Winter Greenhouse Research

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Acknowledgements

- SARE – provided funds for instruments
- Greg Michna – SDSU Greenhouse modeling
- Elmer & Staff – modeling 2D & 3D
- LBNL & Staff – window modeling
- Qiang Zhang – U Manitoba - research
- Carol Ford & Chuck Waibel
  - The Northlands Winter Greenhouse Manual

Background

- Chinese in Northern China since 1980s
  - Plastic Solar Window
  - Sand Filled north wall
  - 650,000 acres under roof
  - Supply 90% of fresh produce (2004)
- U Missouri since 1988
  - – Double wall 6 mil plastic at 45 deg
  - – 20 55-gal water barrels in 24 ft
- University of Manitoba 2002 – most like SD

Introduction

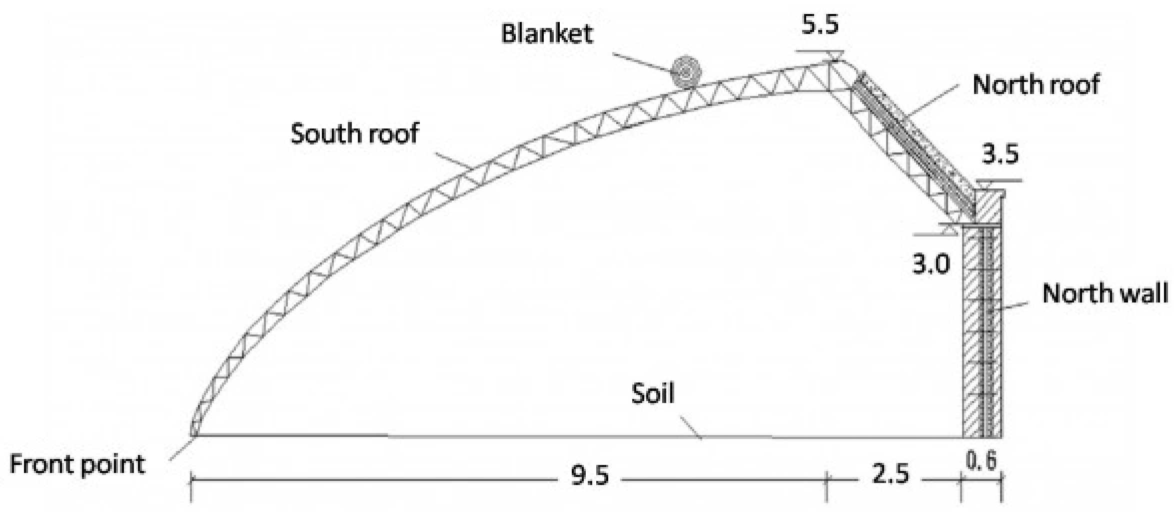
- Began construction Fall 2006
- Objective was completely passive heating
- Various solar window materials tried (6 mm plastic)
- All walls and ceiling insulated with R19 fiberglass
- North ceiling covered with Reflectix
- Concrete slab perimeter insulated to 4 ft with R19 foam (summer 2009)
- 8 mm twin wall polycarbonate glazing
- South wall – snow off window – shadow effect

Solar Window

- At local noon @ winter solstice optimum angle of Solar Window from horizontal = Lat + 23 deg
- To determine optimum angle need consider growing period
- At 44.4 deg lat from Sept – March 60 deg best
- At 44.4 deg lat from 12/1 – 1/31 70 deg best
  - Nelson recommends Lat + 15 deg
- Solar irradiance most needed at this time
- 45 deg Solar Window about 10% effect
- Solar Window angle affects size of window relative to other physical constraints.

Introduction

- SARE Grant September 2009
- Began Collecting Data Winter 2009
  - Onset Data Logger
  - 4 Temperature Sensors
  - 2 Pyranometers
  - Solar Panel
- 16 55-gallon water-filled barrels
- Solar Curtain added January 2010
- Added Thermosiphon Winter 2010



Chinese Solar Greenhouse
External Thermal Blanket, Heat Storage in North Wall

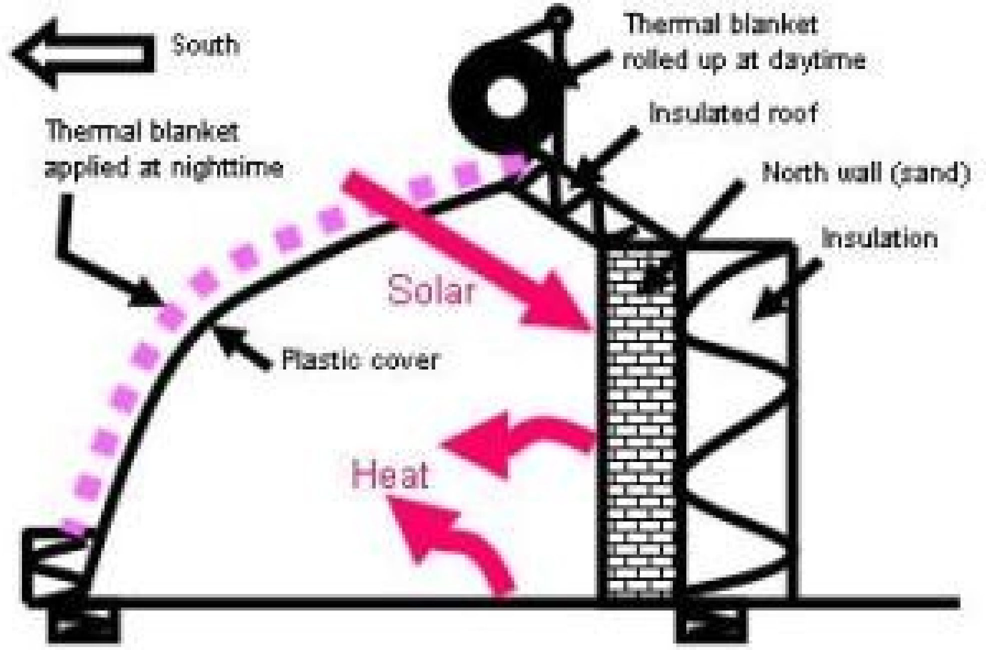


Figure 1. Schematic illustration of a solar energy greenhouse

Zhang's Chinese style winter
greenhouse in Manitoba

Zhang's Greenhouse in Manitoba
Note plastic solar window & thermal blanket

Garden Goddess Greenhouse Milan, MN
Solar window extended on south, east and west walls

Solar Window Area Considerations

- Solar window on South Wall
  - Diminish shadowing effect
  - Snow covers it usually
- Replacing insulated wall with solar window
  - R value wall similar to 10 X solar window
    - Loss through window >> Loss through wall
  - Solar Gain depends upon Form Factor
    - East/West windows low form factor
    - East/West gain primarily diffuse sky irradiance

Greenhouse Heat Losses

- Conductive – by contact
- Convective
  - Natural (gravitational) inside
  - Forced on outside – function of wind velocity
- Infiltration – velocity dependent
- Radiative through solar window
- All can be viewed as driven by Temperature difference between inside & outside
- 70% of solar radiation evaporate water (Hanan)
  - Empty greenhouse can be misleading

Greenhouse Models

- Takakura (1965)
  - 2D time dependent solution, inc insolation
- Nelson empirical model (2003)
- Zhang (2006)
  - 1D time independent model
- Tong (2009)
  - 2D time dependent CFD Fluent, inc insolation
- My 1D model, results similar to Nelson model

$$\dot{Q} = \left(\frac{A_s}{R_s} + \frac{A_g}{R_g} + \frac{A_f}{R_f} + \rho_a C_a V_g \dot{v} \right) (T - T_o)$$

A_s = Area of Solar Window

A_g = Area of Greenhouse Walls + Roof

A_f = Area of Greenhouse Floor

R_s = Thermal Resistance of Solar Window

R_g = Thermal Resistance of Greenhouse Walls

$R_f = \frac{\bar{R}}{2F}$ = Thermal Resistance of Floor

$\rho_a C_a V_g \dot{V}$ = Infiltration Loss

Model Heat Losses

- Wall & Roof – convective & conduction losses
- Floor – conduction & natural convection losses
- Solar Window – convective, conduction, & radiative losses.
- Convective R about 25% of Conduction R
  - Implies convection loss > conduction losses
- Roughly equally divided amongst Wall, Solar Window, Infiltration, & Floor

Model Heat Loss Savings

- Perimeter of Greenhouse insulated down to 4' with R-15 – 38% reduction in Floor Loss
- Solar Curtain (hopefully) no difference during day
- Solar Curtain at night reduces solar window convective, conduction, & radiative losses
  - Radiative ~ 30% of total window losses
- Solar Curtain – about 40% reduction in Solar Window losses (roughly agrees with Bailey)
  - 12% overall reduction

Nelson Heat Loss Model

$$K = -0.06 + 0.00266 * W + 0.01333 * dT + 0.0000666 * W * dT$$

$$W = \text{Wind Speed (mph)}$$

$$dT = \text{Temperature difference (deg F)}$$

$$WL_i = 0.08 * WallArea_i \left(ft^2\right)$$

$$RL_i = 0.08875 * RoofArea_i \left(ft^2\right)$$

$$\dot{Q} = K * \sum_{i=1}^{N} \left(WL_i * CW_i + RL_i * CR_i\right) \left(MBtu/hr\right)$$

