Protecting Orange Saplings from Irreparable Frost Damage

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Executive Summary

Nocturnal frost and freeze damage can have a major impact on the survival and fruit production of young citrus trees. When temperatures fall below -4^oC irreparable damage occurs. Because of this damage, many methods, including insulating sapling trunks and building soil banks have been used to help reduce the rate at which these trees lose heat in sub-zero conditions. This study focused on the effect a combined insulation-and-metal-stake method has on preventing frost and freeze damage of Washington Navel Orange saplings by looking at increase in trunk temperature using this system and comparing it to trunk temperatures in both an insulation only system and a bare tree system. It was found that the rod had little effect on trunk warmth but trunk insulation helped significantly – the thicker and denser the insulation, the better.

Introduction

Nocturnal frost and freeze damage can have a major impact on the survival and fruit production of young citrus trees. These trees have little canopy to retain heat and are therefore particularly susceptible to cold weather conditions. The significant form of nocturnal heat transfer for the citrus tree is thermal conduction. Convection is only significant during the day due to active transpiration stream flows. Nocturnal radiation loss is negligible due to the insulating canopy. When temperatures fall below -4^oC irreparable damage occurs. Because of this damage, many methods, including insulating sapling trunks and building soil banks have been used to help reduce the rate at which these trees lose heat in sub-zero conditions. This study will focus on the effect a combined insulation-and-metal-stake method has on preventing frost and freeze damage of Washington Navel Orange saplings by looking at increase in trunk temperature using this system and comparing it to trunk temperatures in both an insulation only system and a bare tree system. Our model will consist of an aluminum rod inserted into the ground directly next to and touching a Washington Navel Orange sapling with a fiberglass insulation wrap around the sapling-rod system. Steel and copper rods as well as Styrofoam insulation will also be considered.

Design Objectives

The main objective of investigating this system is to devise a way to prevent irreparable damage to saplings when temperatures fall below freezing. We believe that protecting the sapling trunk via insulation and aided heat conduction from the ground may prevent this irreparable damage. In order to test our hypothesis we modeled our sapling system in GAMBIT, creating a mesh, and imported our 3-D mesh into FIDAP, where we modeled the thermal region surrounding the sapling trunk in order to assess potential irreparable damage affects. We used a variable temperature over a 24 hour time period in our simulation. In order to assess these affects we:

- Found trunk temperatures in the insulation-and-metal-rod system, insulation system, and bare tree system.
- Compared the insulation-and-metal-rod system to the bare tree.
- Compared the insulation-and-metal-rod system to the insulation alone.
- Did a sensitivity analysis of the system by contrasting insulation thicknesses, rod materials, insulation materials, and convection coefficients.
- Drew conclusions on the effectiveness of the insulation-and-metal-rod system.
- Made recommendations about how to protect saplings from frost/freeze damage using the above contrasted techniques.
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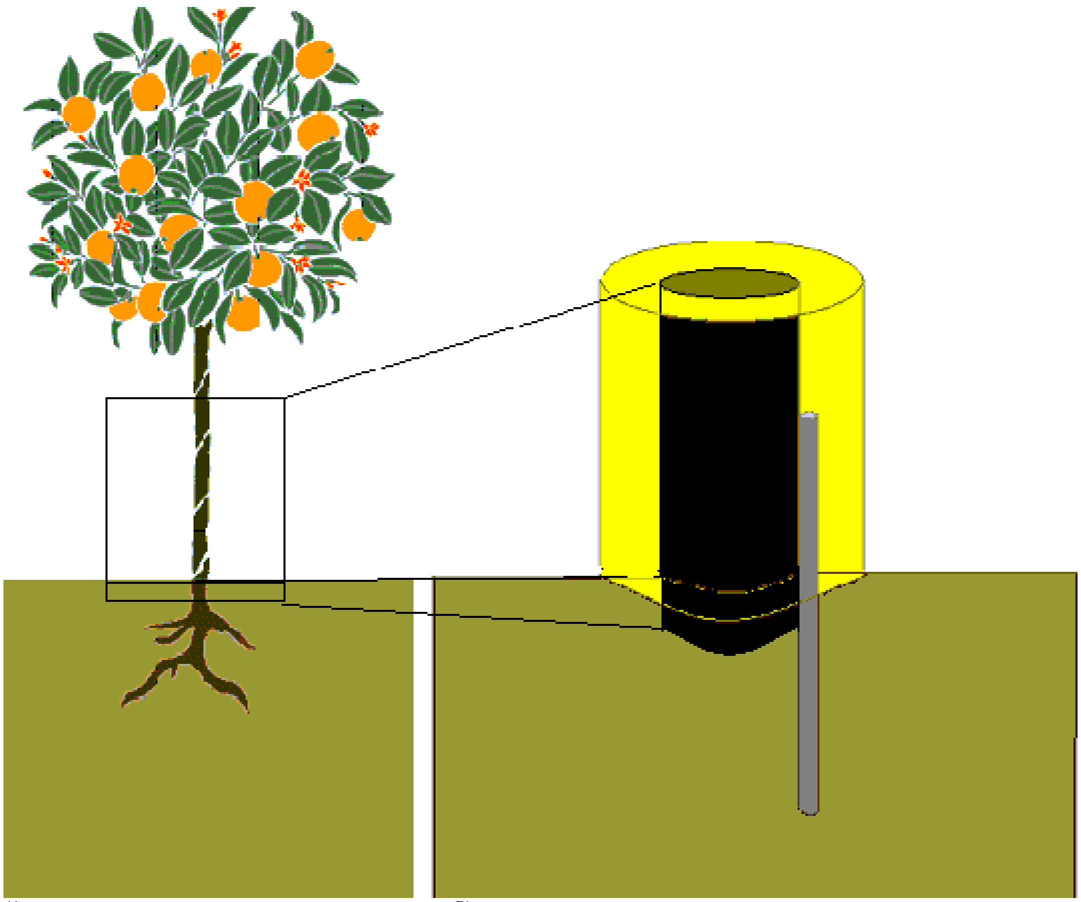
Realistic Constraints

When designing this system for real world applications we considered constraints beyond mere thermodynamic testing. The most important constraints considered for implementation were cost effectiveness and manufacturability. We found that every item used in the rod-insulation system is readily available and sold on the marketplace, and therefore the system manufacturability is very viable. Table 1 lists costs of insulation and rod materials. These costs must be considered in comparison to effectiveness in warming for our final design as well as a cost-benefit analysis of profits saved versus the cost to save those profits.

