lightning damage to a variety of trees included a cited difference between thin and thick-barked trees, ring and diffuse porus trees, and associated stem architecture-based extent of tree damage. Due to internal tree structure and current level needed to attain flash-over, some tree attributes led to different types of damage. (Taylor 1977) Figure 8 shows the strength of different tree structural types under compression and in tension.

The ability to sustain stress and strain of both impact and rebound from a lightning shockwave is partially based upon living wood strength. Different species of trees can handle different internal forces better than others. Most ring-porous trees can handle quite large pressures in both compression and in tension. In comparison, many diffuse porus trees are more easily damaged by shockwave initiated forces. Conifers handle compressive forces well, but not tension forces.

LIGHTNING
1.   **TRICKLE**
2.   **FLASH-OVER**
3.   **SHOCK WAVE**

TREE
4.   **MASH**
5.   **STRETCH**
6.   **SPLIT**

INJURY
7.   **BREAKING**
8.   **DAMAGE FOCUS**

Figure 3: Typical tree lightning strike path development outline.

LIGHTNING

1. TRICKLE

Initial trickle of current rolls along phloem and xylem cambium-initials and rapidly builds in strength causing tissue heating and disruption of intercellular connections

2. FLASH-OVER

Capacity of charge exchange pathway inside tree is limited as current flow rapidly builds. Suddenly, a majority of current flow breaks out onto bark surfaces (a surface "flash-over")

3. SHOCK WAVE

A pressure wave formed by an almost instantaneous heating of air at the center of the charge exchange path is usually focused along a narrow portion of bark and wood.

Figure 4: Typical first three steps of tree lightning strike path development.
.

TREE

4.   MASH

The large pressure wave first compresses bark and wood toward center of tree with a surface compression wave moving around the tree.

5.   STRETCH

Tissues are then subjected to an almost immediate tension force as the tree rebounds from the shock wave.

6.   SPLIT

Wood and bark, alternatively compressed then stretched, splits. Tree tissues deconstructed and interconnections shattered, leading to internal and external injuries.

Figure 5: Typical second three steps of tree lightning strike path development.
.

INJURY

7. BREAKING

Compression and tension portions of shock wave within tree can lead to annual ring separations, breakage along old compartment lines, loosening of bark and wood pieces, and the propelling of loose tissue pieces away from tree.

8. DAMAGE FOCUS

Structural faults, injury modified wood, open spaces, gaps, cavities, drill holes, imbedded metal objects, and insect galleries concentrate compression and tension forces along their edges leading to fiber separations. Trees tear apart along compartment boundaries.

Figure 6: Typical last two injuring steps in tree lightning strike path development.
.

LIGHTNING

1. **TRICKLE**
An initial trickle of current rolls along the phloem and xylem cambium-initials and rapidly builds in strength causing tissue heating and disruption of intercellular connections.

2. **FLASH-OVER**
The capacity of the charge exchange pathway inside the tree is limited as current flow rapidly builds. Suddenly, a majority of the current flow breaks out onto the bark surface (surface "flash-over").

3. **SHOCK WAVE**
A pressure wave formed by an almost instantaneous heating of air at the center of the charge exchange path is usually focused along a narrow portion of the bark and wood.

TREE

4. **MASH**
The large pressure wave first compresses the bark and wood toward the center of the tree with a surface compression wave moving around the tree.

5. **STRETCH**
Tissues are then subjected to an almost immediate tension force as the tree rebounds from the shock wave.

6. **SPLIT**
The wood and bark, alternatively compressed then stretched, splits. Tree tissues are deconstructed and interconnections are shattered, leading to internal and external injuries.

INJURY

7. **BREAKING**
The compression and tension portions of the shock wave in a tree can lead to annual ring separations, breakage along old compartment lines, loosening of bark and wood pieces, and the propelling of loose tissue pieces away from the tree.

8. **DAMAGE FOCUS**
Structural faults, injury modified wood, open spaces, gaps, cavities, drill holes, imbedded metal objects, and insect galleries concentrate compression and tension forces along their edges leading to fiber separations. Trees tear apart along compartment boundaries.

Figure 7: Summarry of the eight step tree lightning strike path development
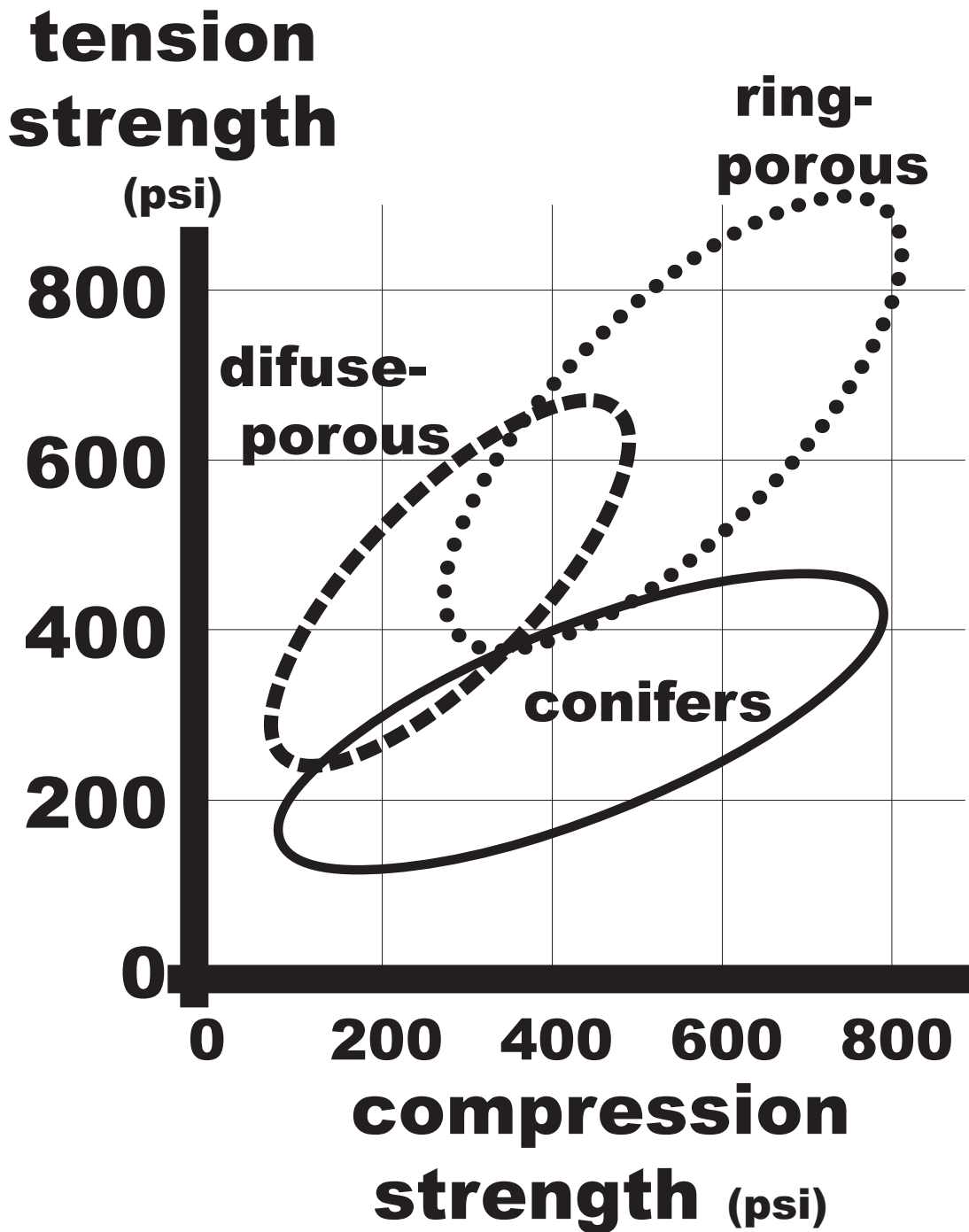
Figure 8: Estimated tension and compression strengths perpendicular to the grain of living wood for various North American tree species.

Thin Bark

Periderm appearance has been cited as an outward sign of potential lightning strike damage. Thin-periderm trees tend to have damage which is shallow and wide, while thick-periderm trees tend to have damage relatively deep and narrow. Thin-periderm trees, and trees with diffuse-porous xylem architecture, usually sustain little deep damage from lightning strikes. Thin-periderm trees with smooth, flat bark quickly allow surface flash-over and present little deep damage in stem tissues. Because of a strong shock wave radiating around a stem, large patches or sheets of bark can be loosened or pushed-off. Figure 9. (Rakov & Uman 2003; Uman 1971; Taylor 1977)

Thick Bark

In thick-periderm trees, and trees with ring-porous xylem architecture, damage can occur deep into sapwood with narrow portions of periderm and wood being pushed off a tree. Thick periderm species more commonly show lightning damage than thin barked species, and tend to have one or two narrow spiraling lines of damage. Along the center-line of these narrow injuries can be a thin compressed line of phloem tissues, or a radial crack moving into the wood. The radial crack can range in depth of less than one growth increment to more than four growth increments. Width of these injuries can range from 3-10 inches wide. Figure 10. (Taylor 1977)

Periderm and several layers of xylem (wood slabs) can be blown off and away from the injury. Figure 11. Thickness of the wood loss depends upon the depth of radial cracking. Pieces (slabs) pushed off a tree will be approximately one-half width of the whole injury. In other words, wood and periderm slabs loosened or blown off a tree will be of various longitudinal lengths with horizontal widths comprised of two halves. In some instances, a radial crack is present and a growth increment (ring) separation has occurred in sapwood, but wood was not blown away from a tree. (Taylor 1977)

Tissue Problems

Periderm on roots, stems, and twigs are different from one another due to weathering, compression, thickness, and age. New thin periderm on juvenile twigs can be on the same tree which has coarse, thick, corky bark on the mature stem. Historic field observations of tree lightning damage by bark type integrates many types and levels of observations into a single trait. It is clear that many tree features influence portions of the ground streamer strength (field enhancement) and charge exchange path.

Twigs and branches, where current moves internally until surface flash over (approximately the top 20% of tree height), can be disrupted and damaged severely enough to lead to decline or death. This stagheading or partial crown mortality is a common symptom of a lightning strike. Stem openings, cavities, or open insect galleries can concentrate forces which tear tissues apart. Root damage and death from current dissipating (grounding or earthing) are much more difficult to diagnosis than above ground damage. Branches may wilt and decline because of root damage. Roots killed in the grounding process can lead to later wind-throw because of lack of soil contact and loss of structural integrity.

Clean-Up

Pests are a secondary problem attacking physical injury sites and attracted by volatile tree materials released into air. A good example is pine. It is estimated that 31% of all pine beetle spots are due to a lightning strike at a center tree. A lightning strike to a pine can throw a debris shower up to 150 feet, exposing a tree to attack and scattering wood, periderm, and resin particles across a site. This lightning debris field is a large biological attractant area for many pests. Because of many internal gaps and fiber separations, pine pitching (resin exudate production) is reduced. Internal changes within a tree to prepare defensive materials reduces supplies of growth materials.

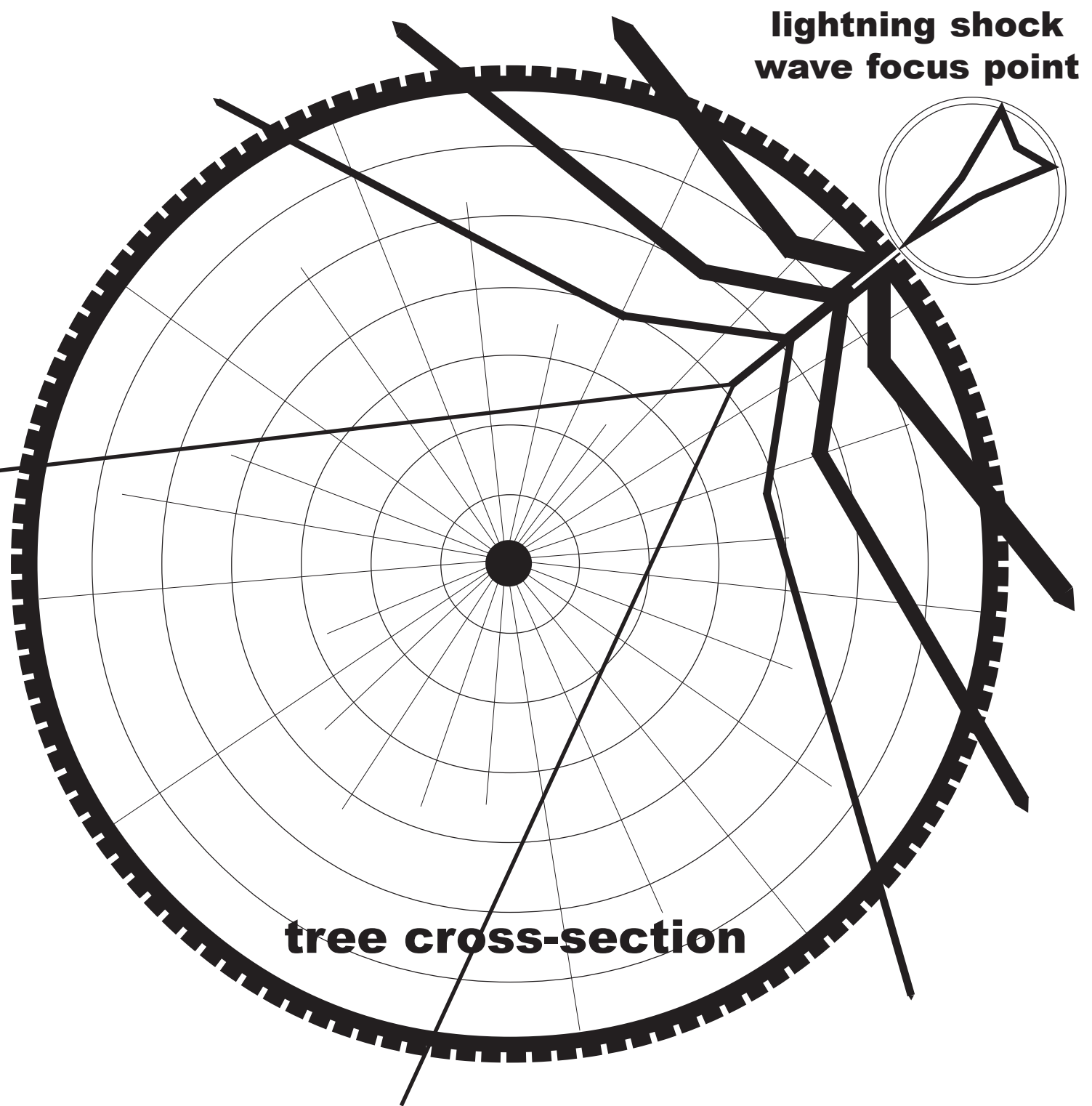**lightning shock wave focus point**

tree cross-section

Figure 9: Lightning shock wave impact and rebound inside stem of diffuse-porous thin-barked species, or non-porous xylem species with no density differences within a single growth increment.

tree cross-section
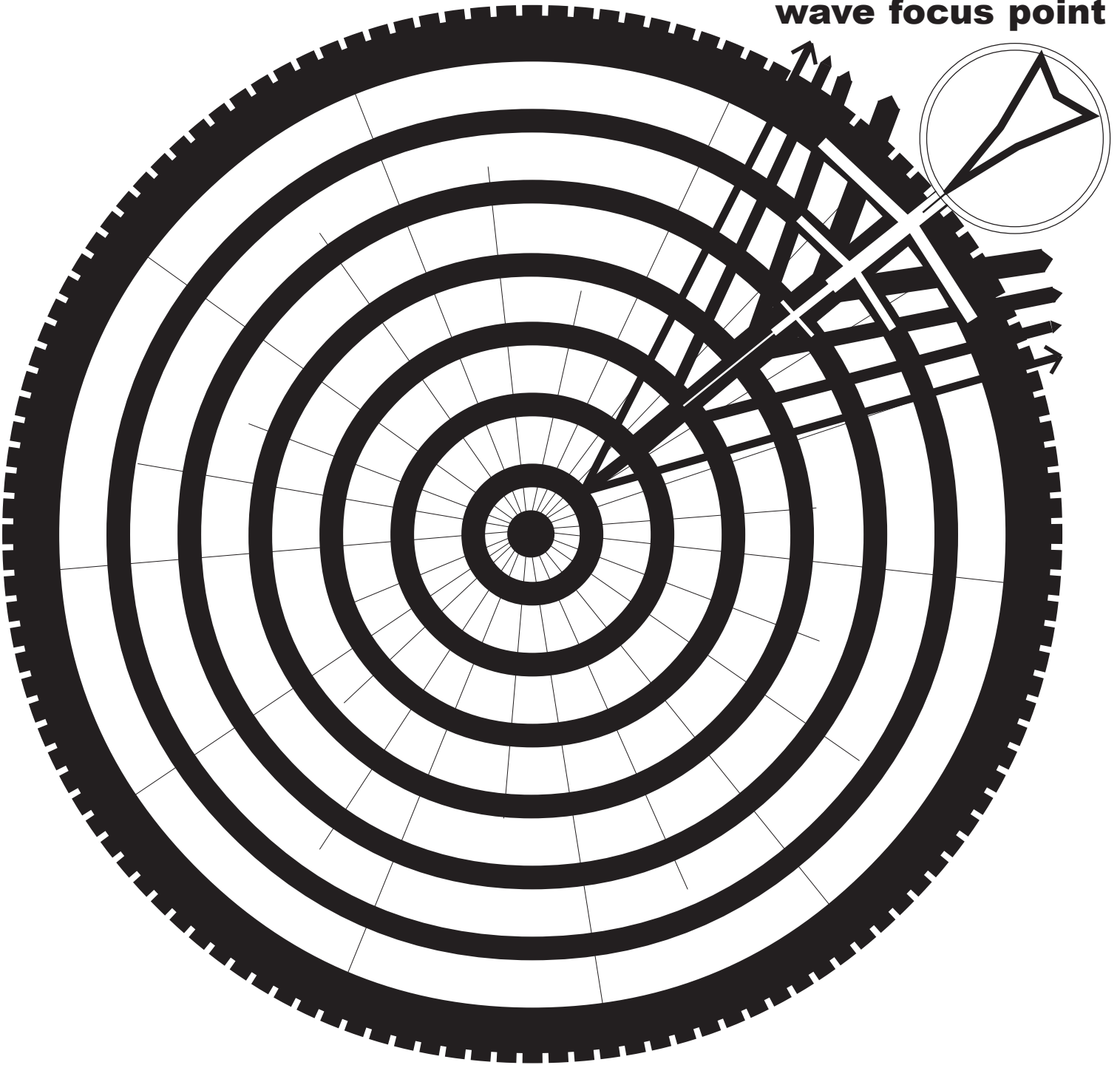
lightning shock wave focus point

Figure 10: Lightning shock wave impact and rebound inside stem of ring-porous thick-barked species, or non-porous xylem species with large density differences within a single growth increment.

tree cross-section
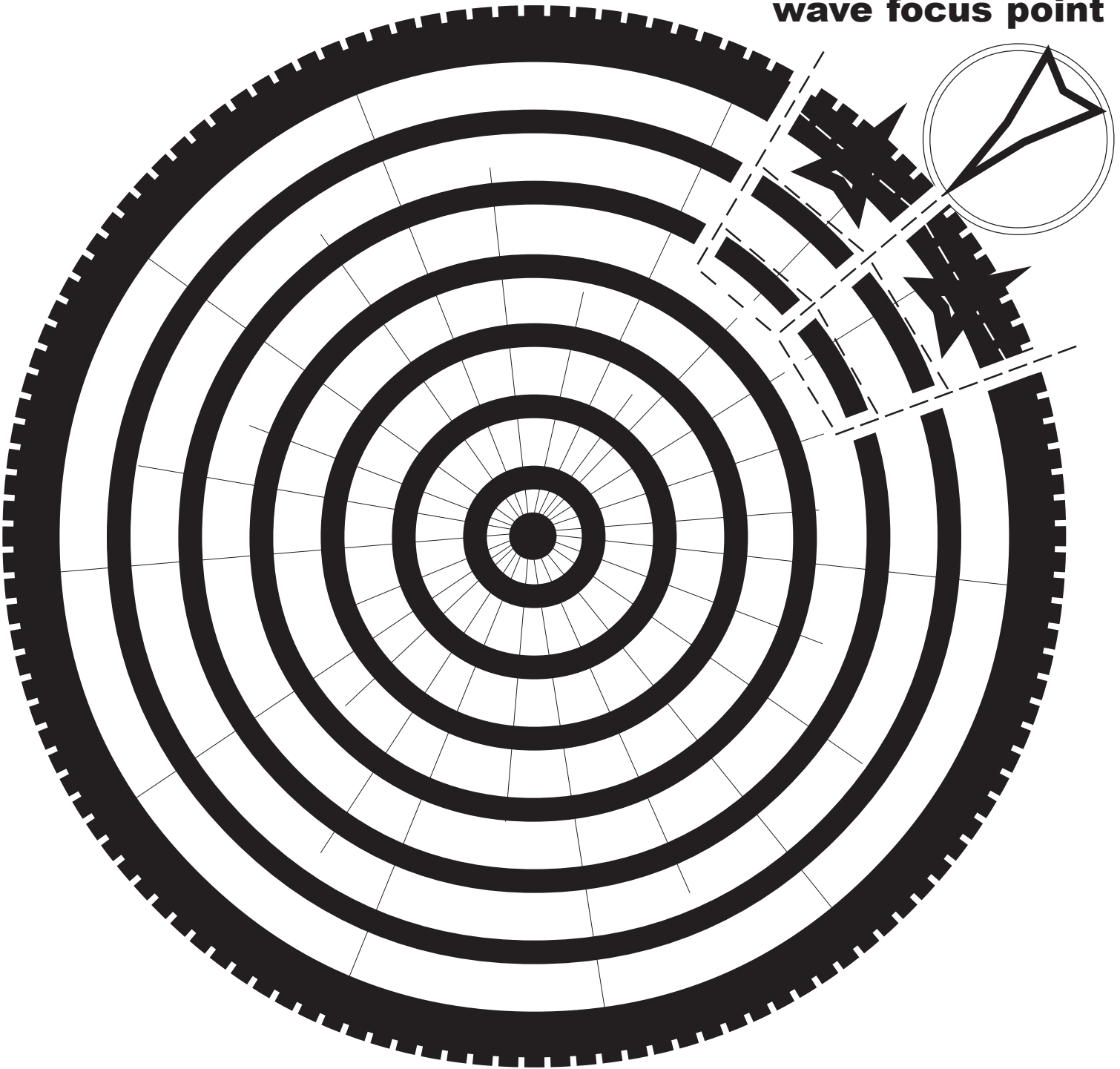
lightning shock wave focus point

Figure 11: Lightning shock wave loosening and potentially removing bark and wood slabs in a stem of a ring-porous thick-barked species, or non-porous xylem species with large density differences within a single growth increment.

Reactions To Damage

Many trees are not visibly damaged by a lightning strike. It is difficult to ascertain if a tree has been struck if no injury is seen. Better sensing and measurement systems are required. Years after a lightning strike, a "lightning ring" may be visible as a defensive boundary among growth increments. These increment rings are similar to false rings generated by drought, pests, and floods except for the defensive chemicals deposited throughout the cell walls. A shock wave from a lightning strike initiates a standard compartmentalization defense in and around the broken tissue connections and separated tissues layers. Cambium and ray cells set compartment lines around electric current flow pathways. Dead and damaged cells at the site of injury are sealed off.

The narrow spiral injuries seen along stem surfaces are not usually girdling. Because of crown dynamics in wind, and tree attempts to adjust for torque (twist), fiber orientation (grain) in a stem may be at some angle to the longitudinal axis of a stem. This spiral grain can be followed by the charge exchange pathway initially, leaving a spiral injury. Many vascular connections are still intact among surface injuries and function normally. If less than 25% of the stem circumference is damaged, defensive capabilities and means of resource transport should remain viable in a tree. (Taylor 1977)

Strike Symptoms

Symptoms of a lightning strike on a tree begin with a disruption and reduction in water movement capacity. In addition, resin flow is greatly reduced in species with standing resin systems. Chemical defensive compounds are rapidly generated and/or moved requiring significant reallocation of growth materials. Permanent leaf wilting on a single major branch is usually the first noticeable symptom of a lightning strike if the tree was not clearly blown apart or killed.

Another form of damage is a recoverable foliage wilting that comes and goes over several months, sometimes leading to eventual twig death. This process of sense and correction within a tree provides bark-resident pathogens avenues to effectively attack. The least noticeable symptom is a slow decline of a branch or tree over 1-3 years with various pest and site constraints limiting new growth processes. (Taylor 1977)

Fire!

Approximately 12,000 fires per year are lightning initiated in the United States. Ignition is usually at the base of a tree where fine fuels are available. Constant current during a lightning strike between individual strokes can be between 100-400 amps. This constant current provides enough energy input and duration for sustained heating, leading to ignition. Approximately 20% of all lightning strikes have this constant current. A majority of lightning strikes on trees do not cause sustainable ignition as the shock wave blows fuels and heated surfaces apart. Many charred fine particles can be found in lightning strike debris fields, but are not usually sites of ignition. (Taylor 1977)

Groups of Trees

Regardless of how we focus and concentrate our field and analytical views onto a single tree with a single strike, lightning-initiated damage and death of groups of trees demand attention. Orchards, especially in high resistance soil areas, have been decimated by single lightning strikes. In most group strikes, only one or two trees in the center may show visible above-ground injuries. Root damage from grounding impacts are the causal agent of death. (Taylor 1977)

Susceptible Tree Lists

Since humans have been noticing lightning struck trees, there have been lists compiled of trees most likely to be struck. Few of these lists have any statistical controls for area proportionality, crown

class / tree height differences, ecological system typography and openness characteristics, species proportionality, or identification of other species and site attributes influencing ground streamer strength. Making a list is a pleasant observational study for a local area, but species differences have no influence on modifying ground field enhancements, and mean little along an average 35kA lightning charge exchange pathway.

Tree First Aid

Risk reduction and installation of a lightning conductance system in trees before a strike is the best way to minimize damage. Once a tree is injured, time until treatment is critical. The faster treatments commence, the better the biological results. Starting treatment processes within 8-24 hours, especially if little drying of tissues has occurred, can provide a window of treatment using watering and water loss prevention, and using pressure to reattach tissues. After 16-36 hours, compartmentalization processes have been initiated and reinvigoration actions to the whole tree are more appropriate.

BMPs

Due to site, tree, and injury differences, no specific treatment procedure can be defined. General best management practices (BMPs) should include a number of considerations.

-- If a tree will survive, consider if installing a tree lightning conduction system is warranted.
-- Water / watering is essential. Institute a specially targeted / zoned irrigation program for
    at least two growing seasons, if drainage can be assured. In exceptional cases,
    install crown misting and wind protection for at least one full growing season,
    if warranted.
-- For loosened bark and wood, consider use of a pressure belt. Use belts and surface
    pressure to pull / push slightly displaced tissues back into near original position
    for six weeks.
-- Cover the area with a temporary water conserving covering. Apply white plastic
    sheeting over injuries to minimize water loss for four weeks. Pruning paints can
    be used to slightly slow water loss and cover the injury, but do little to assist
    in recovery.
-- Remove clearly dead and seriously damaged branches. Do not over-prune. Delay
    green-wood pruning until tree allocation priorities are clear, or least one full
    growing season.
-- Remove and clean-up shattered tissues. Do not scribe or cut into living tissue.
-- In some areas and with some specific pests, an application of a preventative pesticide
    on and around wounds may be appropriate. Be sure pesticides and their carriers
    or stickers do not damage new parenchyma cells generated on xylem surfaces.
-- Delay nitrogen fertilization one full growing season.
-- Protect soil surface and soil health across the tree's rooting area including use of a
    thin layer of light mulch over small amounts of composted organic matter.