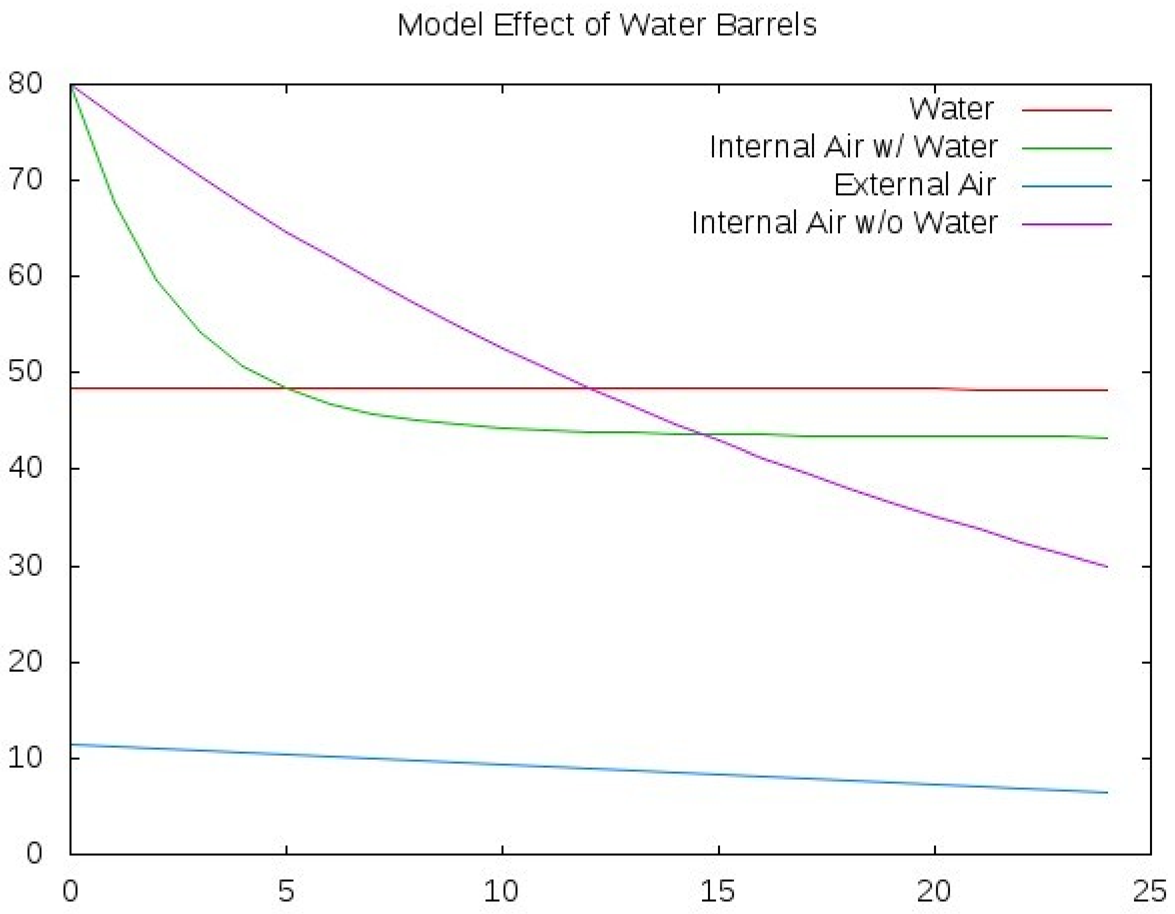
$$CW_i \text{ and } CR_i \approx \text{Thermal Conductivity } \left(Btu/ft^2 - hr - F\right)$$

Effect of Water Barrels

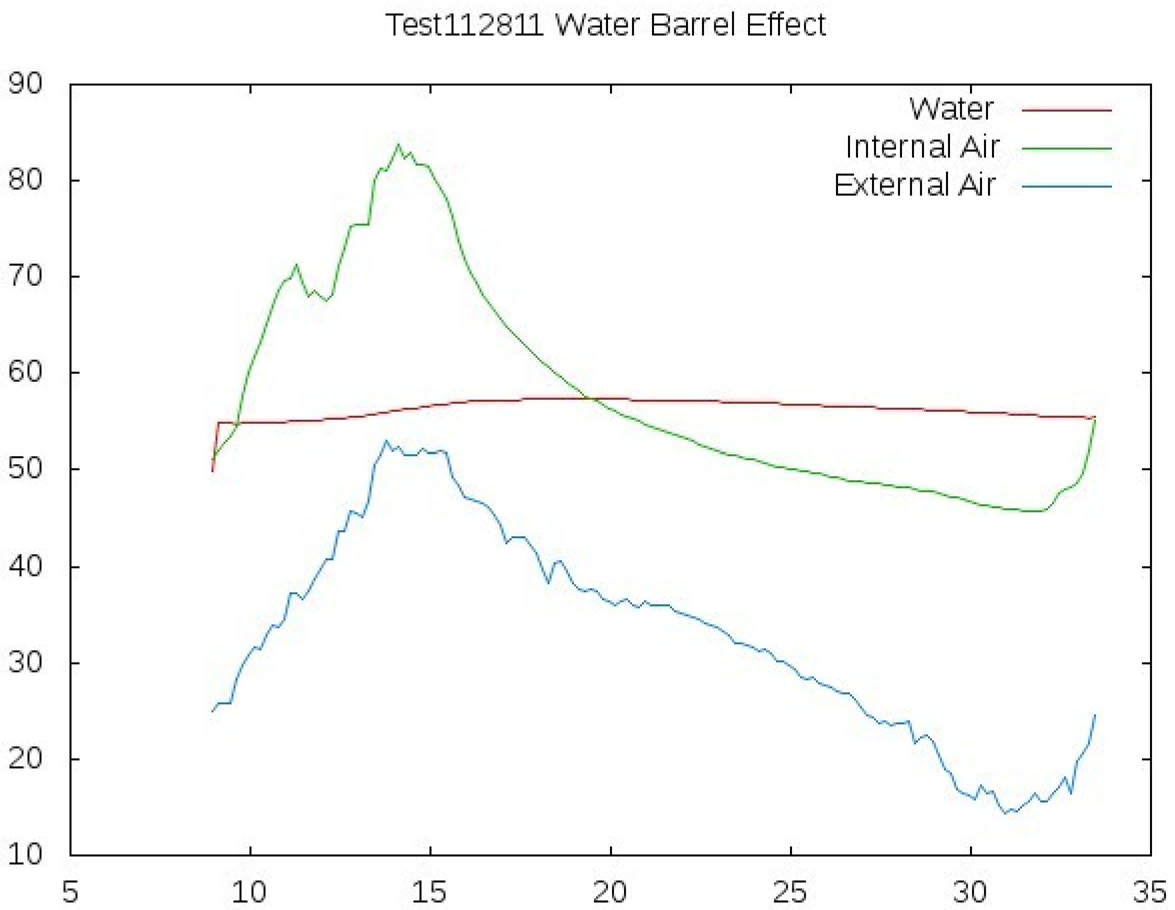
$$\rho_a C_a V_a \frac{dT}{dt} = -\frac{A\left(T - T_o\right)}{R} + \frac{A_w\left(T_w - T\right)}{R_w}$$

$$\rho_w C_w V_w \frac{dT_w}{dt} = -\frac{A_w\left(T_w - T\right)}{R_w}$$

Least Squares fit of three parameters to data T, Tw, and To



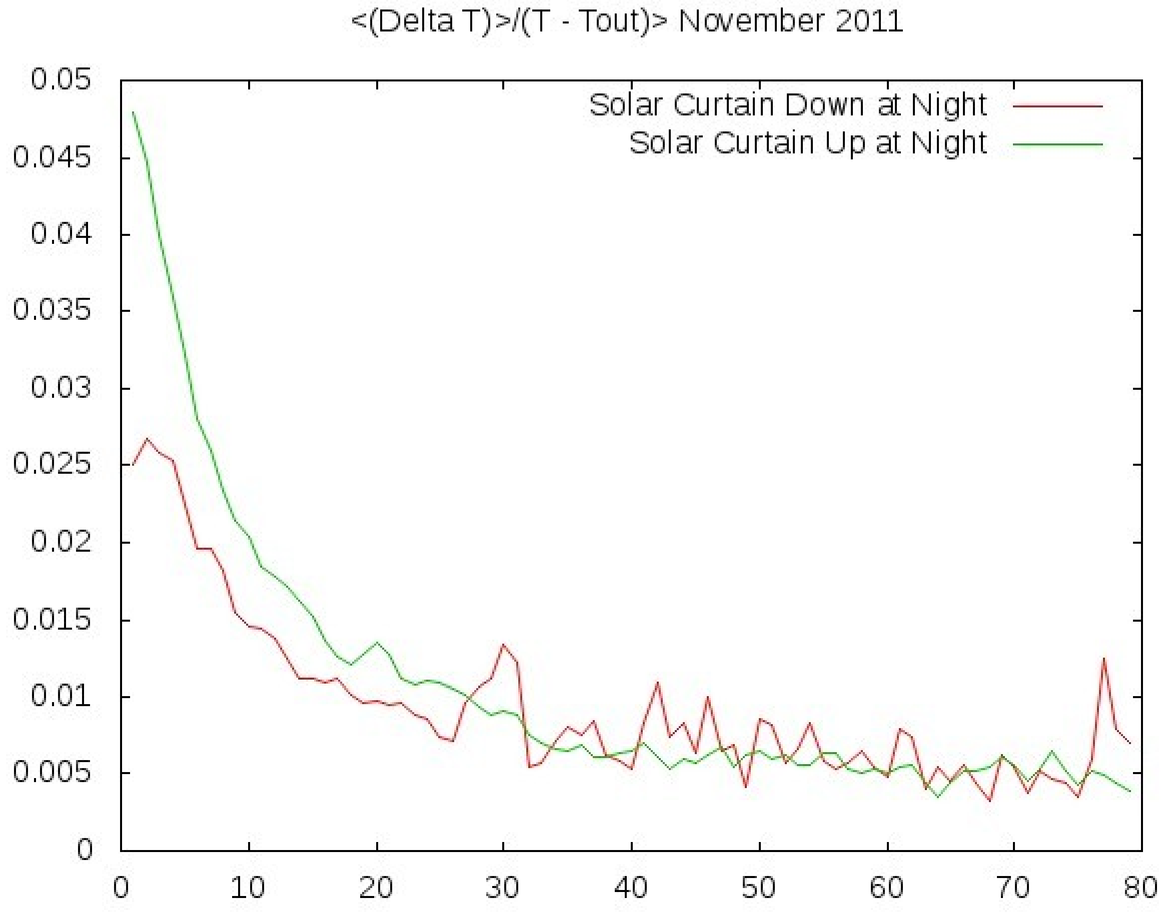
Model predicts 15 deg boost from water barrels



Note similarity between data and model once internal air temp drops below water temp

Solar Curtain

- Despite model predictions and reports of the importance of a solar curtain, I cannot reliably measure an effect.
- LBL windows code: Twin Wall R = 1.83 sqft-hr/Btu
  - Twin Wall with Reflectix R = 5.93 sqft-hr/Btu
- Statistical problem: Only one greenhouse. This means that cannot have a simultaneous control
- Try to overcome this problem by alternating for two weeks nights with curtain down and up.



