Phase I Final Report

Practical Green Greenhouse Development

A Joint Research and Development Project of

Synergistic Building Technologies

and

Cure Organic Farm

February 2011

SBT TR 11-601 **February 2011**

Phase I Final Report

Practical Green Greenhouse Development

By

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Prepared by

Synergistic Building Technologies
Cure Organic Farm

Prepared for

The Colorado Department of Agriculture

Under the Advancing Colorado's Renewable Energy (ACRE) Program

N.B. All readers of this final report are welcome to comment on its form and content. Please direct feedback to Larry Kinney, Project Director, at LarryK@SynergisticBT.com or at the address and phone below.

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Acknowledgement

A number of people have contributed substantially to this research project. Most have been paid very little or nothing, yet all have retained great enthusiasm for the endeavor. They donated their time and energy because they shared the vision that it is possible to build and operate greenhouses that produce well all year around while using but little fossil fuel.

Key contributors include “Farmer John” Ellis whose expertise in operating a range of farm equipment to accomplish tasks not likely to have been envisioned by its designers is unparalleled; Mark Jackson, a man who can construct almost anything and fix the rest; Larry Meeks and his talented crew members, who installed two tons of cellulose blown to high density in a single day; Michael Brame and Matt Graham, fearless roofers who made sure the roofs didn’t leak water but did reflect sunlight; Derek Lindberg and Todd Bergeson who designed and tweaked much of the electronics; Marco Chung-Shu who provided abundant practical wisdom on moving hot, moist air from the top of the greenhouse to the soil under the plants; Bryan Bowen and Brian Crawford of Bryan Bowen Architects who provided expert architecture services for a decidedly unique building; and Gary Cler, delightful friend and devoted colleague, who provided a variety of mechanical engineering services to the project involving the shutters and most other systems. We mourn Gary’s premature death of October 2010.

Dr. Marc Plinke, a skilled engineer and businessman, also became infected with the vision of a giant leap forward in greenhouse design. So he rolled up his sleeves and contributed to every aspect of the design and execution of the research facility. Indeed, Marc has become so involved in the mission that he accepted the thankless task of becoming Synergistic Building Technology’s President. This allowed Larry Kinney to become the company’s Chief Technology Officer, a distinct honor and delight.

Dr. Michael R. Stiles, a research physicist with a long-term interest in energy-efficient buildings in general and with earth-coupled structures in particular, produced an elegant mathematical analysis of greenhouse thermal responses to thermal mass and fenestration configurations. This will be useful in the design of a host of energy-efficient growing facilities in various climate zones (Appendix A).

Stacy Romero, our project officer at the Colorado Department of Agriculture, has been supportive of our ambitious project from the beginning. He has shared project findings with the Board of Directors of the Department of Agriculture and with many others. His enthusiasm prompted the team to produce a videotape from which all parties learned a great deal.

Most of all, we appreciates the role played by farmer Anne Cure. She has supported the project and provided leadership from the beginning, often when it seemed that the project was more trouble than it was worth. As recent results of energy and growth performance clearly show, we are pleased to find that our efforts were not in vain.

Larry Kinney
Project Director
February, 2011

Executive Summary

Especially in winter, much of the food we eat comes from thousands of miles away, often by airplane. Food destined for such long journeys must be produced and containerized for travel, a process that favors neither excellence of taste nor quality of nutrition. The alternative is to produce food in cold months in greenhouses. Unhappily, most conventional greenhouses require large quantities of energy to keep their soil warm. Thus, oil can be used for flying food over long distances or for keeping inefficient greenhouses from freezing plants. Neither option is sustainable.

Toward seeking a viable solution, this project involved the design, building, instrumentation, and analysis of a 1000 square foot research greenhouse at the Cure Organic Farm in Boulder County, Colorado. It uses a number of principles of building science including heavy perimeter, wall, and roof insulation, automated insulating shutters, high solar heat gain glazing, systems for controlling solar light and heat to maximize growth, plenty of thermal mass, and carefully-controlled ventilation. Only passive solar is used to supply light and heat for the greenhouse.

Seeds planted on Thanksgiving, a month shy of the shortest day of the year, are producing twelve varieties of summer veggies faster than under optimal summertime conditions. Tomatoes whose seeds were planted on Thanksgiving had vines close to three feet high 62 days later.

Sixty five sensors in the research greenhouse and a nearby hoop house of similar footprint and orientation measure solar light, temperature, and humidity. Temperatures have never dropped below 48 F in the research greenhouse even on a night when the outside air temperature dropped to -18F. Air temperatures in the greenhouse averaged 64F in December and January; the high was 92F. Soil temperatures 2.5 inches below grade average 62F and vary less than 5F from the average. The hoop house frequently freezes.

The technology under development can be employed in a range of greenhouses. These include attached units that supply heat—as well as food a few steps from the kitchen—to large commercial units that produce fresh food all year around for customers of local farmers' markets, restaurants, and grocery stores. All sizes can maintain remarkably tiny carbon footprints even without photovoltaics, net zero or better with them.

The research project was funded by the Colorado Department of Agriculture and co-funded by the research team. A report on Phase II of the project will be available by the end of the summer of 2011.

The illustration on the following page is a slide from a recent presentation on the energy future of Boulder, Colorado.

