THE APPLICATION OF ENGINEERING FUNDAMENTALS TO ARBORICULTURE

by G. Rex Redden

Abstract. Applications of geometry, calculus, bending and twisting moments and mechanics of solids toward better pruning and climbing techniques are suggested. New to arborists this is a non-traditional topic, a basis for a pruning method using ancient and modern mathematical tools to analyze the forces that exist in and act upon trees.

Résumé. Les applications de la géométrie, du calcul intégral, des moments de flexion et de torsion et de la mécanique des corps solides pour permettre de meilleures techniques d'élagage et de montée dans les arbres sont suggérées. Nouveau aux arboriculteurs, c'est un sujet non-traditionnel, une base pour une méthode d'élagage utilisant les outils mathématiques anciens et modernes pour analyser les forces qui existent et agissent dans les arbres.

A picture of Hiroshima taken in 1945 appeared in *Newsweek* forty years later. The tree in the picture should be an inspiration to arborists. The main stem and downwind members withstood the wind force from an atomic blast. Everything man-made collapsed around it.

If you wish to erase fear of sound trees from the psyche of your clientel, this is a good starting point. In wind velocities exceeding two hundred miles per hour the sound tree still did not significantly contribute to the damage of man-made structures. (To the reasonably well educated, thoughtful segment of an arborist's clientel that statement is superflous, even humorous, afterall what could significantly contribute to damage compared to that done by an atomic weapon. But everyone in the field of arboriculture must deal from time to time with unwarranted fears on the part of a few individuals who own trees. For these folks the atomic bomb exploding and a limb falling are one and the same. This irrational fear is manipulated and amplified with great expertise by the tree topper who unfortunately has no corresponding expertise to apply to trees.)

After millions of years of adaptation, it should surprise no one that a tree's structural integrity surpasses that of most human designed dwellings. Man's building habit is a scant few thousand years old.

With the publication of Dr. Alex Shigo's book, *A New Tree Biology*, a few halting steps were taken in the direction of recognizing the tree structurally for what it is: a system, bound together primarily by cantilevered joints, with inherent characteristics that allow it to bend and twist in response to wind, snow and ice loads, as well as support its own changing weight.

What hasn't happened yet, what needs to happen now, and what the major point of this essay advances is the idea that the tree system can be described mathematically by application of engineering mechanics to each of the ways that a tree forks, bends, twists, adds wood, carries more sap, bears the weight of fruit and accomodates for wind load, snow load and ice load.

Without this kind of knowledge, tree pruning will remain inexact and nonscientific.

I am not suggesting that every arborist become a mathematician or an engineer. However, to date, terms as specific as "leverage" and as general as "a lot of weight up there" are used by tree toppers and tree pruners to equal advantage. Once calculation of bending moments and twisting moments or torques are correctly applied to the tree system, the advantage is to the pruner alone and the tree topper is left standing unsupported by his extravagant claims with regard to tree safety.

From this point on, I am going to attempt four things: 1) teach you to be skeptical of apparent truths when the subject is tree care, 2) apply a set of engineering principles to a model that explains the behavior of the Hiroshima tree, 3) look at the physics of a tree top falling in order to explain why injury and death can occur when a climber fails to appreciate the difference between cutting the top out of a tree and felling a tree while standing on the ground, 4) use geometry to describe the forces that a climber exerts on a tree when he is climbing.

Math is the primary tool used in setting up and solving any kind of engineering problem. Generally speaking, engineers use different branches of mathematics than do plant scientists.

A plant scientist will describe to an arborist in his book or research paper how a tree should be fertilized at least to the dripline and then turn around and ask the arborist to calculate the area to be fertilized by finding that of a square or a rectangle, rather than that of a circle.

Because the "area = length X width" formula is familiar to the least practiced of us, I will use it to illustrate my first point.

Suppose I am a client with a high value tree that I want protected by a fence. I also have a budget. After you have given me a price per foot I tell you I can afford two hundred feet of fence, but I want the area contained by that fence to be the largest possible.

