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Tree Damaging Forces Generated By Lightning

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Most trees grow to a height and in locations where lightning is not a significant risk. As trees grow taller, their modification or enhancement of 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 along its height.

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^{o}F for microseconds. Figure 2. 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 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 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 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 among different periderm and annual xylem increment structures. Ring-porus and thick-barked trees tend toward narrow injuries, while diffuse-porus 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 microseconds) 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 large electrical resistances. Figure 3.

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 a 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 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 which 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 across the tree diameter 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 electrical resistance heated water and turned it into steam as a primary force damaging trees. In living tree tissues, water contents are large. Super heating water instantaneously (<5 microseconds) 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 the extent and pattern of any 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. Figure 4. Not all of this force is focused on a tree, but a significant portion impacts the tree stem. The reflection (rebound) of this initial compression wave impacting the stem is returned as 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.

The most visible result of the strong shock wave is splitting of 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 develop an explosive force.

Citation:

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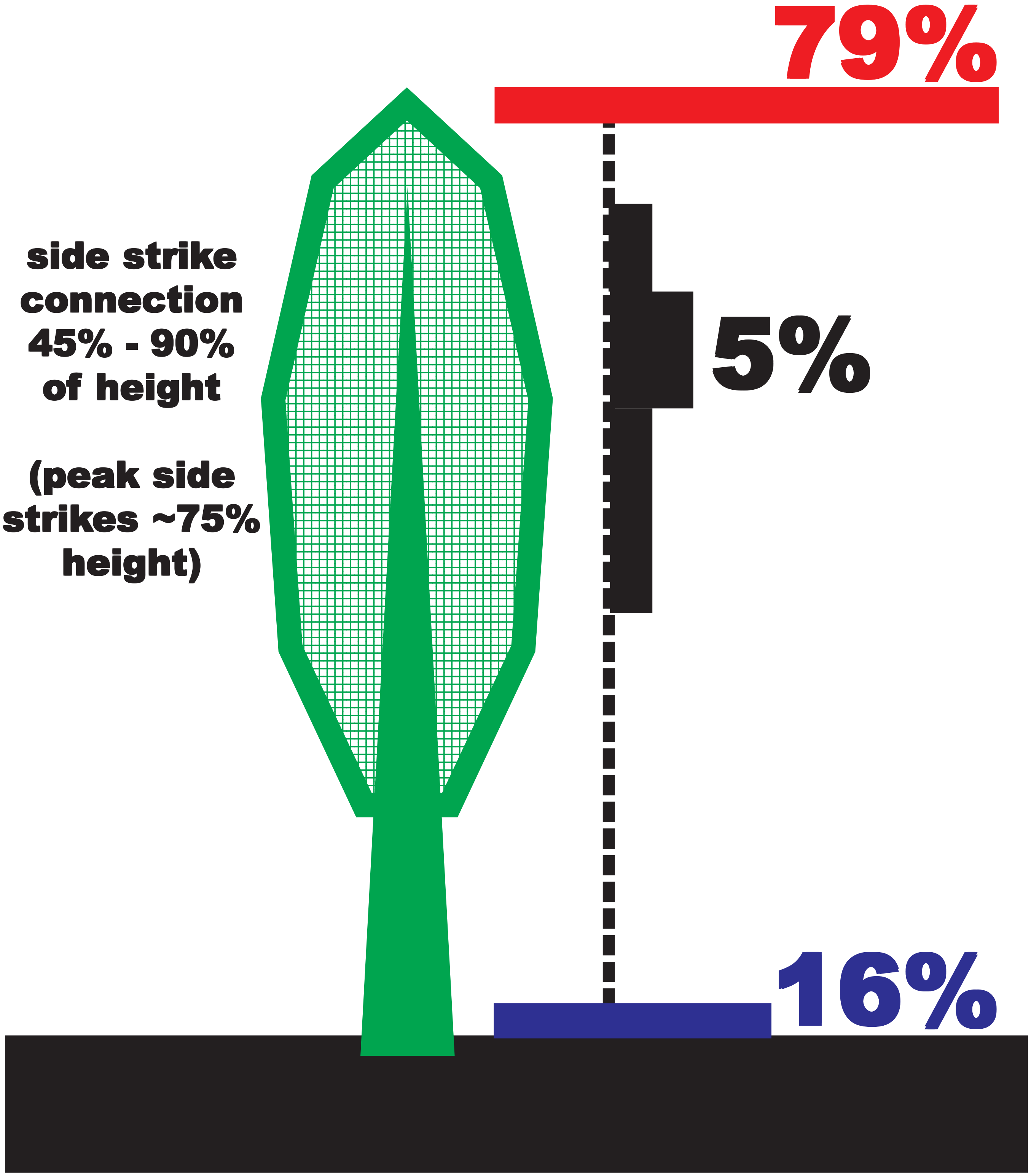
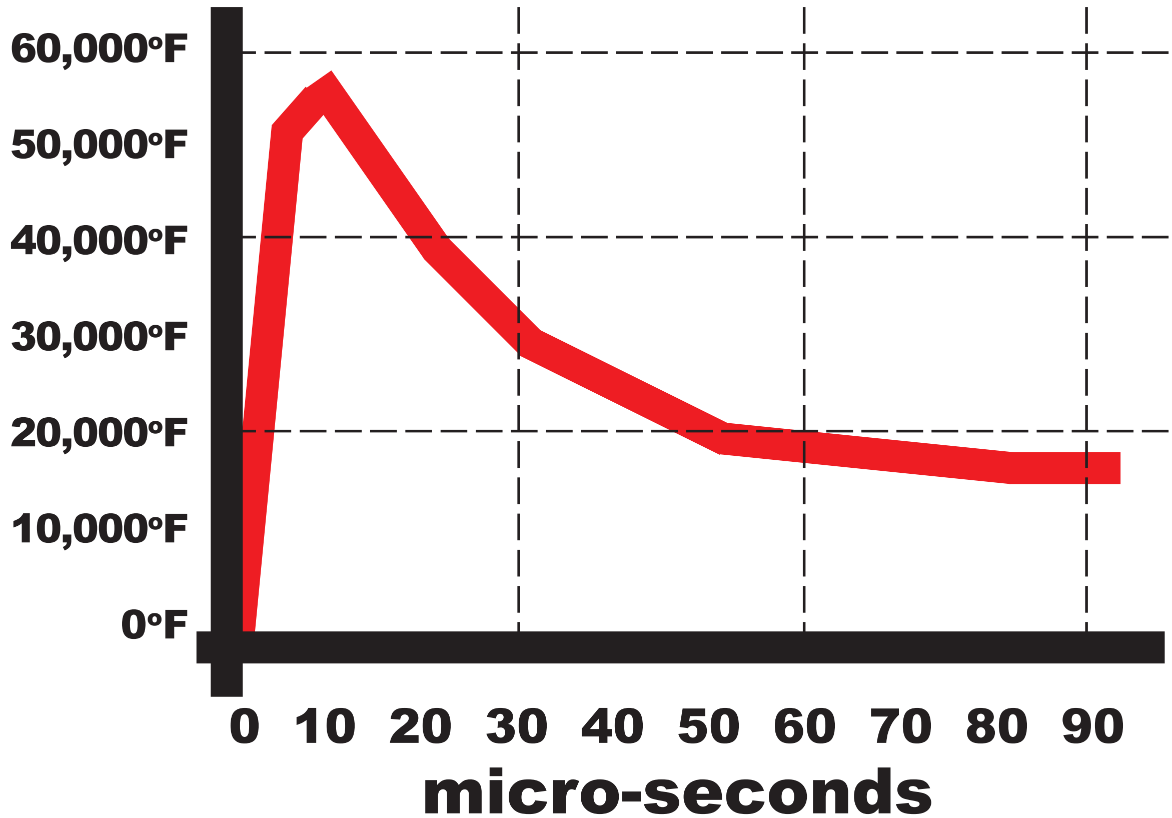


Figure 1: Potential locations and numbers of lightning strikes on a single, isolated, tall (>100ft) tree.
(derived from Zhang et.al. 2009)

LIGHTNING CORE TEMPERATURE



(1 micro-second = 0.000,001 second)