Lightning Strike Risk Assessments

Storm clouds with the right internal conditions can generate large numbers of electric charges separated by miles of air. When and where cloud leaders and ground streamers will connect is impos-

sible to precisely predict. The strength of ground streamers (ground field enhancement) can be estimated based upon different objects or neighborhoods on the ground. Risk assessments are concentrated on ground streamer strength while leader / streamer connectivity is highly variable depending upon the storm.

Ground streamer strength (field enhancement) is based upon many factors which can be increased to a point where any cloud leaders in the area (i.e. within 5 to 6 times tree height above the tree) will interconnect and exchange charges. A tree's topographic position and height above surrounding objects or structures play crucial roles in determining where lightning will strike. Isolated, tall trees would have the potential for strong ground streamer strength and serve as a conduit of charge exchange exceeding simple random probabilities. Valuable trees along the path of potential lightning strikes, where risk is based upon ground streamer strength factors, should be evaluated.

Two simple and quick risk analysis methods are presented here. They are based on an educational summary of lightning risk factors in trees and neither should be used as a single source in determining lightning conduction system requirements for trees.

Height Method

The first assessment method for gauging lightning risk to trees is the Coder Tree Height Assessment for Lightning Risk used to help tree health care providers in discussions with clients as to whether a tree lightning conduction system should be installed. This risk assessment process is based only upon historic lightning ground strike information for the tree location (i.e. annual lightning ground strike density per square mile), and tree height. (derived from Bazelyan & Raizer 2000)

Figure 12 is a graph comparing tree heights in feet with lightning ground strike per square mile per year at four different risk levels. Risk levels are provided for 1 in 25 years (4%), 1 in 50 years (2%), 1 in 100 years (1%), and a 1 in 200 years (0.5%) chance of a lightning strike. Higher risk values, like 1 in 10 years (10%) and 1 in 5 years (20%), are considered so likely to occur, risk assessment is not required. The fewer lightning strikes per year at any location, the greater tree height at which various risk levels of a strike occur.

Figure 13 shows the great risk variation in tree heights. Notice above a lightning strike density of about 18 ground strikes per square mile per year, there is little difference in tree risk based upon tree height. Below this strike density, tree height differences do differentiate risk levels more clearly.

Figure 14 provides heights (in feet) for single, isolated trees at the greatest risk for lightning strikes depending upon tree location (i.e. lightning ground strike density per square mile per year.) For example, if your location sustains 15 lightning ground strikes per square mile per year, an 81 feet tall single isolated tree would fall into the 10% annual risk category and is considered a super high risk of a lightning strike. If a similar 80 feet tall tree in the same area is at least 35 feet above surrounding structures and other trees, then this tree would fall into 2% annual risk category and is considered only a moderate risk of a lightning strike.

Coder-Cripe Method

The second assessment method for gauging lightning risk to trees is the Coder-Cripe Ground Effects Lightning Risk Assessment method. This assessment uses a number of lightning strike risk factors (i.e. enhanced electric field -- ground streamer strength factors) associated with trees. Tree height, relative height of a tree within its surroundings, location on landscape, closeness of neighboring trees and structures, and historic number of ground strikes per square mile per year are all incorporated. The result is a simple assessment for determining if a lightning conduction system is warranted. It does not (can not) include tree values or benefit / cost analysis. This assessment is a training guide for determining potential lightning strike probabilities on trees. (based partially on Robert E. Cripe's work).
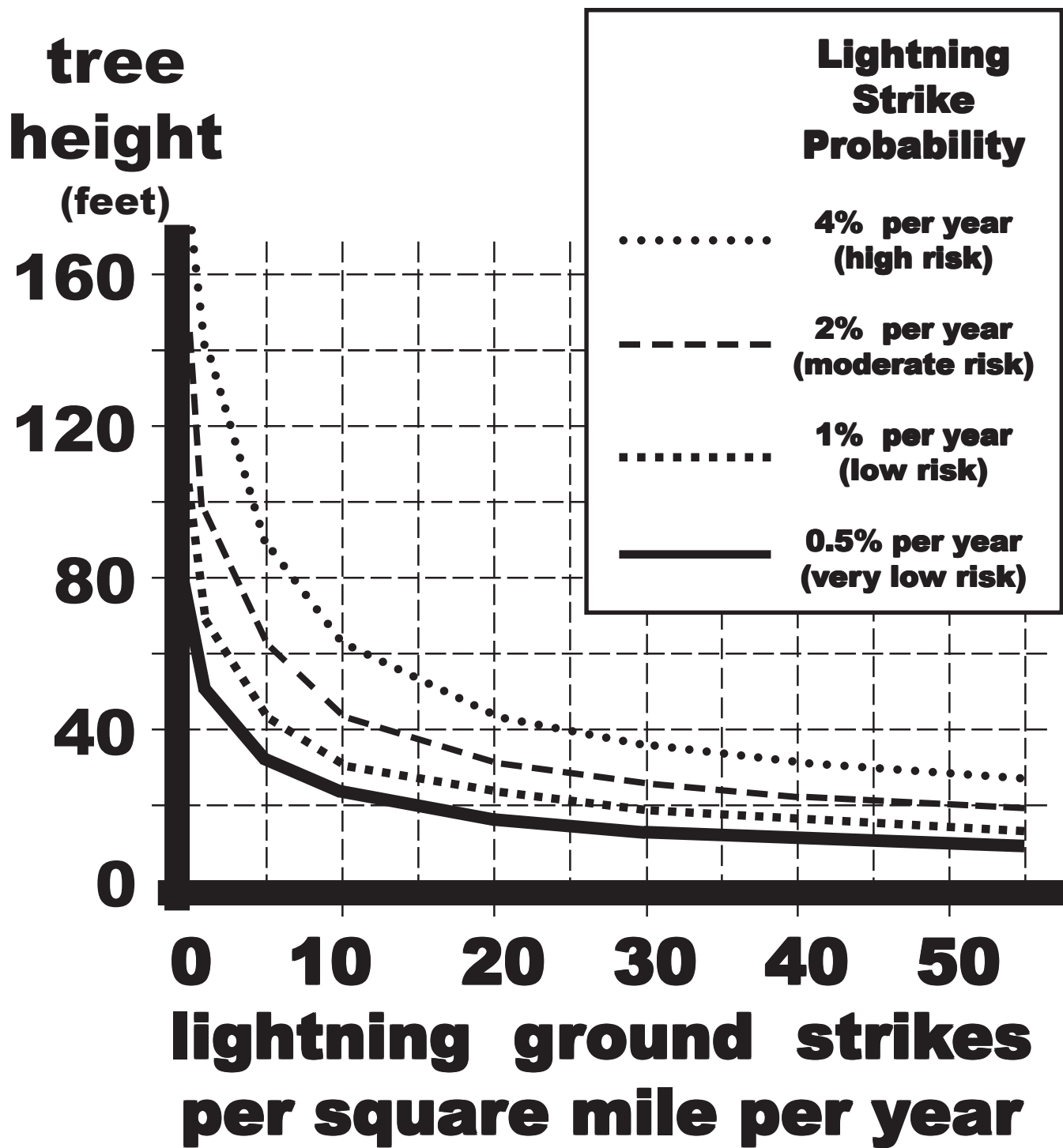
Figure 12:   Risk level for tree lightning strikes based on tree height in feet across lightning density values measured in ground strikes per square mile per year.
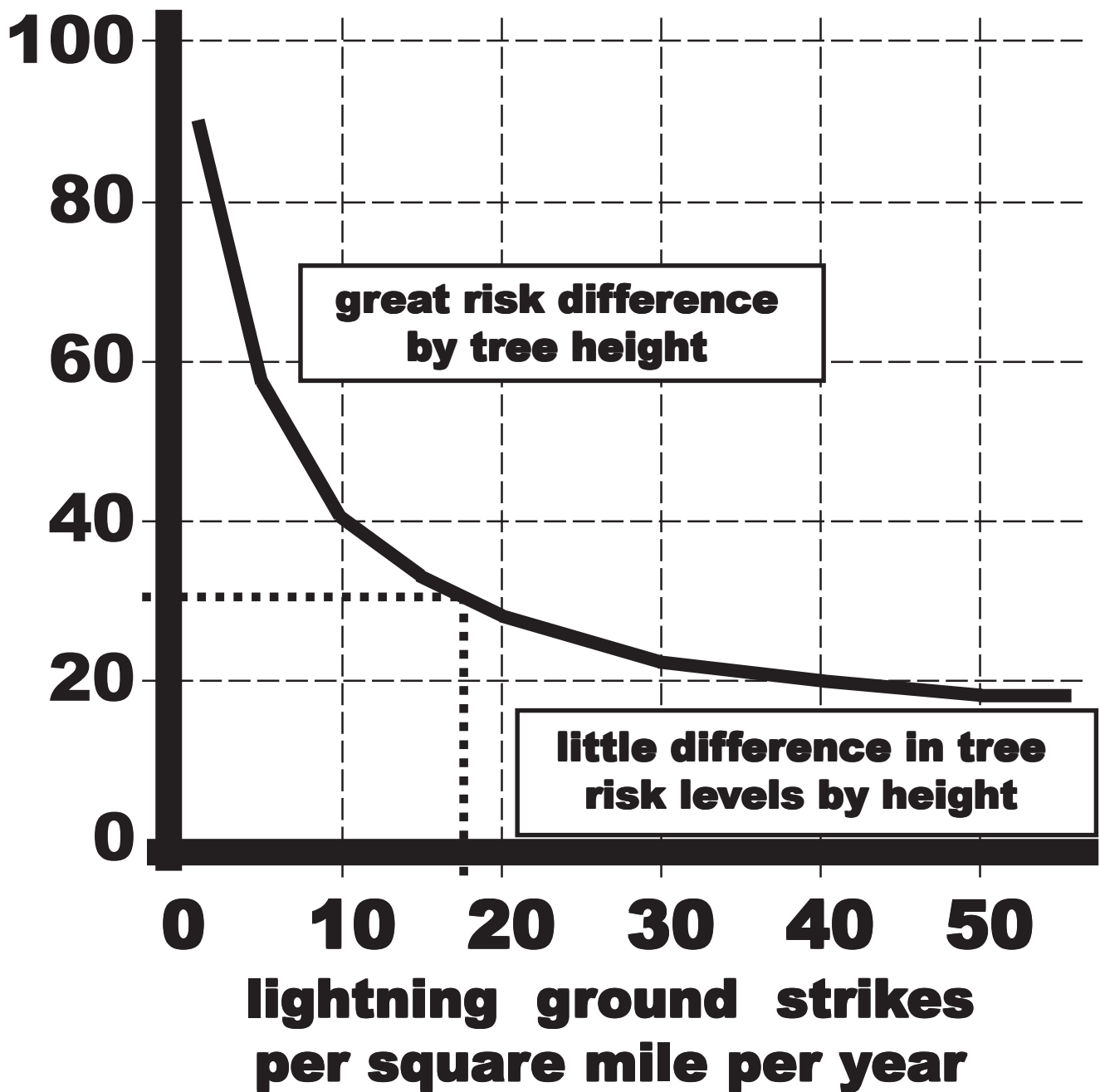(derived from Bazelyan & Raizer 2000)

Figure 13: Average risks for tree heights (between high and very low risk) across lightning density value measured in ground strikes per square mile per year. Dotted lines represent 30 feet height and 18 ground strikes.

(derived from Bazelyan & Raizer 2000)

lightning strike density (mile²/year)	lightning strike annual risk level			
	20%	10%	4%	2%
2	–	–	140	95
5	–	140	85	60
10	140	95	60	40
15	110	80	50	35
20	95	70	40	30
25	85	60	35	25
30	80	55	35	25
35	70	50	30	20
40	65	45	30	20
45	65	45	25	20
risk levels =	severe	super high	high	moderate

Figure 14: Single, isolated tree heights in feet within the greatest risk catagories for lightning strikes depending upon tree location (lightning ground strike density per square mile per year.)
(Coder Tree Height Assessment for Lightning Risk)

Determinations

To use this assessment aid, you will need several pieces of information about the assessed tree and site. An accurate tree height and neighboring structure height are essential. Use a clinometer, hand altimeter, or height stick with a 100 feet tape to record height and distance measures.

Figure 15 represents risk factor #1 -- where is the tree located topographically in the landscape. Higher locations, compared with low growth sites are more likely to have strong ground streamer strengths. Large scale, landscape level positions which accentuate a tree's effective height and ground streamer strength carry higher risks. Trees on hilltops will usually have stronger ground streamer strength than trees in valley bottoms. Determine the risk percentage closest to the assessed tree's topographic location.

Figure 16 represents risk factor #2 -- relative height of the tree crown. Determine relative tree height compared with neighboring trees. The more a tree crown rises above neighboring trees, the stronger its potential ground streamer strength. This figure shows tree crowns and names of crown classes (relative height values). The classic crown class descriptions are used to determine if the assessed tree is taller (an emergent crown class) than its surrounding tree neighbors. Pick the risk percentage closest to the assessed tree's crown class. Single isolated trees with no surrounding trees would be assessed at 100%.

Figure 17 represents risk factor #3 -- tree crown openness or view aspect. Determine how open a tree crown is from the sides. Trees open to water, fields, large open spaces, or facing areas with vegetation significantly shorter in height, will leave the sides of their crowns open and more likely to produce strong ground streamers. This figure shows tree crowns from above clustered around the assessed tree (i.e. the darkest circle) and various levels of openness of the assessed tree crown. Risk percent is equal to degrees of openness between 0° & 360° divided by 3.6. Figure 18. Single trees standing alone are open on all sides and tend to have the strongest ground streamer strength. As neighboring trees close in on different sides, the openness risk factor declines. A risk percentage for the degree of tree crown openness should be determined.

Figure 19 represents risk factor #4 -- relative height of other structures in the neighborhood. A direct measure of the single tallest structure or tree in the neighborhood is compared to the assessed tree. The neighborhood distance on the ground is a radius three times assessed tree height (3 X tree height) away from the assessed tree. Within this neighborhood distance, calculate the relative height difference for the single tallest structure or tree. The taller the tree is in its neighborhood, the stronger its potential ground streamer strength. Figure 20. A risk percentage for how tall the assessed tree is compared to the tallest structure in the neighborhood should be determined.

Figure 21 represents risk factor #5 -- proximity of human or property targets. When lightning strikes a tree, collateral damage can result. The risk of a tree lightning strike impacting structures, electronics, animals and humans in the vicinity is a major concern. A risk assessment must determine the spacial relationship between trees and these targets. The closer and taller the assessed tree is to a target, the stronger ground streamer potential, and the more likely target damage and injuries (possibly death) may occur if lightning strikes. Structures surrounded by, or overhung with, tree branches should have their own lightning protection system. The distances listed for risk assessment are based upon radial distances away from the base of the assessed tree stem at the ground surface. A risk percentage for collateral damage to targets close to the assessed tree should be determined.

Once the first five risk factors have been determined, the percentage numbers (not decimal percents) should be added together. The total sum should be divided by 500 yielding a value < 1.0. The result is called a Composite Risk Factor since it combines or averages the first five risk factors together. Figure 22.

= 100%

= 85%

= 60%

= 25%

= 1%
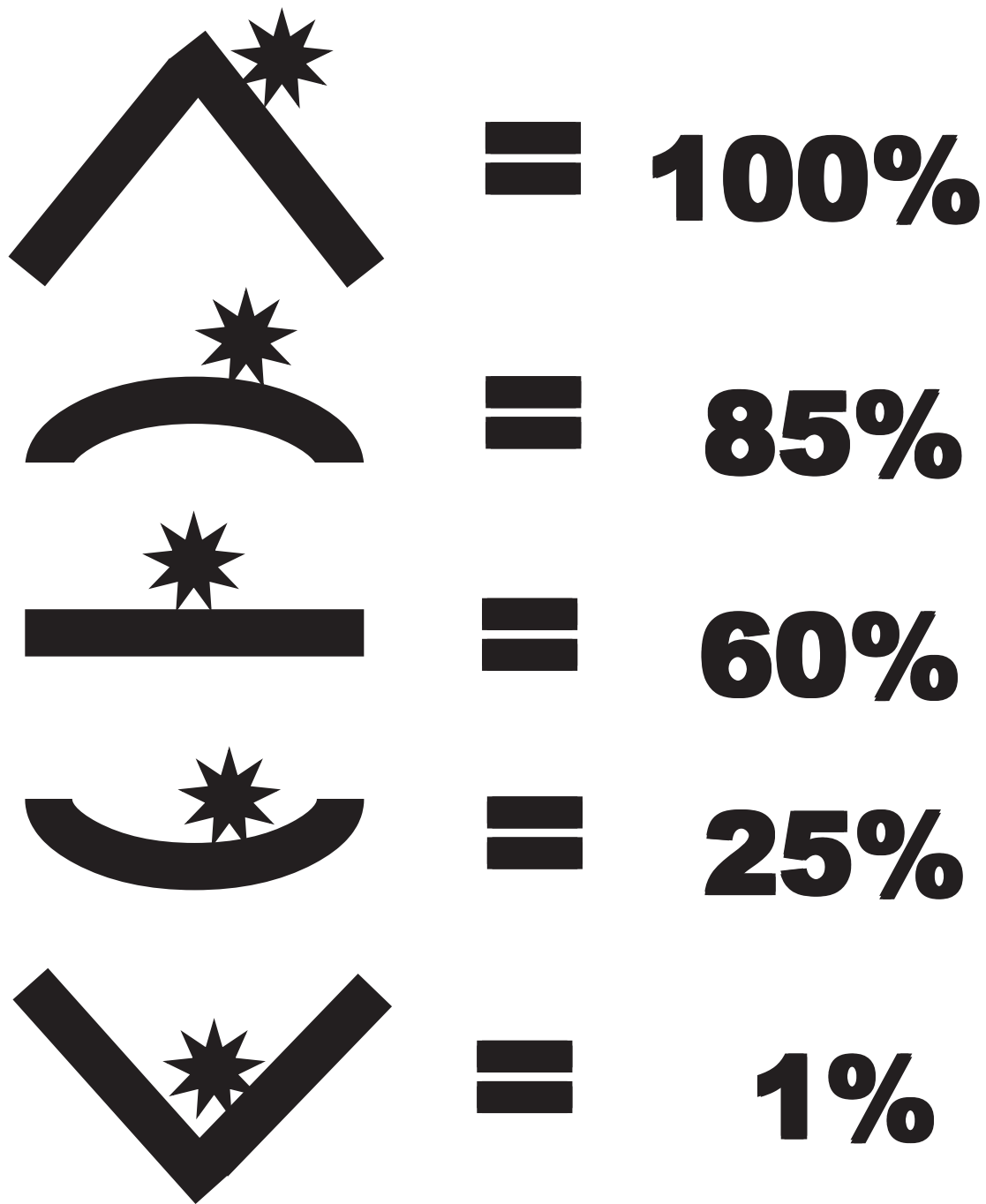
✴ = topographic position of tree in landscape

Figure 15: Risk Factor #1 --
Topographic Location in Landscape.
Determine where on the landscape tree is growing. Select risk
percentage closest to assessed tree's topographic location.

emergent
100%

co-dominant
60%
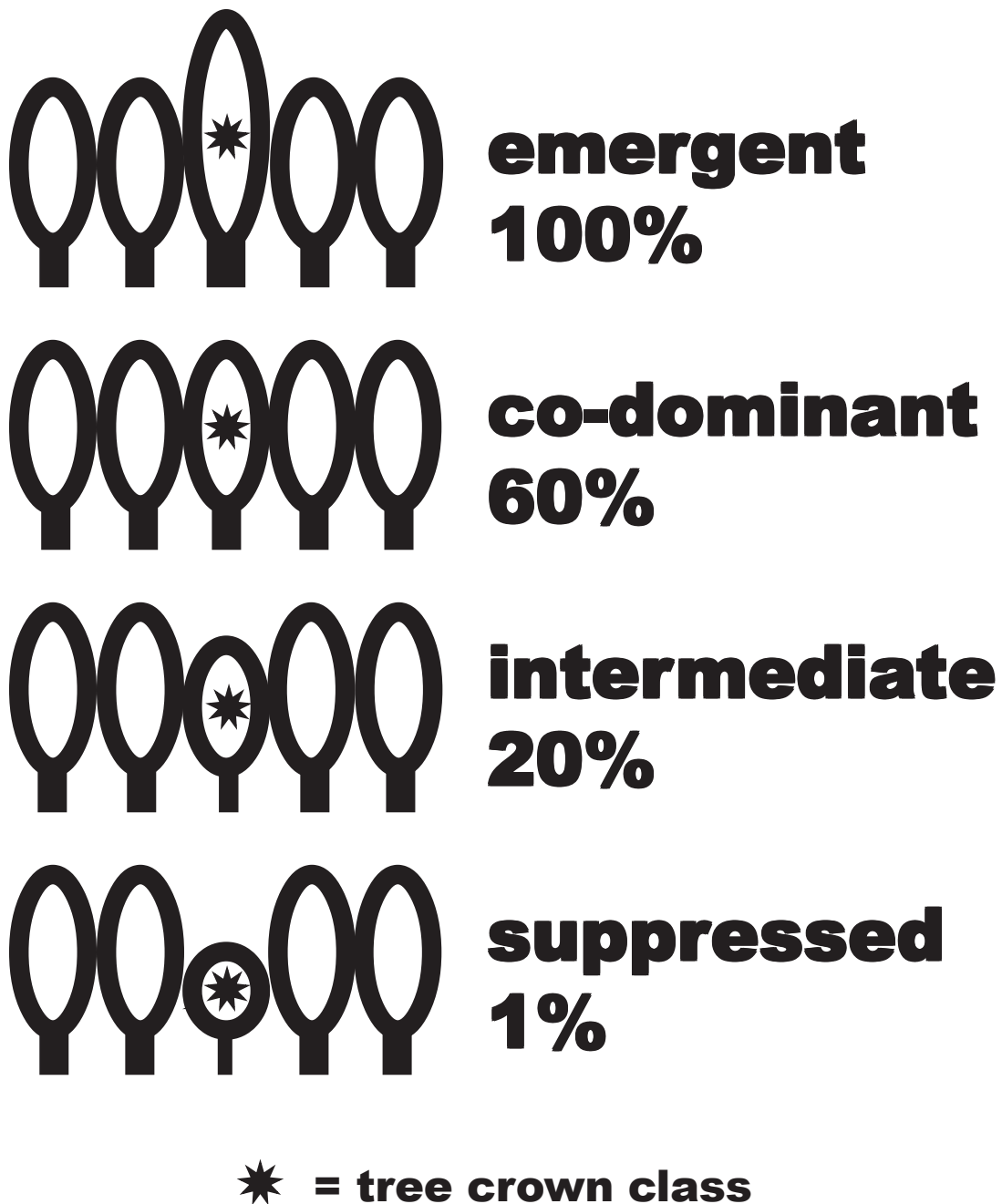
intermediate
20%

suppressed
1%

✸ = tree crown class

Figure 16: Risk Factor #2 --
Relative Tree Height
Determine relative tree height compared with neighboring trees.
Select risk percentage closest to assessed tree's crown class.

360°
100%

315°
88%

229°
64%

166°
46%

120°
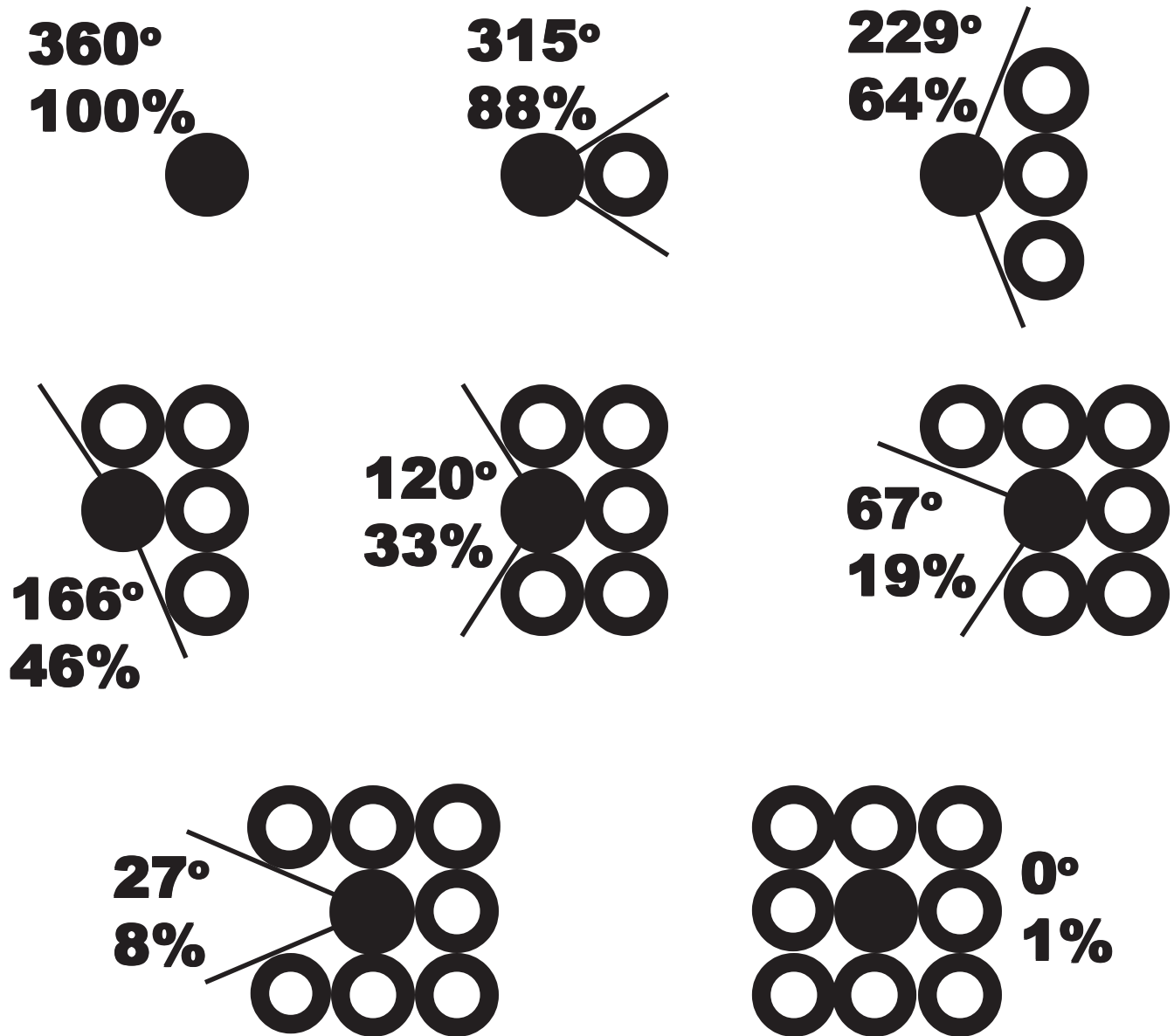**33%**

67°
19%

27°
8%

0°
1%

Figure 17:   Risk Factor #3 --
Tree Openness
Determine how open tree crown is on
sides compared with other surrounding trees.
Shown are tree crowns viewed from above with assessed tree
(filled circle) and neighboring trees (open circles). Select risk
percentage closest to assessed tree's crown openness.

Figure 18: Risk Factor #3 - Tree Openness
Graphical determination of tree crown openness
and risk of lightning strike.