Models proportionality to thermal conductance
Perhaps convective losses increases through night

Solar Curtain

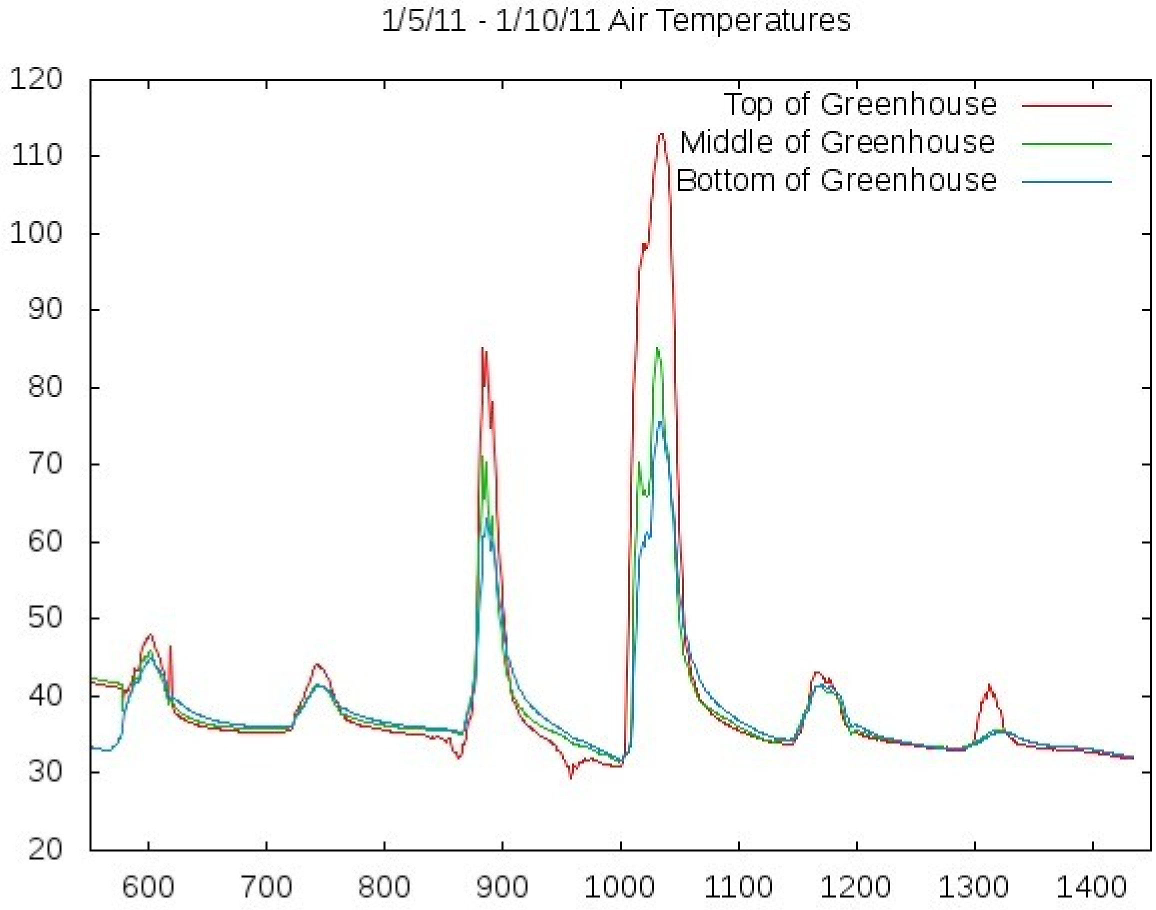
- Took average of dT/(T - Tout)
  - Measure of Greenhouse Thermal Conductivity
- Results indicate that curtain has a significantly lower conductivity early in the night, but after a few hours difference indistinguishable
- Believe the problem is that solar curtain not sealed at edges, creating significant convective losses.
- Problem is to create a seal cheaply
- Chinese & Zhang solar curtain on outside
  - Argon tried by Zhang
- Will try to construct horizontal thermal screen.

Thermosiphon

- Solar Collector sets up small density gradient through temperature gradient
  - Producing fluid flow without fan or pump
- Problem that Reservoir is high in greenhouse where air temperatures are at their peak
  - Ford & Waibel pump this heat through rock bed
- Nelson noting that total solar insolation during the winter is no more than 500 Btu/sqft/Day, while fuel oil provides 100,000 Btu/gal, questions the efficiency of thermosiphon

Why Water & Not Air

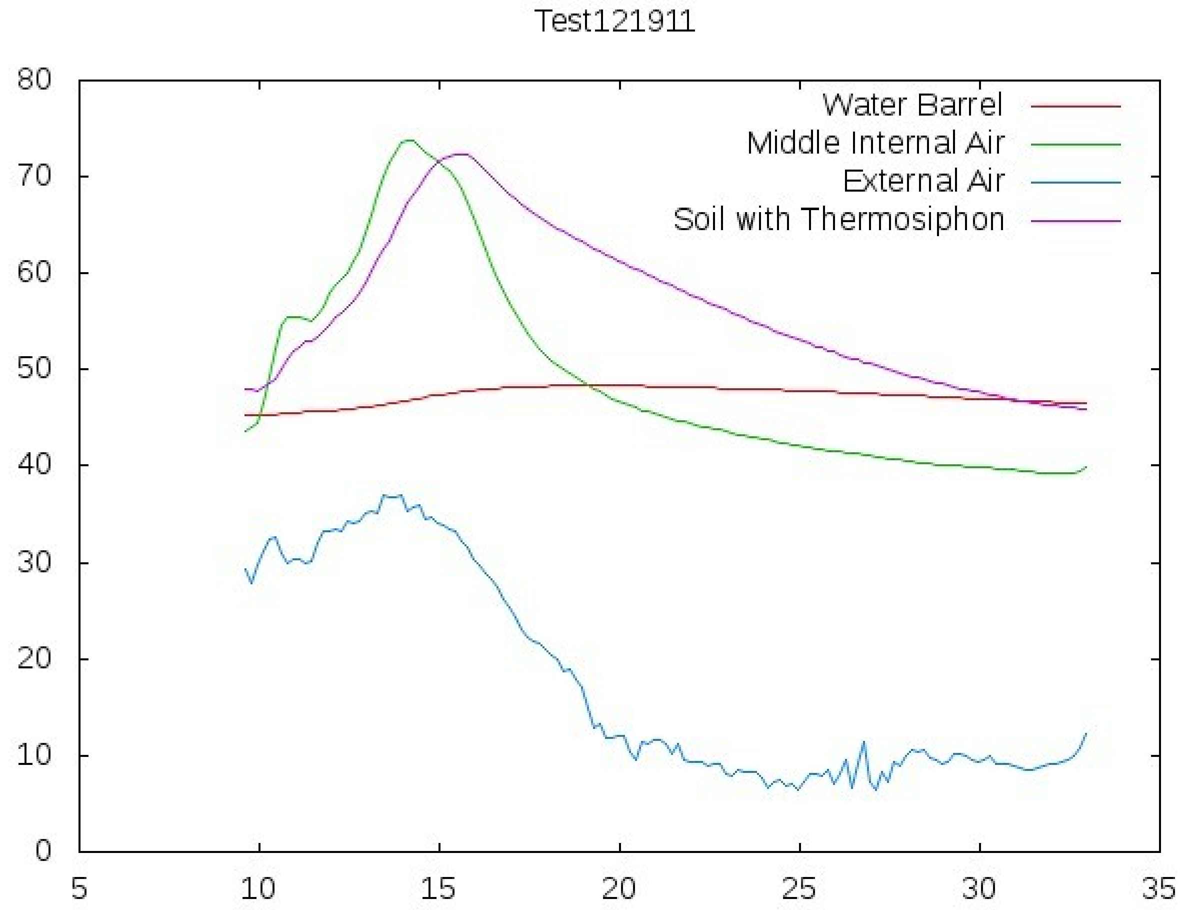
- Specific Heat of Water 4X greater than Air
- Density of Water 1000 times greater than Air
- For same change in temperature 1 cu ft of water can store as much heat as 3400 cu ft of air
    - About two greenhouses of air
- Why there are 16 55-gal barrels of water and not barrels of air
    - But get heat directly into the soil