I would expect you to figure 50 feet to a side and decide that the maximum area is 2500 square feet. You might check your intuition by adding 10 feet to one side and substracting 10 from another. 60 X 40 = 2400 square feet and it would appear that the square will contain the largest area.

But I want the most value for my dollar. Since the tree is on a riverbank, I ask you to use the 200 feet of fence but let the river act as one barrier. Your problem is now this (Figure 1):

If you again calculate the area of a square, 200/3 = 66.7 squared = 4444.4 square feet, you have shorted your client.

Try this:

$A = x(200 - 2x)$

$f'A = 200 - 4x$

$0 = 200 - 4x$

$x = 50$ feet

$200 - 2x = 100$ feet and the Area = 50 X 100 = 5000 square feet

Subsequent checks will reveal this figure to be the maximum possible area. You have just used the single most important idea in the calculus, that of a limit.

But had you chosen to fence the tree against the riverbank in a semicircle you could have fenced in an area of 6366.2 square feet, the lesson being that every kind of geometric structure, has its unique characteristics.

In the case of a tree, the roughly cylindrical limbs and stems allow a tree to use the least amount of bark to protect the largest amount of wood. In terms of how many cells must die to protect the living, the tree is an extremely economical unit.

The geometry of a tree must be understood in order to comprehend how a tree withstands the forces of nature that act upon it. The Hiroshima example is a good one since the downwind members that remain are the simplest to describe mathematically when they are bearing a load.

To further simplify I have created a model from which three members emerge from a single joint (fork) (Figure 2). Each is 20 feet long. Each weighs 200 pounds. Each has its center of gravity at its midsection.

What we want to know is with no external load, when the tree is just standing there, what bending moment is acting on the joint. (The joint will have to withstand a larger moment than any other point on the limb.)

The total moment acting on the joint is the sum of the individual forces applied times the distance from the applied force to the joint. The dotted line indicates the moment axis through the joint.

$$\begin{array}{llll} & \text{vertical} & \text{oblique} & \text{horizontal} \\ M = & 200\,(0) + & 200\,(7) + & 200\,(10) \\ = & 0 + & 1400 + & 2000 \\ = & 3400 \text{ lb-ft} & & \end{array}$$

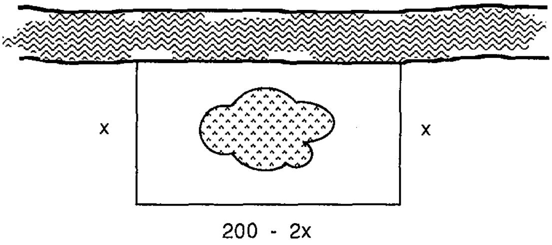

Figure 1. Fenced area.

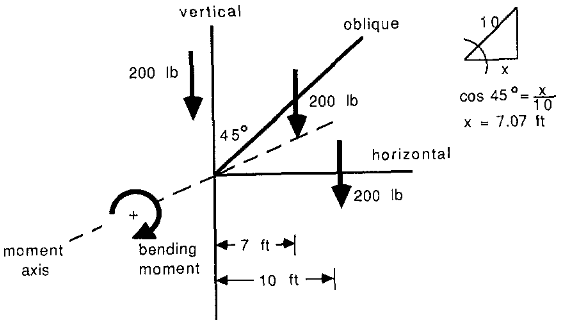

Figure 2. Hiroshima tree schema—no load conditions.

The important thing to observe is that under no load conditions, the moment acting on a joint increases as a limb's natural position becomes more horizontal.

Next we use the same model but add a wind force which when resolved over the total surface area of the limb is found to be the equivalent of 200 pounds acting through the midsection (Figure 3).

$$\begin{array}{llll} & \text{vertical} & \text{oblique} & \text{horizontal}\\ M= & 200\,(10) & +200\,(.7)(10) & +200\,(0)\\ = & 2000 & +\ 1400 & +0\\ = & 3400\ \text{lb-ft} & & \end{array}$$

Now we observe that under load, the trend is reversed. The moment acting on a joint decreases as a limb's natural position becomes more horizontal. Don't forget that the weight of the members still exerts a moment on the joint.