TOP VIEW

1HT 2HT 3HT
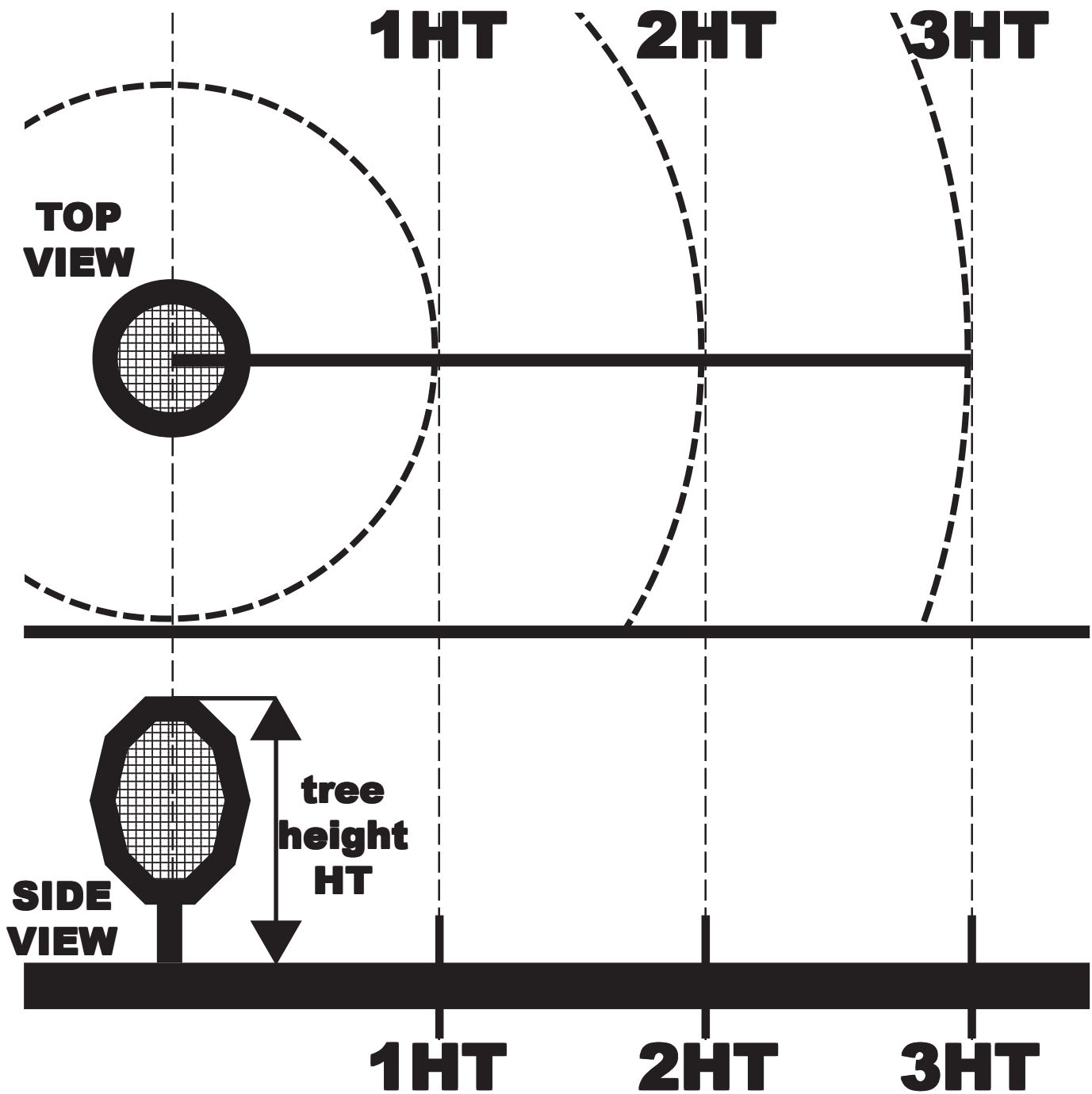
SIDE VIEW

tree height HT

1HT 2HT 3HT

Figure 19: Risk Factor #4 --
Relative Neighborhood Height Differences

Measure height of single tallest structure or tree within three (3) tree heights of assessed tree. The taller a tree is in its neighborhood, the stronger its ground streamer strength.

number of times taller than assessed tree	risk assessment value (%)
2.5 times taller	2%
2.0 times taller	10%
1.5 times taller	25%
1.25 times taller	55%
same height	80%
shorter	100%

Figure 20: Risk Factor #4 --
Relative Neighborhood Height Differences
Measure height of single tallest structure or tree within three (3) tree heights of assessed tree. The taller a tree is in its neighborhood, the stronger its ground streamer strength.

tree position relative to target	assessed risk value (%)
tree as tall / taller & touching	100%
overhanging target	95%
within 1/2 tree height	90%
within 1 tree height	80%
within 2 tree heights	60%
within 3 tree heights	25%
beyond 3 tree heights	1%

Figure 21:   Risk Factor #5 --
Tree Target Proximity

Risk of lightning strike impacting structures, electronics, animals and humans in vicinity. Risk assessment must determine spatial relationship between trees and potential targets. Height distances listed are based upon radial distances away from base of assessed tree stem.

Figure 22: Tree Lightning Risk Assessment
(Part A of three calculations)

A) Record all assessed values for risk factors #1 through #5 below. Risk factor values will range from 1% -100%. Note: Use percent values in whole numbers not decimal percent values (i.e. use 90% instead of 0.90).

RISK FACTOR #1: _____% +

RISK FACTOR #2: _____% +

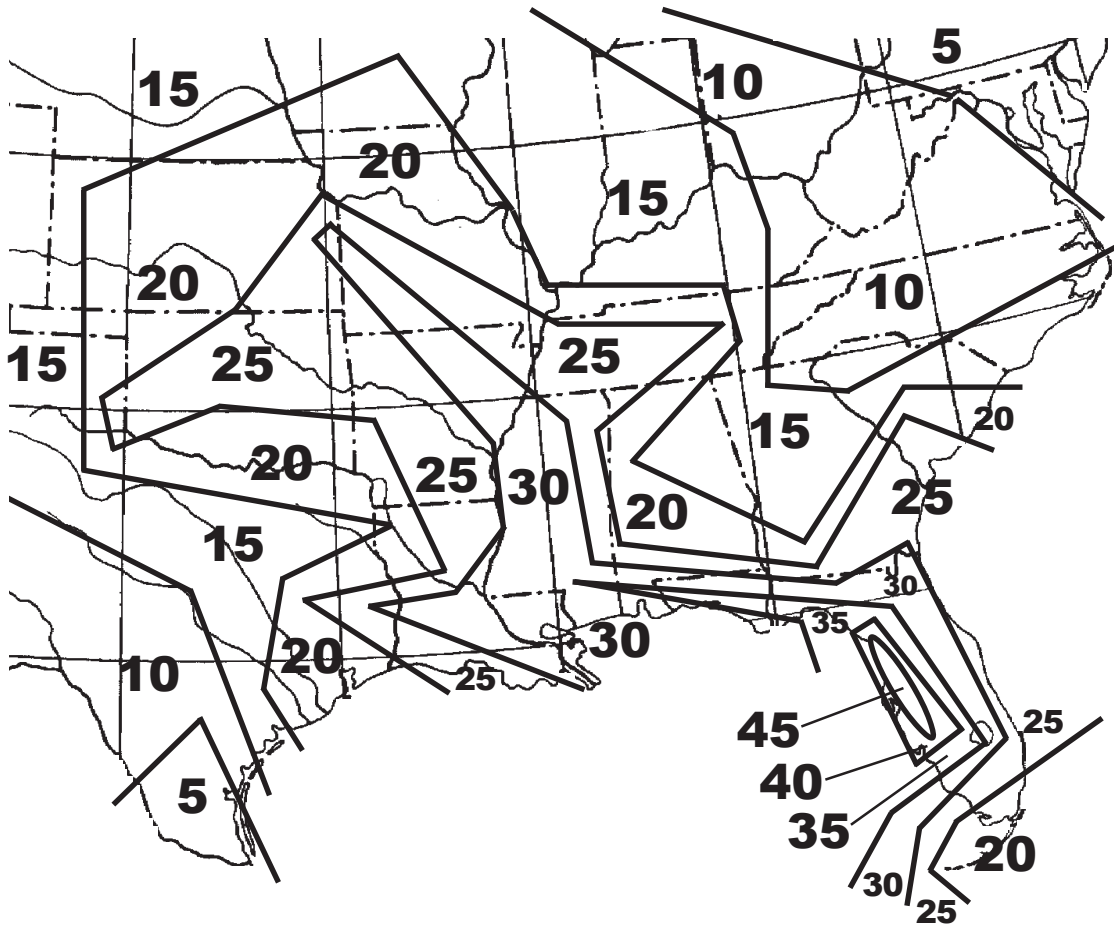## RISK FACTOR #3: _____% +

RISK FACTOR #4: _____% +

RISK FACTOR #5: _____% =

ADD RISK FACTORS #1 - #5: _____ / 500 =

COMPOSITE RISK FACTOR   =

_____

Annual Lightning Strike Probability =

lightning strike number from map X
[3.142 X ((tree height in feet) X 3)² / (5,280)²]

Figure 23: Risk Factor #6 --
Annual Lightning Strike Probability
From map above (or using any other map source) select
a lightning strike number per year per square mile
value for your site. Insert this value into the annual lightning
strike probability formula given above.

Taking Chances

Figure 23 represents risk factor #6 -- annual lightning strike probability. Different places across globe have different lightning strikes per square mile per year. The map represents the number of lightning strikes per square mile per year for the Southeastern United States. This map provides the lightning strike number to be used in the calculation for Risk Factor #6. The other value needed is the height of the tree. These two values are placed in the following formula:

Annual Lightning Strike Probability   =

lightning strike number X [3.142 X ((tree height in feet) X 3)^2 / (5,280)^2]

The Annual Lightning Strike Probability value represents a risk value for a single tree standing alone in a flat landscape with nothing taller in its neighborhood. An Annual Lightning Strike Probability risk factor should be determined.

The Composite Risk Factor (determined from Risk Factors #1 - #5) should be multiplied by the Annual Lightning Strike Probability (Risk Factor #6). The result is the Total Tree Lightning Strike Risk Value. Figure 24. If the Total Tree Lightning Strike Risk Value is greater than 0.05, then there is greater than a 1 in 20 chance a tree may be struck by lightning each year. This is considered a severe risk of tree damage. If the Total Tree Lightning Strike Risk Value is 0.01, a 1 in 100 chance exists a tree may be struck by lightning each year. This is considered a low risk. Figure 25.

Unfortunately this risk assessment does not include expected tree life-span, or historic / cultural values of the tree. A tree expected to live another 300 years, and culturally valuable, would have a much greater risk, and much higher remorse factor if lost, than this assessment tool would determine. A Tree Lightning Risk Assessment Worksheet is provided in Figure 26.

Fighting Myths

There has developed over many years a series of tree associated lightning protection concepts. Figure 27 shows the work of Makela's team in field testing these traditional ideas. The two fundamental ideas are: 1) when trees are most likely to be struck; and, 2) lightning attributes which cause more tree damage. Some of these traditional concepts are supported by field observations. One specifically requires more research -- in a forest landscape, the tallest tree is not most likely to be struck.

Designing Tree Protection Systems

Trees have great value. The architectural, ecological, aesthetic, engineering, and cultural assets trees represent to a homeowner or a community is large. A small portion of asset value must be reinvested in sustaining health and structural integrity. Installation of lightning conduction systems in trees is a significant investment. System installation is a professional specialty within arboriculture. Only historic, socially significant, and high value trees usually merit the attention and expense of a lightning conduction system. As more recreational activities are impacted by liability risks associated with weather, many more average trees (but critically positioned) are candidates for protection.

Storms have great forces which load a tree -- ice, wind, rain, snow, hail, etc. Trees adjust to average wind conditions over time with specialized structural materials positioned in key locations, plus a variable safety factor. Lightning events cannot be prepared for by a tree's growth system, only responded to. Lightning can heat, burn, blow apart, kill, and shatter tree structures. In one flash, a one-hundred-year-

---

B)   Record risk factor #6, the annual lightning strike probability below.

RISK FACTOR #6:
ANNUAL LIGHTNING STRIKE PROBABILITY   =

_____

C)   Multiply composite risk factor (Part A) & annual lightning strike probability (Part B).

COMPOSITE RISK FACTOR   X
ANNUAL STRIKE PROBABILITY =

TOTAL TREE LIGHTNING STRIKE RISK VALUE

_____ X _____ =

COMPOSITE RISK FACTOR   **ANNUAL   LIGHTNING STRIKE   PROBABILITY**

_____

TOTAL TREE LIGHTNING STRIKE RISK VALUE

CALCULATED TOTAL TREE LIGHTNING STRIKE RISK VALUE	RISK DESCRIPTION
> 0.05	severe risk (installation recommended)
> 0.03	high risk
> 0.02	moderate risk (consider installation)
> 0.01	low risk
< 0.005	very low risk (no installation)

Remember that risks can be low, not zero, and lightning strikes, especially smaller current strikes, can still occur.

Figure 25: Tree Lightning Risk Assessment Response --
(based on calculations of risk in Part A, B, & C)
Risk description suggests whether a lightning conduction / tree protection system should be installed.

Figure 26: Field worksheet.

TREE LIGHTNING RISK ASSESSMENT WORKSHEET

Dr. Kim D. Coder, Warnell School of Forestry & Natural Resources, University of Georgia, Sept. 2013

RISK FACTOR #1:
TOPOGRAPHIC LOCATION IN LANDSCAPE   = _____%

RISK FACTOR #2:
RELATIVE TREE HEIGHT   = _____%

RISK FACTOR #3:
TREE OPENNESS   = _____%

RISK FACTOR #4:
RELATIVE NEIGHBORHOOD HEIGHT DIFFERENCES   = _____ %

RISK FACTOR #5:
TREE TARGET PROXIMITY   = _____ %

ADD RISK FACTORS #1 - #5 TOGETHER   TOTAL   = _____

DIVIDE TOTAL BY 500   = COMPOSITE RISK FACTOR   = _____

RISK FACTOR #6:
ANNUAL LIGHTNING STRIKE PROBABILITY   = _____

COMPOSITE RISK FACTOR X
ANNUAL LIGHTNING STRIKE PROBABILITY =
TOTAL TREE LIGHTNING RISK VALUE

_____ X _____ =

COMPOSITE RISK FACTOR   ANNUAL LIGHTNING
                               STRIKE PROBABILITY

TOTAL TREE LIGHTNING RISK VALUE

TOTAL TREE LIGHTNING RISK VALUE	
> 0.05	severe risk
> 0.03	high risk
> 0.02	moderate risk
> 0.01	low risk
< 0.005	very low risk

Tree most likely struck:
-TRUE-
-- open grown or edge trees
-- growing under dry soil conditions
    (soil moisture & wet surfaces protect tree)

-FALSE-
-- tallest ***
-- growing in high resistance soil
-- certain species
-- close to other ground

Cause of more damage:
-TRUE-
-- positive lightning strikes
-- higher peak current

-FALSE-
-- strikes with more strokes
-- continuous current

Figure 27: Field tests of traditional lightning and tree concepts.
(Makela et.al. 2009)

old tree can be destroyed and lost. More people are realizing the values in their trees and are taking active steps to defend trees from most lightning impacts.

Candidate Trees

Installation of a properly designed and grounded conduction system made of the proper materials can minimize lightning damage to trees. Some considerations for installation of a lightning conductance systems in a tree are:

-- Rare, valuable, and specimens, especially when centers of landscapes;
-- Shade or frame recreational areas like golf courses, pools, ball diamonds, bleachers, boat houses, and patio areas;
-- Of special significance, like historical or culturally important trees;
-- In high lightning risk areas or presenting strong ground streamer potentials (enhanced field effects);
-- Large or important trees around and along parks, streets, and public buildings in order to minimize liability risks;
-- Where people or animals will shelter under or run to in a storm;
-- Closer than 30 feet to, or a crown overhanging, unprotected structures or buildings;
-- Within 30 feet of a metal well casing, metal water or gas lines, or metal irrigation systems;
-- Representing a significant appraised value in a landscape.

There are many reasons for a tree to be a candidate for a lightning conduction system. Protecting the current and future benefits flowing from a tree with a lightning conduction system is good management and a good investment.

Protection Concepts

Tree lightning conductance systems are a health care option to consider in especially valuable or vulnerable trees. Lightning conductance systems have a number of unique components which tree health care professionals need to understand. What follows is a brief review of definitions. It is critical to understand coverage here is not meant as an installation guide. Always seek assistance of professional lightning conductance and tree protection specialists. You must seek out and consult the most current national standards, industrial installation guidelines, and best management practices for installing lightning systems in trees. Figure 28.

Functional System Name

The hardware placed in a tree to effectively conduct lightning between cloud and ground is termed a "lightning conduction system."   Installation of a lightning conduction system in a tree is to minimize damage to trees for a large proportion of lightning strikes, and is termed "tree protection." Lightning conduction systems in trees do not significantly attract more lightning.

System Purpose

The purpose of a lightning conduction and tree protection system is to effectively conduct electrical charge potential between cloud and ground in a way which minimizes tree damage. Trees are not good conductors of electricity but can act as a better conduit than air. Lightning conduction systems do not prevent all tree damage, just minimize injury. Extremely large (>250kA) and extremely small (<3kA) lightning discharges can not be completely handled by most lightning systems in trees
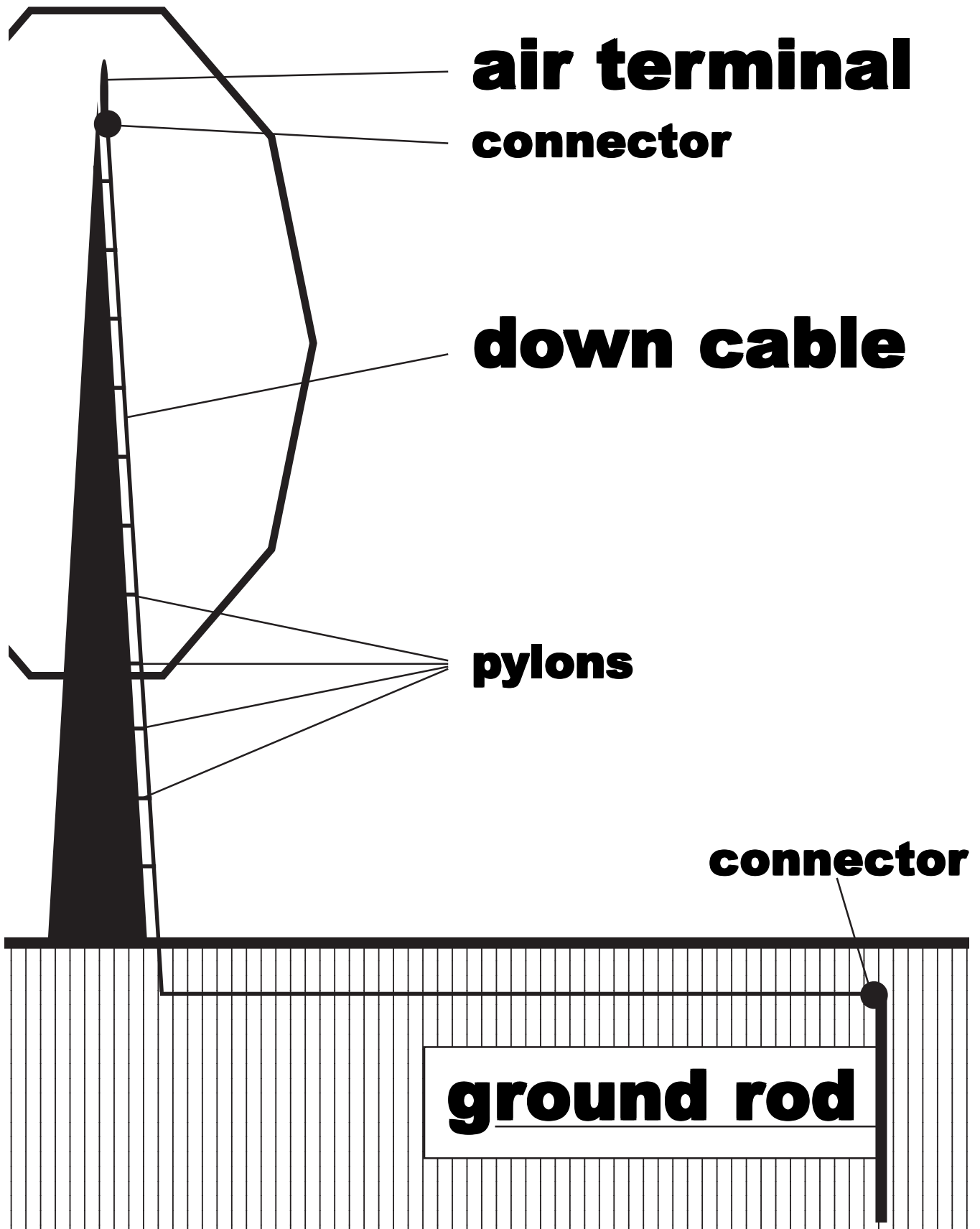
air terminal

connector

down cable

pylons

connector

ground rod

Figure 28: Diagram of a lightning conduction
system installed in a tree.

Cost-Effectiveness

Tree lightning conductance systems are relatively expensive in labor and materials. Not all trees are candidates for installation of a protection system. Lightning conduction systems must be installed properly with correct materials to insure long term protection. For example, aluminum should not be used for any component or link in a system. It is essential to consult with a trained arborist or urban forester, and a lightning conductance system installer, before designing a protection system for a tree. Use lightning strike risk assessments on candidate trees to help determine the need for installation.

Air Terminals

A primary component of a tree lightning conduction system is an air terminal (air point). The top of the down-cable should be attached firmly to an air terminal. This is either a rounded or pointed solid copper alloy object which provides an effective ground streamer anchor point near the top of a tree. The air terminal is held away from the stem several inches by metal pylons. The air terminal is shallowly but firmly screwed into the stem. Air terminals should not be attached using any type of bands running around the circumference of the stem.

Air terminals or points should be firmly attached as high into the tree crown center as can be safely accessed. Ideally air terminals should be placed in the crown at least 80% of the height of the tree. Air terminals are acceptable as low in the tree crown as just above major branch attachment points, understanding the tree portion above the air terminal can be severely damaged by any lightning strike.

Down-Cables

One of the primary components of a tree lightning protection system is the down-cable. A down-cable should run between the highest accessible part of a tree, along the stem, into the ground, and away from the tree. The top-most terminal end of the down-cable should be tightly fastened to the tree and to a solid copper or copper-bronze air terminal. The bottom-most terminal end should be tightly fastened to a solid copper or copper-bronze ground rod.

A multi-strand, woven, hollow-core copper or copper alloy cable can be used for the down-cable. Any bends in the cable should be minimized and then be gently sweeping, not abrupt and sharp. Down-cables are attached to the tree and held several inches away from periderm by metal pylons spaced about three feet apart and shallowly screwed or tacked into the tree.

As the cable is attached to hold-off pylons along a tree stem, the tree should be divided into three segments based upon stem movement. The lower third should not significantly sway and will only wobble up and down across the root plate no more than about 3/4 inch. The middle third of the tree is subject to significant bending, twist, and swaying in the wind. The upper third or outer third of the tree is subject to large deflections approaching 70-80 degrees. The down cable must be installed in such a way to allow for these normal tree movements and not pull out connectors or pylons. The amount of cable slack must be progressively increased with height.

In extremely large stemmed or widespreading trees with large crown volumes, two down cables with separate grounds on opposite sides can be installed. The above ground portions of this double system should be interconnected at least every 30 feet.

Approaching Ground

As a down-cable is placed down the stem and installation approaches the soil surface, a gentle curve should be installed to allow the cable to run away from the tree horizontally 1-2 feet below ground parallel to the soil surface. The curve should not exceed an 12 inch radius, or reach or exceed a 80º angle.

A neutral, soil, or bark colored, loose open conduit or casing (i.e. 3mm thick polyethylene pipe) should surround the down cable from about 1 foot above the soil surface to 1 foot below the soil and away from the tree base several feet. The open lower end of the conduit must provide drainage of any accumulated precipitation or irrigation water. This conduit should be anchored below ground along with the down cable. In special circumstances, conduit 3-10 feet above the soil surface on the stem may be used if animals, humans, or machines could damage the integrity of the system, or have touch contact in a storm. Side flash and step voltage will not be significantly changed.

Cable Lay-Out

The down-cable runs along a tree stem and into the ground at the tree base. The down-cable is gently bent in a wide curve from the stem base into the ground. The down-cable is then put into a soil trench at least 1-2 feet deep in soil and extended away from a tree. The distance away from a tree depends upon grounding efficiency / electrical resistance, potential tree damage, and other site features. The down-cable should be gently curved or turned down at its far end (ground rod end) and ran downward to connect with the vertical ground rod driven 1-2 feet below the soil surface. This is a connection at greatest risk of failure and needs periodic visual inspections.

Ground Rods

Another primary component of a tree lightning conduction system is the grounding rod. Lightning conduction systems must be properly grounded in order to provide for a low resistance charge exchange pathway. Vertically driven, solid ground rods should be at least 1/2 inch in diameter and 8 feet long. Buried wire or woven cable should not be substituted for solid rods. Always test the ground system for actual electrical resistance. Ground rods are usually copper or copper bronze. They are driven into the soil and below the surface. Lightning conduction systems must be properly grounded in order to provide a low resistance electrical charge exchange pathway. Ground rod resistance should always be measured, never assumed.

Rod Installation

It is essential that ground rods be driven vertically until they are at least one to two feet below the soil surface and then fastened tightly to the down-cable end. Rods must be driven into the soil to assure a firm contact. Do not dig out soil and bury rods unless the soil can be firmly tamped around the full length of the rod. If soil depth is limited, horizontal rods packed into trenches or many shorter vertical rods are viable alternatives. The more connections required, the more expensive and more prone to failure over time grounding components become.

Rod ends must be driven into oil to be below any expected soil freeze level, as well as into and below water table level, if possible. The top of vertical ground rods should be a minimum of one feet below grade, but must be placed to remain accessible for inspection. The location of the rod top and the down cable connection point should be recorded or marked for ease of visual inspection and tightening of bolt connectors over time. If multiple vertical rods are required, the distance between rods should be a minimum of 13 feet for eight feet long rods, and 16 feet for ten feet long rods.

Rod Placement

Grounding methods differ in different soils. Normally, driving a rod vertically into soil producing lengthwise soil and soil-water contact is sufficient. Where soil space is limited or soils are shallow, forking the cable and burying (tamped in firmly!) several rods in separate trenches as deep as possible is acceptable. Grounding rods should be placed at some distance from the stem base, depending upon a

number of soil, site, and tree features. Minimizing significant root damage is one aspect of effective ground rod placement. Ground rod depth, distance between rods, and the amount of moist soil contact are critical for proper grounding.

If soil depth is limited, horizontal buried rods arranged in several configurations within trenches are viable alternatives. The coarser the soil texture, and the more gravel, rocks, or cobbles present, the longer the trench and number of interconnected rods required. Shallow soils with large components of sand and gravel should have a minimum 25 feet long rod buried horizontally at least 2 feet deep. Shallow soils composed primarily of clay should have a minimum 15 feet long rod buried horizontally at least 2 feet deep.

Ground Effectiveness

The effectiveness of grounding rods is dependant primarily upon soil water contents. Dry soil problems (high resistance values) occur around foundations, basements, or tunnels where soils have been modified or materials added to prevent water movement. These areas should be avoided for ground rod installation. Soil amendments, organic material, or mulch which lighten or protect soils can have a high resistance when dry. These materials fluctuate greatly in wet and dry cycles. Artificial soils and soils mixed for a variety of landscape purposes may not provide good contact or effective grounding volumes, and so, should be avoided for rod installation.