Material	Cost
Fiberglass Insulation	$12.83/sheet
Styrofoam Insulation	$26.22/sheet
Aluminum Rod	$9.58/3ft.
Copper Rod	$9.34/3ft.
Stainless Steel Rod	$5.84/3ft.

Table 1. Matrial costs, obtained from McMaster-Carr’s catalogue.

Schematic



A) B)

Figure 1. A) Orange sapling (http://www.stencilkingdom.com). B) Schematic of insulation-trunk-rod system.

Figure 1 (above) shows a schematic of the insulation-trunk-rod system. We chose to model a section of the trunk and ignored branching effects for simplicity. The trunk was 14cm in diameter, the rod was 4cm in diameter and the outer insulation diameter ranged between 20cm and 40cm. Further geometric definitions can be found in the Appendix.

Results and Discussion

Using sensitivity analysis we looked at the effects of various parameters on our final result (figures and further discussion can be found in the "Sensitivity Analysis" section). Convection is one of the greatest determinants for heat loss from the tree. High convection coefficients, like those that would occur on a windy night can quickly rob the tree of its heat. While natural convection proved to be ideal, it is not a realistic parameter. The rest of our sensitivity analysis was run for 4hrs with an outside temperature of -10°C, and a convection coefficient of 6 $W/cm^2 K$. First we determined that more insulation for the tree does provide additional benefit against the wind and thus slows the initial release of heat. A disadvantage is that it is also slower to heat back up as the temperature rises. We also tested the use of Styrofoam insulation. The Styrofoam proved to be a slightly better insulator because of its lower conductivity and higher density. However the use of Styrofoam comes with another set of challenges, mainly its rigid structure would require pre-formed insulation wraps that would be difficult to fit to the wide variety of tree trunk sizes.

We also varied the make up of the metal each with different conductivity coefficients. We modeled the system with copper ($k=4.00 W/cm^2$), aluminum ($k=2.21 W/cm^2$), and steel ($k=0.5\ W/cm^2$) rods. The copper rod showed the best heating and steel and aluminum were similar. In general the differences were minimal between all three types of rods.

We then wanted to determine if the rod actually would provide heat for the tree over a 24 hr period. We designed a program the change the temperature sinusoid ally with a maximum of 13°C occurring at the beginning and ending and dipping to -10°C. We used a convection coefficient of $6\ W/cm^2\ K$ with medium insulation around the tree. We chose to use the medium fiberglass insulation because we felt it best modeled the real situation. In one trial we did not use a rod and in other we used a steel rod. We chose the steel rod because it was a cheaper material and proved from the sensitivity analysis to be just as effective as aluminum. In both trials we monitored two nodes: one on the tree surface but not near the rod, and one on the surface of the insulation to observe the change in outside temperature (figure 2, figure 3). In both situations the temperature on the surface of the tree reached 4°C. The rod appears to have helped when we compare contours after the 24hrs, but this was minimal. Close observation of the pictures reveals small changes in temperature between the control and the tree with the actual rod (see figure 4). Core temperatures in both trees dropped dramatically and we found if any heating did occur it was insignificant.