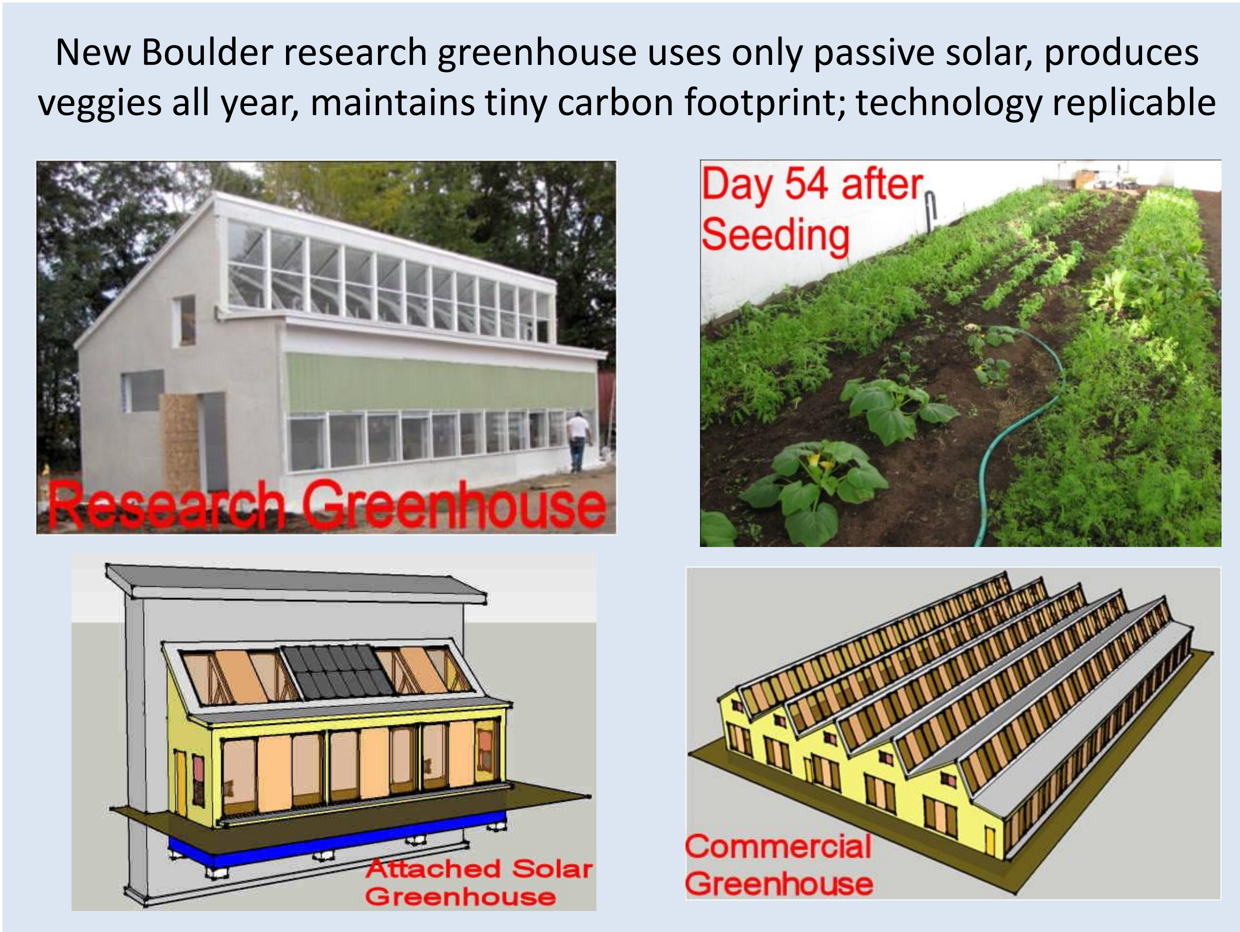


Figure ES-1. Slide from presentation at a Clean Energy “Slam” about Boulder’s energy future, February 3, 2011

Section 1
Introduction

This is a contractually-required final report on Phase I of a Colorado Department of Agriculture-supported research project. The project's aim is to investigate promising strategies and practical techniques for designing, building, operating, and controlling a new class of greenhouses capable of producing food all year around with minimal use of fossil fuel energy. A focus of the project is the design, construction, instrumentation, operation, and study of a 1000 square foot research greenhouse on the Cure Organic Farm in Boulder, Colorado.

The two-phase project was launched by the research team in mid March, 2008; the Phase II Final Report is scheduled to be delivered in August, 2011.

As of the present date, February, 2011, three other main deliverables have been produced on this project. A two-volume Phase I Interim Report (one written, the other in presentational form) was delivered to the Agriculture Department in November, 2009. A Phase II Interim Report focused on controls and modifications of key greenhouse systems was delivered in November, 2010. Finally a 15 minute videotape on the entire research project aimed principally at the Colorado Department of Agriculture's Board of Directors was delivered in December, 2010.

This report covers

- Background of the project and design principles;
- Key findings and accomplishments to date;
- Problems encountered and mitigating circumstances; and
- Next steps

Appendix A uses mathematical modeling to explore the role played by thermal mass and fenestration in the thermal response of greenhouses. Appendix B furnishes an explanation of key technical terms relevant to greenhouse design. Appendix C gives contact info for members of the research team and provides backgrounds on the principal authors of this report.

Feedback on both the form and substance of this report—or indeed the project itself—is most welcome.

Section 2
Background of the Project and Design Principles

Background
Per-capita energy use of non-renewable energy in America is greater than any other nation on earth save for Canada. Every sector contributes to profligate energy use, but the production, transportation, and consumption of food and dealing with associated waste products results in particularly large energy consumption. Especially in winter, much of the food we eat comes from thousands of miles away, not infrequently via airplane. Accordingly, the food destined for such long journeys must be produced and containerized for travel, a process that favors neither excellence of taste nor quality of nutrition. Further, a gallon of jet fuel that costs $4 is the energy equivalent of almost two person months of labor.

The alternative is to produce food during cold months in greenhouses. Unhappily, conventional greenhouses require large quantities of non-renewable energy to keep their soil and air temperatures sufficiently warm for food production. Short days in midwinter make the production of all but the heartiest of vegetables in conventional greenhouses virtually impossible even if they are warmed by furnaces or boilers.

In brief, oil can be used for flying food over long distances or for keeping inefficient greenhouses from freezing plants. Neither option is consistent with long-term sustainability.

Saving follows waste. This generalization is virtually without exception, and certainly applies to the dilemma of food production and transportation. Indeed, opportunities for limiting waste are multifold. No doubt, many involve improving the efficiency of transporting and storing food. But in the pages which follow, we concentrate on opportunities for designing and operating more efficient greenhouses whose use of non-renewable sources of energy is quite modest, but whose capabilities for supporting plant growth quite robust.

Design principles
Building energy-efficient greenhouses is very much a matter of detail. But there are some key design principles the team has developed that we have found to be useful in informing details of the process.

- Keep the time constant of the building as high as practical;
- Insulate, insulate, insulate;
- Integrate as much thermal mass into the conditioned envelope as practical;
- Control the flow of solar flux, both light and heat; and
- Control the temperature and flow of air

Each of these points is discussed below.

Time constant

In winter, if a building that has been heated during the day turns off its heating system at night (when there is no solar gain), the temperature inside the building begins to drift downward. The amount of time it takes to reach 37% of the difference between the indoor air temperature at which the drift was initiated and outdoor air temperature is termed the building's "time constant." The time constant is the product of the building's overall R-value and its thermal mass (t = RC). Well insulated and air-sealed buildings with lots of thermal mass have long time constants so drift in temperature slowly even on cold winter nights. Poorly insulated structures with modest thermal mass have short time constants, so drift rapidly in the absence of heat. Examples of structures of short time constants include older mobile homes and conventional greenhouses. An example of a structure with a long time constant is the research greenhouse built under this project. Figure 2-1 shows a snapshot of the 24 hour period of the shortest day of the year, the winter solstice of 2010.