For most grounding, an electrical resistance of less than 25 ohms is acceptable and less than 10 ohms is desirable. Measure electrical ground resistance of tree lightning conduction systems. If large resistance values are measured, installation of extra ground rods will be necessary. The whole system is worthless if not adequately grounded. When measuring electrical resistance in a tree lightning conduction system, any noticeable increase in resistance over time would suggest impending system component failures (usually connectors), corrosion of surfaces and connectors, or long-term or short-term soil water changes.

Coder Grounding Distance

The down cable should be buried in a radial trench running away from the tree base and end with a rod connection a minimum of 16 feet away from the tree base. Under normal, non-soil limiting conditions, the minimum distance away from a tree where the grounding rod (or first grounding rod in a multi-rod system) should be driven is calculated using the Coder Tree Grounding Distance formula as follows:

Minimum Distance in feet from Tree Base for Driving First Ground Rod =

(0.45 X tree diameter in inches) + (1.6 X grounding rod length in feet)

Figure 29 provides the minimum distance in feet away from the tree stem base for inserting a vertical grounding rod which is 8 feet long. The objective in using the Coder Tree Grounding Distance formula is to minimize and avoid major tree root impacts.

Connectors

Everywhere component touch and are connected, they must securely overlap by 2-3 inches. Clamps, bolts, and heat / arc bonding should be used. All connectors should be made of copper / copper-bronze. The value of all parts of a tree lightning conduction system lies in how each is connected. The tree protection system is only as good as its poorest connection. Down-cables and associated connectors are impacted with thousands of foot pounds of mechanical and magnetic force, plus rapid heat expansion

stem diameter (DBH inches)	distance from stem to rod (ft)	stem diameter (DBH inches)	distance from stem to rod (ft)
<8in.	16ft	30	26
		32	27
10	17	34	28
12	18	36	29
14	19	38	30
16	20		
18	21	40	31
		50	35
20	22	60	40
22	23	70	44
24	24	80	49
26	25		
28	25	90	53
		100	58

Figure 29: Minimum distance in feet (rounded values) away from tree stem base for inserting vertical ground rod (8 feet long) in order to avoid major tree root impacts. (Coder Tree Grounding Distance).

forces, with each lightning stroke. Connectors and any curves in the down-cable are where these forces can be concentrated.

All connection hardware must be easily located for visible inspections. Connectors that cannot be readily inspected put systems at risk of failure over time. Cable connectors which tightly hold and over-lap cable ends can be used along the down-cable, but should be minimized above ground and never used below ground. Any connector in the system must hold at least two inches of cable overlap and be able to accept more than 250 lbs of tension and compression force. Bolt connectors between cables and rods are always preferable to any crimped connectors.

Stand-offs Pylons

Pylons are short metal pegs which keep the down-cable at least 2 inches away from the periderm surface. The are positioned every 3-5 feet along the down cable and firmly attached to the tree.

Site Interconnections

When trees with a lightning conduction system grows near a structure / building, lightning behavior suggests a set-back or gap between the protected tree and structure be installed. Figure 30 shows the set-back space needed around a tree with a lightning conducting system installed. The air gap is much larger than the soil gap. For average lightning strikes, the tree grounding system should be separated by at least 8 feet from the structure's foundation and underground services, and by at least 14 feet between air terminal and down cable components of the tree system and above ground structures.

Figure 31 provides an image of the setbacks between the tree system and the structure both above and below ground. The separation between soil metal, utility services, metal well casing, and various pipes and wires is shown. These values are minimum distances. If tree system grounding systems are going to be closer, a firmly attached and large surface area electrical connection between the tree system and any underground metal service should be made. This figure also provides the ratio between above and below ground set-back distances.

Because peak lightning currents are determined by probability only, a few traditional installation guidelines have been developed over many years. If a tree lightning conduction system is within 30 feet of other lightning conduction systems, metal water pipes, or metal well casings, bonded interconnections should be made. Trees with crown or root base lighting, wiring, metal cables, or other hardware should have all hardware interconnected with the lightning conduction system. Interconnect tree lightning protection system with all metal (like cable and bracing) within the tree growing area.

Trees do not protect adjacent or shaded structures from lightning. Trees within 30 feet of a shorter building, or with branches overhanging a building, should be protected. All lightning systems coming within 30 feet of each other, like a system on a building and a tree system, should be interconnected. In multiple rod, horizontal or vertical ground systems, the grounding systems center and edge should be located. In these cases, the edge of the system should be a minimum of 16 feet away from the tree stem, and moved out away from a tree using the Coder Tree Grounding Distance formula.

Historical Grounding Concerns

In the past, solid or mesh grounding plates or metal sheets were used to lower electrical resistance under severe soil limitation conditions. The use of grounding plates is an expensive and high maintenance system for any reduction in electrical resistance gained , and is not recommended.

In the past, salts were added to help the short term effectiveness of a ground, and would generate false resistance measures. Do not use salts to lower resistance in systems as this leads to temporary changes only, and corrodes system effectiveness. Any surrounding metal objects in a salt laced soil will also be affected.
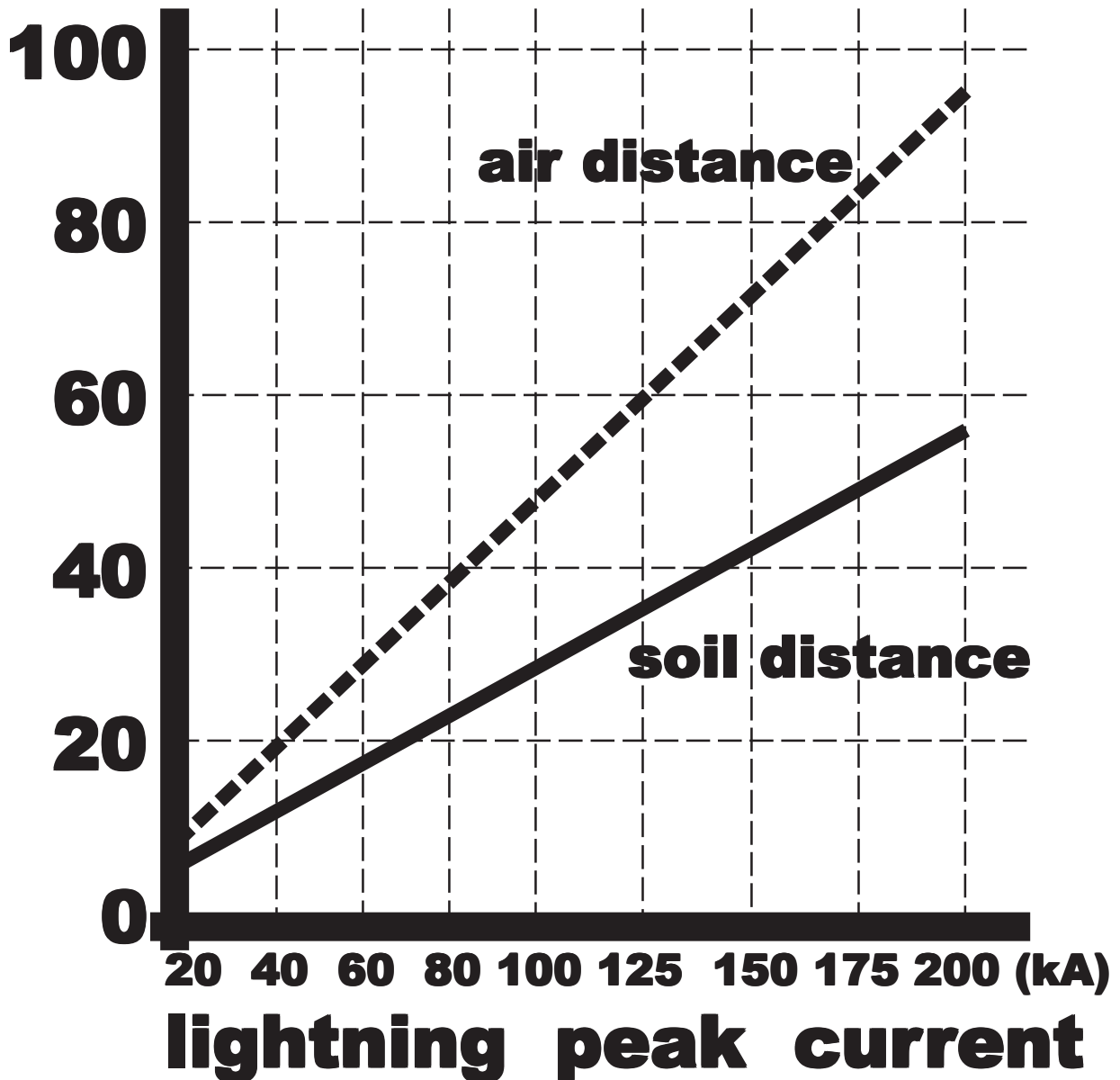
Figure 30: Minimum air and soil distances (in feet) between a lightning conduction system and above ground structures / metal services within a soil for lightning peak current.
(Rakov 2012)

air distance = 1.7 soil distance
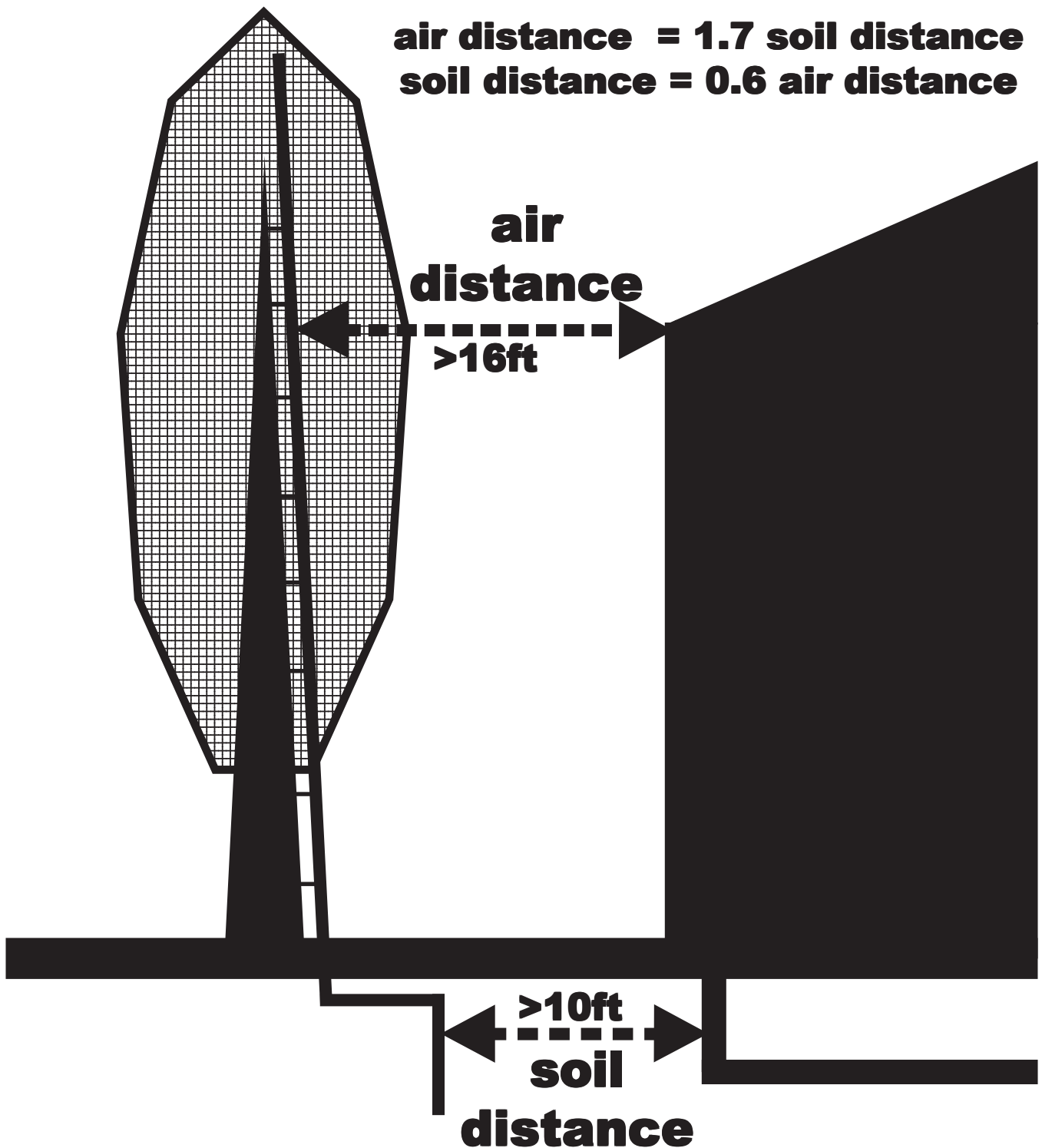soil distance = 0.6 air distance

air distance
>16ft

>10ft soil distance

Figure 31: Minimum distances, and ratio between air and soil distances, between lightning conduction system in tree and surrounding structures / metal services above ground and below ground. (Rakov 2012)

Never mix different types of metals in below ground parts of a tree lightning conduction system. Different metals in a moist soil environment will react together leading to corrosion. Managerial notice should be issued for accelerated corrosion of other metal parts in the soil area, even if not connected directly to the grounding system. For example, nearby iron water or gas pipes can corrode more quickly near a copper cable, rod, or connector. Aluminum and bare iron should not be present in soil near a tree lightning conduction system.

System Identification

All tree lightning conduction systems should have an identification tag attached with the installer's contact information or unique code number. Maintenance is required to check and reattach connections, and prevent damage to the down cable especially where it enters the soil. All system components should be inspected at least every year, and in particularly valuable trees, after every major storm event.

Side Flash

Because of tree resistance to current flow, side-flash from a tree to objects near them has a strong probability. Trees should be maintained with a minimum of 10 feet clear horizontal crown clearance from any structures. Trees taller than a structure should have a horizontal clearance from that structure amounting to 40% of the structure height. Any lightning system components on the structure (like a down cable) should be open and facing the tree to facilitate conductivity of side-flashes.

Standards & Practices

There are a number of lightning conduction and tree protection system standards, specifications, and information available to assist a tree health care providers understand installation procedures. These materials usually have a creation date and sometimes have a sunset date attached. Use only the most recent approved information. Note a number of building, structural, utility, and communication protection specifications may have a small section on tree protection. Remember, lightning conduction systems for communication towers and tall buildings are not biologically nor structurally designed for living trees.

System Considerations

Examining sites and trees for potential installation of a lightning conduction system requires accurate calculations and measurements. Effectively minimizing lightning damage to trees and minimizing waste in purchasing lightning conduction materials requires careful planning. Tree protection professionals need to "rough-out" installations by estimating placement and amount of materials needed. It is critical to review and follow national and state standards and specifications for lightning conduction systems and for proper tree protection. Remember this manual is not an installation guide but an educational primer of design considerations.

The three methods of determining air terminal and system effectiveness is by using the rolling sphere method, the cone (or angle) of protection method, or the fractal method. Note the rolling sphere and protective cone methods represent nearly the same protected volume beneath a tree. The fractal method suggests a larger protected volume for relatively short air terminal placements like in most trees.

Protection Cones

For relatively short structures like trees, lightning conduction systems have been historically designed using "cone of protection" concepts. A cone of protection is the idealized area (a right circular cone shape) beneath an air terminal within which most lightning damage should not occur, and is a simple

way for visualizing the protected area under an air terminal. Figure 32. Remember, there is little protection from low current (<3kA) lightning strikes which comprise less than 0.5% of all ground strikes.

The protection cone (right circular cone) apex is at the air terminal. The volume beneath the apex or within the cone is considered protected from most lightning strikes. The cone protection angle is one-half the apex angle. For increasing tree height, the cone protection angle (i.e. one-half the cone apex angle) narrows and becomes smaller in order to maintain the same protection effectiveness. For the same height of tree, the smaller half the apex angle, the greater (or more sure) the protection level.

The size and shape of a cone of protection is a function of cone angle (a) in degrees and air terminal height (ht) in feet. Figure 33. A cone of protection model is valuable for defending space below an air terminal, and easy for visualizing and system design. A number of historic and current guidelines for lighting protection utilize a specified cone of protection. Figure 34.

Different cone angles provide different levels of protection. Figure 35. For example, if the air terminal height (ht) is one and the cone of protection angle (a) is 45°, the ground distance radius of the cone of protection (r) will be one multiplied by the air terminal height (1.0 X ht). Continuing with another example, if air terminal height (ht) is one and cone of protection angle (a) is 26°, then the ground distance radius of the cone of protection (r) is 0.5 multiplied by the air terminal height (0.5 X ht). The effectiveness rating represents the middle of expected lightning strike peak currents.

Figure 36 provides a graph showing tree protection levels. For example, a cone angle (a) of 45° yields a 1:1 ratio of cone ground radius to air terminal height, and is considered to provide strong protection from lightning strike damage. A cone angle (a) of 63° yields a 2:1 ratio of cone ground radius to air terminal height, and is considered to provide moderate protection from lightning strike damage. In extreme protection situations, a cone angle (a) of 26° yields a 1:2 ratio of cone ground radius to air terminal height, and is considered to provide a high level of protection from lightning strike damage. (derived from USDoD, 1987).

Some cone angles have been cited in international, national, and state structural guidelines. Figure 37 shows cone angles used to attain specific lightning protection effectiveness for given tree heights.

Rolling Sphere

The rolling sphere method is another means to visualize protected volume below an air terminal. The rolling sphere method for determining the protected area beneath an air terminal is used for many types of lightning protection systems. The lightning strike distance used for design and installation of a tree lightning conduction system is represented by the radius of the sphere. Usually a standard sphere radius is used representing the effectiveness of any system installed. The volume below and outside the sphere is considered protection from a majority of lightning strikes, but small and extremely large current lightning strikes would not be defended against.

Structural protection volumes below air terminals around buildings and trees have been delineated by the rolling sphere method. Figure 38. As a sphere of a given radius is rolled over and around any structure, the sphere touches the ground and structure's air terminal. Beneath the edge of the sphere (sphere surface) between contact points defines the limit of the protection area. Figure 39. Various levels of structural protection are reached by using spheres with different radii (sphere size). Figure 40. Smaller radius spheres are used to provide a greater level of protection. Figure 41. For example, a 150 feet arc radius would represent a protection area for ~91% of lightning strikes which include peak currents between 10-100kA. (IEC 1992; Volland 1995)

For trees, the 150 feet arc radius rolling sphere is normally used in North America. Trees taller than rolling sphere radius selected would need additional protection to maintain the protection effectiveness. Figure 42.
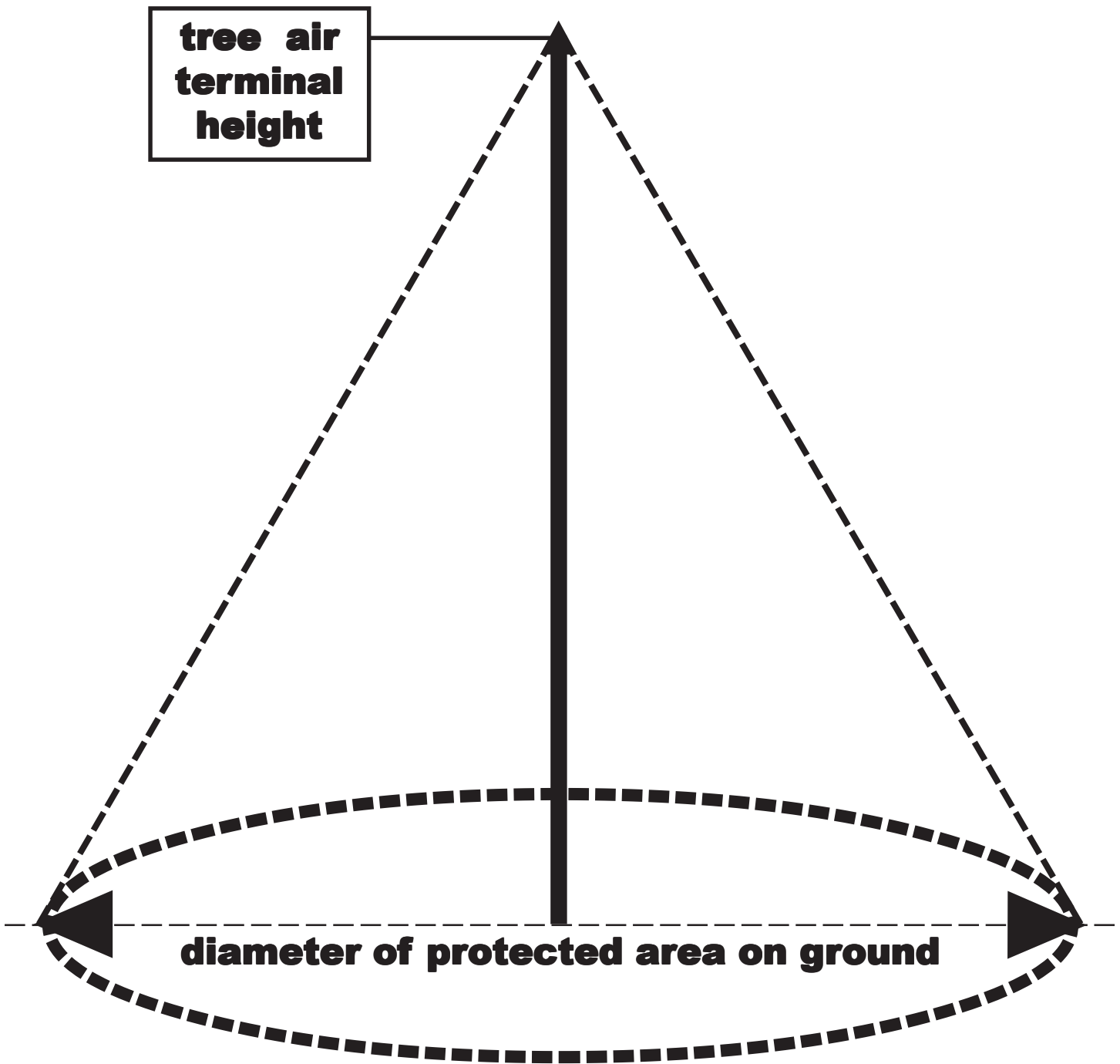
tree air
terminal
height

diameter of protected area on ground

Figure 32: Description of a right circular cone shape whose
apex is the air terminal of a lightning conduction system.
(Bouquegneau 2010)

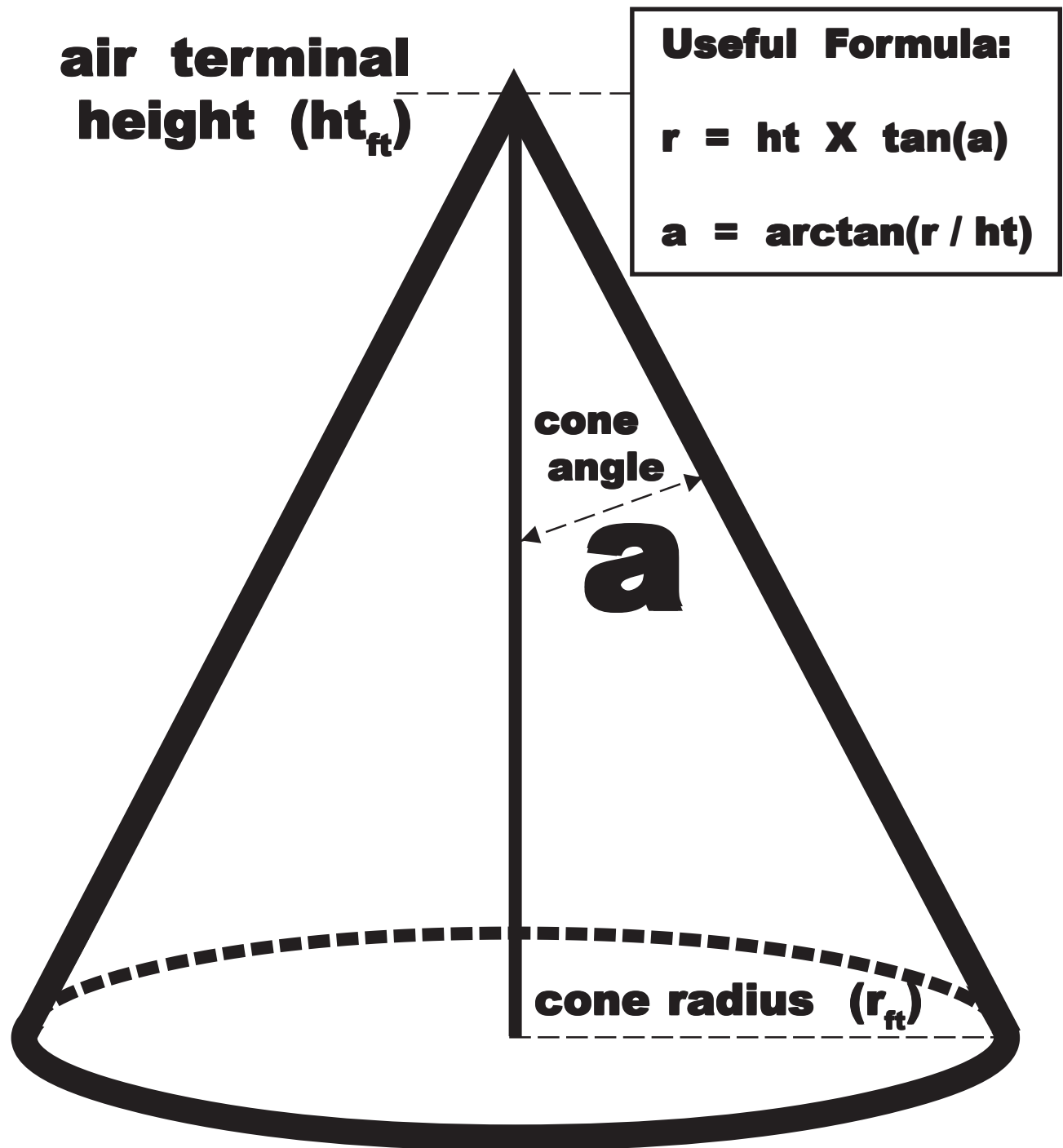**air terminal height (ht$_{ft}$)**

Useful Formula:

$$r = ht \times \tan(a)$$

$$a = \arctan(r / ht)$$

cone angle

a

cone radius (r$_{ft}$)

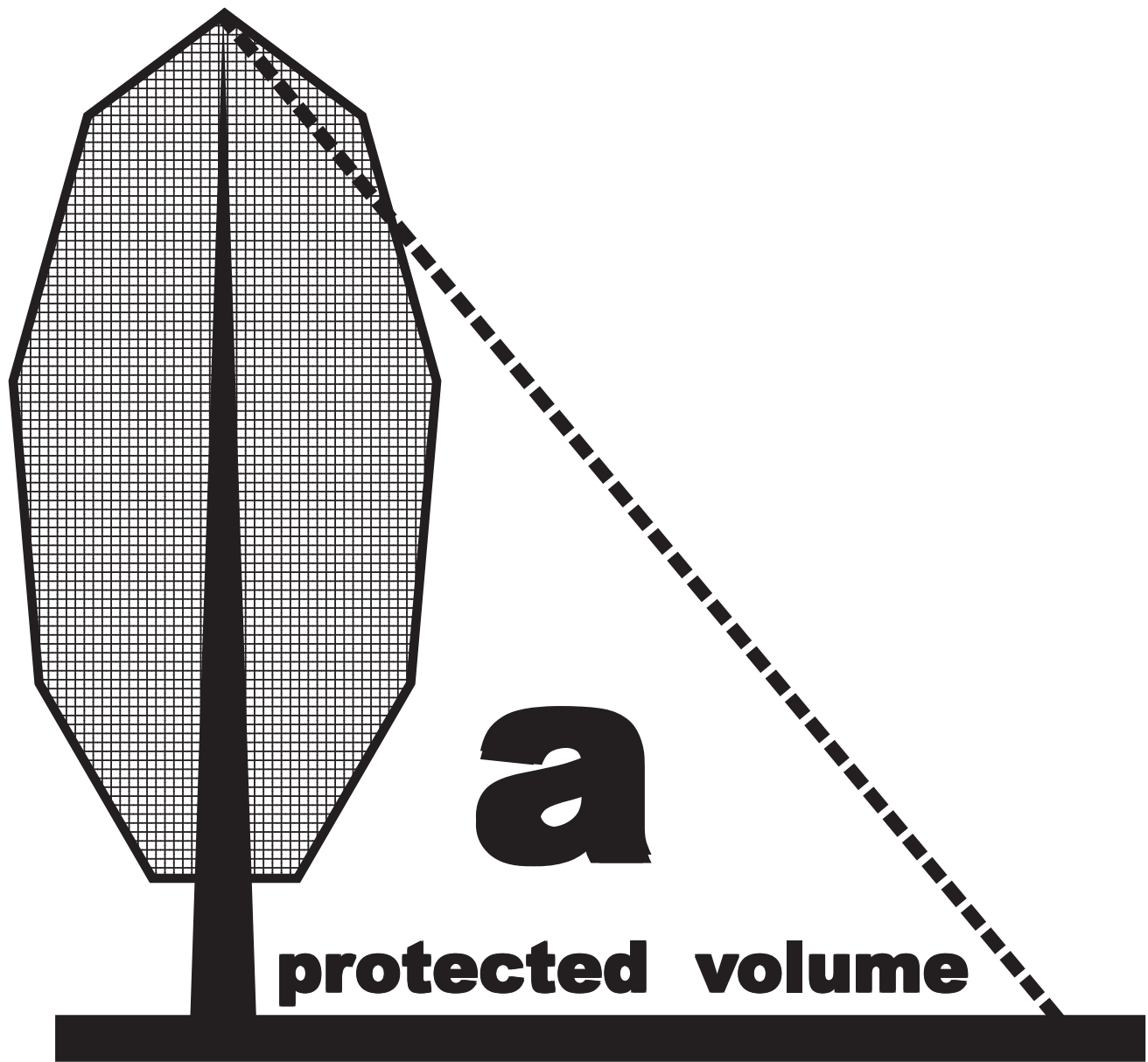Figure 33: Diagram of tree lightning conduction system "cone of protection" dimensions beneath an air terminal. Cone angle "a" is 1/2 apex angle.