Why does breakage occur at all? In upwind and crosswind conditions, the tree is not so handy at dealing with changes in force applications. The layout of the reaction wood causes the members to have inherent strength when a downward force is applied. The opposite is true when an upward force is applied. Rather than use the Hiroshima example which would be speculative, let me use a familiar situation to describe bending.

Here we have a climber who has been removing limbs on his way up to take the top of a tree (Figure 4). Each branch exerts a downward bending moment around an axis through a representative point within the xylem of the tree trunk. In the area of attachment the xylem has been exerting an equal and opposite counter moment.

Taken altogether the forces exerted by the limbs on the tree trunk act together staticially to stablilize the trunk.

When the climber cuts off a limb, if the xylem in the trunk is not resilient enough to withstand the removal in just a few seconds of the forces that have been acting upon it for years or decades or centuries, the xylem checks.

As a pruning technique, large limb removal is undesirable in the sense that the internal checking sets the tree up for future failure.

As the climber limbs his way toward the top, if the trunk diameter is not sufficiently large, the climber will feel the trunk enliven as he moves.

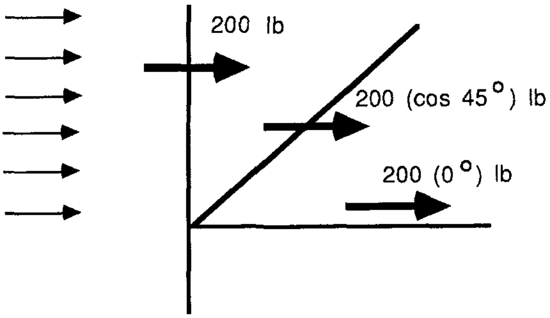

Figure 3. Hiroshima tree schema—partial wind load conditions.

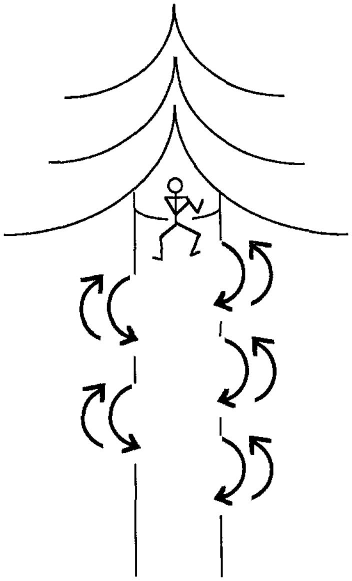

Figure 4. Moments and their components contribute to tree stability.

Figure 5. Eccentric axial loading.

What may be happening is this: Without the stablizing presence of the forces created by the branches, the trunk bows slightly and undergoes axial, eccentric loading, illustrated in Figure 5.

As the climber moves the direction of the bow changes until another type of motion is possible. Simple harmonic motion can occur with the trunk moving slightly back and forth above and below a node somewhere below the climber.

After the limbs are removed and the climber begins to cut the top out of a tree, interesting and sometimes dangerous things happen.

In pure bending (Figure 6) there is a neutral axis which experiences no tension or compression, while the inside curve of a bend experiences compression represented by the arrows pointing together; the outside of the material being bent experiences tension represented by the arrows pointing away from each other.

In pure bending the material being bent will fail at a point predictable for the kind of material it is. Failure of a particular alloy of steel or wood of a particular grade and kind may be predicted.

But when you cut the top out of a tree, the bending that occurs is not pure, not simple. Many kinds of stresses occur in the region of the cut and they change as the cutting continues and the face closes.

After he cuts the face, the climber begins the back cut. At once he creates irregularities (Figure 7).