Figure 2: Lightning core temperature in degrees Fahrenheit (°F) over time in micro-seconds (millionth of a second).
(Few 1995; MacGorman. & Rust 1998; Uman 1971,1987)

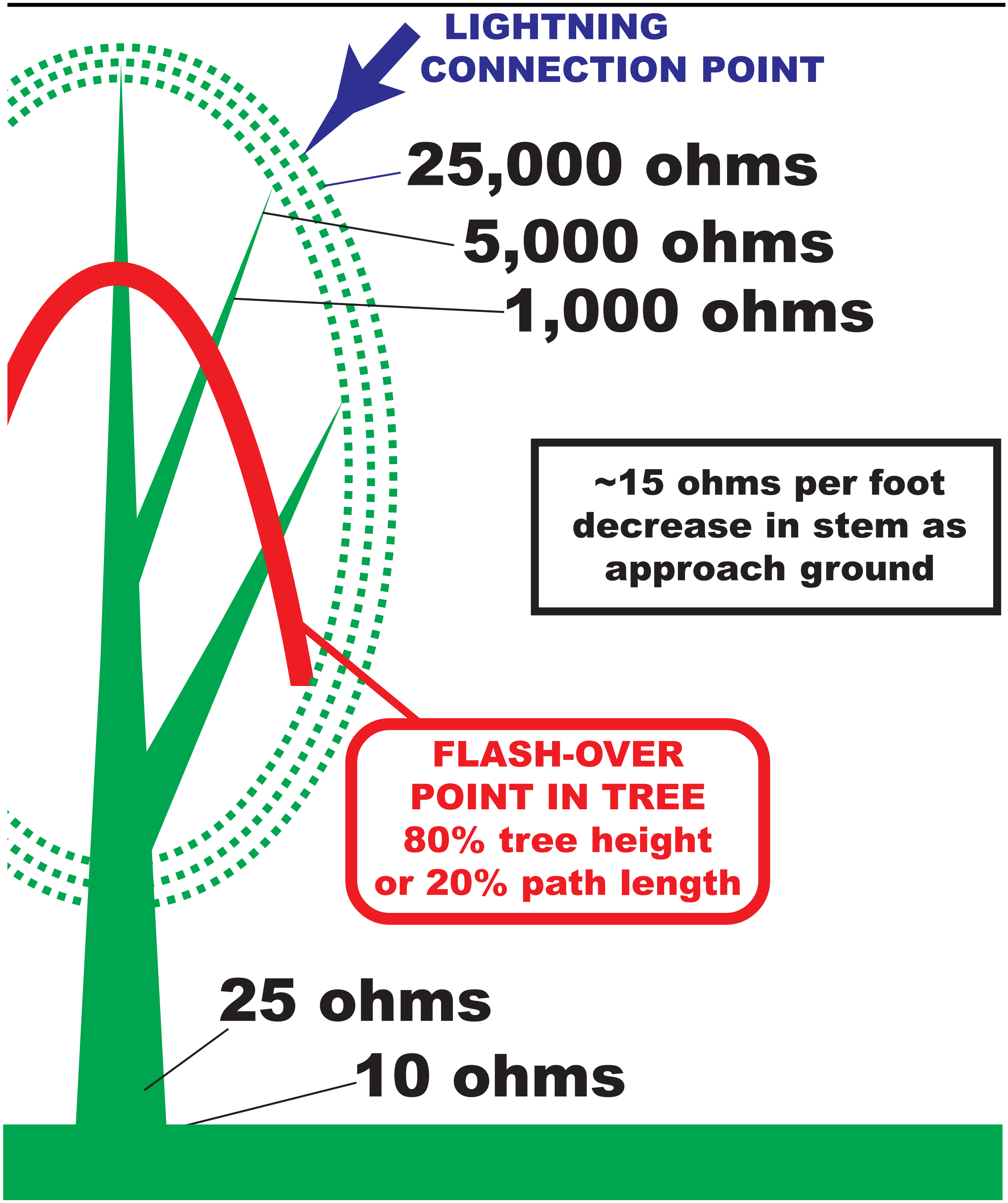


Figure 3: Model-based tree resistance value estimates from leaf surface to the ground. (Defandorf 1956)