Figure 34: Two-dimensional side view of a protection cone (right circular cone) beneath an air terminal in a tree. "a" is the protection cone angle (1/2 apex angle) in degrees.
(Bouquegneau 2010)

tree with lightning conduction system

★ = air terminal height in tree

★ air terminal

14° 26° 37° 45° 56° 63° = cone angles in degrees

.25ht .5ht .75ht 1ht 1.5ht 2ht

ground distance away from tree in air terminal height units
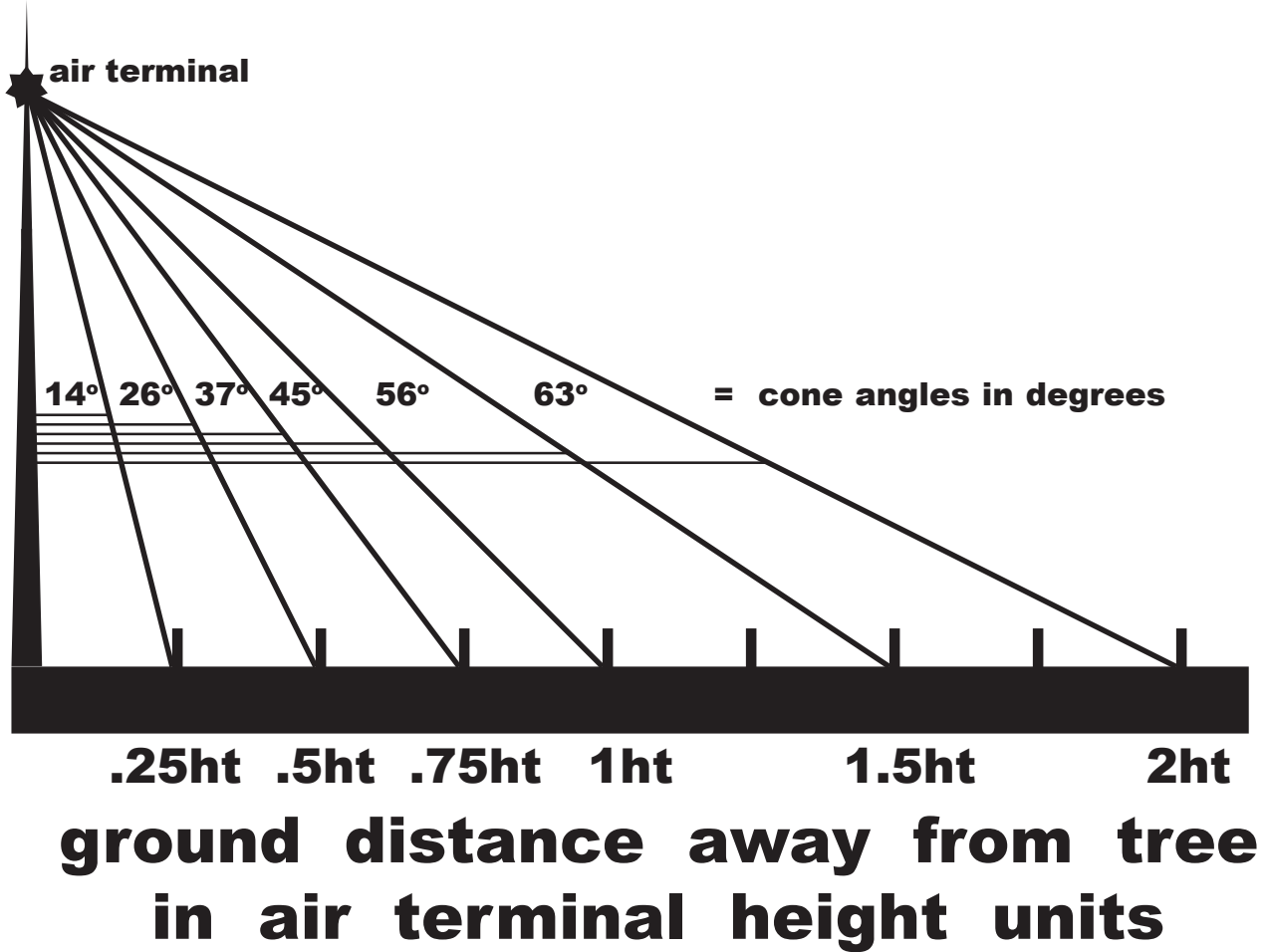
Figure 35: Two dimensional side view for series of three dimensional "cones of protection" beneath a lightning conduction system air terminal. The ground distance and cone angle are shown. (derived from USDoD, 1987)
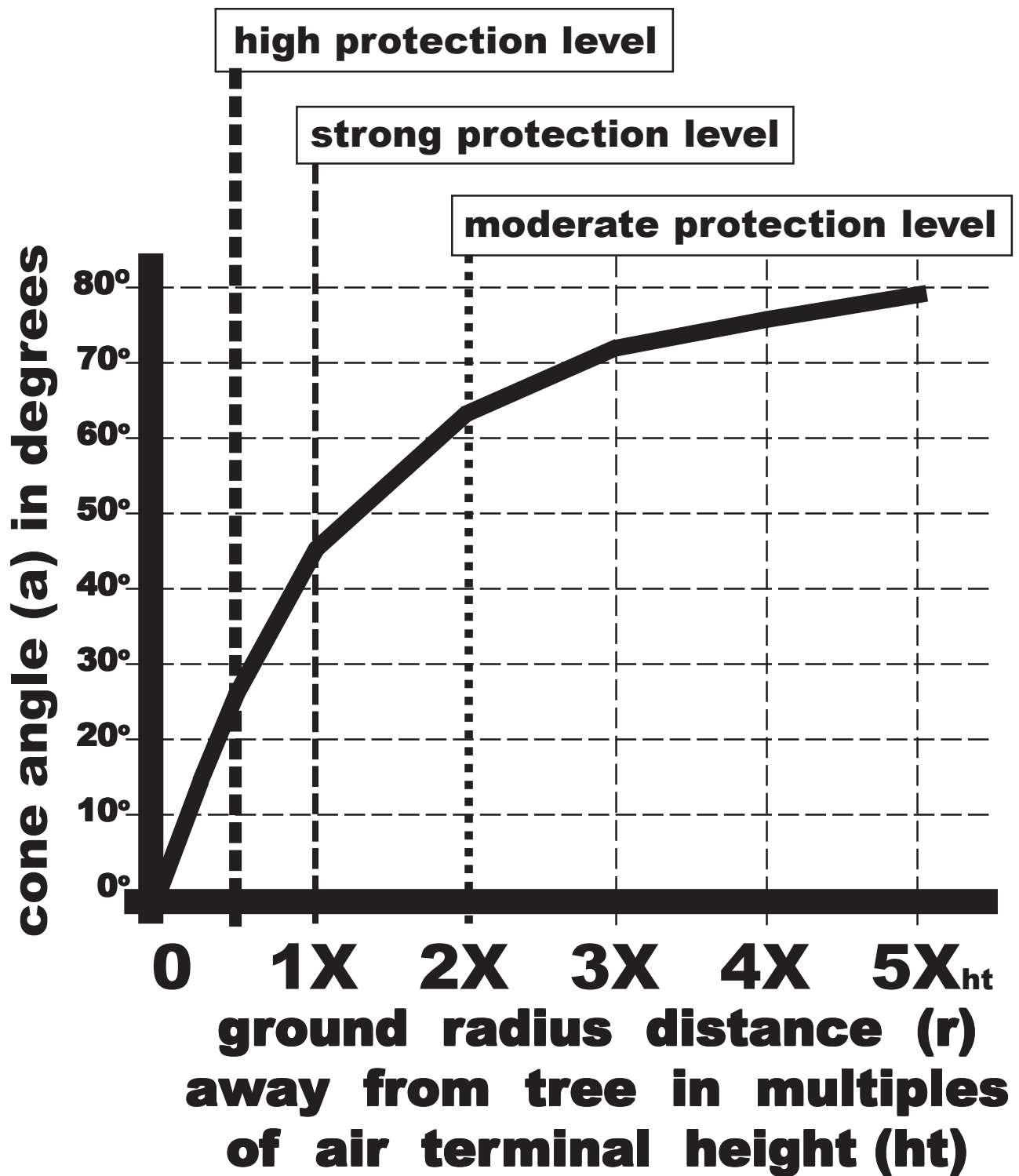
Figure 36: Graph of cone angle (a) and ground radius distance (r) using cone height (ht) units. (i.e. 2X ground radius = two times the cone height). (derived from USDoD, 1987)

Figure 37: Protection cone angle for various tree heights (in feet) and for different levels of lightning protection (in percent). (Bouquegneau 2010)

ROLLING SPHERE

radius
or SD

radius
or SD
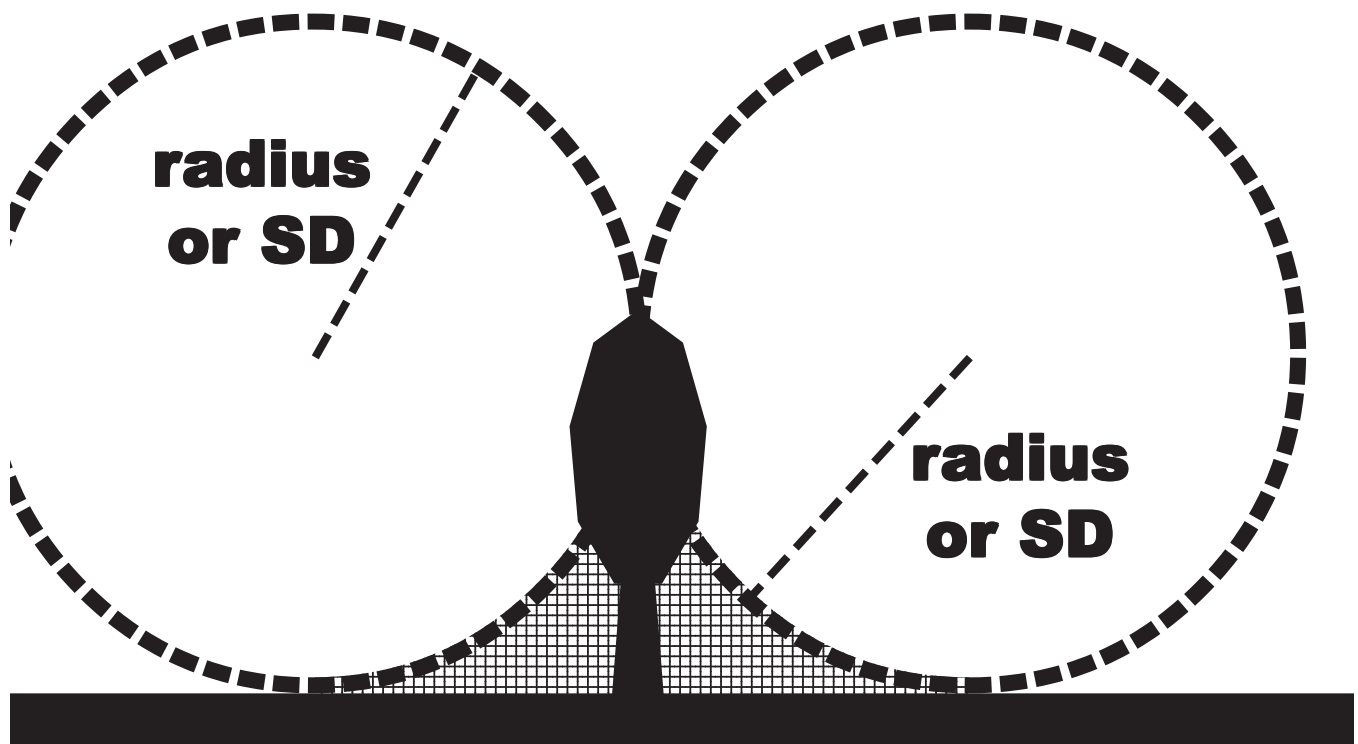
Figure 38: Rolling sphere method for determining volume
protected beneath (shaded area) an air terminal of a
lightning conduction system in a tree. (Rakov 2012)

air terminal position

rolling sphere radius
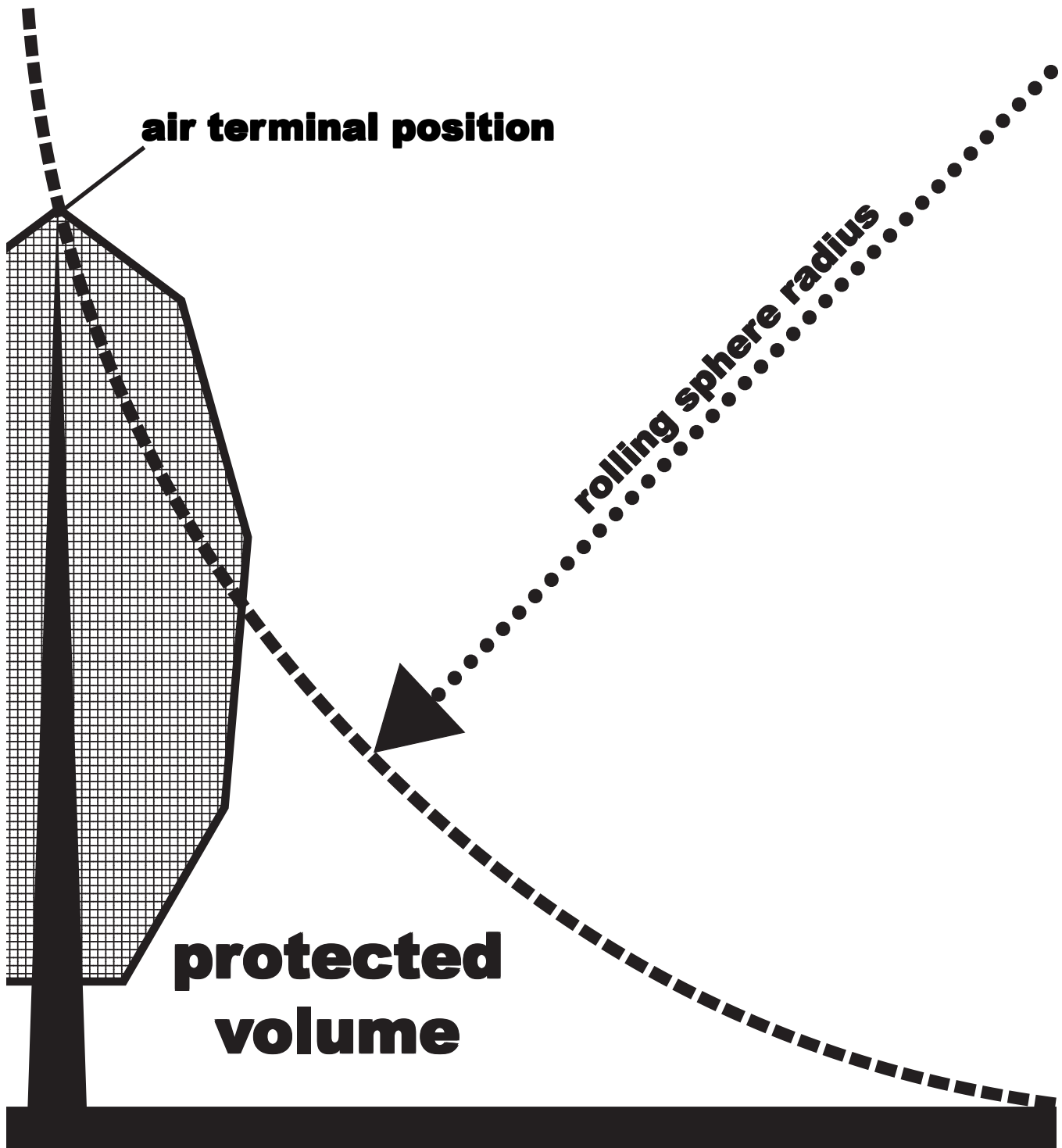
protected volume

Figure 39: Two-dimensional side view of a volume of space around a tree beneath an air terminal determined by the rolling sphere method considered protected for some level of lightning strikes. (Bouquegneau 2010)

tree protection effectiveness

150ft radius sphere = 90% effectiveness

100%

95%

90%

85%

80%

75%

0   50ft   100ft   150ft   200ft

arc radius rolling sphere (ft)
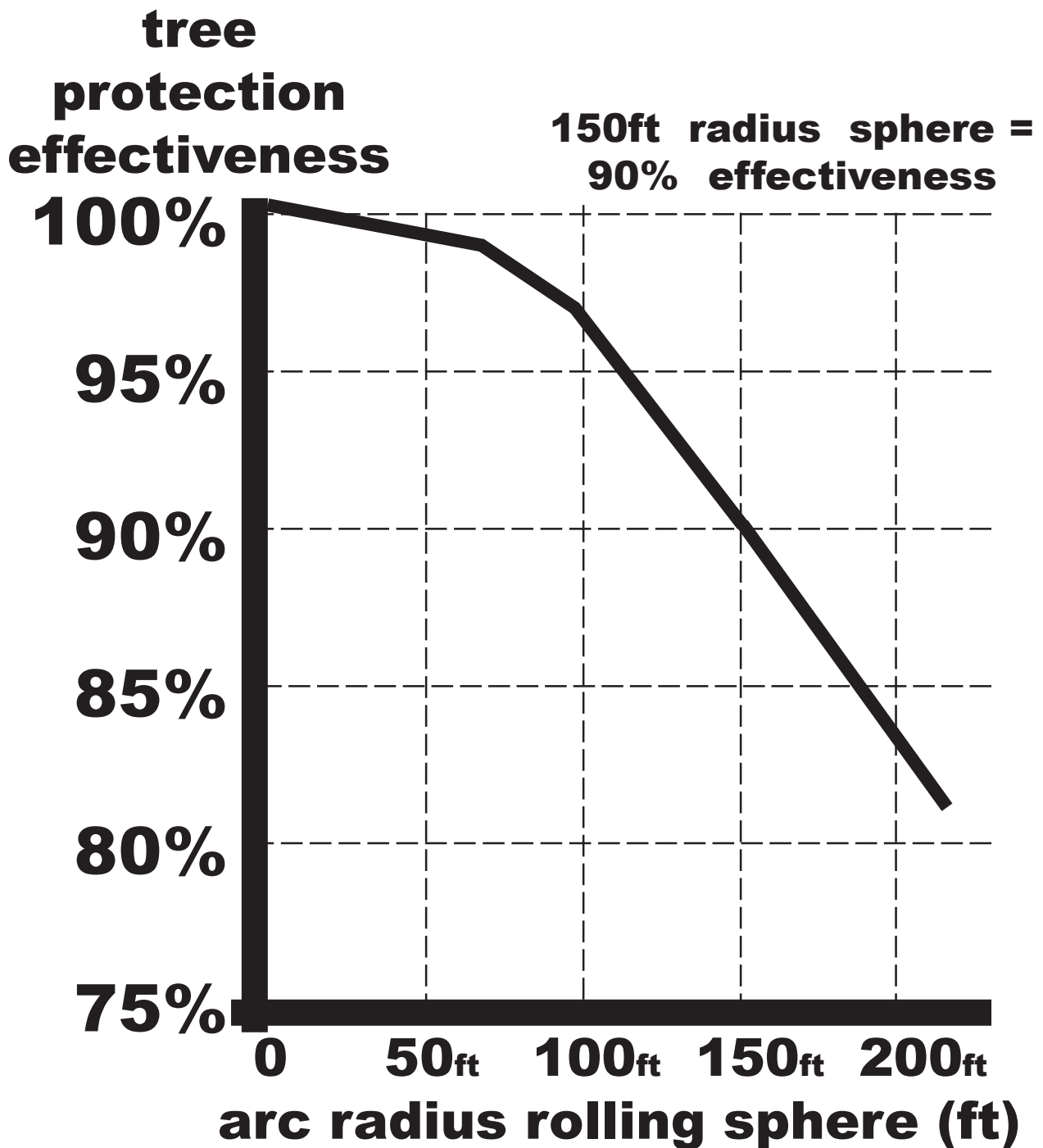
Figure 40: Protection effectiveness using the rolling sphere method in determining the protection area below an air terminal in a tree. (derived from IEC, 1992; Volland 1995))

International Standard (IEC)
Classes of Lightning Protection

class	protection value	current	rolling sphere radius
I	99%	3-200kA	~ 66ft
II	97%	5-150kA	~100ft
III	91%	10-100kA	~150ft
IV	84%	15-100kA	~200ft

Figure 41: International lightning protection standrad values for using the rolling sphere method.   (Bouquegneau 2010)
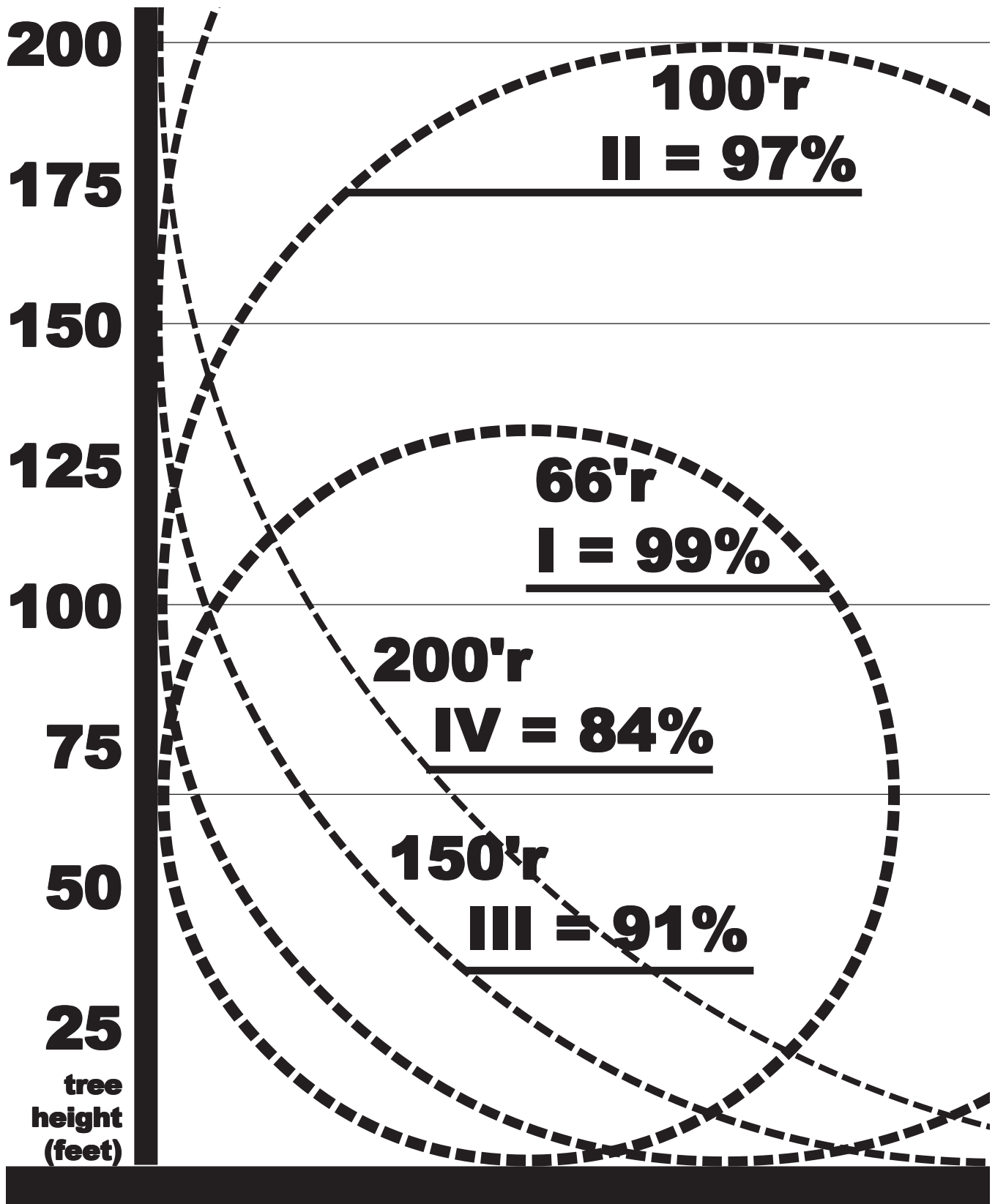
Figure 42: Comparing the relative sizes of rolling sphere radius values for tree lightning protection. (Bouquegneau 2010)

Around the world, different rolling sphere radii are placed into standards and installation guides, usually associated with building or structure protection, not trees. Figure 43 shows the two most common tree associated radii and the horizontal extent of their protection zone based upon a 50 feet air terminal height. International protection standards using the rolling sphere method give a range of protection effectiveness provided in peak current (kA) range coverage and rolling sphere radius in feet. Many tree installations are made at the class III level trying to meet greater than a 91% protection effectiveness.