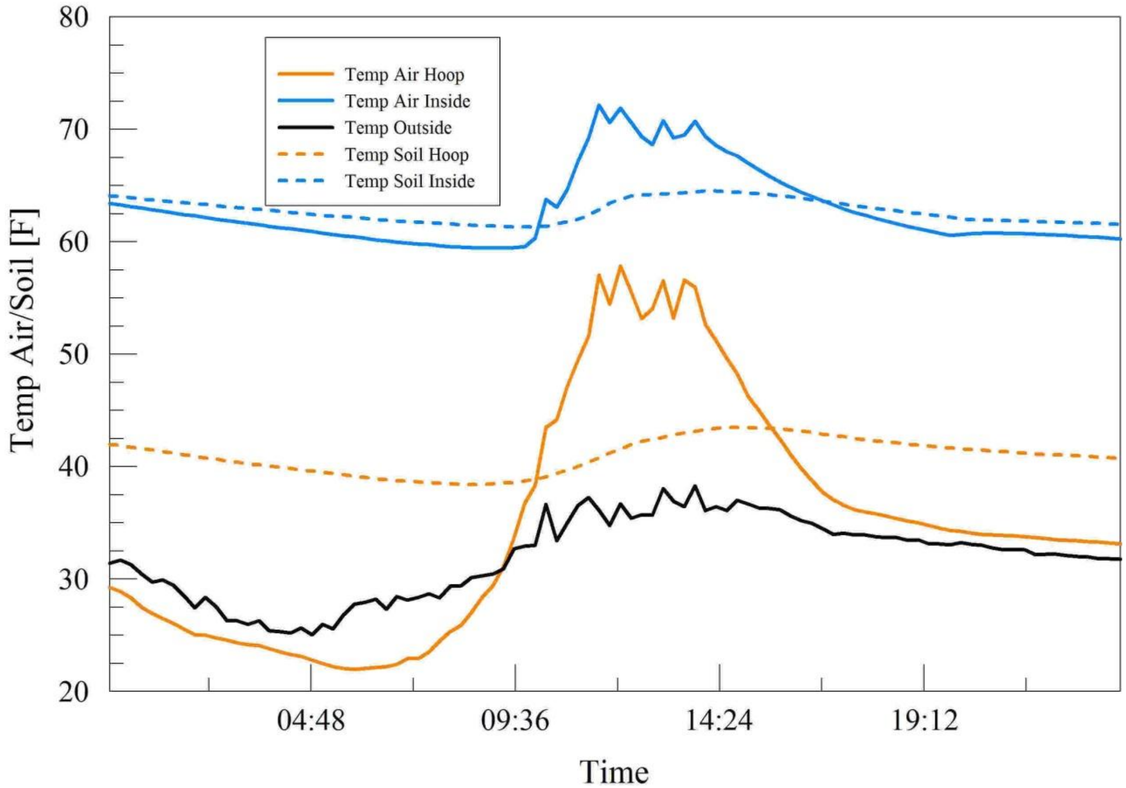


Figure 2-1. Plot of outside air temperatures versus ground and air temperatures in the research greenhouse and a nearby hoop house on December 21, 2010.

The data plotted on the graph come from three HOBO data loggers which were set to measure temperature at 15 minute intervals. Only solar heat was a source of energy gain. Note that the outdoor temperature (black curve) was at 31F at midnight, dropped to a low of 25F in the early morning hours, went to a peak of 38F in the middle of the day, and was back down to 32F at the next midnight. This pattern of outside air temperatures, a diurnal (24 hour) swing of only 13 degrees, is characteristic of a partly cloudy and relatively mild day for this time of year.

Meanwhile, the hoop house began at 29F, dipped to 22F in the early morning, rose to 58F for a few hours in mid day, then descended to 34 by the next midnight, a diurnal swing of 36F. Meanwhile, the research greenhouse began at 63F at midnight, descended gently to 60F nine hours later, then gradually climbed to 72F in the middle of the day and back to 60F at midnight, a swing of 12F. Note that the soil temperatures of the research greenhouse varied 3F over the 24 hour period, averaging 63F while hoop house soil temperature varied only 4F over the period but averaged 41F. (In both cases, the temperature sensors are about 2.5 inches under the surface of the soil.)

Particularly in a climate such at Colorado's that often features clear skies (and thereby substantial nighttime radiant cooling as well as useful daytime solar heating), there are several key advantages of buildings with long time constants. First, they drift downward at night sufficiently slowly that they are very unlikely to approach freezing. Second, they are less prone to overheat on sunny days. In short, a building with a long time constant is more like a ride in a Lincoln than in a heavy-duty work truck. Most important, plants seem pleased and respond by growing quickly.

The key question thus becomes how to build greenhouses which have a long time constant. The answer is to insulate, air seal, and include lots of thermal mass.

Insulation

Glass is a poor thermal insulator, as is clear plastic. Yet both allow radiant heat transfer of solar flux, in the form of both light and heat. Consequently, conventional greenhouse designs use a lot of glass or plastic in both walls and ceilings, the aim being to support photosynthesis. But in the middle of winter when days are at the most 10 hours long and nights 14, these unprotected surfaces allow a great deal radiant heat transfer to clear cold skies. Accordingly, auxiliary heat must be used to keep plants from freezing (yet it too is rapidly lost through radiation to the night sky.)

Toward dealing with this problem, the window industry has developed a number of techniques for lowering window heat loss. Examples include using multiple layers of glazing to provide more dead air spaces, employing thin coatings or films that diminish radiant emissions in the mid to far infrared (Low E and other selective coatings), and replacing air between glazings with inert gases. Each of these techniques helps to lower the heat transfer of glazing (its U value, measured as Btu/hr sq ft deg F of indoor/outdoor temperature difference.) But each also diminishes both the visual transmittance (Vt, the portion of available light that is transmitted rather than reflected or absorbed) and the solar heat gain coefficient (SHGC, the net portion of solar radiation—UV, visible, and IR—that is transmitted rather than reflected or absorbed). Further, insulated glazing units with particularly low U values are substantially more expensive than are simpler glazing systems. (Appendix B explains these terms in more detail.)

Since it is critically important to get sunlight on plants, this trade-off of U value versus Vt and SHGC is usually settled on the side of Vt and SHGC. So U-values are high (and the inverse, R-values are low) and nighttime energy losses are substantial. The greater the glazing area, the greater the losses…

In the light of these problems, the strategy our team has developed is as follows:

- Keep the glazing area as small as possible consistent with ensuring plants have plenty of light falling on them and the surrounding earth to ensure proper growth and to provide adequate solar energy to meet the thermal needs of the facility.

- Use moveable insulation that automatically insulates all glazed areas when solar light availability is low and energy losses exceed gains.

- Use inexpensive glazing that has high Vt and SHGC. In addition, maximize light and heat gathered by windows with highly-reflective light shelves or roofing materials in front of south-facing glazing. (This also enhances light gathered from the sun in earlier and later portions of the day while reducing the glazed area required to meet plant growth and thermal needs.) Also ensure that interior surfaces (other than the earth and plants) are reflective so that as much solar light as possible ends up being absorbed by plants themselves or areas that promote growth. (The glazed area of the research greenhouse is 474 square feet, 47% of the nominal footprint of the 1000 square foot structure, 20% of its insulated wall and ceiling area. These numbers are substantially lower than conventional wisdom holds are minimums, yet the research greenhouse produces extraordinary growth rates of summer veggies in mid winter.)