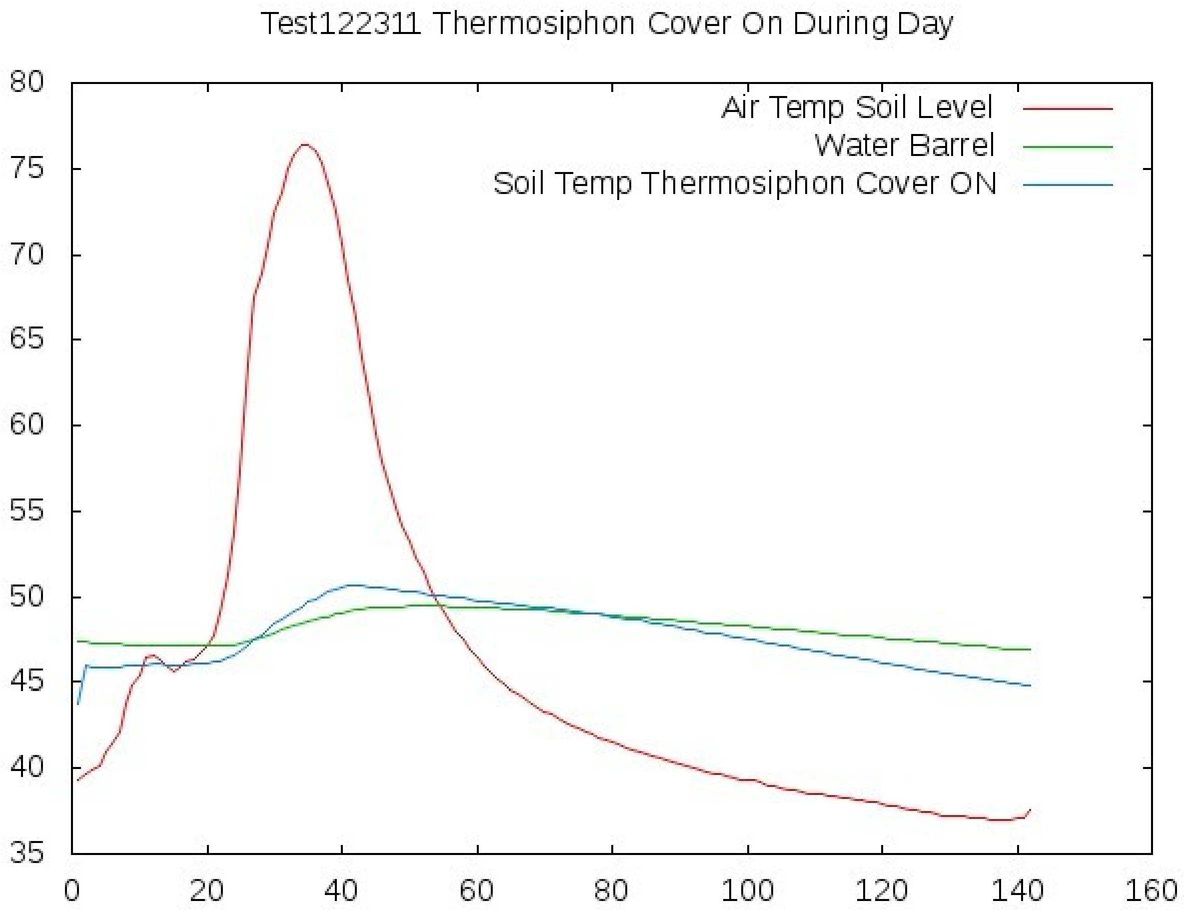
First two & last two days overcast or snowy

Thermosiphon

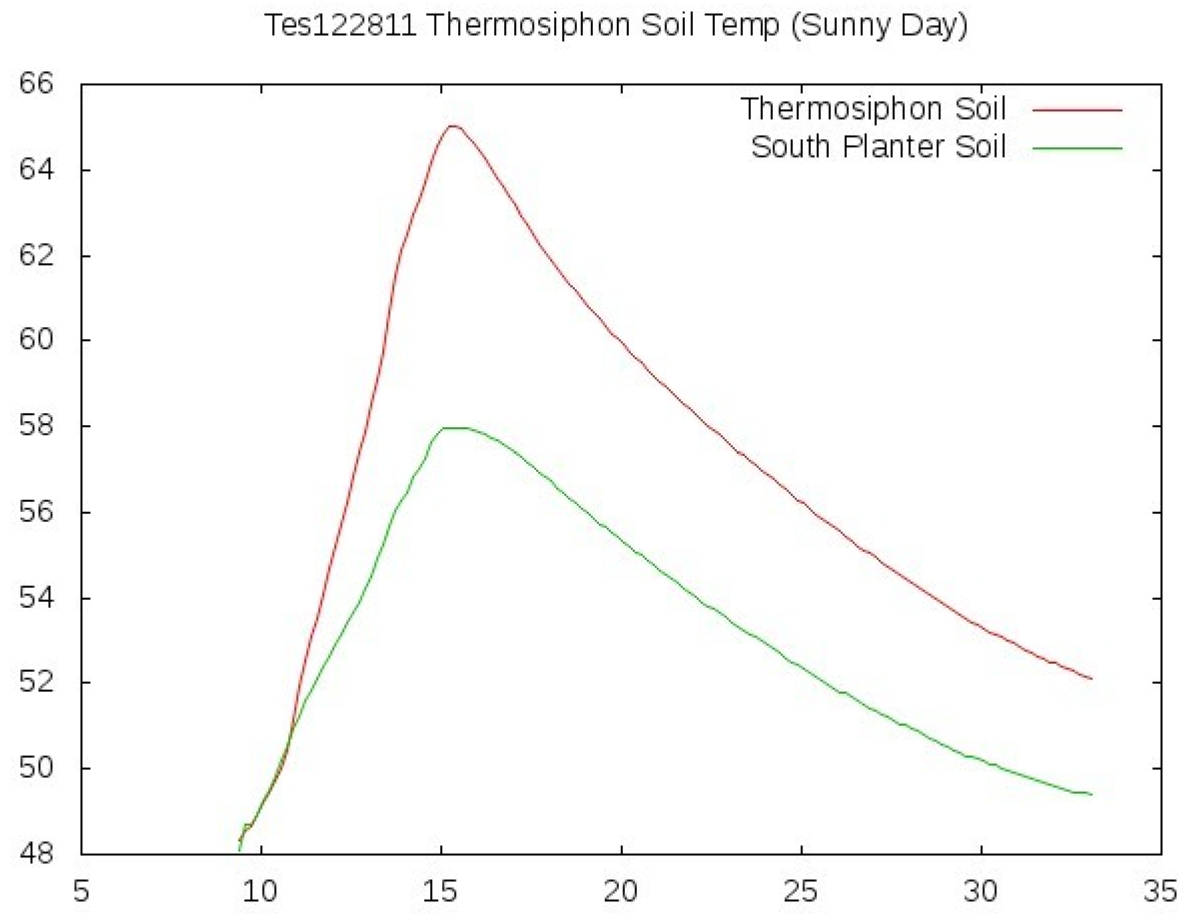
- Dimensions: 18” X 55” - 6.875 sqft
- Three ½ “ copper pipes each 80” long
- North Planter 90” X 15” - 9.375 sqft
  - At 6” depth about 440 lbs soil
  - Solar no more than 500 Btu/sqft/Day in SD January
  - At 65% efficiency about 2235 Btu/Day in soil (Nelson)
  - Specific Heat of Soil = 0.4537 Btu/lb-F
  - Neglecting losses soil temp increases about 11 deg F
- 10 deg F increase in soil temp needs about 0.65 sqft of collector surface to each sqft of soil surface
- Want to verify Thermosiphon is working



Soil Temp with Thermosiphon over 20 degrees higher than water barrel temp, which changes little.



Without solar heating of thermosiphon water, soil temp remains close to water barrel temperature.