While the face is closing, a component of the force exerted by the top is downward and rearward, causing the trunk to be pushed, bending backward away from the falling top. The layer of wood that would ordinarily be in tension has been severed by the chain saw. As a result the wood being compressed bears an increased load after the face closes. Intensity of forces, pressure, increases. Separation between the side walls of the cells can occur. This is the phenomenon commonly known as "barberchair". When that happens the top begins to sit down on the tree trunk, the split continues to enlarge and lengthen until the top finally separates. In the meantime the climber's rope has grown taught around the swelling trunk and either he or his equipment or both will eventually fail (Figure 8).

Bending of the trunk and the slingshot effect it has on the climber after the top breaks free may be eliminated or at least minimized by the way the climber sets up his face. Climbers who continue to

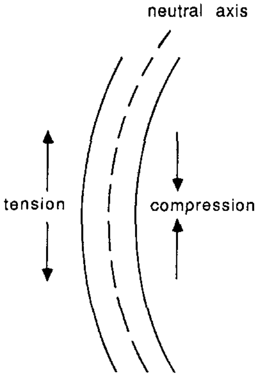

Figure 6. Pure bending.

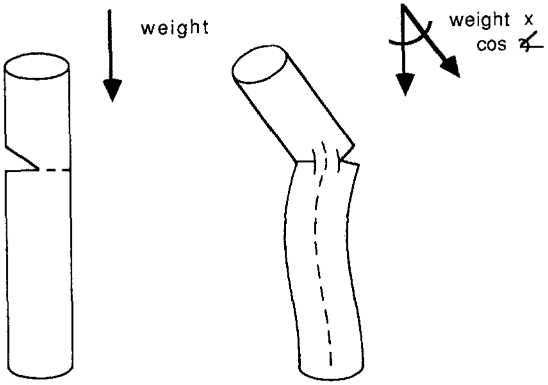

Figure 7. Weight redistribution in the moving top pushes the tree trunk, bending it away from the direction of fall.

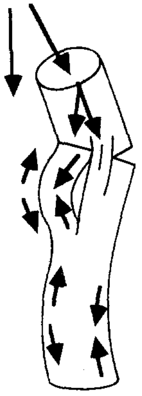

Figure 8. After the face closes pressure in that area increases. Shearing stresses (beyond the scope of this paper) brought on by the increase may induce "barberchair".

ignore this point will continue to get themselves injured and occasionally die. When the axe was the cutting tool used to chop out the face, barberchair was not as likely to occur. An axe pentrates wood better when applied at a steep angle to the grain. A saw penetrates wood better when it is applied normal to the grain.

Having said this, let us create a model, set up a problem and prove or disprove the wide face theory.

I propose that the top be twenty feet long, weigh 1000 pounds and have a center of gravity at its midsection.

If the climber cuts a 15 degree face on the trunk, such as he might do when operating the saw while standing on the ground, the top will travel through an arc of 15 degrees before the face closes and the top begins to exert force on the part of the trunk under the face (Figure 9).

The moment created by a component of the weight of the top acting through its center of gravity may be calculated like this:

$$\begin{aligned} M &= L \quad \times \sin O \quad \times W \\ &= 10 \quad \times .259 \quad \times 2000 \\ &= 5176 \text{ lb-ft} \end{aligned}$$

If the moment created by the top does not exceed the ability of the holding wood to offer a resisting moment, the top will sit in place, not tear loose, greatly increasing your chance to experience barberchair.

If the moment exerted by the top barely exceeds the ability of the holding wood to offer a restraining moment, the top will rip loose slowly over a period of several seconds, pulling the trunk in the horizontal direction of the falling top. Barberchair can still occur, but will be shorter lived since the top will eventually break loose.

It is highly advantageous to a climber concerned with safety—all the hardhats in the world won't help you here—to set up a face as close to 90 degrees as is practical. (This is what the axemen once did naturally because it was easiest.)

Let's use the same principles of calculus that were a part of the simple area problem to explain why I am choosing 90 degrees for the face.