- Make sure that all non-glazed surfaces of the greenhouse's thermal envelop are well insulated, R-20 or more. (The walls and ceilings of the research greenhouse average R-35).

Thermal mass

Deep earth temperatures tend to be the average of annual temperatures while the surface temperature tracks within a few degrees of the ambient temperature. Unless the soil at a building site is exceptionally conductive (usually due to high moisture content), at only four feet under ground, annual fluctuations in temperature are usually less than 8 degrees F from the annual mean. The deep earth temperature is about 51F to the east of the front-range mountains in Boulder County. Accordingly, installing insulation around the perimeter of a building between wall insulation and four feet below grade effectively ***couples*** the structure to deep earth beneath the footprint of the structure. Equally important, it ***decouples*** the structure from the surface of the earth immediately surrounding the structure, thereby isolating the building from soil whose temperatures vary substantially from season to season. The net result is that a thermal bubble builds up under the structure that if left alone may approach 60 F in the second year of the operation of a greenhouse. This contributes enormously to the thermal mass of the structure, smoothing out the extreme effects of both cold nights and hot days and extending the time constant. As of January 30, 2011, the temperature at 4 feet under the soil or the research greenhouse averaged 60F, while that outside the greenhouse at 4 feet averaged 51F.

Concrete is energy intensive in its manufacture, but it has structural and thermal properties that make it attractive for use as thermal mass. It weighs 144 pounds per cubic foot, has a specific heat of 0.2 Btu/lb/F and can carry enormous loads in compression. In our case, the sting of energy intensity is mitigated to a significant degree because companies that provide concrete in mixers to construction sites have a need to dump any residue from the day's work in order to leave their machines clean for the following day. Thus, they routinely fill up forms that make blocks designed for forming walls and barriers (Figures 2-2 and 2-3).

Figure 2-2. Stacked blocks form retaining wall. The rebar hook in the top middle enables manipulating blocks with a back hoe or similar farm tool.

Figure 2-3. Foundation and north wall of research greenhouse.

As it works out, Boulder Ready Mix, which is only two miles from the construction site of the R&D Greenhouse, sold us 2 x 2 x 6 foot blocks for $10 apiece (346 pounds per dollar!) Accordingly, a total of 84 of these blocks were integrated into the foundation and the north wall. In both cases, heavy rigid insulation was used outside of this mass. The result is the ability to store a great deal of thermal energy and increased likelihood of a long lifetime of the structure at modest maintenance expenses.

Controlling Solar Light and Heat

Apollo and Mother Nature dish out a wide variety of weather conditions. Although the past and future positions of Apollo's bright chariot is known to many decimal places and the radiation emitted from its surface is close to constant, what Mother Nature does to the resulting solar flux in the last few miles of its journey to the surface of the earth is substantially less predictable and more variable. In all events, in order to function efficiently, buildings must be designed and operated to respond creatively to the weather of the moment.

In general, greenhouses may be allowed to have temperature excursions of 50 degrees or so, circumstances most people tolerated in their homes and work places until about a century ago. In fact, the research greenhouse routinely has much lower thermal excursions and soil temperatures stay within a few degrees of 65F throughout the winter.

We employ a variety of strategies to control solar flux in the R&D Greenhouse to optimize the environment for photosynthesis and healthy plant growth while controlling thermal losses and gains. These include:

- The aforementioned reflectors in front of the windows, light shelves below and a white roof in front of the vertical windows above.

- Two types of insulating shutters automated to button up the thermal envelope on cold nights enable the use of low-cost glazing that has both high Vt and SHGC. Both shutter systems are equipped with surfaces that are reflective in the visible but highly reflective in the infrared spectrum. When fully open, the swinging shutters in the roof tend to direct light downward to the earth and plants below. Both shutter system s can be manipulated to reflect solar flux back outside to the degree desired. This helps to control for potential overheating in summer. The shutters can also play a key role in expediting a brief mid-winter freeze if necessary for natural pest control by opening at night and closing during the day.

Controlling Air Temperature and Flow

Just as with other buildings built for energy efficiency, greenhouses should be sealed so that air infiltration/exfiltration is low when ventilation is not desired, yet able to be thoroughly ventilated when it is. Vents should be able to be fully opened and tightly closed and they should be located both toward the bottom and top of the greenhouse to take advantage of the buoyancy of warm air. Opening doors and vents at the bottom and top of the greenhouse and at each end promotes natural ventilation from both the wind and from stack effect forces due to temperature gradients between the bottom and top of the envelope.

The aim in the greenhouse is to use as little fan power as possible, but some fan use is essential. Sometimes fan power is necessary on still days to supplement natural ventilation. The R&D Greenhouse is equipped with a ventilation system that includes a fan at one end, vents at both ends, and the medium for a direct evaporative cooling system. We use a 5,000 cubic per minute (cfm) with stainless steel blades and frame whose motor draws 538 watts.

Separating the fan from the evaporative cooling medium allows for more efficient use of the fan for ventilation and flexibility of cooling options. Both the fan and medium employ exterior moveable insulation so they can be effectively inside the insulated envelope during cold months or when ventilation is not needed. This minimizes thermal holes in the insulated envelope and ensures that the water associated with the evaporative cooling medium will not freeze.

Section 3
Key Findings and Accomplishments: Energy

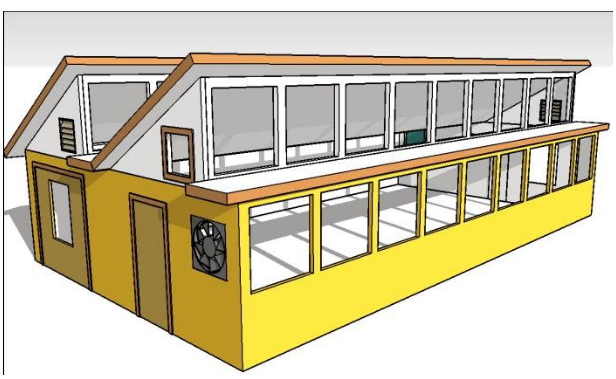
Design Work and Prototype Development

The principles discussed in Section 2 were applied to the design and research work that has been accomplished during the project. As of the present writing, early February, 2011, the greenhouse has been built, instrumented, and planted. Seeds for 12 varieties of vegetables were planted on Thanksgiving day.