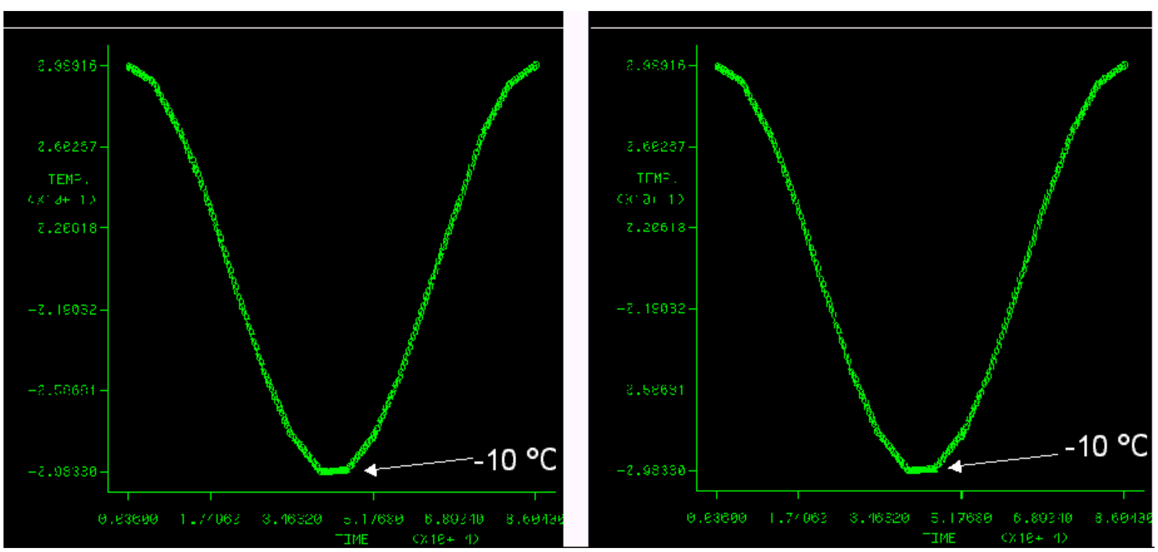


Figure 2. Node on side of insulation. Left: control, Right: experimental

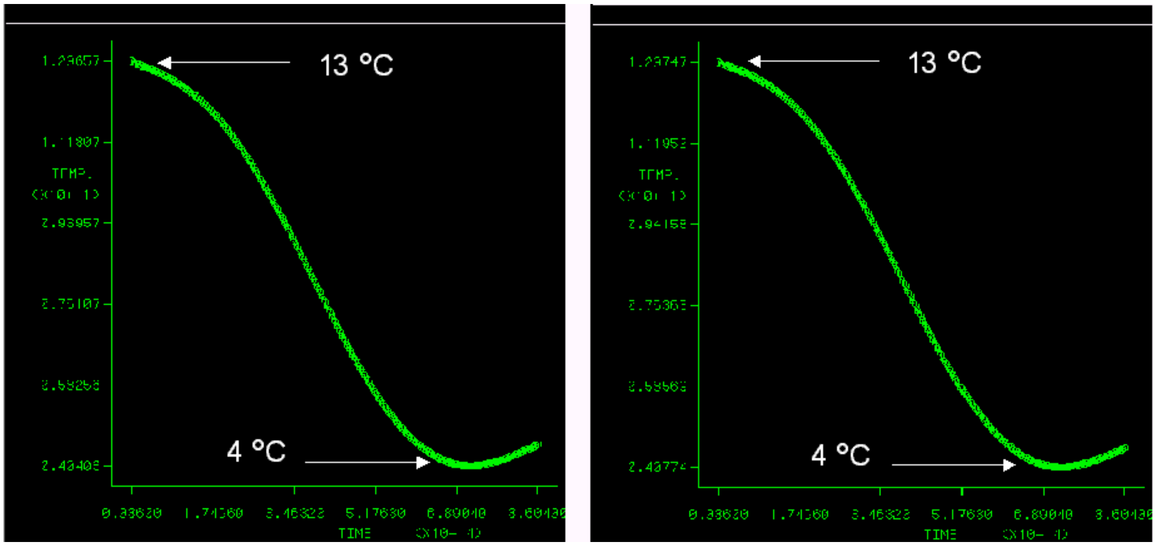


Figure 3. Node on side of tree. Left: control, Right: experimental

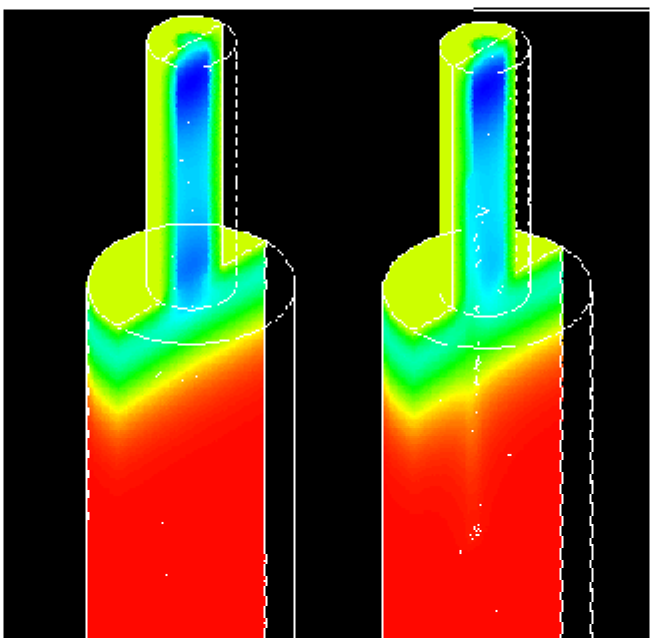


Figure 4. Temperature contours Left: control – no rod, Right: wit rod

Sensitivity Analysis

We performed 4 different types of sensitivity analysis: rod material (conductivity), insulation thickness, insulation material (conductivity), and convective coefficient. For the rod material we simulated aluminum, stainless steel, and copper rods. Temperature contours are shown in figure 5 below. We found that the copper rod, which had the highest thermal conductivity (see appendix for constants), was the most effective in keeping the tree warm, followed by the aluminum rod and stainless steel rod, respectively. However, we also found that the benefit was small and therefore concluded that the material used for the rod was not important.

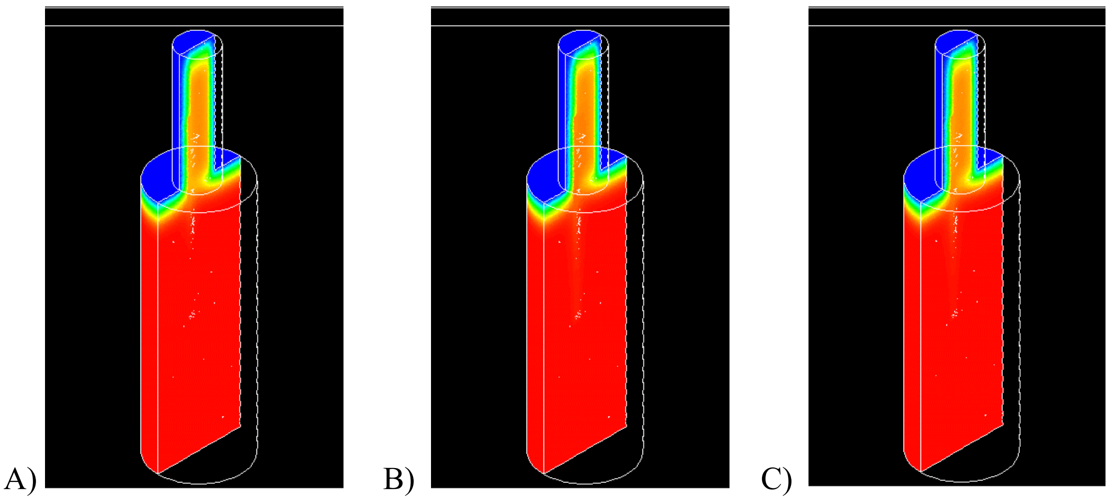


Figure 5. Temperature contours of A) stainless steel, B) copper, and C) aluminum rods.

When we did sensitivity analysis of the insulation thickness we used thicknesses of 3cm, 8cm, and 13cm. As can be seen in figure 6 below the thickness of the insulation had a large effect on the warmth of the sapling trunk. The thicker the insulation was, the more heat was retained.

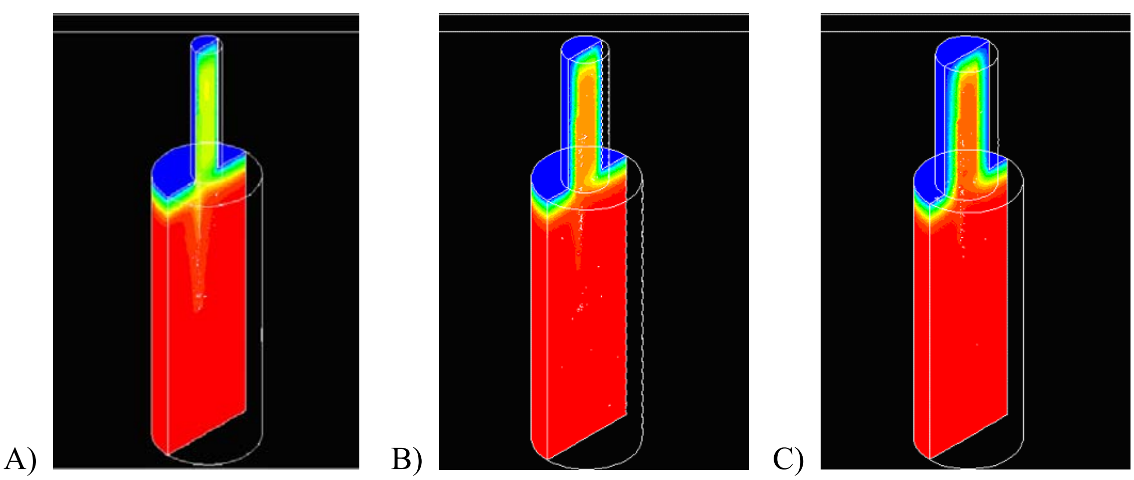


Figure 6. Insulation thickness variation: A) 3cm, B) 8cm, C) 13cm

A sensitivity analysis of the insulation material yielded conclusive results. The Styrofoam insulation had much better heat retention than the fiberglass insulation as can be seen in figure 7 below.