I want to find the face angle that will create the largest moment force at the instant the face closes (Figure 10). Here is the solution:

$$\begin{aligned} M &= LW \sin\theta \\ d(M) &= d\,(LW \sin\theta) \\ &= LW \cos\theta d\theta \\ \frac{dm}{d\theta} &= LW \cos\theta \\ 0 &= LW \cos\theta, \text{ L and W are not zero} \\ 0 &= \cos\theta \\ \theta &= 90^\circ \end{aligned}$$

The moment created by a component of the weight of the top acting through its center of gravity is this:

$$\begin{aligned} M &= L \sin\theta\ W \\ &= 10 \times 1 \times 2000 \\ &= 20{,}000 \text{ lb-ft} \end{aligned}$$

Now you have the top creating a moment of 20,000 lb-ft, which should greatly exceed the restraining moment offered by the holding wood. Detachment of the top occurs in an instant rather

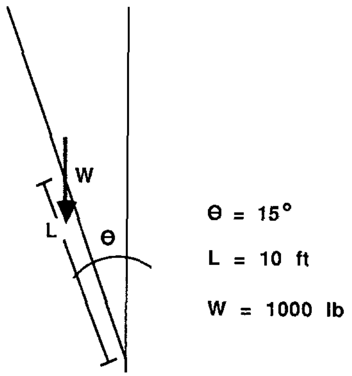

Figure 9. Schema—15 degree face.

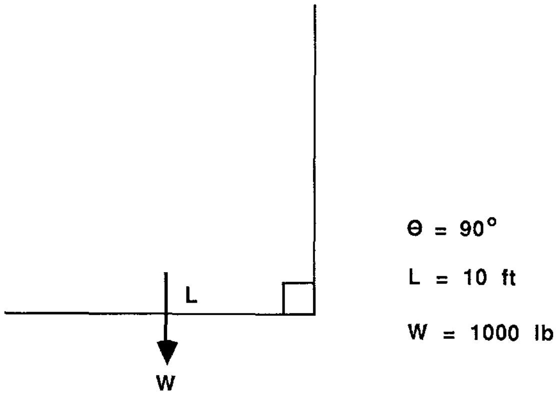

Figure 10. Schema—90 degree face.

than over a period of several seconds. The component of the weight of the top over the trunk when the tearing loose occurs is very small. In fact very few downward and sideward forces are present at this time.

Top climbers should have a practical knowledge of this fact since immediately following detachment is when we use our hands to lift the butt of a falling segment of trunk in order to control the number of flips that will occur in order to make it land flat on the ground. (You didn't think your strength alone allowed you to do that did you?)

We have discussed bending moments. Twisting moments, torque, also exist. Torque is familiar to everyone, since it is the name of the commonplace tool, the torque wrench. Mathematically, it is again the force applied times the distance from the applied force to the point acted upon.

The excessive drop-crotcher creates net torques by leaving heavy, unpruned lateral limbs (Figure 11).

As the lateral grows its surface area enlarges, and the wind force acting upon it increases. At the same time decay organisms are destroying the strength of the wood in the area where the torque is being applied.

What the evidence points to is that every kind of limb and configuration has inherent characteristics and configurations that allow it to deal with conditions in the area it was genetically designed to habitate.

To prune effectively is to develop a method of inspecting forks, decayed areas, split/broken areas, necrotic areas and removing problem members or parts of problem members in such a way as to reduce bending and twisting moments.

Drop-crotching often creates net twisting moments and "rooster tail" pruning—removing all the side limbs on the stem or leader, leaving a heavy top—will create excessive local bending moments.

If that is not enough to think about, there are also internal, unobservable forces to be reckoned with—recall the case of the climber removing heavy side limbs—and don't forget all the traditional knowledge of physiology, pathology and entomology you are supposed to be carrying aloft with you.

Many of the time honored pruning methods stand up very well to mathematical scrutiny. If a climber will simply prune evenly throughout the trees he works in there will be fewer breakage and decay problems.

Part of the reason this does not often happen in full size trees is that there are fewer trained tree climbers than there are tree companies.