Initial Design Concepts

The initial design had three features that were subsequently dropped. We envisioned building the structure as a pole barn, with wooden 6 x 6 inch posts on 8 foot centers resting on concrete pads four feet underground. These were to be 12 foot long timbers pressure treated with a new technique that is environmentally benign, "Timbersil." (See http://www.shakeandshinglesupply.com/timbersil.php.) However when the team discovered the opportunities offered by quite inexpensive concrete blocks, we elected to use these not only for foundation material but also as a massive, load-bearing wall on the north of the structure. We nonetheless like the concept of a pole barn and believe it has a very viable future, both in greenhouse construction and with inexpensive slab-on-grade housing stock using heavy perimeter insulation to couple it to the earth.

The second alternative that was designed then abandoned may also be quite viable in future greenhouses. It features a two-tiered set of roof monitors, shown in Figures 3-1 and 3-2.



Figures 3-1 and 3-2 show the original greenhouse conception that used a pair of window monitors on the roof.

Note that each set of roof windows has a light shelf in front. In addition, the roofs themselves are white. This approach was changed in the interests of simplicity and economy for the present design—and to enable the greenhouse to have a slightly greater ratio of length to depth. However, the original concept is likely to be more viable for larger greenhouses where light from the south façade becomes less and less useful as the depth of the structure increases. Of course, this will require that increasing quantities of solar light and heat are brought in from the roof.

The third difference from the initial design involved a change in the design of the insulating shutters for the south façade. The original design was akin to that of the swinging shutters in the roof. However, we needed to get more glazing closer to the plants on the ground on the one hand, yet ensure that shutters would not be in the way of either farmers or plants on the other. So we designed a more robust "pocket" shutter system. It has improved energy performance while being isolated from adverse conditions of temperature and humidity on both sides of the conditioned envelope.

Final design

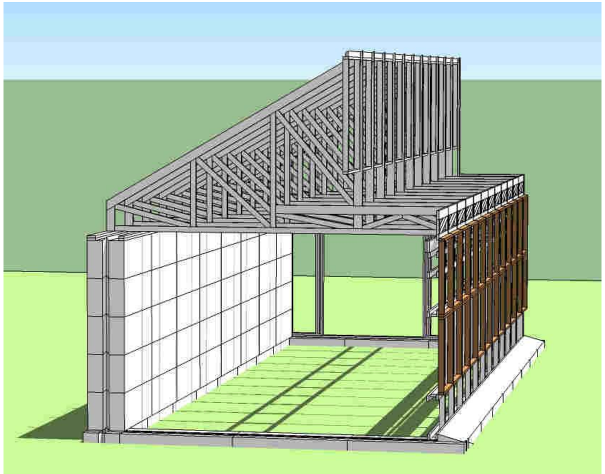
The illustrations in this section are SketchUp drawings that facilitate envisioning three dimensions aspects of the design. The design is of a nominal 1000 square foot greenhouse that is roughly 20 x 50 feet with glazing facing due south.

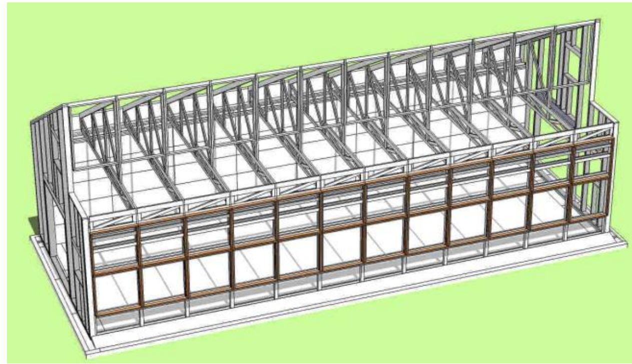
Figures 3-3 and 3-4 show the southwest and southeast elevations.

Figure 3-3. SW elevation showing fan, louver, door within a door (larger for tractor, smaller for people), fixed light shelf on roof, variable light shelves on south side, 12 roof windows and 12 south wall windows.

Figure 3-4. SE elevation.

Figures 3-5 and 3-6 show drawings of the computer-designed trusses. These define the roof and light shelf line, allow room for vertical glazing and swinging shutters, provide spaces for blown cellulose and polyisocyanurate board insulation, and give structural support for roof and snow loads. Figures 3-7 and 3-8 show photos of the installation process.





Figures 3-5 and 3-6. Prefabricated trusses on 48 inch centers.

Figures 3-7 and 3-8. These trusses were lifted in place by a 1947 vintage hay loader.

The roof in front of the windows on the top of the greenhouse is white, which enhances sunlight directed into the greenhouse (Figures 3-9 and 3-10)

Figure 3-9. White roof in front of windows.

Figure 3-10. Sunlight on inside of upper roof reflected from lower roof.

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Each window on the roof is a nominal 4 feet by 6 feet and is divided into two clear single-glazed units. A single shutter consisting of two-inch thick polyisocyanurate insulating board stock bordered by a U channel is hinged at the top of the window frame allowing the shutter to be swung between the window frame immediately behind the glazing through an arc of approximately 60 degrees to a space immediately under the sloped ceiling of the shed roof. In the down position the shutter improves the insulation of the window system by a factor of ten. In the up position it directs a substantial amount of solar light flowing through the glazing to the earth and plants below. The channel provides strength and a clean surface to press against compressible weather stripping that surrounds the insides of the window frame when closed, thus providing a tight seal. The front and back surfaces of the R-13-rated two inch polyiso are made of low emissivity aluminum sheet which has good reflective properties in the infrared.

The shutters are opened and closed by a dc gear motor that drives an acme-threaded screw. This screw is connected between the motor mounted in the sloped roof and a bushing near the bottom center of the window frame. A nut attached to a sliding hinge mechanism at the bottom of the shutter rides the screw and thereby manipulates the shutter. Limit switches at the window frame and ceiling ensure that travel is limited to the desired 60 degree pathway between completely open and completely shut.

Figures 3-11 and 3-12 show swinging shutters in the greenhouse.

Figure 3-11. #1 upper shutter on the far east end of the greenhouse about 20 percent open. Note adjacent exhaust fan and air intake near the top of the shutter.

Figure 3-12. View from the trusses looking east, swinging shutters open, gear motors at top.

Pocket shutters were designed for the windows on the south wall of the greenhouse. The R-13-rated polyiso insulating shutter lives in a “pocket” above the glazing when the sun is shining but slides downward between a pair of single-glazed lites on cold nights. A gear motor at the upper end of the pocket rotates a drive shaft akin to the one used in the swinging shutter. In this case the screw drives a nut that is mounted in the center of the top of the U-channel frame surrounding the shutter. The combination of pocket and glazing area measures a nominal 4 x 8 feet and is sealed both inside and out. As with the swinging shutter, limit switches are used to define and control full open and fully closed positions of the shutter.

Figures 3-13 and 3-14 show the installation process.

Figure 3-13. Shutter ready to roll!

Figure 3-14. Pocket shutter installed.