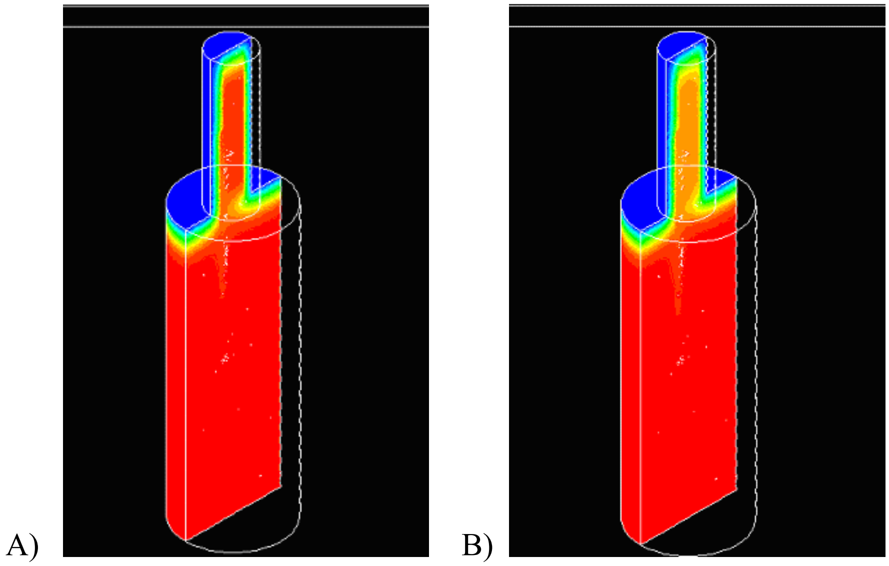


Figure 7: Temperature contours: A) Styrofoam B) Fiberglass

Our final sensitivity analysis involved varying the convective coefficient of the insulation. Figure 8 below shows that the smallest convective coefficient had the best heat retention but the differentiation between the effects of the coefficients was negligible.

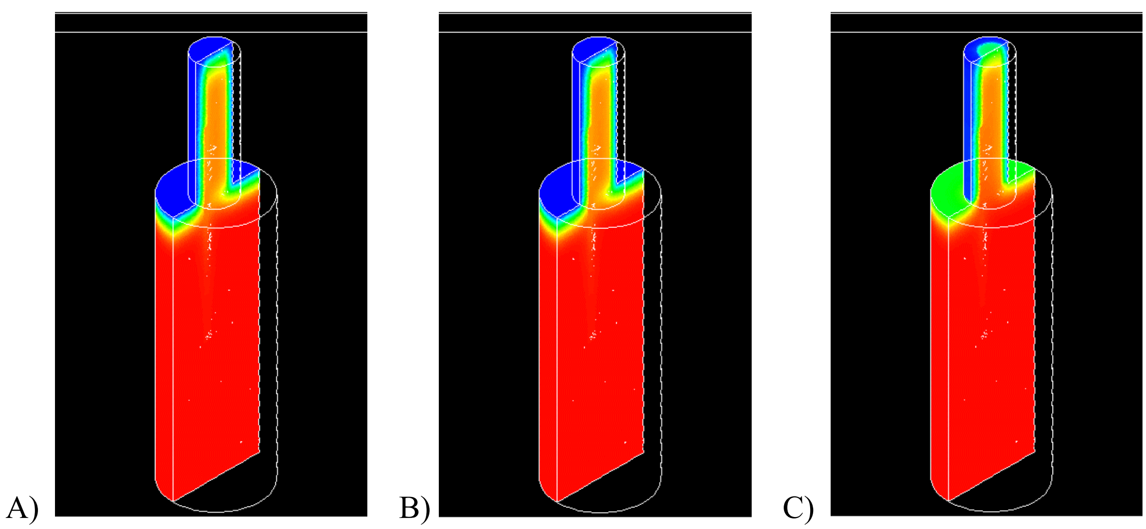


Figure 8: Convective coefficient variation: A) h = 6 W/ cm2 K, B) h = 1 W/ cm2 K, C) h = 5.554E-4 W/ cm2 K

<u>Conclusions and Design Recommendations</u>

From our sensitivity analysis and comparing results with a control tree we see that the rod has little effect on the warmth of the sapling trunk and can therefore be discarded. We also see that the type of insulation we choose makes a big difference. Though the Styrofoam performs better, it is much more expensive than the fiberglass insulation, and because Styrofoam is much denser than fiberglass it is harder to get a close fit between the Styrofoam insulation and the tree trunk so we recommend using fiberglass insulation.

We also recommend using as thick a layer of insulation as possible because the thickness of the insulation layer had a huge effect on trunk temperature retention. We also found that as the temperature of the ambient air warmed up, the insulation was preventing the air from warming the trunk and thus would suggest that the insulation be removed during the day and used over night only. Speaking from a strictly economic standpoint, the cost of protecting the sapling trunks is minimal compared to the benefit from saved orange crops, especially since the insulation is a one-time cost as it can be reused. We would highly suggest the use of thick fiberglass insulation around orange sapling trunks.