Tes122811 Thermosiphon Soil Temp (Sunny Day)
Thermosiphon Soil
South Planter Soil
66
64
62
60
58
56
54
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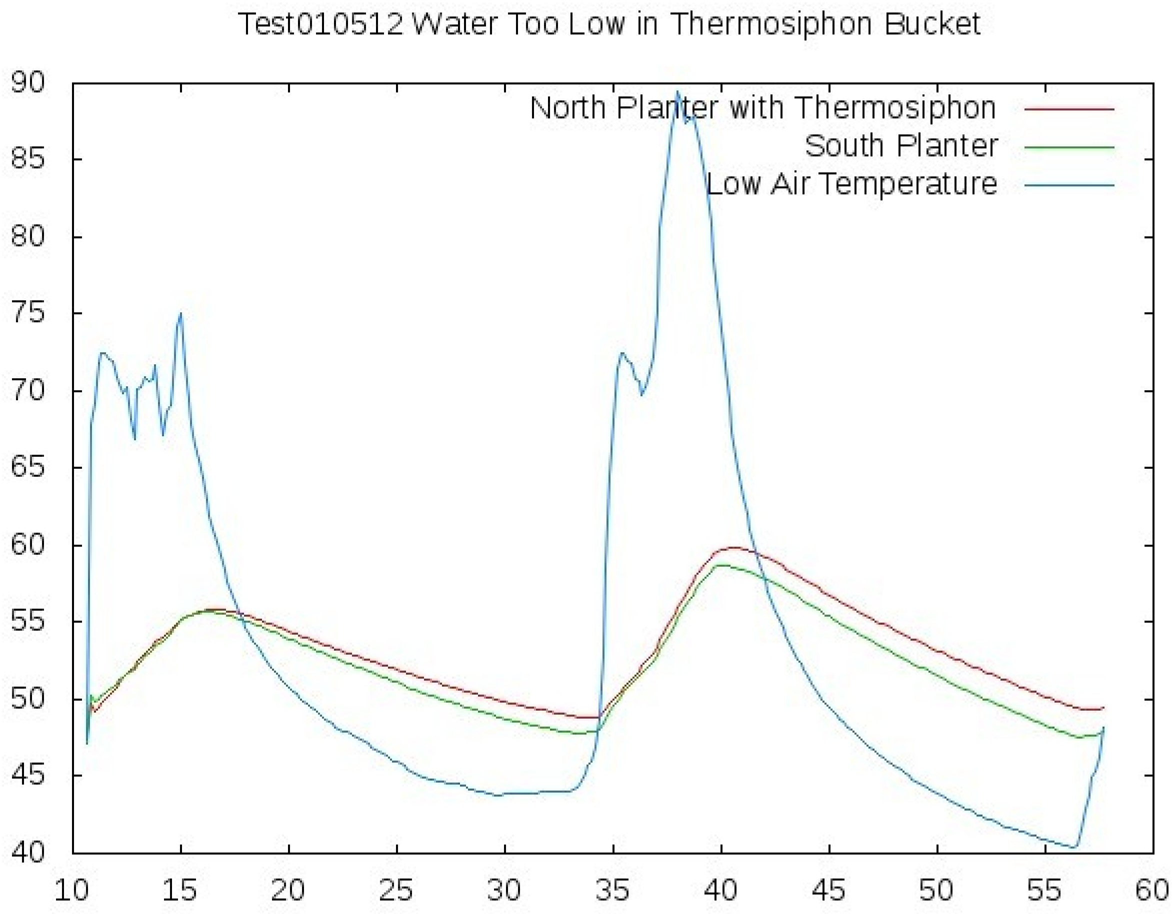
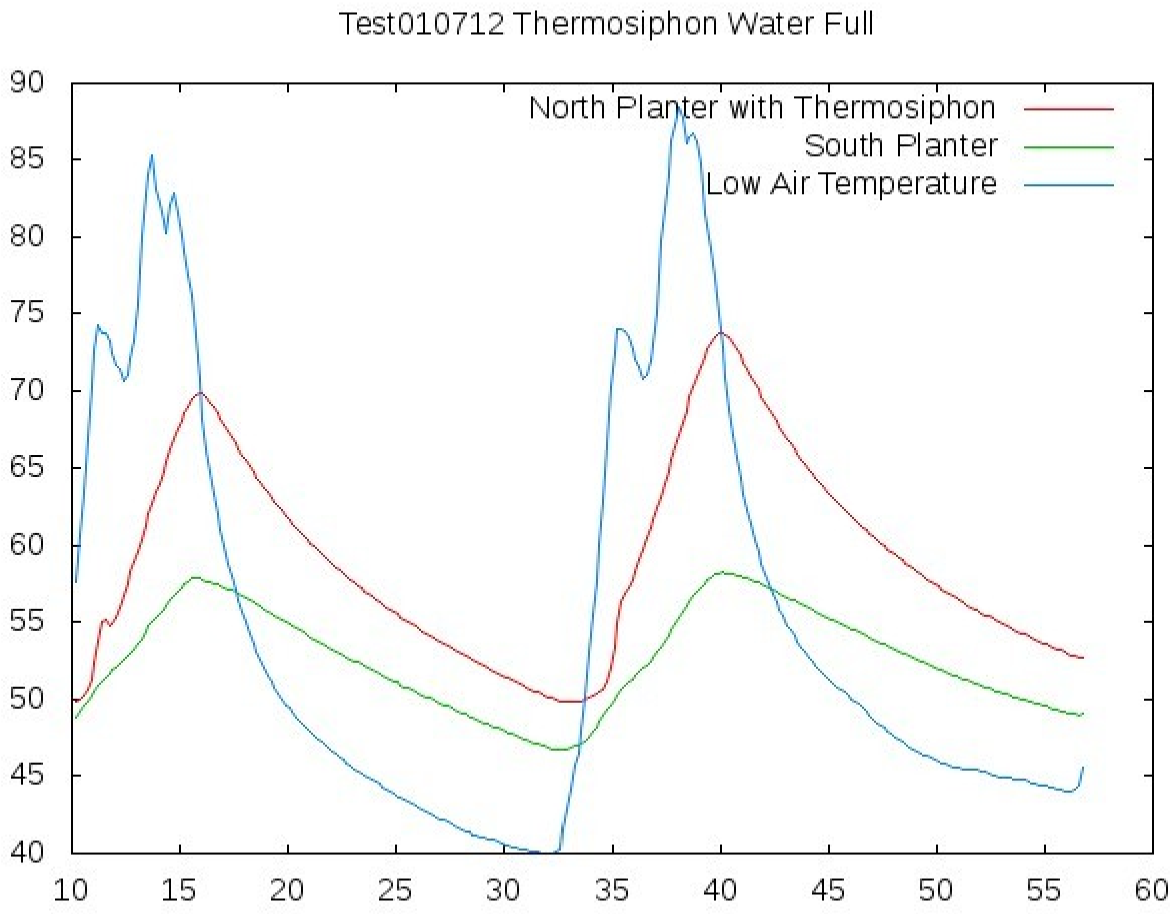
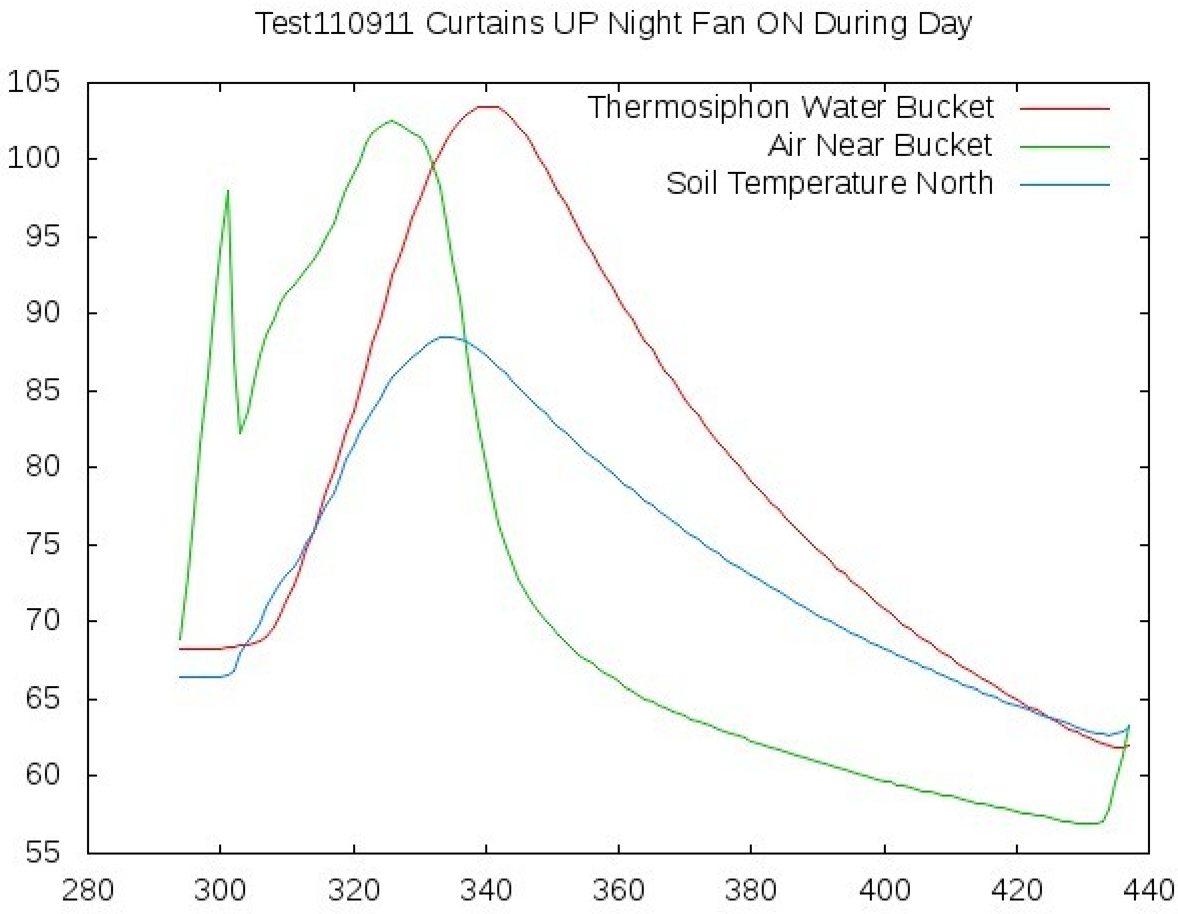
50
48
5
10
15
20
25
30
35



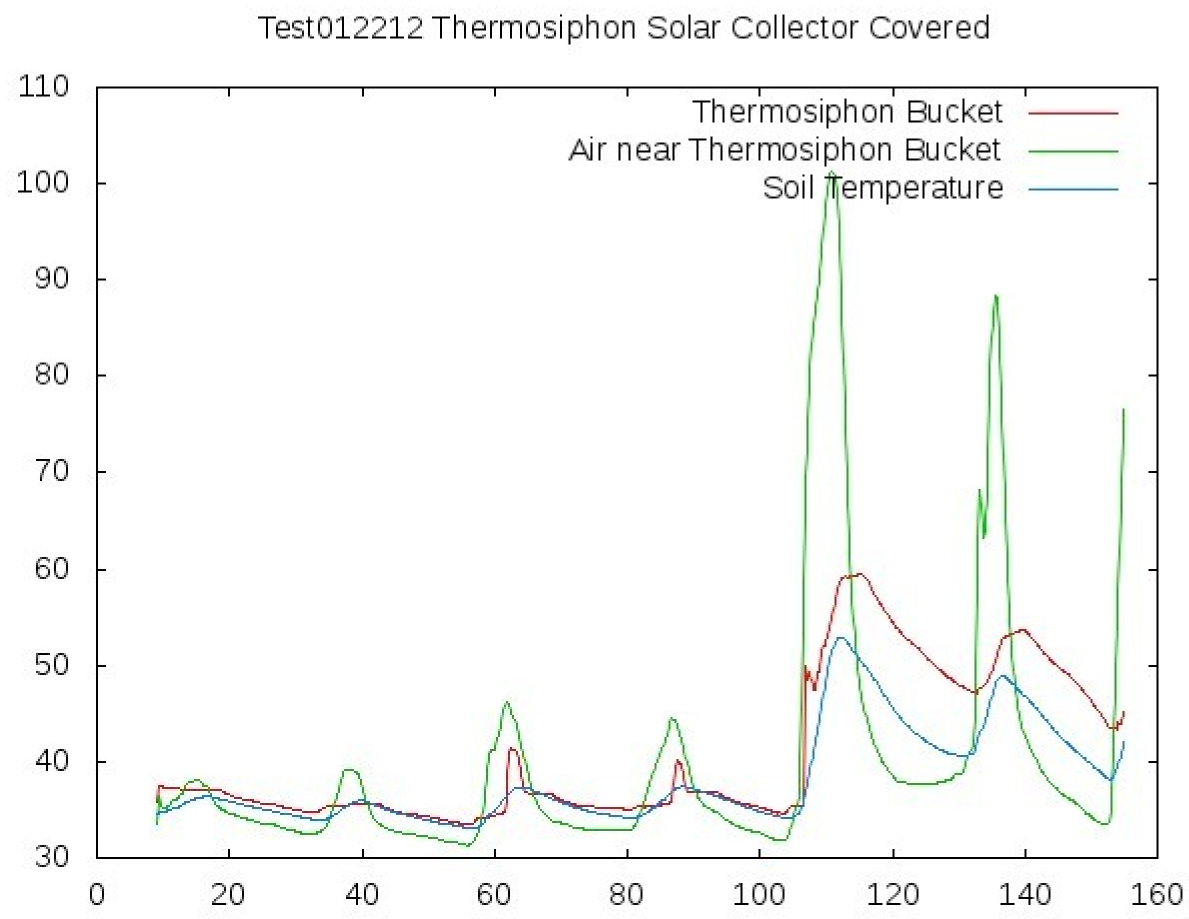
Thermosiphon not working – Note very little difference between North & South planters