The apprentice system works very well to create climbers. But when you have new personnel with specific degrees in plant sciences doing six months to two years climbing in the field before moving into sales or management, you have an industry filled with partially trained climbers who have unjustified high opinions of themselves and their knowledge of the forces involved in large tree pruning.

A quick check on who is trained and who isn't: Does the climber take more time to set up and saw through a small branch toward the end of a limb than he does to set up and saw through a larger limb closer to the trunk? If he does then he is uncomfortable toward the branch tips, and unless he is exceedingly conscientious, as in the case of a good apprentice, he is going to prune more limbs where he is comfortable than where he is not.

When a climber exhibits a radical pruning method, he is in effect practicing a craft without having bothered to learn it. It seems to me that is a case of extreme arrogance, regardless how lax the law is in licensing or registering people who

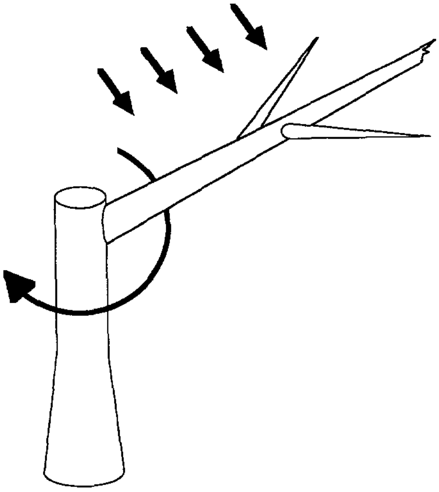

Figure 11. The excessive drop-crotcher creates net torques by leaving heavy unpruned lateral limbs.

work on trees. And it is arrogant beyond measure to profess to be able with a few samurai passes of a chain saw to make a tree "safe". The unfortunate truth is most hazard trees in urban environments are created by the most virulent of pests: man.

Many years ago, when manila was the standard climbing line, a foreman for the company I worked for was assisting the top, having completed his back cut. He pushed with both arms until his taught-line hitch, weakened by age and friction, broke. He fell thirty feet. His large, gear-driven chain saw buried the full length of its bar into the ground, less than a foot from his chest—he was lying on his back.

He was unhurt but a remark about the incident by the manager of the company stuck in my mind to this day. "There's not much pressure on the knot when you're in that position."

Let's look at the circumstance and see what forces exist (Figure 12):

In order to hold up his own body weight, the climber's legs must exert this force:

$$F = \frac{200 \text{ lb}}{\cos 63.4} = 447 \text{ lb}$$

To resolve the horizontal component:

$F = \cos 26.6\ (447) = 400$ lb = tension on the rope snap. Half of that force, 200 lb., will be on the taught-line hitch.

Once the climber raises his arms and pushes on the top with a force of 200 lbs. you have another moment problem.

Moment exerted by the resistance of the top on the climber's arms	Moment exerted by the resistance of the trunk on the climber's legs

$$M = 200 \text{ lb } (2 \text{ ft}) - 447 \text{ lb} \cos 26.6\ (1 \text{ ft})$$
$$= 400 - 400$$
$$= 0 \text{ lb-ft}$$

This is a static condition most easily described by using resisting forces exerted by the tree on the climber (illustrated). The forces continue to exist until the top begins to move, at which point the climber will allow his arms to relax. The moment created by the forces is shown as an axis through the climber's midsection.

The tension on the rope snap is the sum of the horizontal leg force and the force exerted by the arms, 400 + 200 = 600 lbs. The amount exerted on the taught-line hitch is again half of that force, 300 lbs., well within the factor of safety for manila climbing line in good condition.

The manager's intuition was right. However what distinguishes him from many managers today is that he had put in fifteen years as a climber, prior to managing.

Throughout this essay I have moved from applications of math concepts to ground measurements, used statics to solve a simple model, moved up into the tree where I touched on the application of mechanics of solids in order to discuss bending. I have shown how understanding these principles can be applied not just to determine forces acting on and in a tree system, but to perhaps save someone's life.