Appendix

Geometry

- Orange sapling diameter = 14 cm
- Orange sapling trunk height = 100 cm
- Orange sapling trunk height below ground = 50 cm
- Aluminum rod diameter = 4cm
- Aluminum rod length = 150 cm
- Depth rod inserted into soil = 50 cm
- Surface area of rod touching tree = 1/8, remainder touching insulation
- Outer diameter of fiberglass wrap = 40 cm
- Height of fiberglass wrap = 100 cm
- Ground depth = 200 cm
- Ground diameter = 70 cm

Governing Equations

We used the energy equation for our process:

$$(K/\rho Cp) * [\ 1/r\ d/dr(r\ dT/dr) + 1/r^2(d^2T/d\varphi^2) + d^2T/dz^2] = dT/dt$$

Boundary Conditions

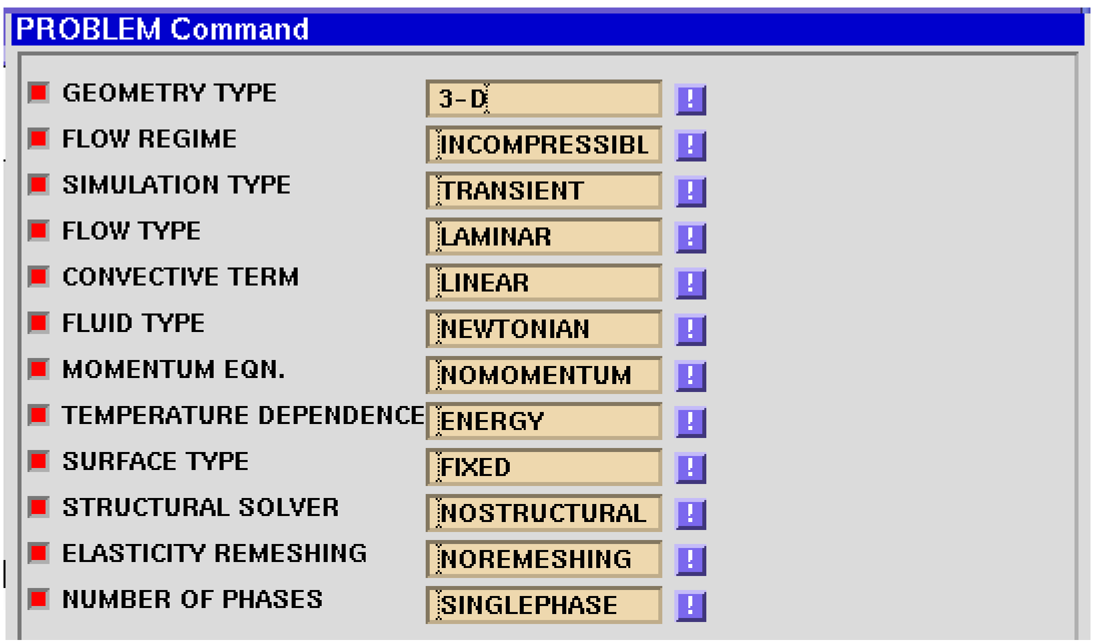
- Night air temperature minimum = -10°C
- Day air temperature maximum = 13°C
- Soil temperature (200 cm depth) = 13°C
- Initial temperature at trunk center = 13°C
- Temp at which cambium freezes = T@ r = -4°C

Input Parameters

- Thermal conductivity of aluminum: 2.21 W/cm-K
- Thermal conductivity of steel: 0.5 W/cm-K
- Thermal conductivity of copper: 4 W/cm-K
- Thermal conductivity of soil with organic matter: 0.005 W/cm-K

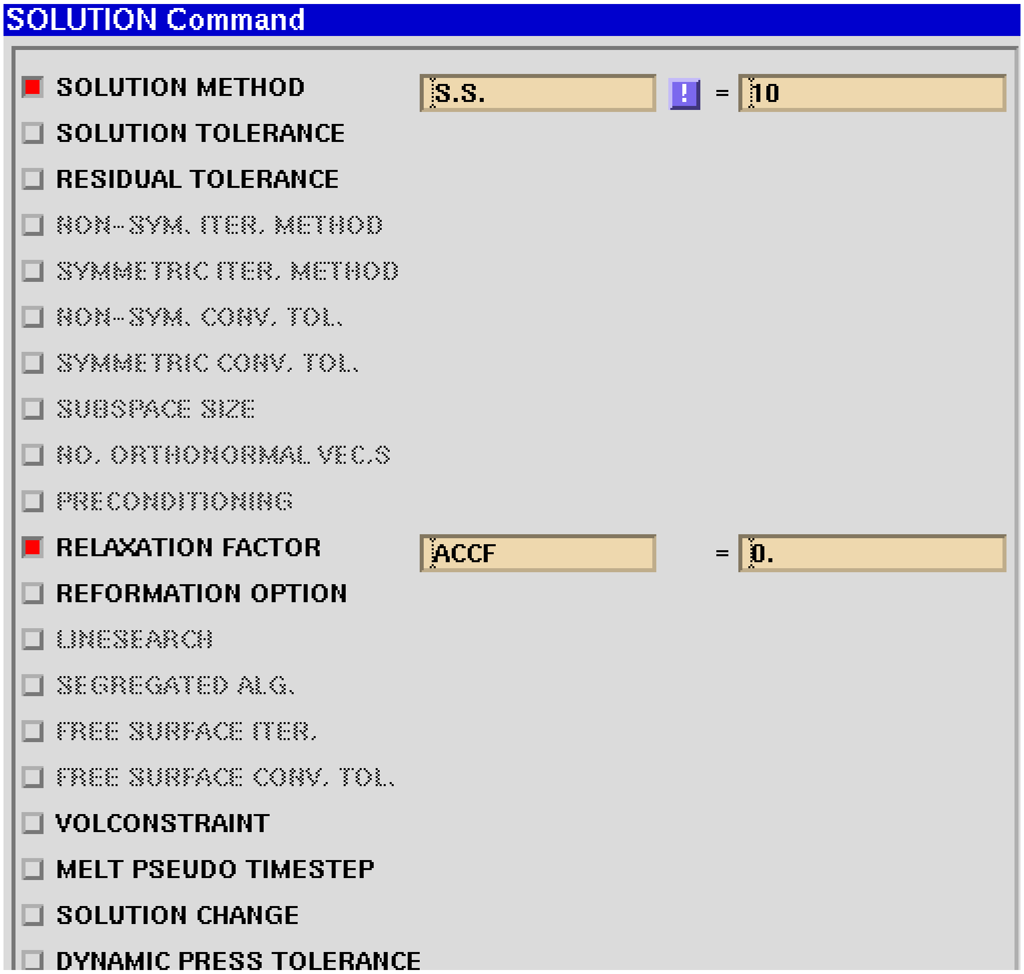
- Thermal conductivity of wet sapling: .00559 W/cm-K
- Specific heat of wet sapling: 2.252 Cal/g-C
- Density of wet sapling: 0.7065 g/cc
- Thermal conductivity of fiberglass: 0.00033 W/cm-K
- Thermal conductivity of Styrofoam:0.001 W/cm-K
- Density of fiberglass: 0.1 g/cm^3
- Density of Styrofoam: 0.012g/cm^3
- Insulation thickness: 3cm; 8cm; 13cm