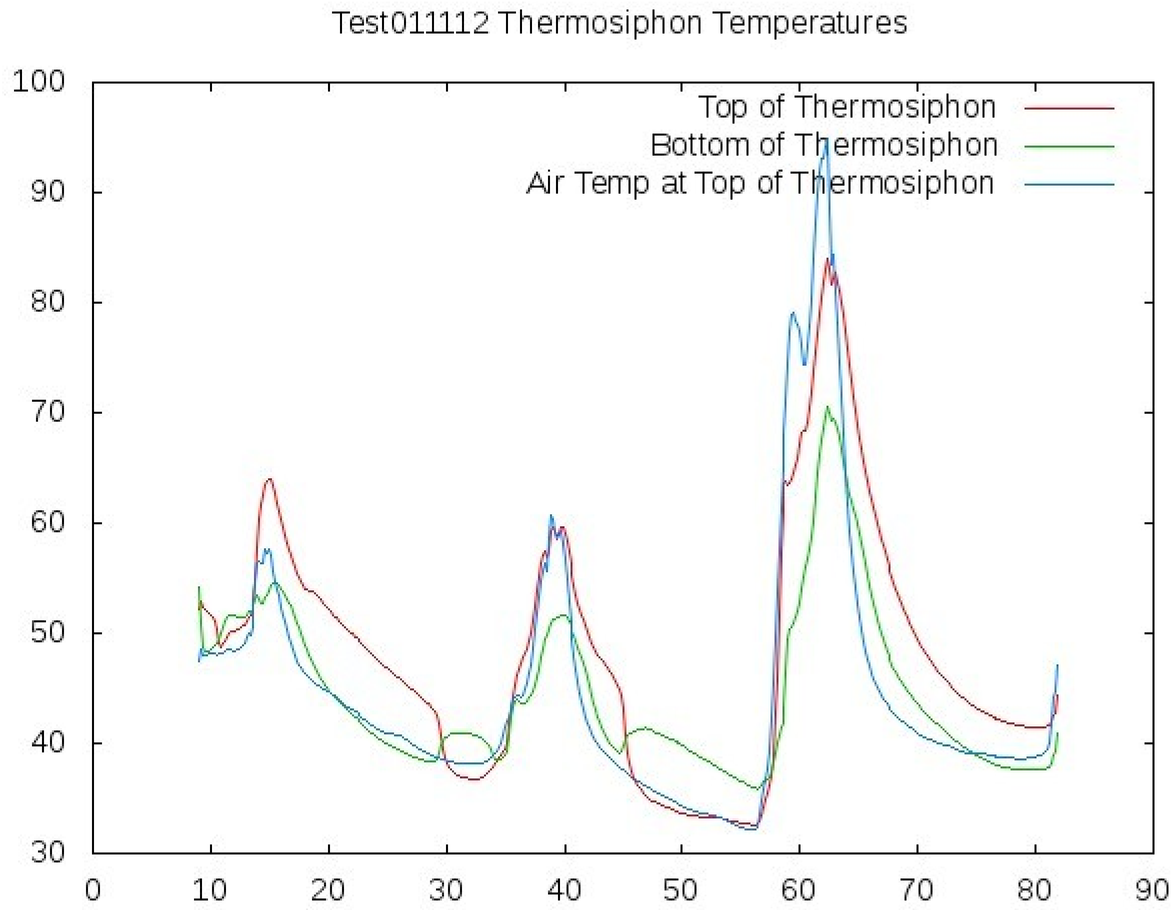
Thermosiphon working – 15 deg peak difference, 4 deg minimum



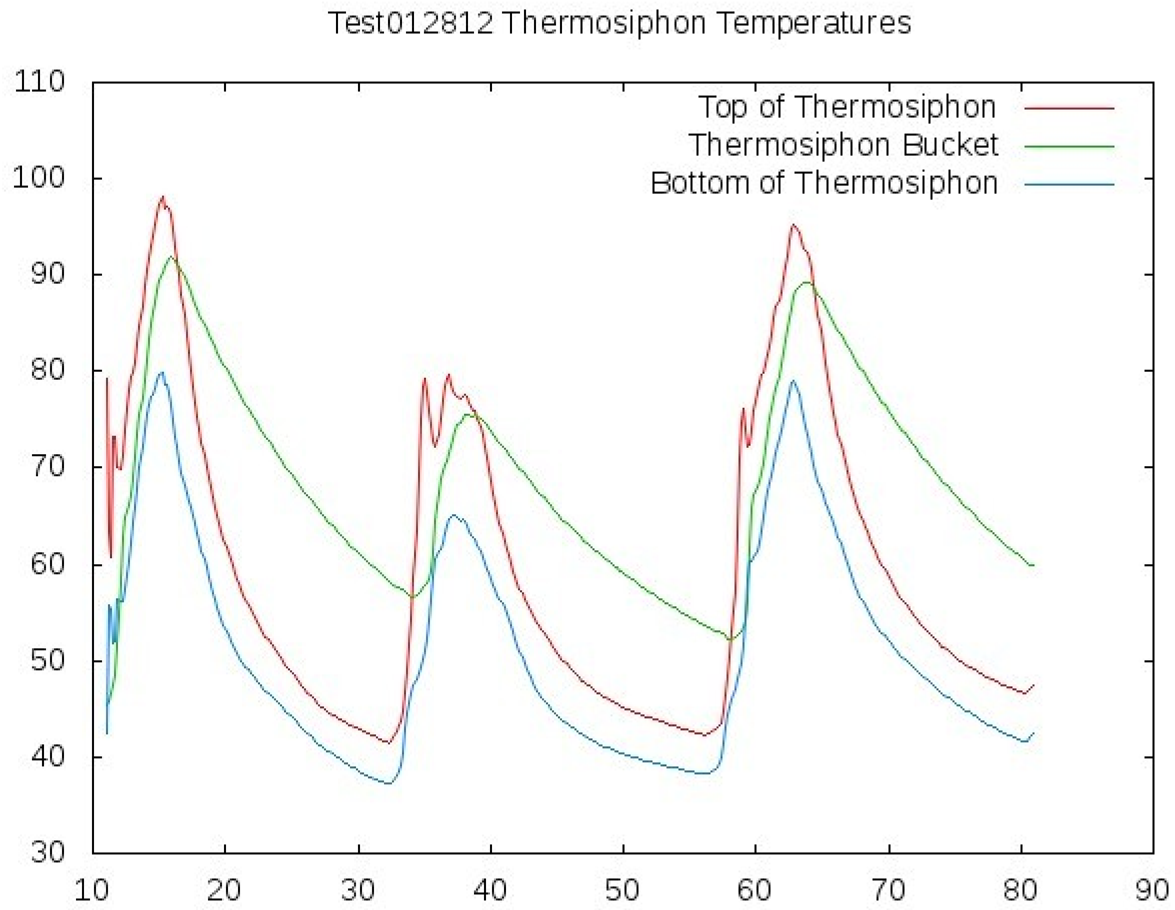
Notice Thermosiphon water bucket temp similar to air temp, with time lag.



Thermosiphon Bucket Temperatures less than air temperatures near Bucket, much less for sunny days, when Solar Collector Covered.



First two days cloudy, last sunny. First day, top temp exceeds air temp; first two days, bottom temp exceeds top late in day; last day, top temp remains above bottom, almost 15 deg difference.
NB: Top Thermosiphon Temp probably < Water Bucket Temp



Top of Thermosiphon Temp > Bucket Temp > Bottom of Thermosiphon

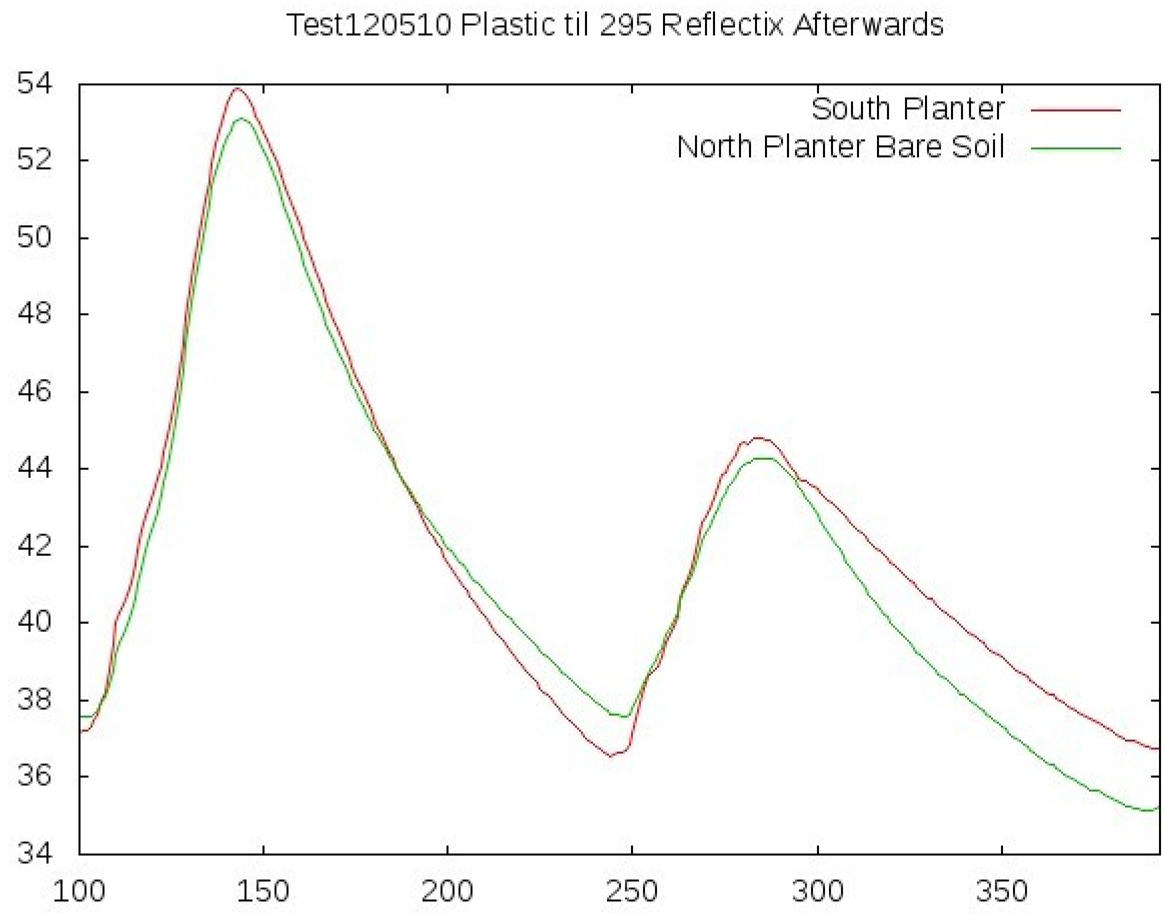
NB: At night Bucket Temp > Top of Thermosiphon

Thermosiphon Working?