Underlying the calculations is another message. A climber must be an orderly thinker, who has an idea of the forces in his environment in order to work safely and reduce, rather than increase the bending moments and torques that act on a tree.

Why plant scientists have not used these tools (Statics was under development in the late Greek, early Roman period; dynamics was developed by Galileo Galilei around 1600 and improved by Isaac Newton a century later.) is more difficult for me to understand than the tools themselves.

Knowledge of statics, dynamics and mechanics of solids, along with the accompanying calculus can all be gotten at the community college level.

If these things interest you, like many of the

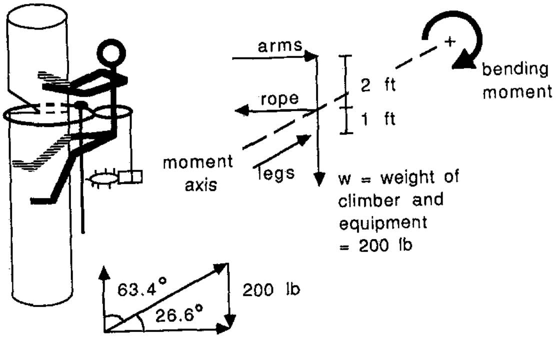

Figure 12. A climber must be able to physically withstand the bending countermoment that the tree applies to him.

situations in arboriculture, you are going to spend money and time and dedicate yourself to acquiring skills and knowledge that will not necessarily make you a dime more in your business. You won't even be able to use your list of coursework effectively on a resume. The courses are not prescribed curriculum for arborists or plant scientists.

My final point is in the form of a question. Given the large number of plant scientists, who through different societies, do not hesitate to ask for research donations, given the large number of corporate managers and their budgets, and generally whoop-oop-de-doo people whose activities fill up the trade magazines and who speak from the podiums of various conferences, why leave it to me, a former tree climber no longer working in arboriculture, to conceptualize, assimilate and present this information to you, without any budget or grant?

Acknowledgment. The computer-generated graphics were prepared by Ms. Sabine Huhndorf of Urbana, Illinois.

61433 Parrell Rd.
Bend, Oregon 97702

Abstracts

STILES, B. 1988. **Evaluate your sales personnel.** The Landscape Contractor. Feb. p27-29.

The focus on sales volume as the sole measure of a saleperson's performance easily can prove misleading. Properly evaluating sales personnel requires a look at many factors that influence their value to a business. You need to establish some common criteria for evaluating all sales personnel. At the same time, ask some specific questions about each salesperson as you proceed through the evaluation process: Does s/he constantly seek new business? Does s/he continuously try to improve product knowledge and selling skills? Does the salesperson handle customer complaints competently? Does s/he assist other sales personnel when the need arises? Does the salesperson work cooperatively with inside people? Does s/he respond to constructive criticism in a positive manner? After using an effective evaluation system in your business for six to twelve months, you should start seeing the benefits on your firm's bottom line. Moreover, you will find better morale among your salespeople.

VIKNER, P. 1988. **The 12 commandments of preventive truck care.** Am. Nurseryman 167(6):61-64.

Most truck owners are experts in their businesses, not in truck care and maintenance. So they either rely on expert dealer technicians, or they try to save money by using non-professionals to perform maintenance work. That's why the owner's manual is so important; it's the bible of vehicle care and maintenance. Every Isuzu truck manual contains the following commandments of preventive truck maintenance. Follow them and any vehicle you own will have a longer, more economical life. Thou shalt realize that all mechanical devices—including trucks—wear out sometime. Thou shalt break in thy new truck with kid gloves. Thou shalt treat thy truck's engine like thine own heart. Thou shalt treat oil as gold. Thou shalt not put water in thy tank. Thou shalt drive with fuel economy in mind. Honor thy tires as thy footwear. Thou shalt regularly change and replenish thy truck's fluids and lubricants. Thou shalt not overburden thy truck. Thou shalt coddle thy brakes. Thou shalt travel lightly on thy clutch. If thou hast questions about repairs or service, thou shalt ask an expert.