Greenhouse Controller

We designed and tested a controller for both the automatic and manual control of the 24 shutters on the south-facing windows of the facility. The controller includes provisions for controlling the ventilation systems as well. It contains a 12 Vdc rechargeable battery that supplies power for its own electronics as well as power to manipulate the shutters. Each shutter is associated with a pair of switches and corresponding light emitting diodes (LEDs). One switch alternates control of its corresponding shutter between auto and manual modes. The second switch has three positions with the center off. It moves the shutter up or down when the first switch is in manual mode. In the auto mode, the electronics senses when weather circumstances are best for shutter opening or closing and moves a bank of shutters to the optimal position. The LEDs indicate when a shutter is being opened (yellow) or shut (red).

In addition to automating the shutters to open and close on a routine basis, the controller is set up to allow for the study of combinations of shutter operating configurations to study effects on light levels, energy, and growth (Figure 3-15).

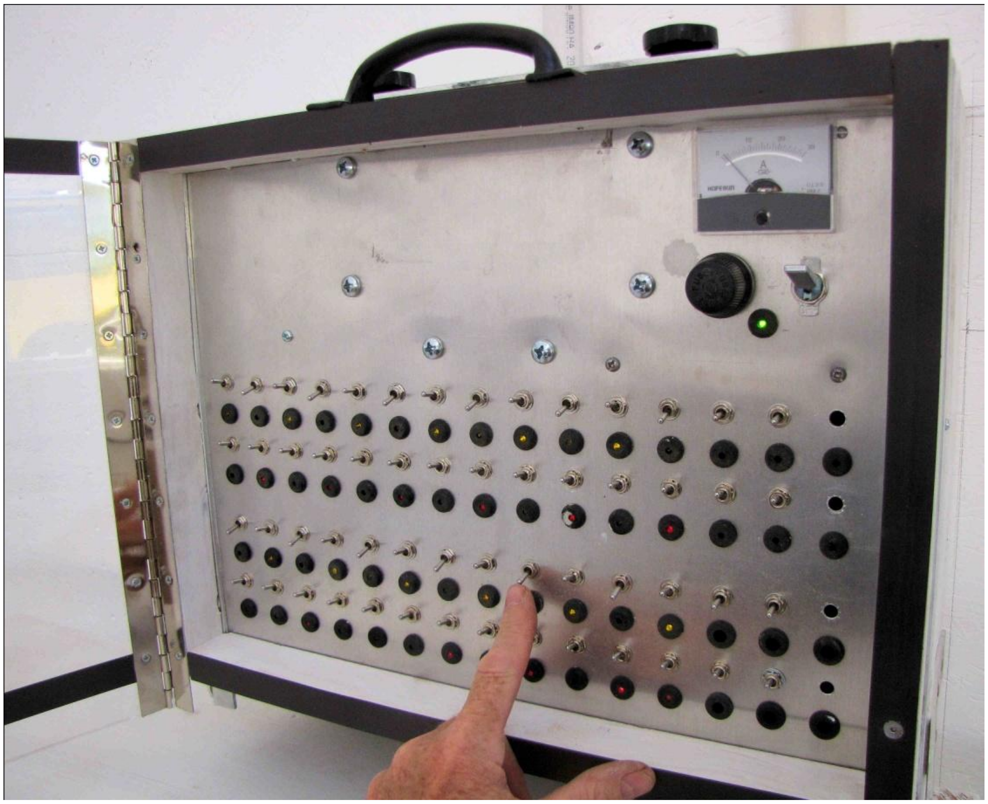

Figure 3-15. Master control box. Note plexiglass cover that hinges on the left.

Instrumentation

The project uses three HOBO U-12 data loggers to gather and record data on air temperatures and relative humidity at each logger, light in lumens/square foot. A fourth channel is configured for a remote temperature sensor. The external logger is mounted on the roof at mid window in the center of the south side of the greenhouse. The remote temperature sensor is mounted under the gable on the north east of the greenhouse where it can never intercept direct beam sunlight. Since the light sensor is limited to 4,000 lumens and levels of over 18,000 lumens are encountered at solar noon, we mounted a filter that diminishes levels by a factor of approximately 5. A second HOBO is installed five feet from the floor of the greenhouse in the center of the east well. A third is in the center of the east wall of the hoop house. The auxiliary temperature sensor on these inside loggers is “planted” about 2.5 inches into the ground.

Figures 3-16 and 3-17 show HOBO data loggers undergoing calibration runs.

Figure 3-16. Center of roof with HOBO and other sensors.

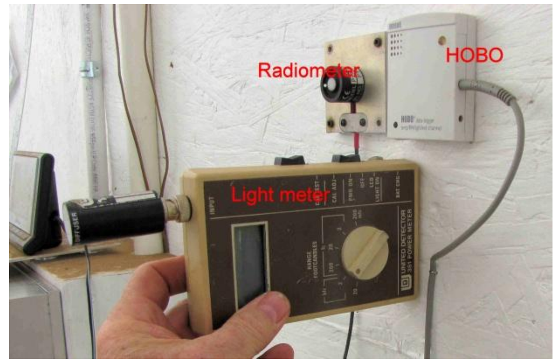

Figure 3-17. East wall of research greenhouse during calibration run.

Energy Estimates

Conventional methods of analysis of annual energy use of a building normally assume that at least part of the energy for heating will be supplied by a furnace or boiler, perhaps fired by propane or natural gas and controlled by a thermostat, thereby maintaining temperatures within a narrow range of values. However, since we made no provisions for supplying heating energy except from that variable source (after its radiant energy has traversed the atmosphere, at least) the sun, it is necessary to calculate heat losses of the envelope under various conditions. In particular, what if there is a sustained period of very little solar gain from the sun in which the temperature is quite cold? Will the greenhouse stay above freezing?

To answer this question, we estimated the insulating (R) value of every area of the greenhouse using proven methodologies from the canonical source of such matters, the *Handbook of Fundamentals* published by the American Society of Heating, Refrigeration, and Air Conditioning Engineers. We then multiplied the cross sectional area of each area to which an R-value was determined by the heat transfer coefficient (U), the inverse of the R-value. We then summed the results to produce an overall heat transfer coefficient times the cross section of the greenhouse. This figure times a temperature difference between inside and out produces an estimate of hourly heat losses due to conduction in Btu/hour.

Convective losses were estimated with the aid of a blower door test on the greenhouse. A blower door is a calibrated, variable-speed fan that fits in a shroud and associated frame that is temporarily mounted in an opening such as a door. When running, the fan produces a pressure difference between inside and outside. If the fan can produce a large pressure difference with little effort (resulting in only modest flow), the structure being tested is relatively well air sealed. (Of course, if it has to work hard to produce very much pressure difference, the structure is quite leaky.) Instruments are used to determine flow rate of air through the fan as a function of the inside/outside pressure the fan induces. With all systems configured for winter operating conditions, the blower door was installed in the east door of the greenhouse and its fan was used to depressurize the structure to a 50 pascal pressure difference, about 0.2 inches of water pressure. As shown in Figure 3-18 and 3-19, the blower door test showed that the greenhouse is quite tight, indicating a flow of 710 cubic feet of minute of air when the greenhouse was depressurized to 50 pascals. This allows for estimating that around 2100 cubic feet per hour of air is exchanged with fresh air on an average hour in the winter. Since the volume of the greenhouse is approximately 13,000 cubic feet, this means the natural air exchange rate is about 0.16 of an air exchange per hour, or a full air exchange is achieved every 6.2 hours.