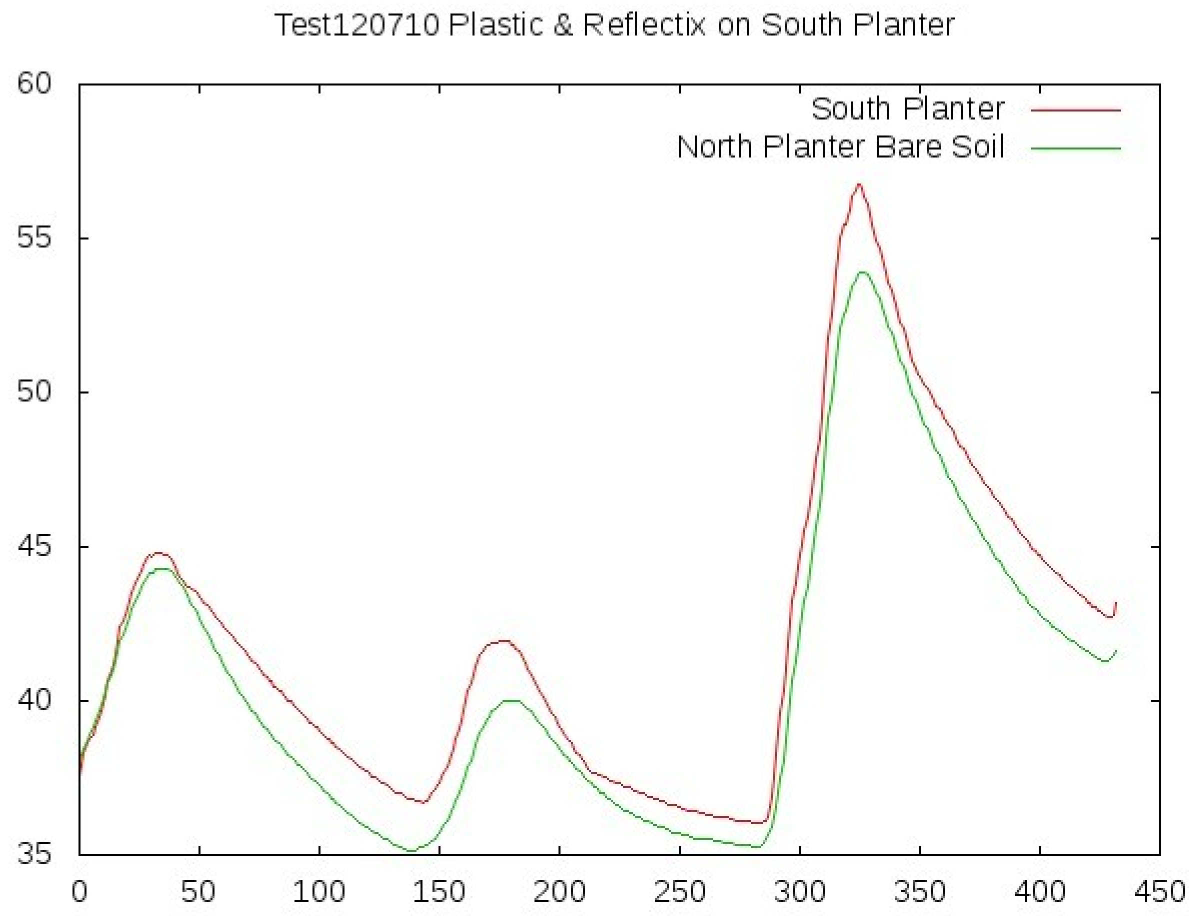
- Thermosiphon soil >> Water barrel
  - Cover on similar
- Thermosiphon soil > 10 deg F warmer
  - Cover on similar
- Thermosiphon water bucket ~ air temp
  - Cover on air temp >> water bucket
- Top Thermosiphon Temp >> Bottom Temp
  - Similar on Cloudy Days
- Top Thermosiphon Temp > Thermosiphon Bucket

Soil Coverings

- Compared two types of coverings
  - Clear plastic
    - High over soil – seems to do little
    - Low over soil – seems to do little
  - Reflectix
    - Low over soil – 2-3 deg boost
    - Low over soil with clear plastic – 3 deg F boost
- Question is whether convection or radiative cooling more important
- Humidity considerations not investigated here

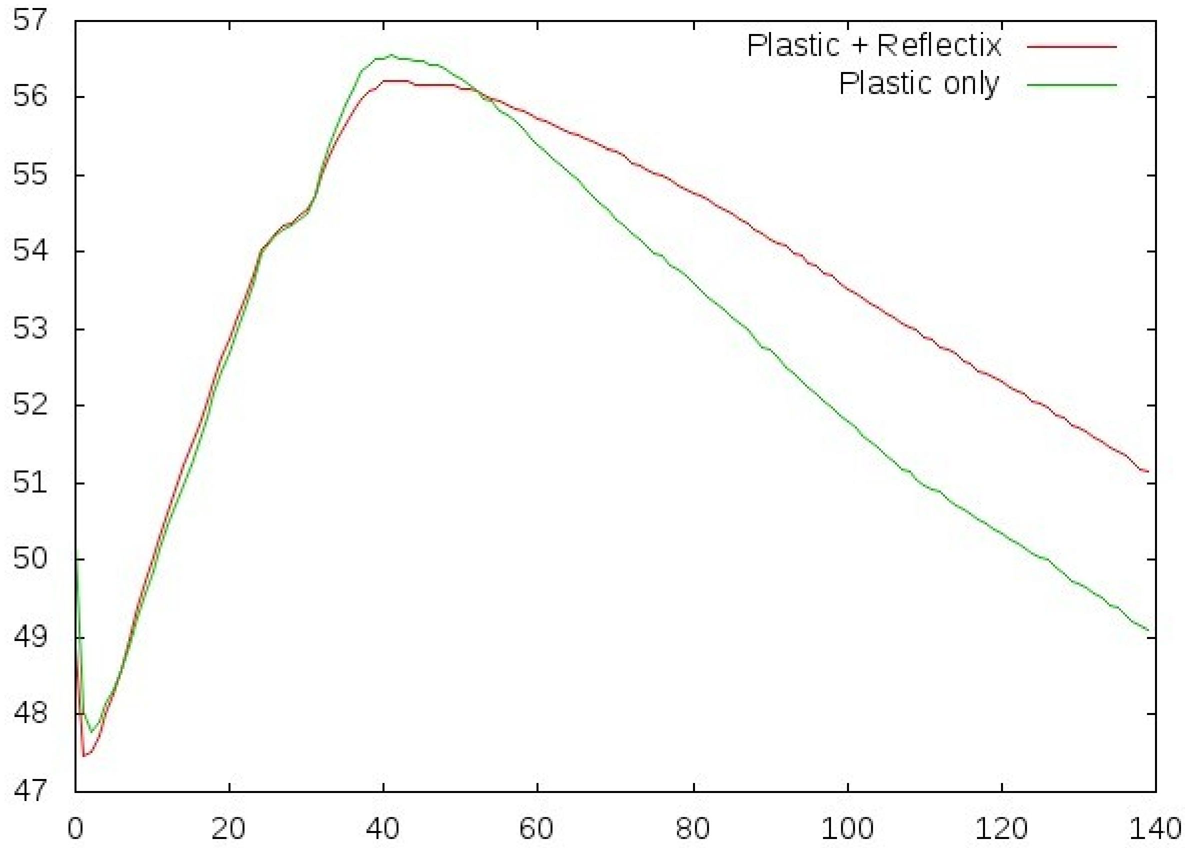


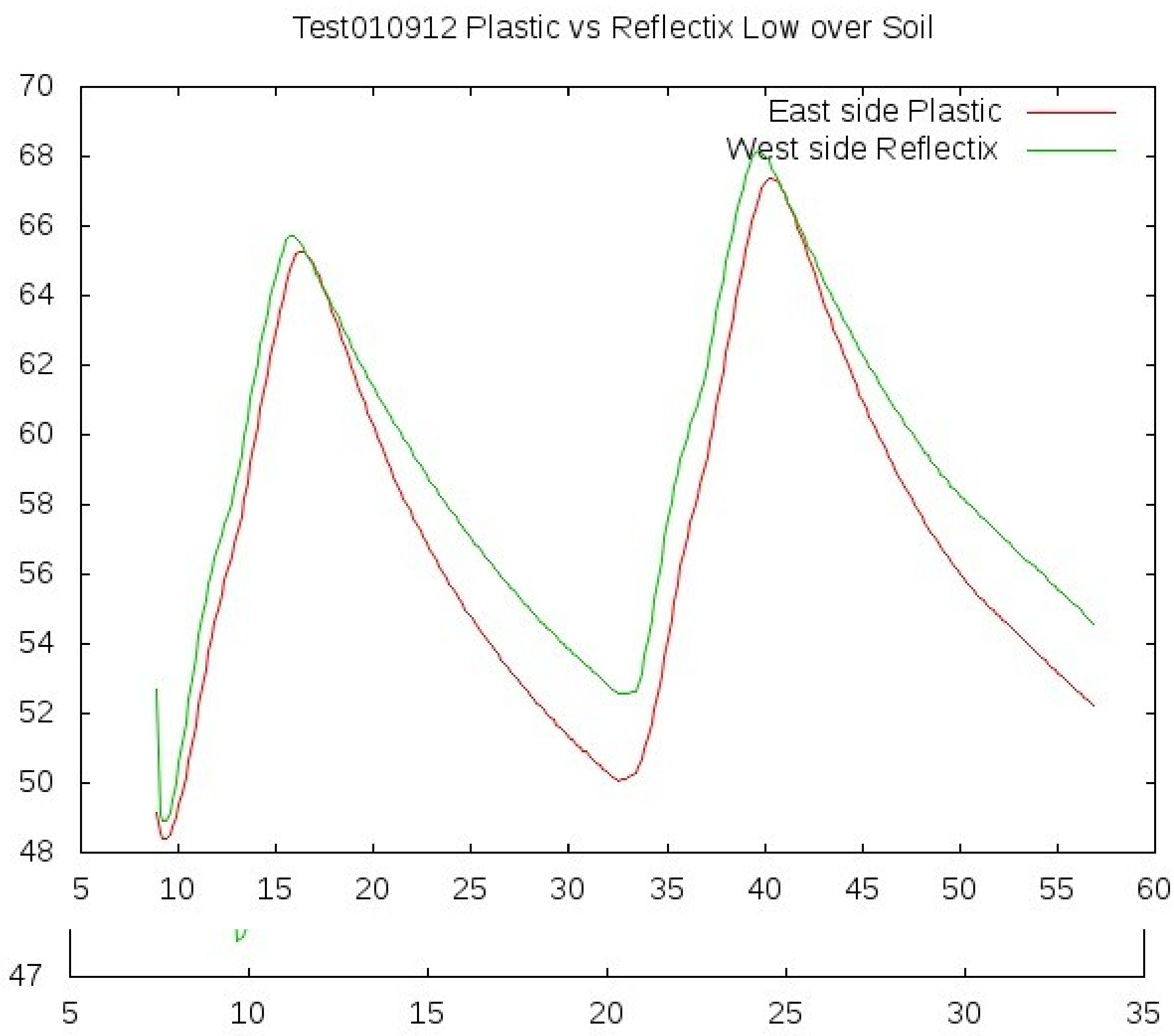
Plastic does little relative to bare ground
Reflectix gives about a 3 degree boost