Figure 44 provides estimated tree protection zone distances and areas below a single air terminal at a given height. This tree protection area is based upon a standard 150 feet arc radius line. Protection area radius, diameter, and area measures are given for the ground beneath an air terminal in a tree using the formulae below:

$$\text{protection area radius} = ((\text{ArcRad})^2 - (\text{ArcRad} - \text{air terminal height})^2)^{0.5}$$

$$\text{protection area diameter} = 2 \ X \ (((\text{ArcRad})^2 - (\text{ArcRad} - \text{air terminal height})^2)^{0.5})$$

$$\text{protected ground area} = (3.142) \ X \ [((\text{ArcRad})^2 - (\text{ArcRad} - \text{air terminal height})^2)^{0.5}]^2$$

$$\text{ArcRad} = \text{rolling sphere radius in feet}$$

For example, a tree with a single air terminal installed at 100 feet above the ground would have a protection area radius below the air terminal following a 150 feet arc radius sphere edge which touches the ground at 141 feet away from the stem center. Diameter of the protection area in this example is 282 feet (2X radius) centered on the tree stem. The protected ground area would be 62,831 square feet of soil surface. Figure 45 graphically illustrates the example. Remember that the lightning conduction system generates a three-dimensional protection volume, requiring design considerations from all views.

Visualizing Rolling Protection

When looking at a tree it is important to visualize the protected volume of space above ground and beneath any air terminal. How much of the tree is covered by any protected space? Figure 46 provides the estimated horizontal distance away from the stem a protection area extends on the ground underneath a single, tree-centered air terminal placed at a given height in a tree for a series of different vertical heights. For example, a tree with an air terminal positioned at 80 feet in height would have an edge of its protection area at 50 feet above the ground located 20 feet radially away from the stem center. These values were generated with the following formula:

Horizontal Radial Distance to the edge of the protection area from tree stem center =

$$(PZr) - [(\text{ArcRad})^2 - (\text{ArcRad} - Vht)^2)^{0.5}]$$

$$PZr = \text{protection zone radius on the ground}$$
$$Vht = \text{vertical height at some distance from stem center}$$
$$\text{ArcRad} = \text{rolling sphere radius in feet}$$

Figure 47 provides the estimated vertical height of the protection area beneath a single, tree-centered air terminal at a given height for a series of horizontal radial distances. For example, a tree with
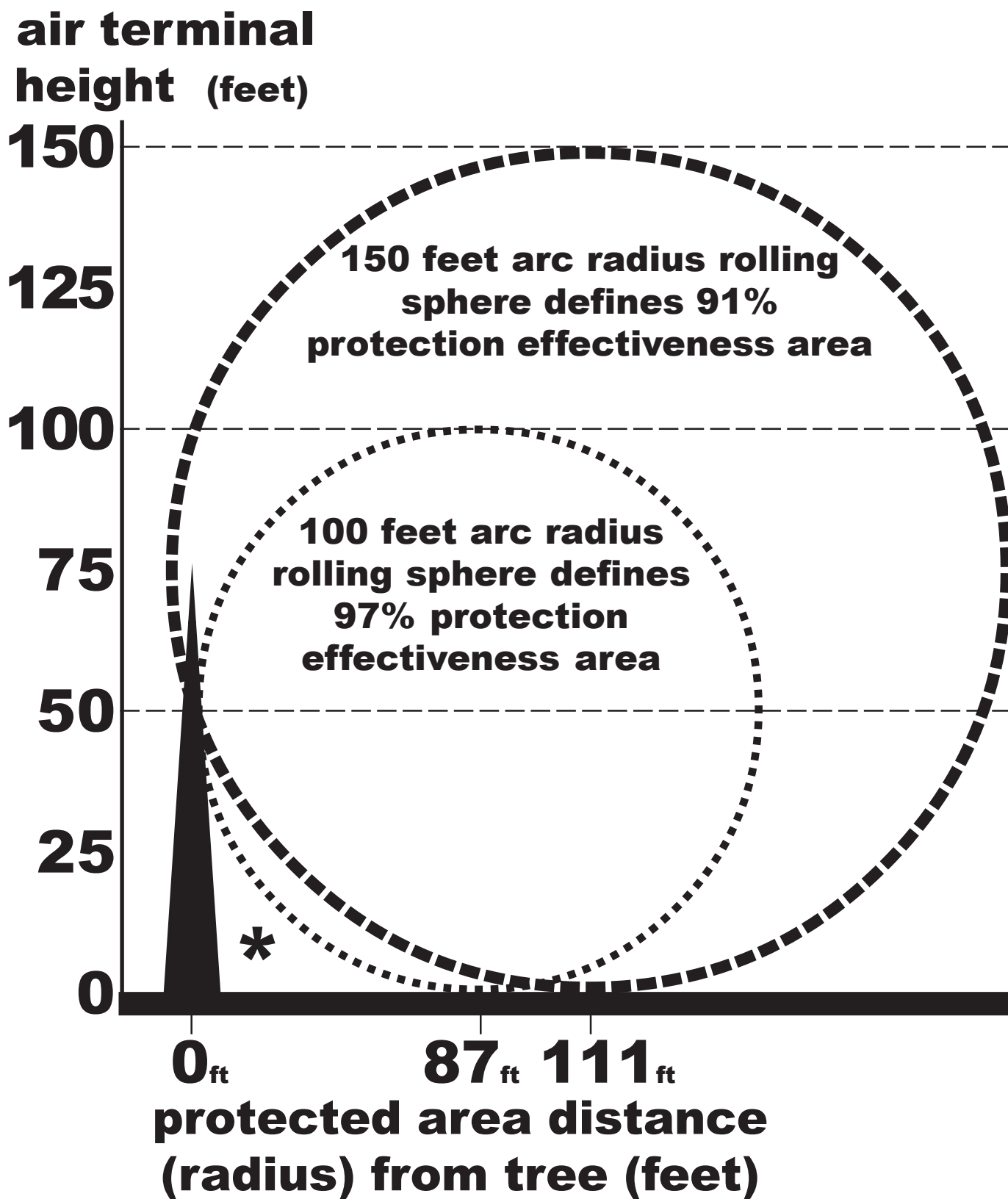
Figure 43: Rolling sphere measures for estimating protection area under a tree air terminal placed at 50 feet above ground.

air terminal height (feet)	protection area radius (feet)	protection area diameter (feet)	protected ground area (sq. ft.)
10 ft.	53 ft.	107 ft.	9,110 sq.ft.
20	74	149	17,592
30	90	180	25,446
40	101	203	32,672
50	111	223	39,269
60	120	240	45,238
70	126	253	50,579
80	132	265	55,291
90	137	274	59,376
100	141	282	62,831
120	146	293	67,858
140	149	299	70,371

Figure 44:   Estimated protection distances (in feet) and area (in square feet) measured on the ground below a single air terminal which is installed at a given height (in feet) in a tree (using an 150 feet arc radius protection zone).
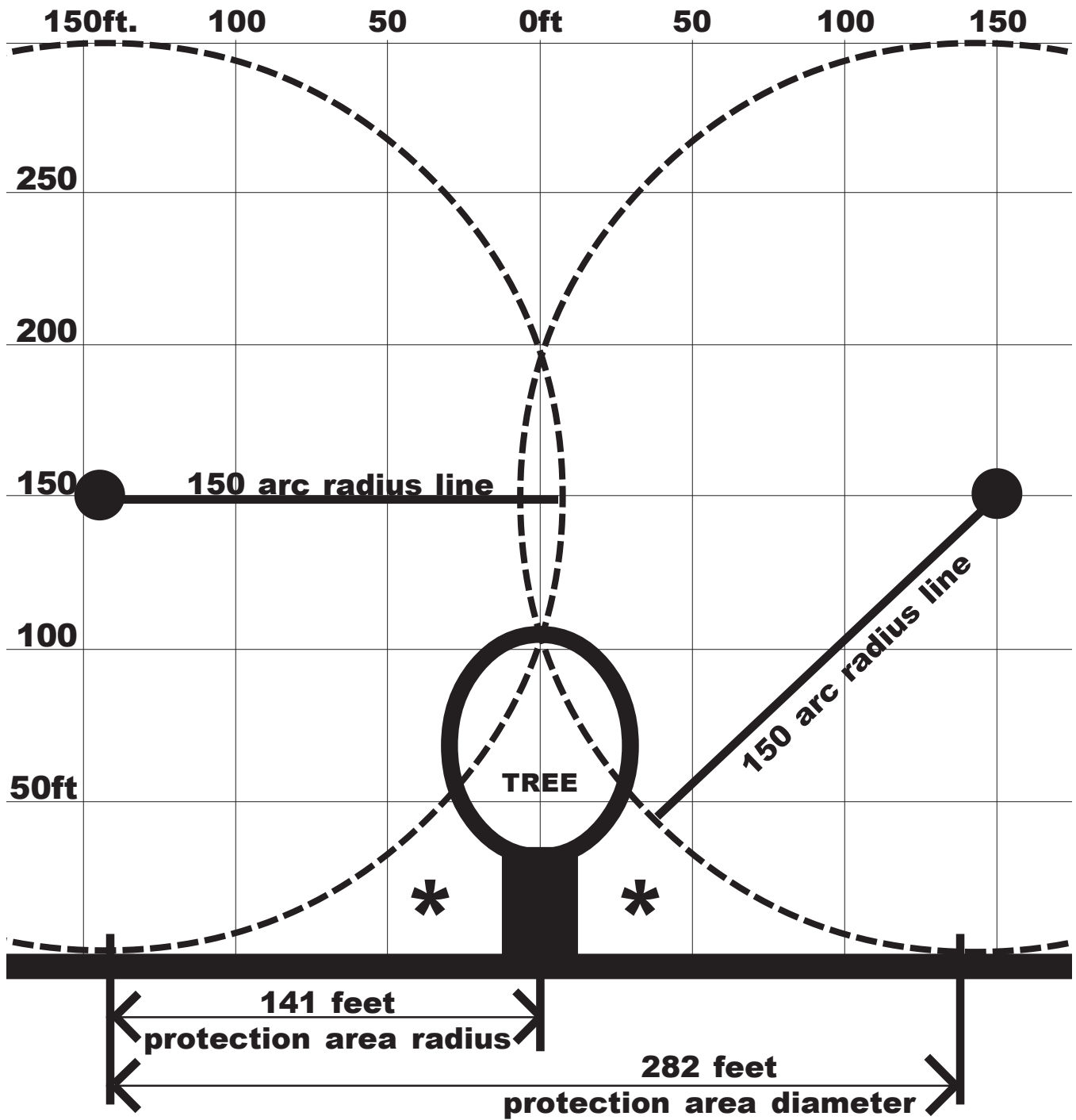
Figure 45: Rrepresentation of protection area (* beneath an air terminal in a tree. When air terminal is positioned at 100 feet height, protection area edge follows an 150 feet arc radius line that touches the ground at 141 feet away from the base.

air terminal height (feet)	vertical distances above ground (feet)											
	10	20	30	40	50	60	70	80	90	100	120	140
10	0ft											
20	20	0										
30	36	15	0									
40	47	26	11	0								
50	57	36	21	9	0							
60	66	45	30	18	8	0						
70	72	51	36	24	14	6	0					
80	78	57	42	30	20	12	5	0				
90	83	62	47	35	25	17	10	4	0			
100	87	66	51	39	29	21	14	8	3	0		
120	92	71	56	44	34	26	19	13	8	4	0	
140	95	74	59	47	37	29	22	16	11	7	2	0

Figure 46:   Estimated horizontal extent of the protection area (in feet) beneath a single tree-centered air terminal at a given height (in feet) for a series of heights. (using 150 feet arc radius)

air terminal height (feet)	horizontal radial distances from stem center (feet)											
	10	20	30	40	50	60	70	80	90	100	120	140
10	6ft	3	1	0								
20	14	10	6	3	1	0						
30	23	17	12	8	5	3	1	0				
40	30	23	17	12	8	5	3	1	0			
50	39	30	23	17	12	8	5	3	1	0		
60	48	38	30	23	17	12	8	5	3	1	0	
70	54	43	34	27	20	15	10	7	4	2	0	
80	62	50	40	31	24	18	13	9	6	3	1	0
90	70	56	44	35	27	21	15	11	7	4	2	0
100	76	61	49	39	30	23	17	12	8	5	3	1
120	86	68	54	43	34	27	20	15	10	7	4	2
140	93	73	58	46	37	29	22	16	12	8	5	2

Figure 47:   Estimated vertical height of the protection area (in feet) beneath a single tree-centered air terminal at a given height (in feet) for a series of horizontal radial distances. (150 feet arc radius).

a single crown-centered air terminal positioned at 80 feet in height would have the edge of the protection area located 30 feet radially away from the stem center at a height of 40 feet above the ground. These values were generated with the following formula:

Vertical Height to the edge of the protection area from ground level =

$$ArcRad - [\,(ArcRad)^2 - (PZr - HRd)^2\,]^{0.5}$$

PZr = protection zone radius on the ground
HRd = horizontal radial distance from stem center at some height
ArcRad = rolling sphere radius in feet

Figure 48 shows how a 150 feet arc radius sphere would be used to minimize risk of a lightning strike on a tree. One-half the crown for a 100 feet tall tree, with a 100 feet height air terminal, is shown at the lower left. The tree diagram has two branches 60 feet long. In this case, the 150 arc radius sphere touches both the ground and the top of the tree at its air terminal location. The area below the line and outside the 150 arc radius sphere dotted line would be within the protection area for 91% of lightning strikes.

For example, a tree with a 100 feet tall air terminal placement would have a protection area which is 23 feet above the ground 60 feet away from the tree stem center, and which is 49 feet above the ground 30 feet away from the tree stem center. This places branch B within the protection area and the furthest portion of branch A outside the protection zone.

Figure 49 provides an idealized two-dimensional view of a tree with an air terminal. The protection area would be below the dotted 150 feet arc radius lines shown. Most trees can be protected adequately with a single air terminal placed high in the tree and centered over the crown. Remember a tree protection system covers a three-dimensional volume which is represented here by two-dimensional drawings.

Figure 50 is a worksheet for drawing out a rough view of the above ground portion of a tree lightning conduction system Use this worksheet to draw the side view outline of a tree to be protected using measures from the field. The dotted lines on the worksheet can be used for any tree to place an air terminal with a height of 120 feet or less. This worksheet uses a 150 feet arc radius rolling sphere value in determining the tree protection area.

Fractal Space
The newest way to design and visualize tree protection systems uses fractal analysis. This system is significantly different from the two preceding methods. Figure 51. For relatively short structures like trees, fractal analysis suggests a much greater volume of protected space.

Effective Grounding

Of all major lightning conduction system components, grounding is most critical for effective performance. Charge exchanges generated by lightning are composed of extremely short duration electron flows which can be effectively neutralized in the soil (grounded). The purpose of the grounding (earthing) rods are to effectively conduct lightning current into contact with soil materials and water which then dissipate the energy.
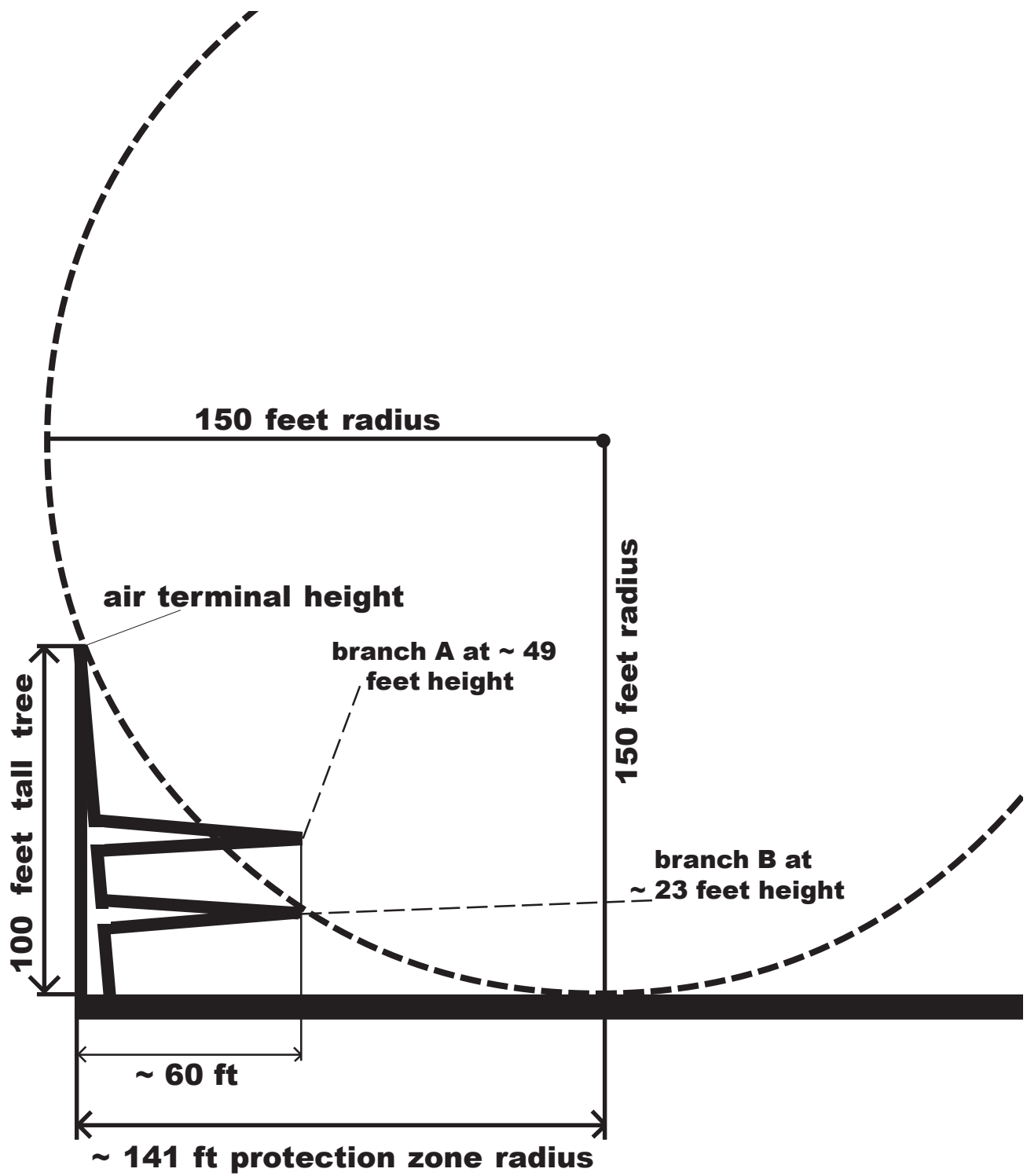
Figure 48: Description of a tree protection area based on 150 feet arc radius delineation line (i.e. dotted circle shown).
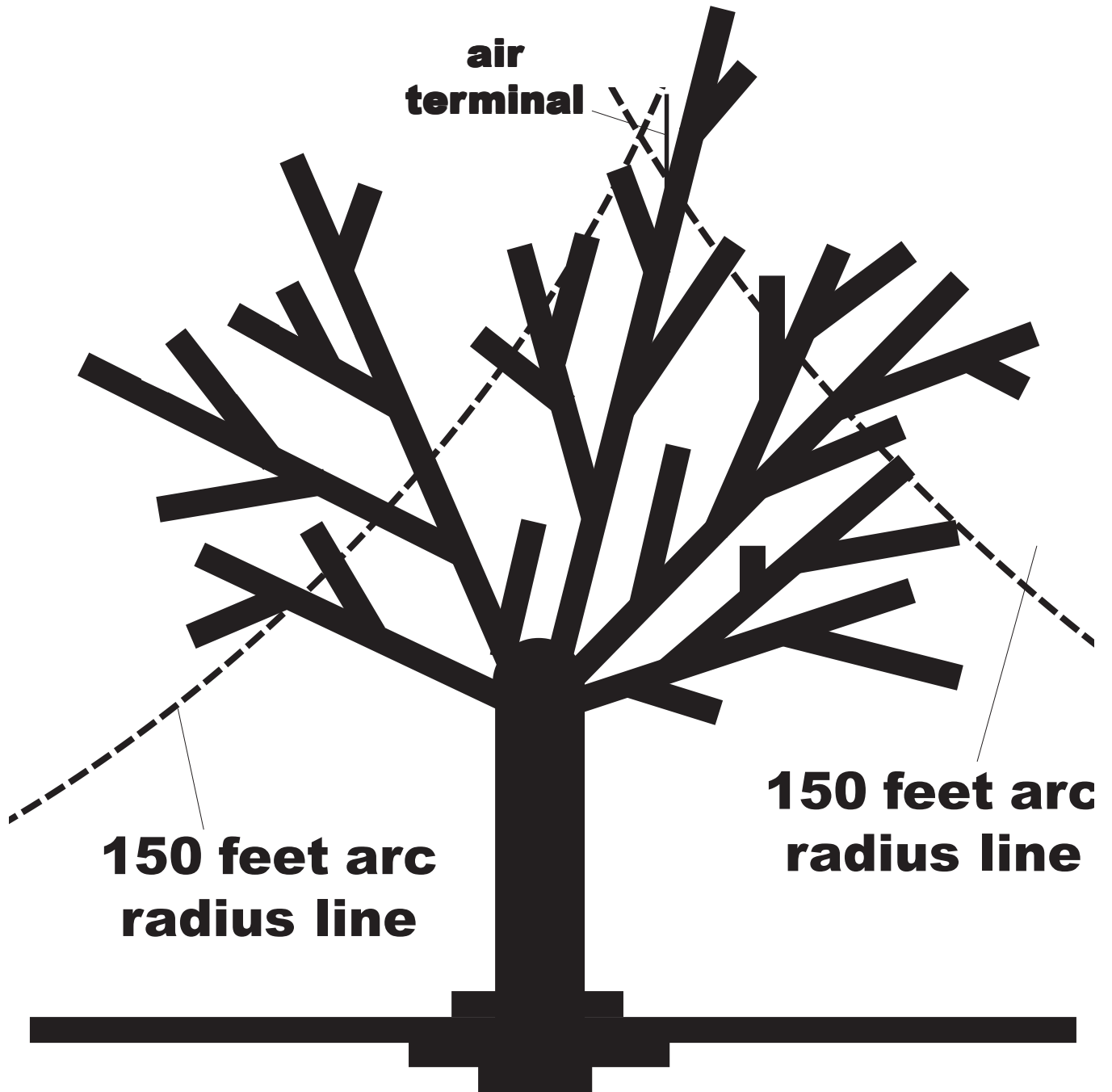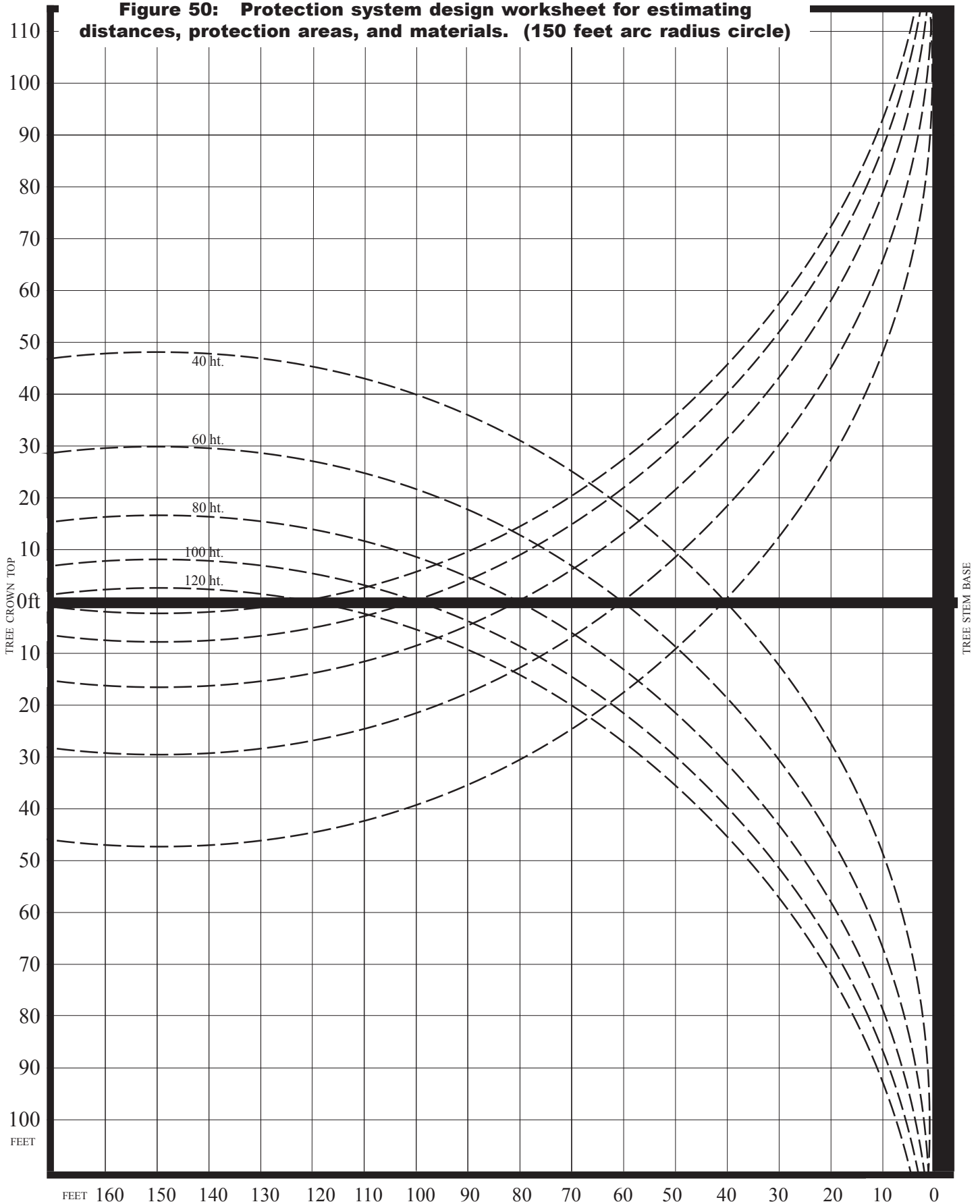
Figure 49: Estimated protection zone beneath an air terminal.