Figure 3-18. Blower door set up, east door.

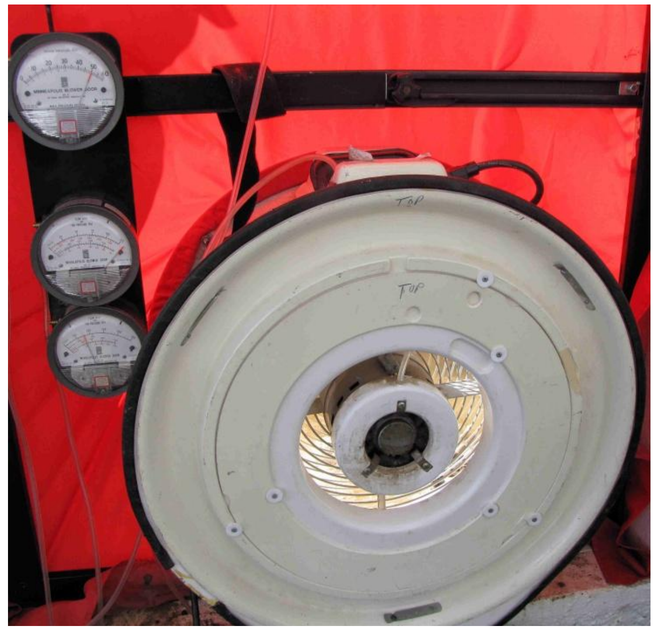

Figure 3-19. Close up with meters. Low flow calibration plate used because structure is quite tight.

Table 3-1 explores conductive plus convective losses through the greenhouse at various temperature differences and configurations, including the entire heating season.

Table 3-1. Conductive and convective losses of key greenhouse elements as a function of temperature (hourly in Btu/hr) and heating degree days in Boulder (millions of Btu per winter).

In/outside temp difference (F)	Heat loss total GH except windows (Btu/hr)	Heat loss through windows, shutters open (Btu/hr)	Heat loss through windows, shutters closed (Btu/hr)	Total GH loss, shutters open (Btu/hr)	Total GH loss, shutters closed (Btu/hr)	Window loss portion of total, shutters open (%)	Window loss portion of total, shutters closed (%)
10	1,000	3,877	404	4,877	1,403	79.5%	28.8%
20	1,999	7,755	808	9,754	2,807	79.5%	28.8%
30	2,999	11,632	1,212	14,631	4,210	79.5%	28.8%
40	3,998	15,509	1,615	19,508	5,614	79.5%	28.8%
50	4,998	19,387	2,019	24,385	7,017	79.5%	28.8%
60	5,997	23,264	2,423	29,261	8,420	79.5%	28.8%
70	6,997	27,142	2,827	34,138	9,824	79.5%	28.8%
80	7,996	31,019	3,231	39,015	11,227	79.5%	28.8%
90	8,996	34,896	3,635	43,892	12,631	79.5%	28.8%
	MBtu/yr	MBtu/yr	MBtu/yr	MBtu/yr	MBtu/yr	%	%
Winter	13.4	52.1	5.4	65.5	18.9	79.5%	28.8%

The first column of Table 3-1 shows indoor/outdoor temperature difference in degrees F. Column 2 shows estimated losses due to conduction from the walls and ceiling of the greenhouse including doors and ventilation areas when their shutters are closed. It includes total convective losses of the greenhouse but does not include window areas. Columns 3 and 4 show estimated losses due to conduction from windows when shutters are open (Column 3) and closed (Column 4) Column 5 sums all greenhouses losses assuming that shutters are always open and Column 6 sums all greenhouse losses assuming that shutters are always closed. The last two columns show the percentage of total losses associated with the windows when shutters are open (Column 7) or closed (Column 8)

The magnitude of these losses are all a direct function of the difference in temperature between inside and outside of the greenhouse. So the rows show the estimated hourly losses at differences in temperature between inside and outside ranging from 10F to 90F, the latter being an actuality on February 1, 2011 when at an hour past solar noon, the greenhouse air five feet above plant level was at 93F when the outdoor air temperature was at 1F. A newly-fallen snow enhanced net solar gain so that the greenhouse produced a great deal of net energy in spite of losses of about 44,000 Btu/hr. A profile of temperature data around this coldest weather on record in the last 12 years is shown below in Figure 3-24.

The last row of Table 3-1 shows an estimate of annual losses obtained by using temperature differences for the whole season. This was derived by using the heating degree days (base 65) for the area in Boulder County where the research greenhouse is located (5600 heating degree days). The result is expressed in millions of Btu per heating season, where a million Btu is ten therms of natural gas.

The results shown in Table 3-1 prompt several observations:

- Note that the numbers are expressive of conductive and convective losses as well as radiant losses through non-shuttered glazing. Virtually all gains are radiant solar gains, but these are not included in the calculations.

- Windows account for a very large portion of the losses, especially when they are not covered with shutters. Of course, the circumstances of conventional greenhouses are just that case, since most do not utilize shutters at all. Note that losses through the windows are ten times greater when no shutters are present than when shutters are in place.

- Windows amount to only 20% of the area of the walls and ceiling; 47% of the nominal footprint of the building. This is much smaller than is the case with conventional greenhouses.

- The 80% of the research greenhouse that is not window area is quite well insulated and the whole building is well air sealed. This is a very important reason it performs as well as it does.

- Losses to the ground were not included in this analysis. Appendix A addresses mathematical modeling of the issue of heat transfer between greenhouses and the earth beneath them. When the greenhouse is at its average temperature for the winter season, 65F, some net transfer of energy goes to the earth, but if it dips below 60F, the earth begins to transfer net energy to the greenhouse.

Of course shutters are manipulated so that when solar radiation is zero--or close to it—and outside temperatures are substantially lower than are inside temperatures, the shutters close. In winter, days are short and useful sunshine averages only 10 or so hours per day. In addition, as the temperature curves in the next section indicate, lowest temperatures are at night, a phenomenon that is especially pronounced in areas like Boulder's where radiational cooling to mostly clear nighttime skies is substantial. (Diurnal temperature swings average about 30F in the Boulder area, both winter and summer.) Accordingly the calculations of window system losses shown in Table 3-2 assume that shutters are closed for 60% ***of the heating degrees days*** of a winter, roughly nighttime hours.