PROBLEM Statement



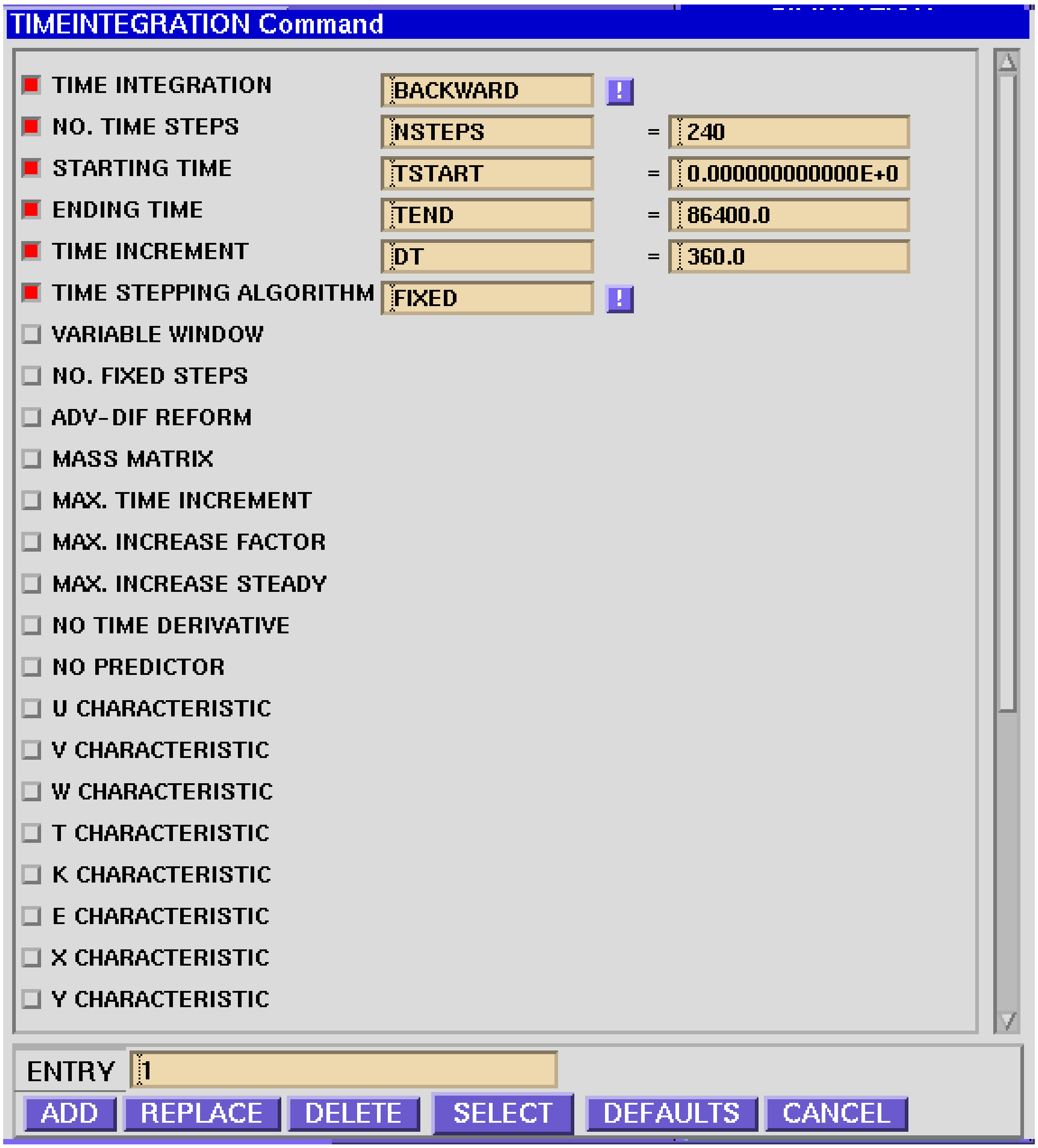
We chose a 3-D geometry with no fluid flow and therefore no momentum. The governing equation used was the energy equation.

SOLUTION Statement



We wanted to solve the system of equations at each step of an implicit time integration system with a maximum of 10 iterations per time step, as indicated by the solution command above.

TIMEINTEGRATION Statement

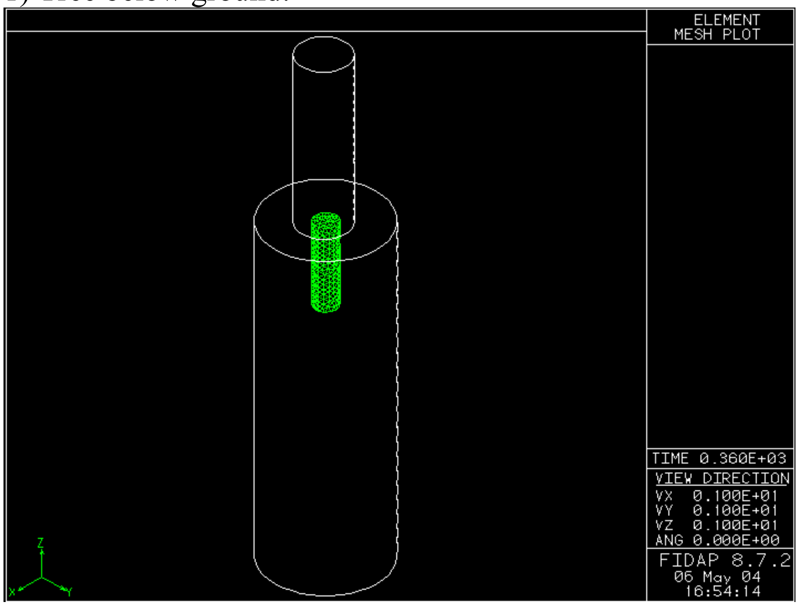


We observed temperature changes in the system over a 24 hour period (86400s) with time steps of 360s. We chose a backward integration so that we would have a finite time analysis with a fixed number of time steps.