Figure 50: Protection system design worksheet for estimating distances, protection areas, and materials. (150 feet arc radius circle)
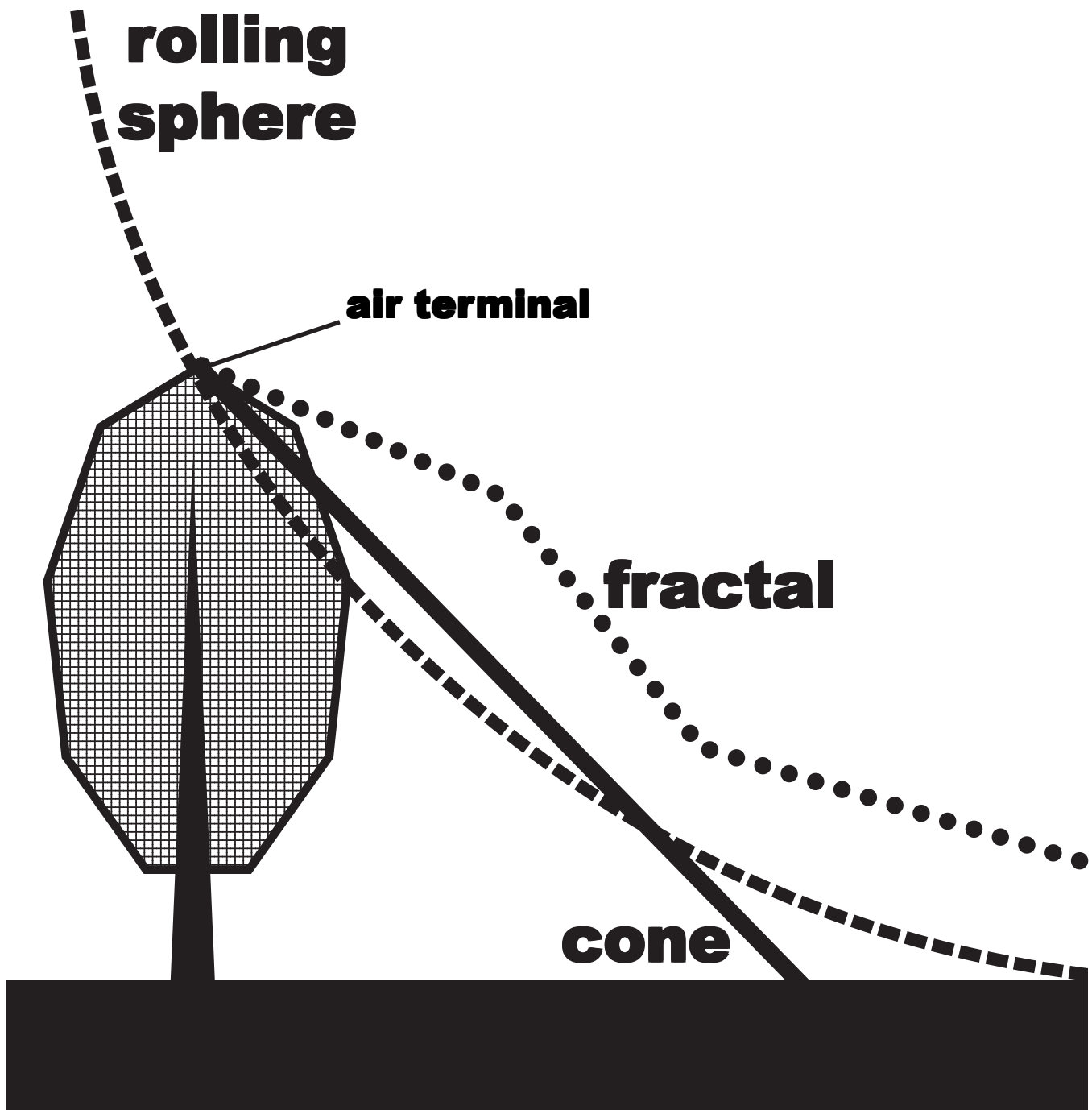
Figure 51: Comparison of cone, rolling sphere, and fractal protection zones (i.e. one-half zone) for tall, isolated tree. Protected areas are below the lines.
(derived from Zhang et.al. 2009)

Tree protection systems cannot fulfil design objectives and meet safety criteria if not grounded correctly. It is important tree protection specialists understand how grounding components of a lightning conduction system function under different circumstances. Remember, this discussion is general in scope and should not be used as an installation guide or engineering standard.

As the massive impulse current and smaller constant current within a tree lightning conduction system occurs, the ground must be able to effectively conduct and allow dissipation of energy. Ground rods provide a means of low resistance access to soil. Ground rods provide the primary interface between a lightning conduction system and soil, where soil represents a large reservoir of charge potential. Electric energy is dissipated by soil water, soil atmosphere, and soil solid materials (both minerals and organics) through rapid changes in their electronic configurations, chemical transformations, and heating. A certain minimal volume of soil is required for any amount of electronic dissipation.

Soil Resistance

The lower the resistance to electron movement, the more effective a tree lightning conduction system. Many standards provide grounding recommendations that theoretically represent the lowest resistance for a particular grounding configuration. These grounding recommendations are targeted at effectively conducting current and generating a grounding resistance low enough to defend tree tissues and growing space. It is important that grounding resistance estimates be verified by actual measurement. Resistance is measured in units called "ohms" with lower numbers representing lower resistances and more efficient movement of electricity.

Soil resistance ranges are estimated by soil type in Figure 52. Generally, the coarser the soil, the greater soil resistance, due primarily to lack of contact between soil solids, water filled pore spaces, and grounding rod surfaces. Grounding rods driven into native soils tend to have better contact with the soil than rods which are buried and packed into soil. Figure 53 graphically demonstrates the relationship between soil resistance values and soil types across various moisture contents. (Saraoja, 1977)

Moisture content of soil plays a dominate role in electrical resistance. Note soil moisture contents above 16% by volume do not vary significantly in resistance. Soil moisture contents below 16% by volume vary greatly in resistance depending upon texture, organic matter, sand and gravel components, soil amendments, temperature, salt content, and bulk density. Resistance of just the water held within a soil can vary greatly. Figure 54 provides soil resistance values over a range of different soil water resistances and moisture content volumes. Soil resistance was calculated using the Hummel formula:

$$\text{Soil Resistance in ohms}_{m} \ =$$

$$[(\ 1.5\ /\ \text{relative volume of water in soil}\ )\ -\ 0.5]\quad X\quad \text{resistance of water in soil in ohms}_{m}$$

As soils dry, resistance to electron flow increases rapidly. Dry soils have a large resistance. Caution in grounding is needed where moisture contents can fluctuate greatly and pass through periods of very dry conditions. Soils modified to protect foundations from water, or where artificial components of soil allow low moisture contents to be reached, greatly increase resistance. All of these high resistance soil situations must be overcome by expanding grounding potentials of a lightning conductance system.

Don't Spare the Rod

To provide adequate grounding (soil volume contact) for a tree lightning conduction system, special metal rods are usually driven vertically into the soil. The number of rods used depends upon reaching a low electrical resistance (i.e. <10ohms). These ground rods are normally composed of copper,

soil type	soil resistance (ohms$_m$)
clay	25 - 75
sandy clay	40 - 300
organic soil	50 - 250
sand	1,000 - 3,000
gravely loam	1,000 - 10,000

Figure 52: Range of soil resistance values for several soil textures. (from Saraoja, 1977)
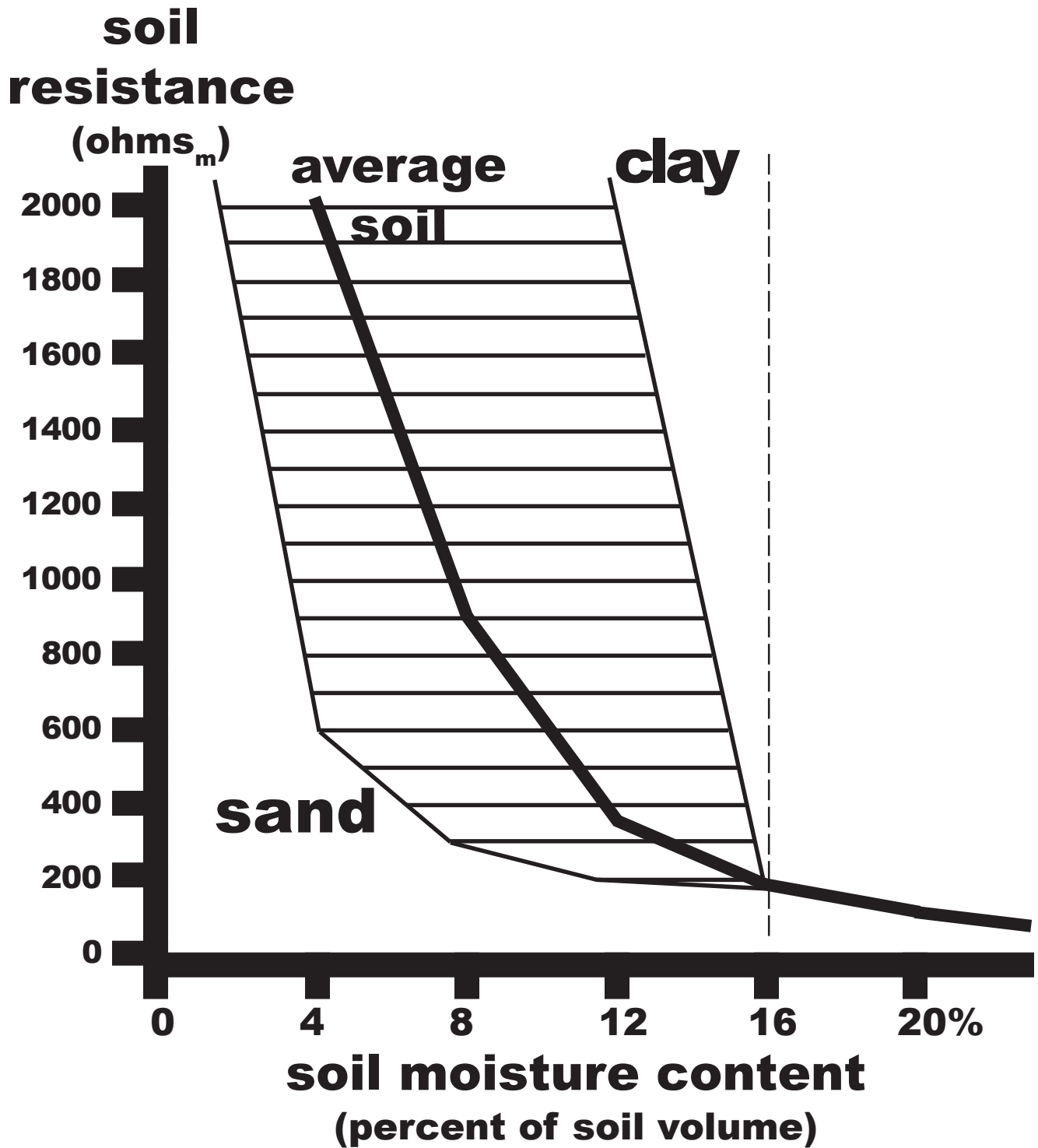
Figure 53: Influence of soil moisture content (percent in soil by volume) on soil resistance (ohms$_m$). (from Saraoja, 1977)

percent of water by volume in soil (%)	resistance of water in soil (ohms$_m$)				
	50	100	150	200	250
2.5%	2,975	5,950	8,925	11,900	14,875
5.0	1,475	2,950	4,425	5,900	7,375
7.5	975	1,950	2,925	3,900	4,875
10	725	1,450	2,175	2,900	3,625
15	475	950	1,425	1,900	2,375
20	350	700	1,050	1,400	1,750
25	275	550	825	1,100	1,375
30	225	450	675	900	1,125
40	163	325	488	650	813
50	125	250	375	500	625
60	100	200	300	400	500
70	82	164	246	329	411

Figure 54:   Total soil resistance values (ohms$_m$) based on percent of water in soil by volume across various soil water resistance (ohms$_m$) values. (Hummel formula)

copper-bronze, copper clad stainless steel, or stainless steel. Mixing different metals in a conducting system can facilitate metal corrosion.

Ground rods of any composition vary by length and diameter. Calculations demonstrate increasing rod diameter adds small increments in lowering resistance while increasing length of ground rods greatly reduces resistance. In application, longer rods are much more effective than larger diameter rods, as long as they can be driven into the soil and not buckle. A specialized thin-rod slap-hammer driver or a power driver can be used to push ground rods into soil.

Distance Apart

The value of each individual ground rod inserted depends primarily upon its length and closeness to other ground rods. For example, Figure 55 lists for various rod lengths, the distance away from the first vertical rod position where conducting and grounding values for a second rod is 66%, 80%, 90%, 95%, or 99% of its total grounding value. Ground rod effectiveness is proportional to the volume of soil impacted. The longer the rod below the soil surface, the greater soil volume available for grounding.

For example, two feet long rods are at 90% grounding effectiveness when placed four feet apart, which represents a small soil volume impacted. Eight feet long rods are at 90% grounding effectiveness when placed 12.6 feet apart, representing a relatively large soil volume impacted. Calculate grounding effectiveness distance for any length ground rod using the formula:

$$\text{Distance From Ground Rod } =$$

$$\frac{ \{ \text{rod length } / \ [\log_e ((8 \ \text{X} \ (\text{rod length})) \ / \ \text{rod diameter}) \ - \ 1] \} }{ (1 \ - \ (\% \text{ effectiveness})) }$$

Spreading grounding effectiveness over large soil volumes, not clustering or concentrating grounding in one small area is ideal. Remember in many soils under many conditions, only one grounding rod can generate an acceptably low electrical resistance for a lightning conduction system. In high resistance soils and on sites with grounding constraints, multiple ground rods may be required.

Rod Length

Figure 56 lists the grounding effectiveness in percent for different length rods which are either 8, 10, or 12 feet away from another vertical ground rod. Values were calculated using the following formula:

$$\text{Rod Grounding Effectiveness Percent } =$$

$$\{ 1 \ - \ (\ [\ \text{rod length } / \ (\log_e ((8 \ \text{X} \ (\text{rod length})) \ / \ \text{rod diameter}) \ - \ 1) \ ] \ / \ \text{rod length}) \} \ \text{X} \ 100$$

For example, an eight feet long rod reaches 90% effectiveness beyond 12 feet. At 10 feet away from the eight feet long rod, its effectiveness in grounding is 87%.

Figure 57 shows a grounding resistance curve for rods of various lengths when soil resistance is 100 ohms and rod diameter is 0.5 inches. This figure suggests rods greater than 14 feet in length are not continuing to lower resistance significantly, and may not be cost-effective. Rods lengths of 8-10 feet perform most efficiently.

MULTIPLE GROUND RODS

rod length (feet)	ground rod effectiveness				
	66%	80%	90%	95%	99%
2	1.2ft	2.0	4.0	8	40
4	2.1	3.5	7.1	14	71
6	2.9	5.0	10	20	99
8	3.7	6.3	13	25	126
10	4.5	7.6	15	31	152
12	5.2	8.9	18	36	178
14	6.0	10	20	41	203
16	6.7	11	23	46	228

Figure 55: Horizontal distance (in feet) at the soil surface away from a vertical ground rod (0.5 inches diameter) of various lengths where another rod has reached a given grounding effectiveness percent. (Saraoja 1977)

rod length (feet)	distance away from other rod (feet)		
	8 ft.	10	12
2	95%	96	97
4	91	93	94
6	88	90	92
8	84	87	90
10	81	85	87
12	78	82	85
14	75	80	83
16	72	77	81

Figure 56:   Various length ground rod effectiveness in percent at horizontal distances of 8, 10, and 12 feet away from another vertical ground rod. Note grounding effectiveness is on a per rod basis.   (Saraoja 1977)
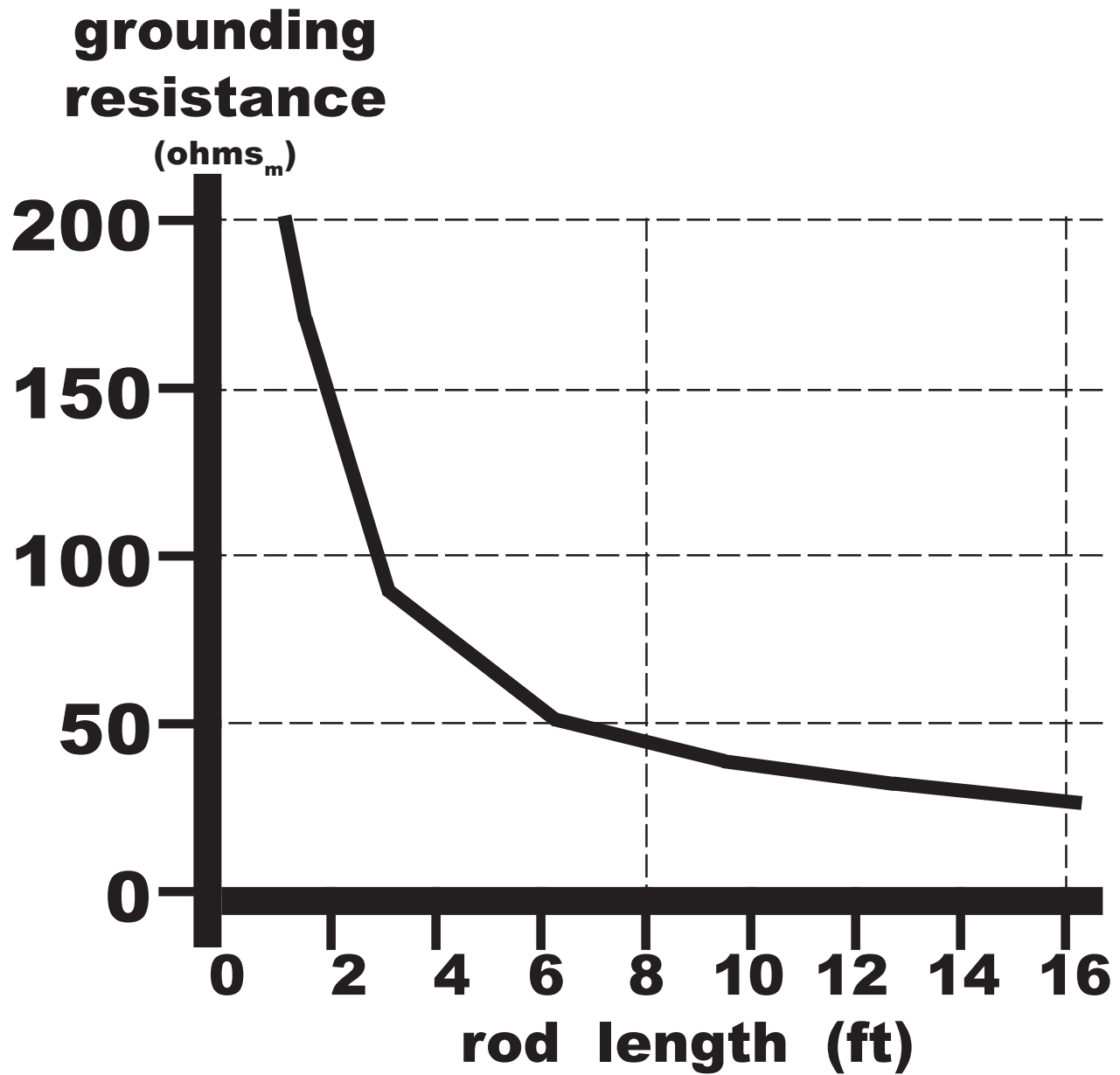
Figure 57: Grounding resistance changes as rod length changes. Soil resistivity is set at 100 ohms$_m$ and rod diameter is 0.5 inches.

Ground Rod Configurations & Testing

Grounding resistance can be reduced by increasing ground rod length. Grounding resistance can also be reduced by using different rod configurations and positions. Rod depth below the soil surface influences grounding resistance. Use of multiple rods, and horizontal or vertical configurations, also impact resistance. (Saraoja 1977) Horizontal grounding rods packed in trenches at some distance below the soil surface may be alternatives to vertically driven rods when addressing severe soil or site constraints, like rock near the surface.

Rod Depth

Figure 58 shows eight feet long, 0.5 inch diameter rods in various configurations at three soil depths. The four configurations include three horizontal grounding lay-outs (A , B, & C), and one traditional vertically driven rod (D). Grounds A and B use two connected rods and grounds C and D use a single grounding rod. Grounding resistance changes (under standard conditions) are shown as rod depth changes. This figure was designed to examine grounding rod depth only and should not be used for comparing configurations. Ground B is best at lowering resistance with increasing depth.

Ground A is a horizontally buried, V-shaped rod fork. Ground B is a horizontally buried, parallel rod system separated by one rod length. Ground C is a horizontally buried, single rod. Ground D is a vertically driven single rod whose depth value is determined from where the top of the rod is below the soil surface. For example, for each of the four rod configuration shown, increasing rod depth below one foot reduces resistance by as much as 25%. Deeper placement maximizes the grounding volume impacted.

Figure 59 demonstrates how soil depth changes grounding resistance for a single, traditional, vertically driven rod (eight feet long, 0.5 inch diameter). This figure demonstrates reduction of grounding resistance as rod depth increases from the soil surface. For example, if the rod is driven three feet into soil, grounding resistance would be reduced by as much as 31%, compared to a rod with its top end at the soil surface. Remember effective grounding reduces electrical resistance.

Rod Arranging

Figure 60 uses three of the same configurations used earlier to show resistance changes due only to configuration of the ground rods. The comparisons in this figure demonstrate how changing horizontally placed grounding systems in various ways change electrical resistances. For example, selecting either configuration A, a double rod fork, or selecting configuration B, double parallel rods, provides different electrical resistances. Selecting configuration B would reduce electrical resistance by 29% from configuration A. Selecting configuration A would increase electrical resistance by 41% from configuration B. Note configuration B has the lowest electrical resistance of all the configurations considered.

Figure 61 compares electrical resistance differences between single rods (8 feet long, 0.5 inch diameter) either placed horizontally at a one foot depth in the soil or driven vertically until the top of the rod is at a one foot soil depth. The vertical rod (configuration D) reduces electrical resistance by 21% compared with the horizontal rod with all other things being equal. A greater grounding rod length, a greater depth of installation, and vertical orientation tends to maximize grounding rod effectiveness and lower electrical resistance in a lightning conduction system.

Multi-Rods

To reduce electrical resistance, multiple vertical rods in a single line away from a tree can be used. Figure 62 shows resistance reduction is achieved with 2, 3, or 4 vertical rods compared with a single vertical rod. For each multi-rod configuration, this figure demonstrates how the distance between
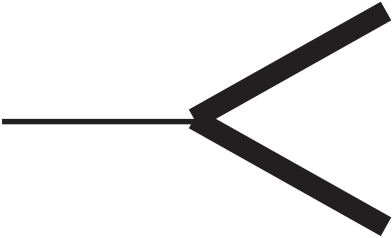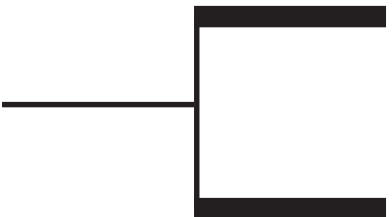
	depth in soil		
	1 ft.	**2 ft.**	**3 ft.**
A double horizontal fork	**X**	**0.91X**	**0.85X**
B double horizontal parallel	**X**	**0.86X**	**0.75X**
C horizontal single	**X**	**0.89X**	**0.81X**
D vertical single (depth is from rod top)	**X**	**0.90X**	**0.83X**

Figure 58: Change in electrical resistance with ground rods (8 feet long, 0.5 inch diameter) in various configurations as depth increases.

depth below soil surface

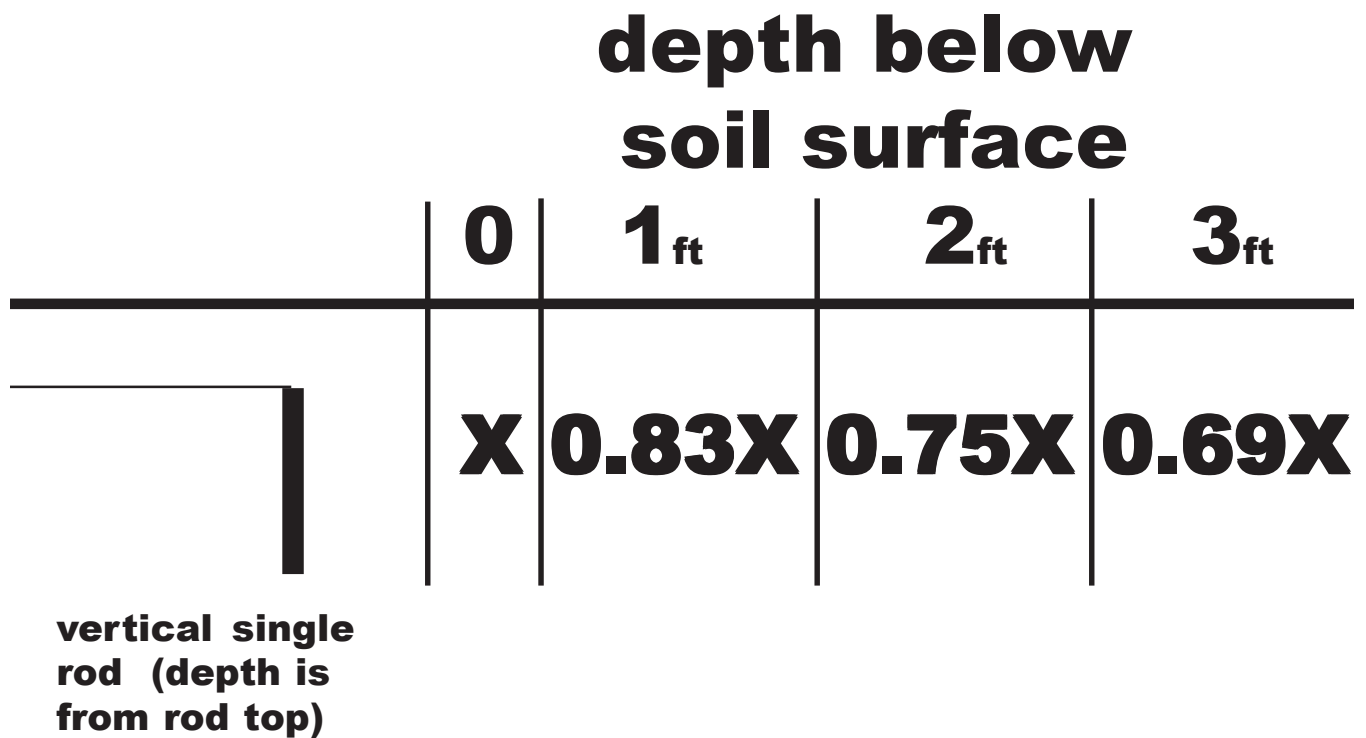| 0	1 ft	2 ft	3 ft
X	0.83X	0.75X	0.69X

vertical single rod (depth is from rod top)