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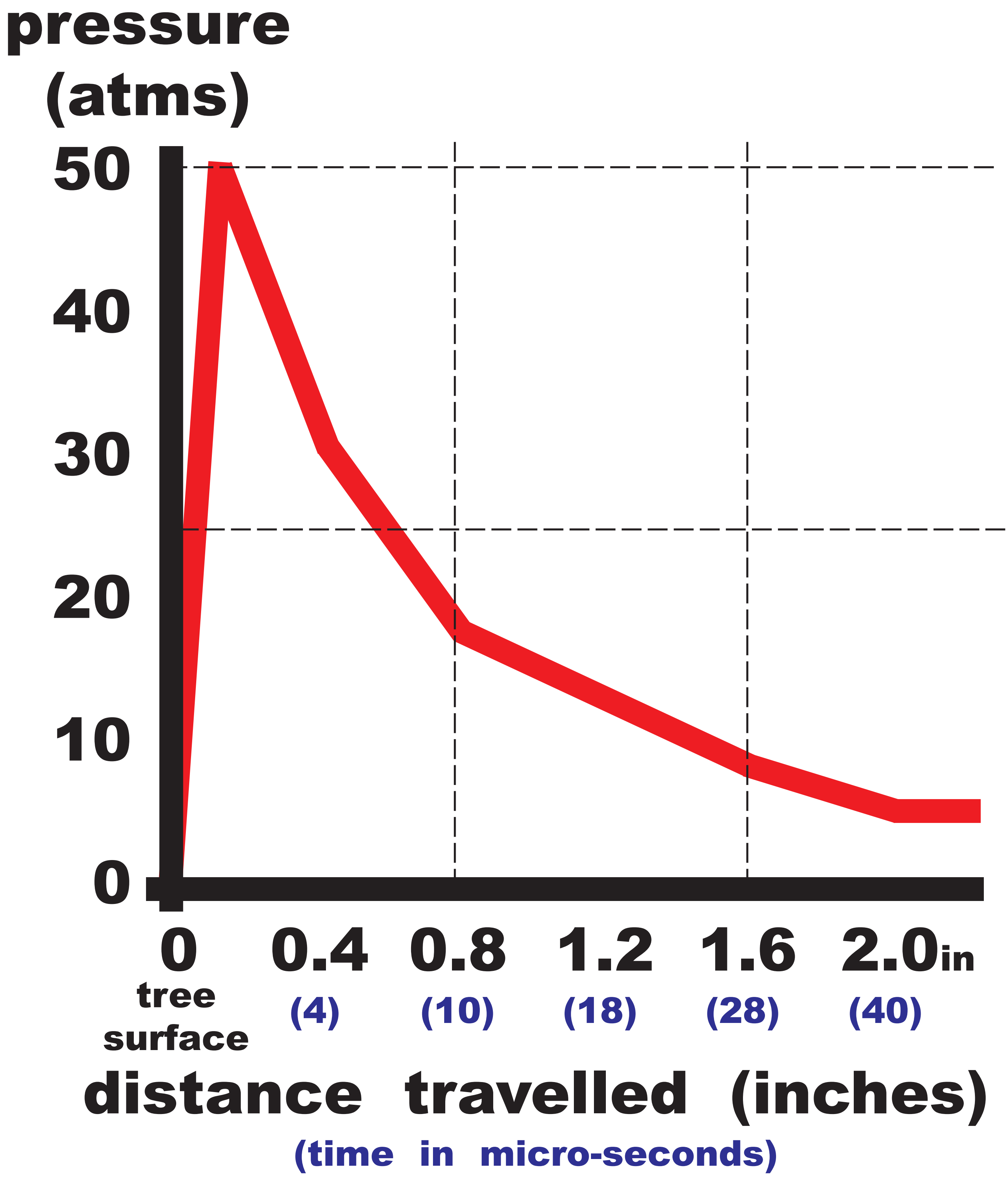

Figure 4: Shock wave pressures,decaying into an acoustic wave over time and space, spreading away from the lightning core. (derived from Few 1995; MacGorman. & Rust 1998)