Kinks in south planter soil temp due to covering with Reflectix

Test122611 High Plastic vs High Plastic + Low Reflectix

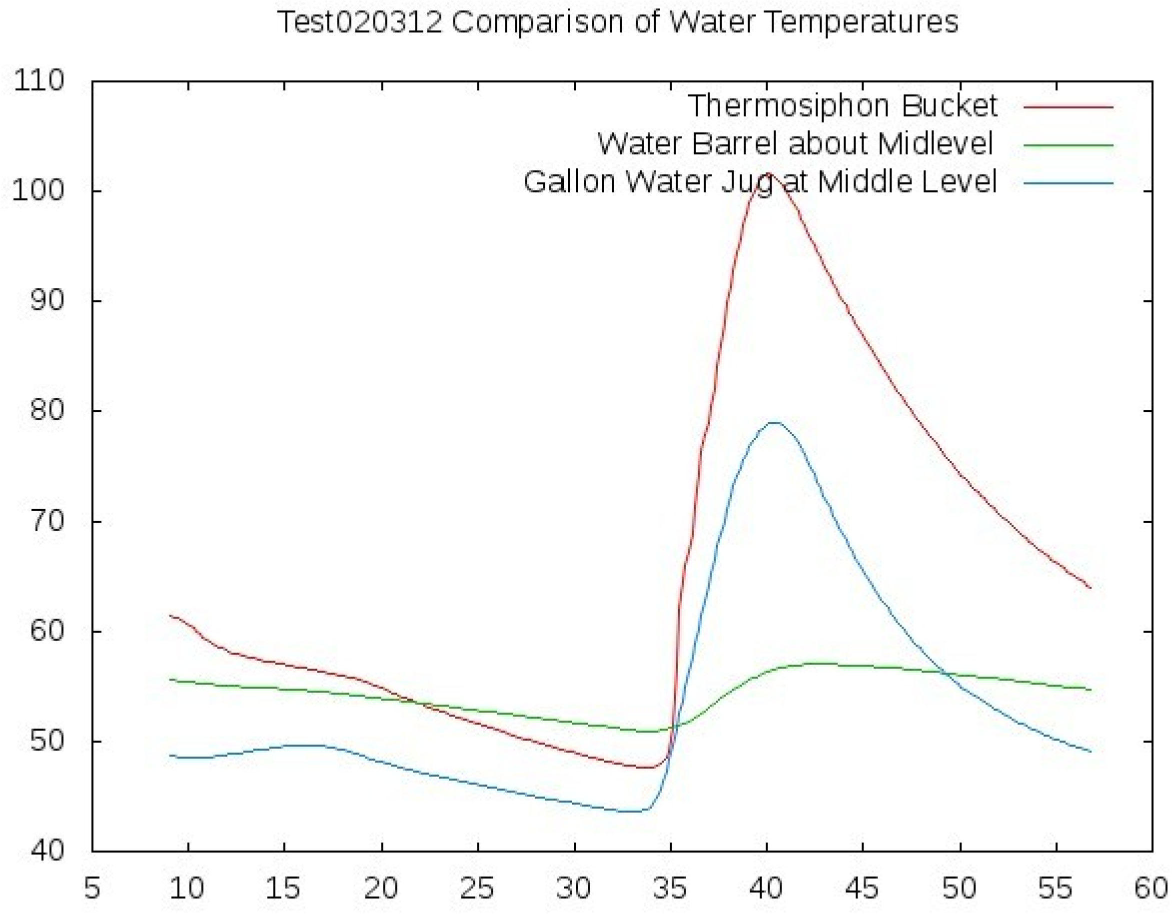




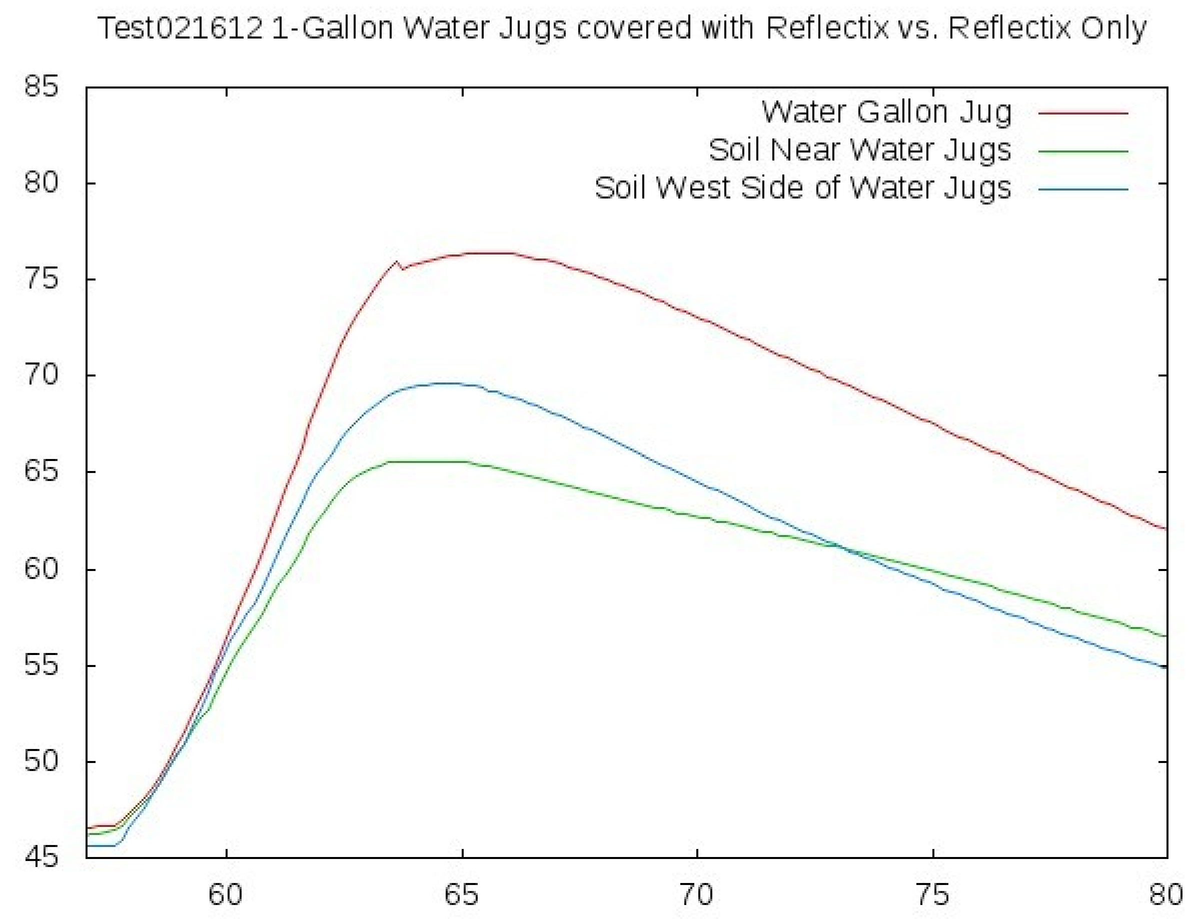
Even when low over soil, Reflectix provides a 3 degree boost with smaller conduction and radiation losses

Increasing Surface to Volume Ratio

- Increasing the surface to volume ratio of water containers will increase the heat gain and heat loss per unit volume
    - Ratio of Heat Exchange per unit volume approximately equal to the ratio of surface to volume ratios
- 55-gallon barrel about 3 deg F temp swing
- 1-gallon jug about 30 deg F temp swing



Gallon Water Jug gains and loses much more heat energy than 55-gal Barrels. Surface to Volume ratio 5 times greater for Gallon Water Jug, which is about the increase in heat exchange per unit volume.



Soil near 4 1-gallon jugs covered by Reflectix at night exhibits 9 deg F drop over night; Soil covered by Reflectix shows 15 deg F drop over night.

Future Work

- 3D modeling with Elmer
- Improve Solar Curtain and validate
  - Horizontal curtain that contains water barrels
  - Challenge is to do it cheaply
- Large scale thermosiphon systems
- Need horticultural work on temperature dependence of winter greens
  - Root zone heating more critical than air temp
  - Air Temp 50 F no effect upon growth (Zhang)
  - Air Temp of 48 F & soil temp 74 adequate for winter greens (Diver)

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