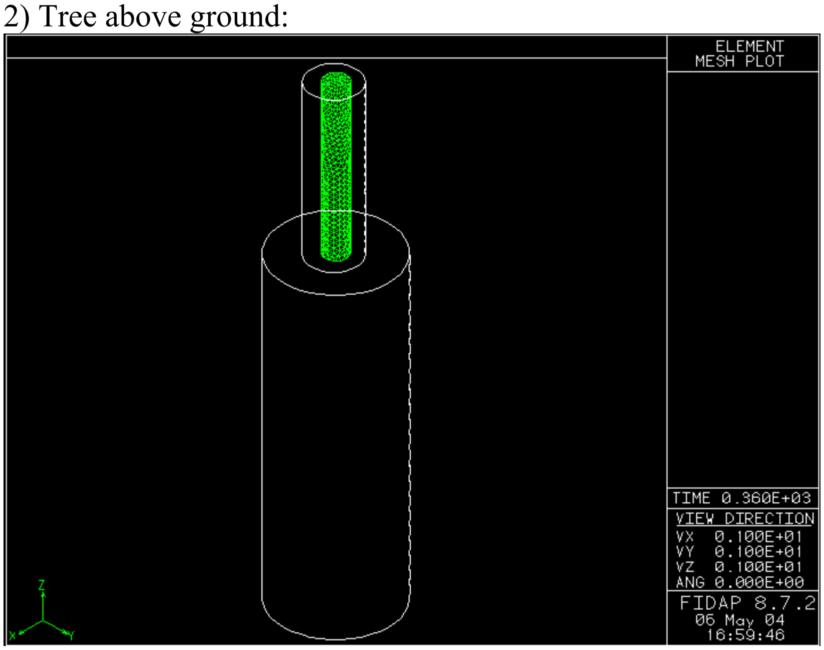
Mesh and Convergence of Solution and Mesh Refinement

The geometry consists of 6 separate 3-D volumes that were created using split and merge functions. Although the problem conceptually only really contains 4 volumes (insulation, tree, rod, ground), when the tree and rod were both split from the ground and insulation the tree and rod were each split into two entities each sharing common faces. The 6 volumes are as follows:

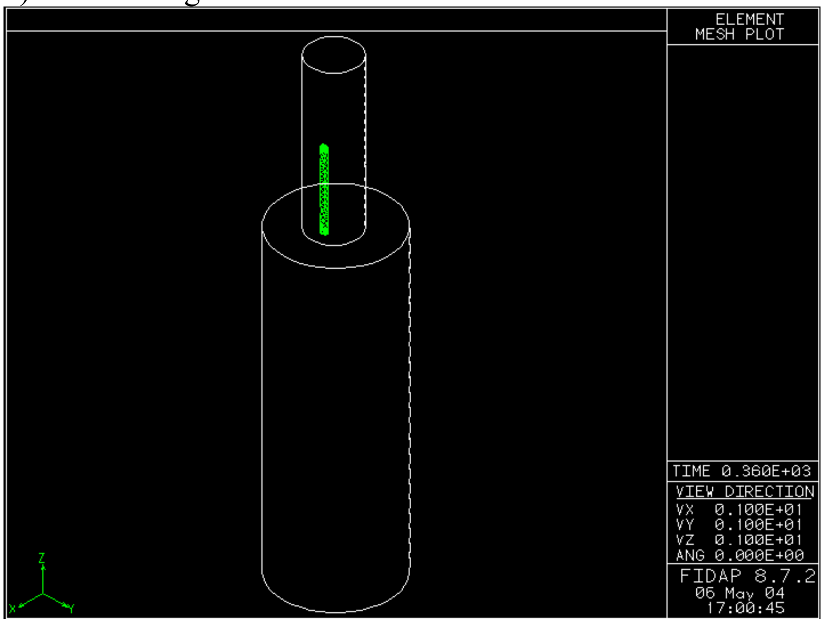
1) Tree below ground:



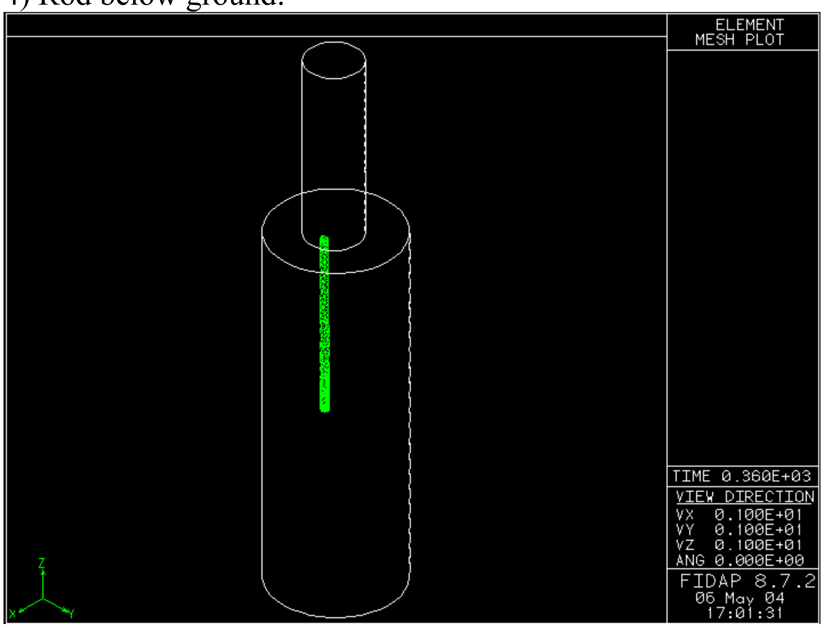
2) Tree above ground:



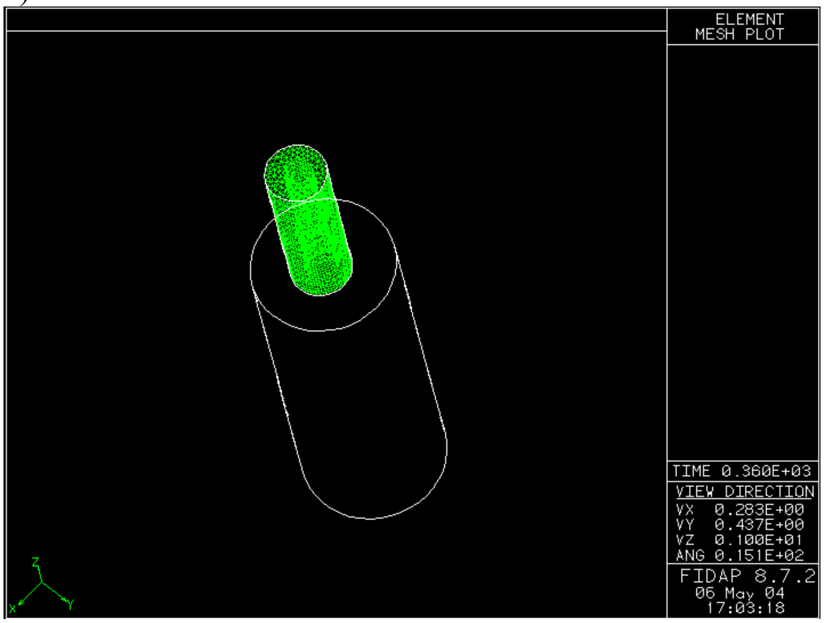
3) Rod above ground:



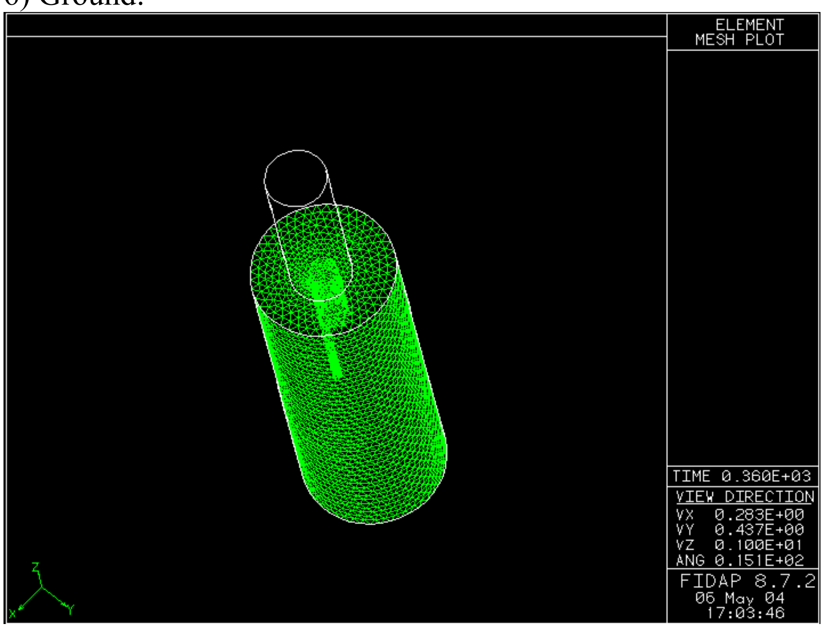
4) Rod below ground:



5) Insulation:



6) Ground:

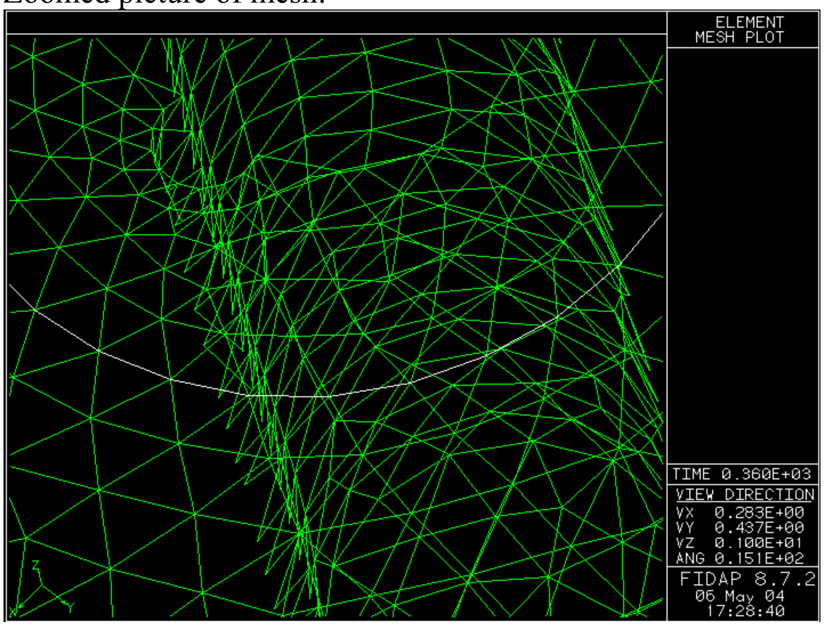


Our Geometry consists of 19 distinct faces, 6 of which carried boundary conditions.

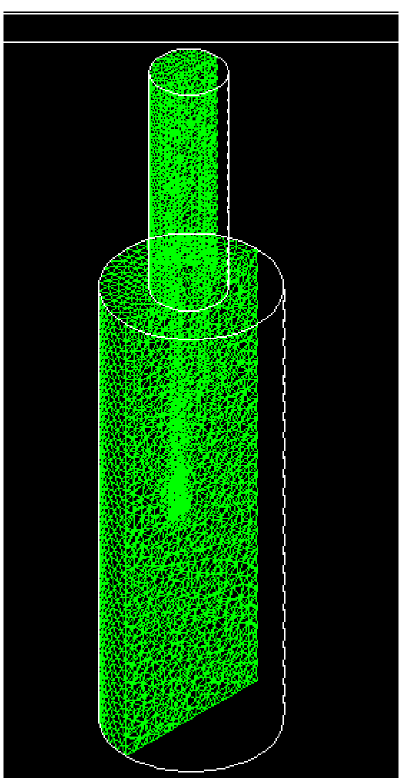
One of the major difficulties in creating the geometry was creating an area of contact between the rod and the tree. Initially we had modeled the rod and tree as two cylinders intersecting at one point. Gambit was unable to create the intersecting edge into an entity. Instead we placed the rod 0.5 cm into the tree, split the two volumes and merged the union of the tree/rod into the tree. This procedure created an intersecting planar face between the rod and tree that gambit was able to identify.

The volumes were meshed using tet-hybrid scheme with t-grid type. It was necessary due to the complex geometry to have a mesh that could 'fit' itself everywhere. Tet mesh was convenient b/c it was automatic and it used prism layers on volume boundaries, which is where heat flow gradient should be greatest. We chose the finest mesh type because while the geometry was difficult the heat transfer problem was a simple one. This fine mesh did not hinder our project by making runtime in FIDAP excessively long due to the simplicity of the heat transfer problem. Additionally, trying to choose a less fine mesh resulted in no mesh being created for this complicated geometry.

Zoomed picture of mesh:



Bisected picture of mesh:



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Special Conditions

While most of the challenges faced with this project occurred during the meshing phase of the project using the Fidap software also created a set of challenges. First it was important to name all of the entities that were sent over with the gambit file. We had no problems with the medium and small insulation problems but working with the large insulation situation was more difficult because of the additional nodes that were added. We were forced to decrease our time integration to allow the solution to converge before increasing the time step. We also spent time learning how to vary the outside temperature to model a real world simulation.