Figure 59: Change in electrical resistance for a single vertical rod (8 feet long, 0.5 inch diameter) as depth increases.
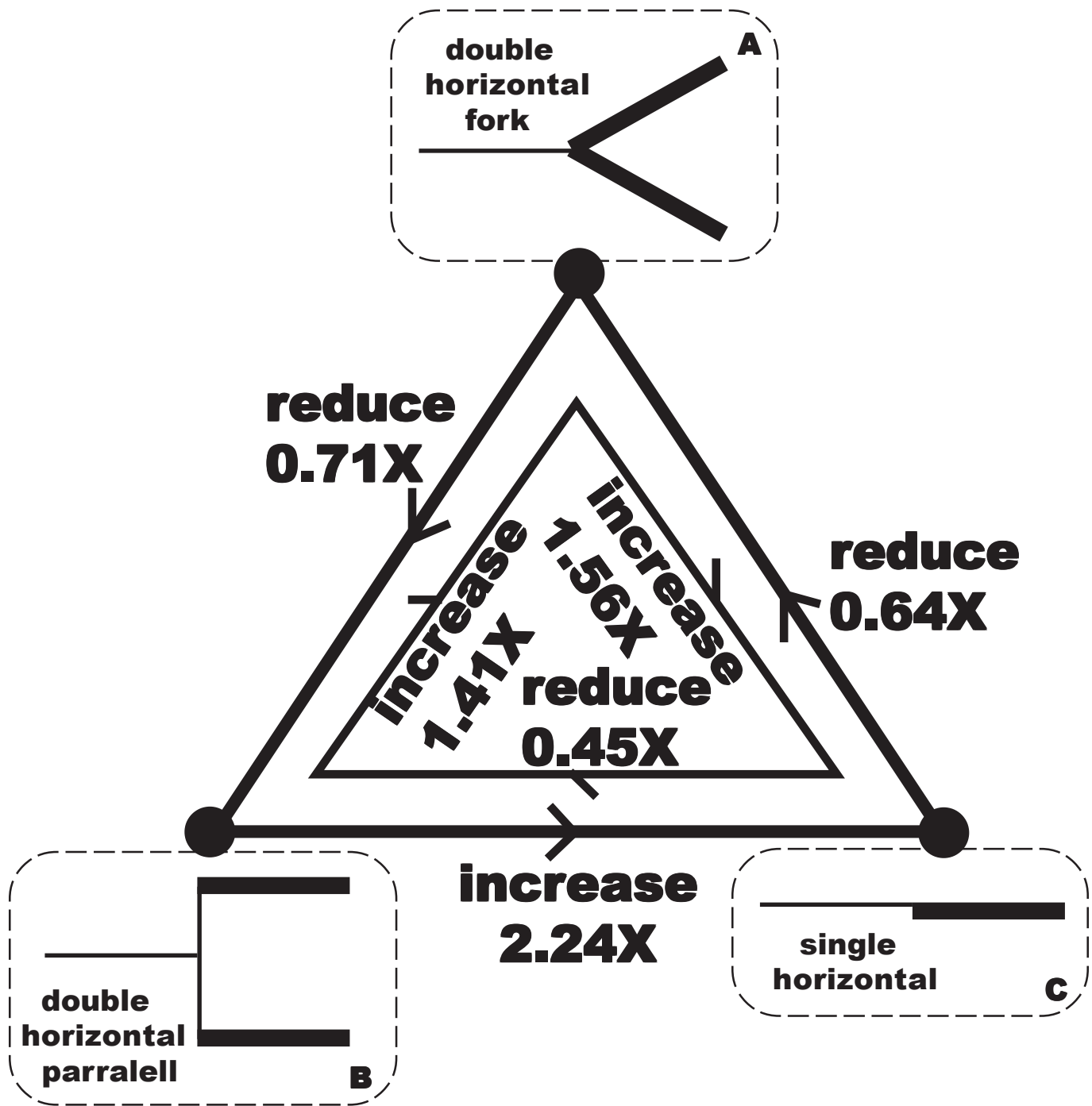
Figure 60: Change in electrical resistance betwen various grounding configurations of horizontally placed rods (8 feet long, 0.5 inch diameter). Here, configuration B has the lowest electrical resistance overall.
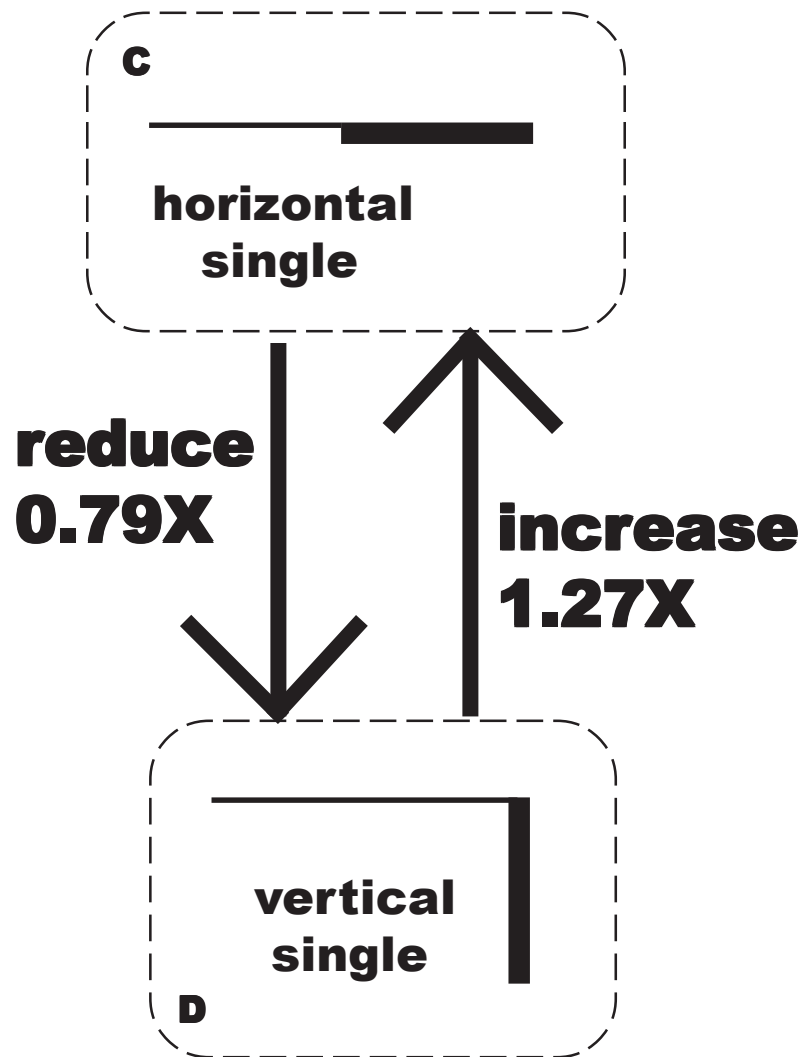
Figure 61: Change in electrical resistance around rods (8 feet long, 0.5 inch diameter) either placed horizontally at a one foot depth in the soil or driven vertically until the top of the rod is at a one foot soil depth. Here, the vertically driven rod has the lowest electrical resistance of the two rod configurations.
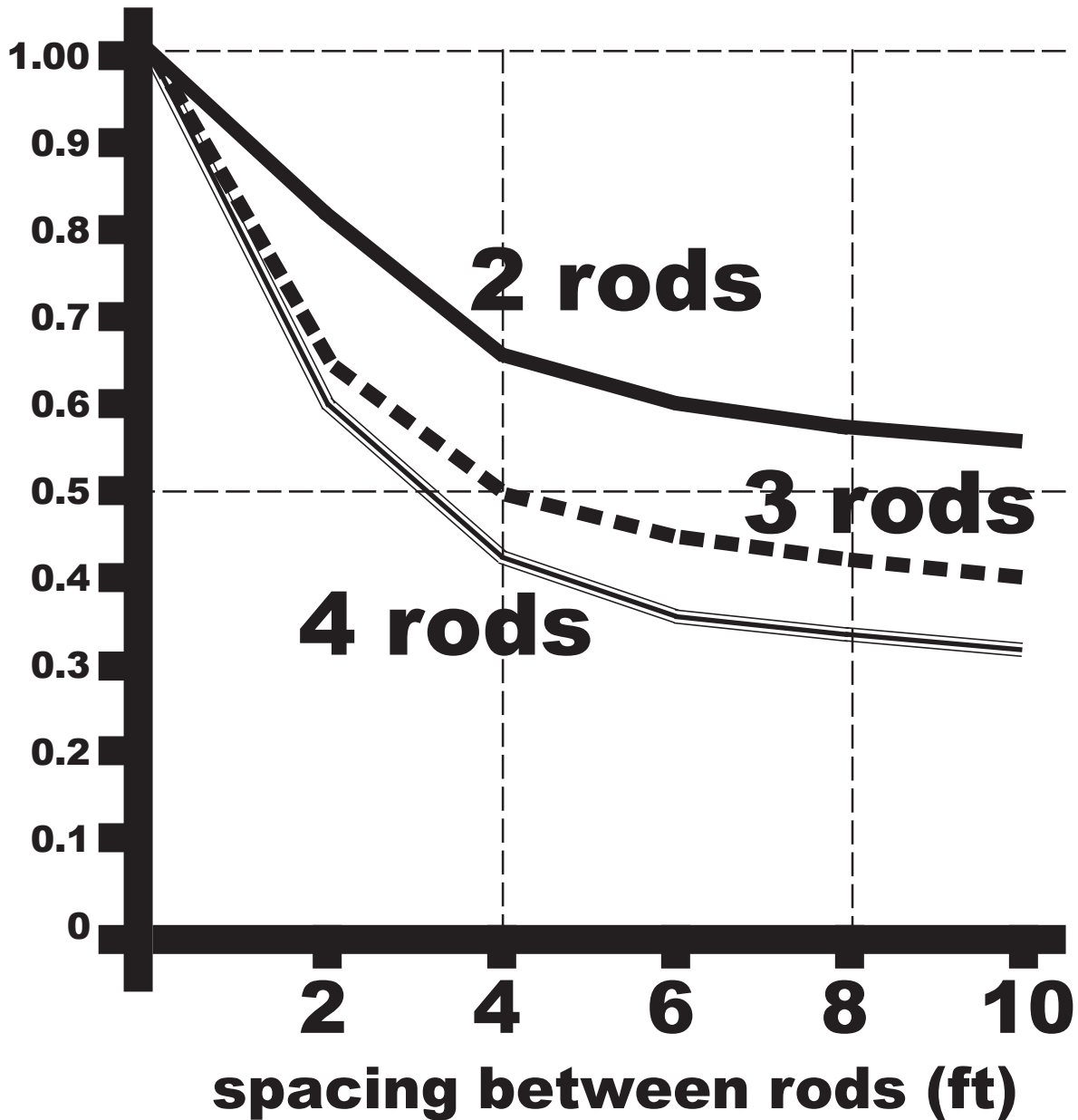
Figure 62: Spacing between rods in a multi-rod, parallel, straight-line system, compared with a single rod, and the associated fractional electrical resistance per rod. All rods are 8 feet long and 0.5 inches in diameter.

rods impacts grounding effectiveness. The wider rod spacings in multi-rod configurations, the more effective each ground rod becomes. Multiple rods placed too close together are not as effective as more widely spaced rods because of overlapping grounding volumes.

A graphical definition of rod placement is provided in Figure 63. This figure represents a single vertical ground rod driven one foot below the soil surface, and its associated grounding volume. Figure 64 represents two vertical rods with a separation of 12.6 feet. At the 90% grounding effectiveness value, the two rods function as only 1.8 rods because of the overlap in their grounding volumes.

Figure 65 shows rods spaced 8 feet apart. With rods 8 feet apart, grounding effectiveness is reduced to 84% of two independent vertical ground rod configurations. The two rods in the figure separated by 8 feet function like 1.68 rods because of overlapping grounding volumes. Ground rods must be placed far enough apart so each is fully functional.

Assuring Grounding

A lightning conduction system must have a low resistance ground component to be effective. As such, it is critical to measure electrical ground resistance. To many tree protection systems depend upon the experience-based opinion of an installer and material quality to assure adequate electrical ground resistance. Because of grounding system configuration, soil properties, and site history, electrical ground resistance can vary greatly. One of the easiest means for measuring ground resistance is using the "fall-of-potential" method. (derived from Saraoja, 1977; USDoD-Military Handbook, 1987).

The quality (i.e. resistance) of tree lightning conduction system grounding components is measured as shown in Figure 66. The system's ground resistance is measured in ohms and determined by:

Electrical Resistance of the Ground System in ohms   =

volts   /   current in amps

This figure demonstrates the lay-out of the measuring system. Electrical wire attachments to the lightning conduction system should be made on the down-cable at the tree just before it enters the soil, or just above any protective conduit present. These electrical connections should be separated by 5 inches from each other on the down-cable.

The location of the system ground rod(s) should be identified. The distances and depth measures for testing are based upon vertical ground rod length (value X). For horizontal long rods, or vertical or horizontal multi-rod configurations, the center of the ground rod system should be determined and the radius to system edge should be used as the ground rod length (value X).

Two stakes or rods, made of the same material as the ground rod should be used as testing probes. The voltage probe should be driven firmly into the soil away from the ground rod at a distance 7.5 times the ground rod length. The current probe should be driven firmly into the soil away from the ground rod at a distance of 12 times ground rod length. These probes should be never less than 1.5 feet in length, and should ideally be at least 1/5 the length of the ground rod. Because of soil and soil/water interactions in the rooting area, AC current should be used, but is not required. The resistance values should be less than 25 ohms, and preferably less than 10 ohms.

Professional Grade

Professional installers use a specialized, high internal resistance, ground resistance meter which provides all the leads, power, and internal measures, directly yielding ground resistance value in ohms. Small electrical multi-meters for use with home electronics should not be used. Professional ground
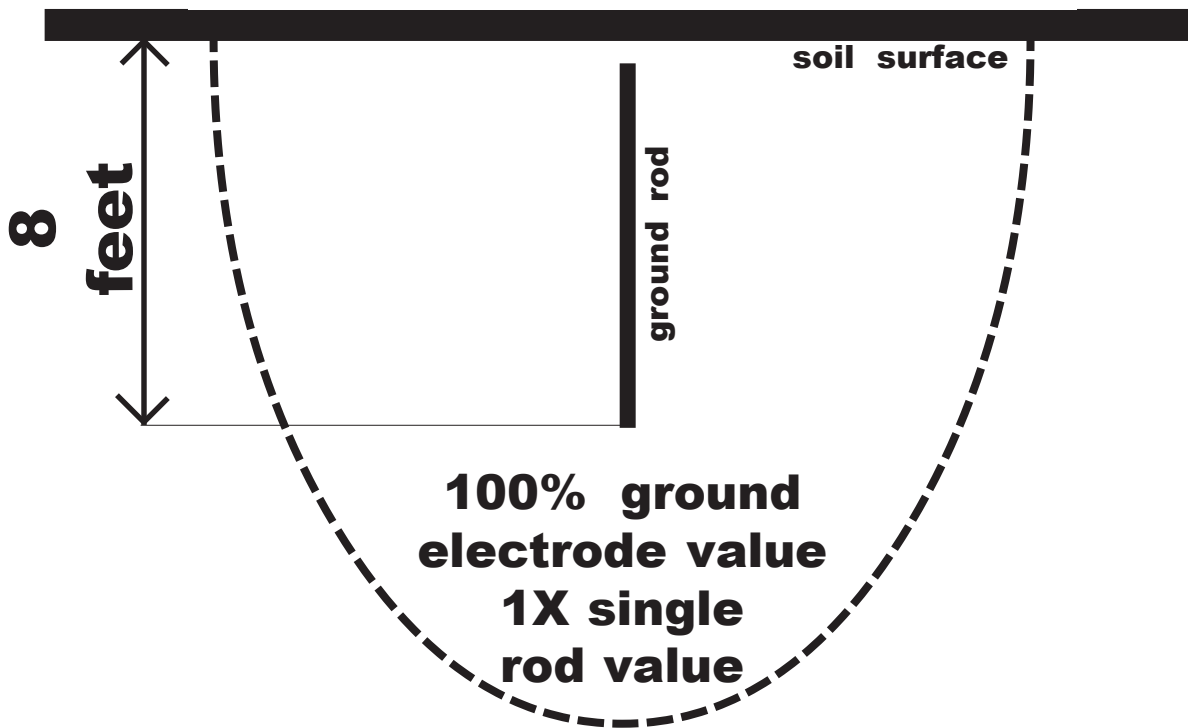
Figure 63: Side view of relative grounding areas for a single vertical rod 0.5 inches diameter & 8 feet long driven into soil.

12.6 feet

soil surface

8 feet

ground rod

ground rod

90% ground electrode value

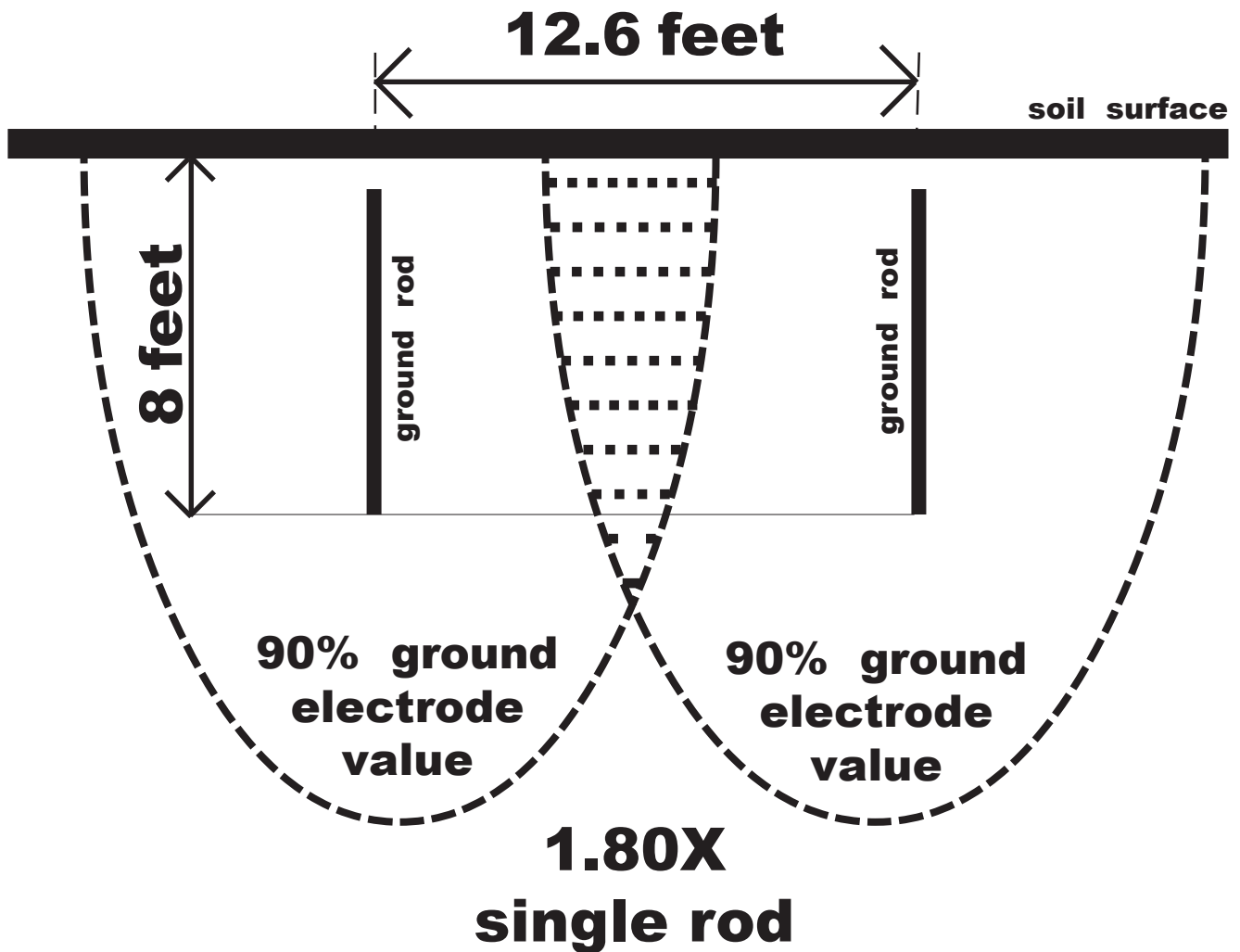90% ground electrode value

1.80X single rod

Figure 64: Side view of relative grounding areas for two vertical rods 0.5 inches diameter & 8 feet long driven into soil 12.6 feet apart.
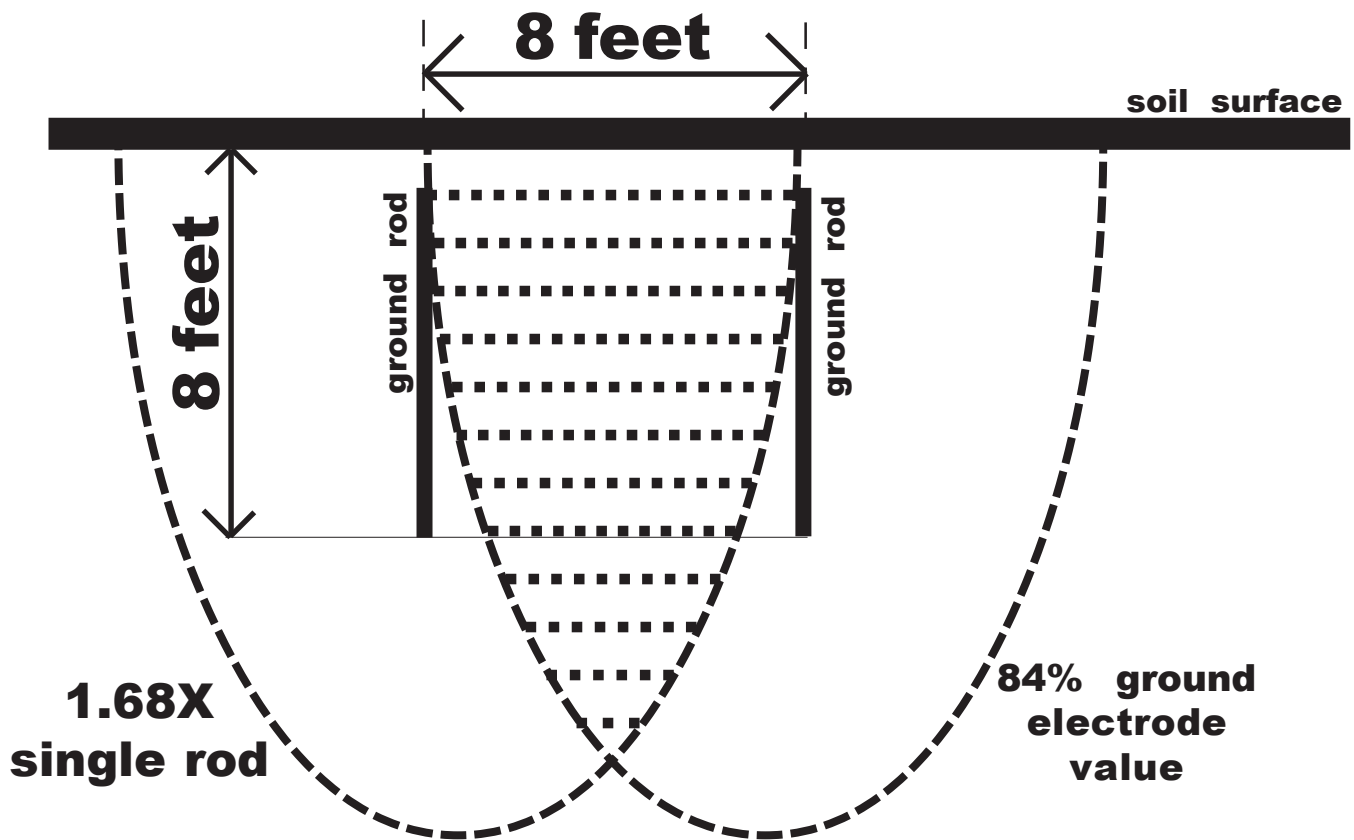
Figure 65:   Grounding area & effectiveness for two vertical rods (0.5in diameter / 8ft long) driven into soil 8 feet apart.
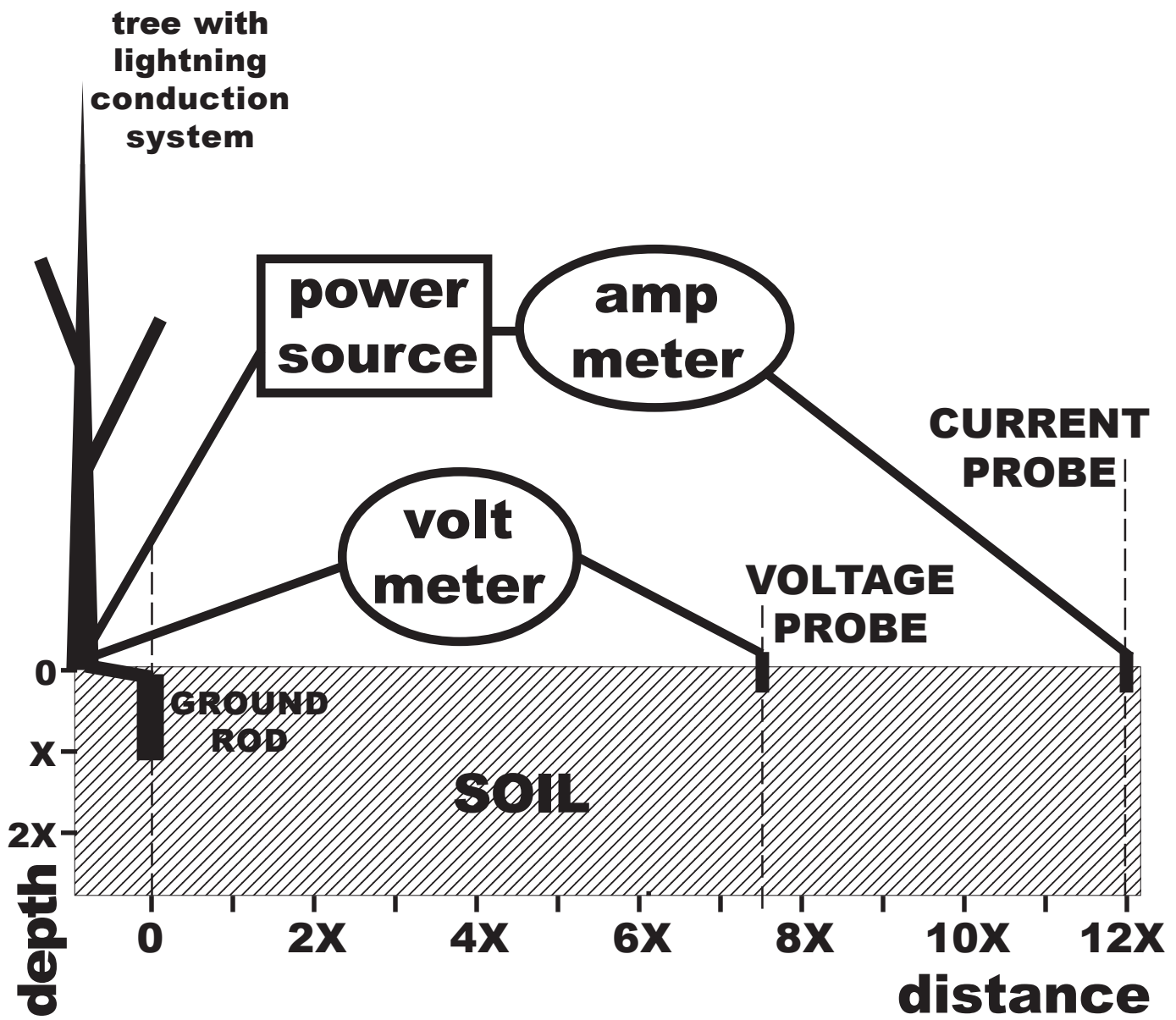
Figure 66: One method (fall-of-potential method) of measuring electrical resistance for the ground of a tree lightning conduction system which, in this figure, uses a single vertical ground rod. (derived from Saraoja, 1977; USDoD-Military Handbook, 1987).

resistance meters and power sources can be purchased for between $1,000 and $4,000 (costs from internet search). Commercial clamp-on meters can also be used for system resistance estimates. Because of the expense and time involved in setting-up the test, few tree lightning conduction systems are properly tested for ground resistance and may not be functioning properly.

Normal Procedures
      Lightning conduction systems, when properly grounded, ensure a quick, low resistance pathway for current flow which minimizes damage to trees. Grounding is key to effective lightning protection. Standard grounding recommendations for tree lightning conduction systems usually involve only one vertical 8-10 feet long rod 0.5 inches in diameter. Under most soil and site conditions this single vertical rod is adequate, upon measurement.
      If soil and site limitations exist which prevent a vertical single rod from attaining a low enough electrical resistance, then multiple ground rods or other alternative grounding means are required. Tree lightning conduction systems are incapable of preventing tree and site damage if improperly grounded. Because grounding hardware and configurations are below ground and out-of-sight, visual inspection is a difficult process and repairing damage is time consuming. Installation of other below ground landscape utilities can damage or destroy tree protection systems. Site and system vigilance are required over the life of the tree.

Conclusions

-- We cannot stop lightning from striking trees.

-- Tree health care providers can develop risk management systems that cost-effectively minimize tree damage, reduce collateral damage around trees, and effectively conduct electrical charges between cloud and ground.

-- Damage from lightning strikes to trees is a unique set of injuries stemming from tremendous physical and electrical forces.

-- Although our treatments are comparably minor in the face of lightning's power, our trees can be helped to survive and thrive through timely, informed, and appropriate actions.

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