A second consideration is analyzed in Table 3-2. The 288 square feet of window area at the top of the greenhouse which uses swinging shutters is single glazed. Such glazing has the advantage of a high SHGC (counting the exterior reflectors, the ***system*** SHGC exceeds unity). However, since its R value is only 1, its losses are substantial. Accordingly, we looked at a case in which two sheets of clear glazing are used to form an insulating glazing unit. This lowers the solar heat gain coefficient by about 9% but decreases conductive losses by half. Losses under several scenarios are shown in Table 3-2.

Table 3-2. Winter Season heat loss with shutters open for 40% of annual HDD and closed for 60% of HDD with 288 square feet of single and double-glazed windows.

Configur-ation	Heat loss total GH except windows (MBtu/yr)	Heat loss through all windows, shutters open (MBtu/yr)	Heat loss through all windows, shutters closed (MBtu/yr)	Total heat loss through windows, shutters optimized (MBtu/yr)	Total GH loss, shutters optimized (MBtu/yr)	Window loss portion of total, shutters optimized (%)	GH Savings over single glazing (%)
Single glazed	13.4	20.8	3.3	24.1	37.5	64.2%	0
Double glazed	13.4	13.1	3.1	16.2	29.7	54.7%	21.0%

Note that this optimization of shutter controls yields much more reasonable annual losses than is the case with a similar greenhouse with no shutters. With the single-glazed circumstance presently installed in the research greenhouse, estimated savings over a super-insulated greenhouse with the same R-values as the research greenhouse but with no shutters are 65.5 – 37.5 = 28 MBtu or 43%.

Switching to a double-glazed insulating glass unit for the upper window systems would save another 7.8 MBtu or 21% over the single-glazed circumstance.

Energy Performance

The present configuration of the greenhouse with its configuration of window-with-shutter system allows for solar gain to more than make up for the 37.5 MBtu of annual losses through the thermal envelope and glazing of the research greenhouse. Quantifying and displaying ***measured*** energy performance is the subject of this section.

It is possible to chop up a freshly-plucked chicken for dinner using a surgeon's saw, perhaps subdividing it at 1 inch intervals. Possible but decidedly inelegant. Dividing it at its natural joints yields more satisfactory results for both chef and diner. By analogy, the natural joints for a structure such as a greenhouse are years, growing seasons, and 24 hour days. Here we concentrate on presenting data based on diurnal cycles, from one midnight to the next.

To illustrate the relative performance of a typical hoop house and the research greenhouse, we show temperature data on both structures gathered at 15 minute intervals. The hoop house is 200 feet from the research greenhouse and has a similar footprint and identical orientation, but smaller volume. It uses double plastic which serves as wall, ceiling, and fenestration. Temperature probes are at about 5 feet above the soil and soil temperature sensors are buried by about 2.5 inches in both cases. Figures 3-18 through 3-21 show a series of plots of temperatures over a 24 hours period of the outside air (solid black lines), inside air of the hoop house (solid tan lines), soil of the hoop house (dashed tan lines), inside air of the research greenhouse (solid blue lines), and soil of the research greenhouse (dashed blue lines). Each plot shows diurnal snapshots of days in December 2010, January 2011, and early February 2011. Figure 3-20 shows a cloudy day, 3-21 a partly-sunny day, 3-22 a sunny day, and 3-23 a cold sunny day with snow on the ground.

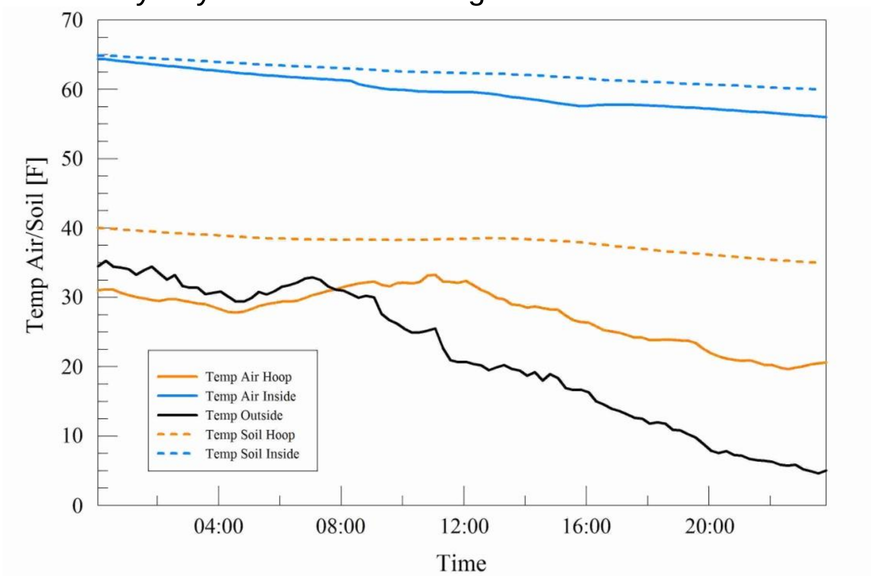

Figure 3-20. Cloudy day, high 36F, low 5F, diurnal swing 31F.

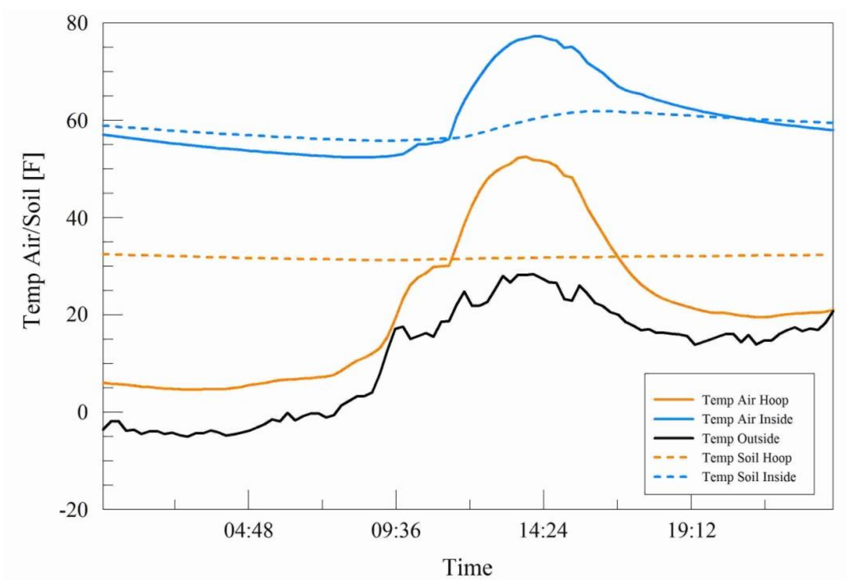

Figure 3-21. Partly sunny day, low -2F, high 24F, diurnal swing 26F.

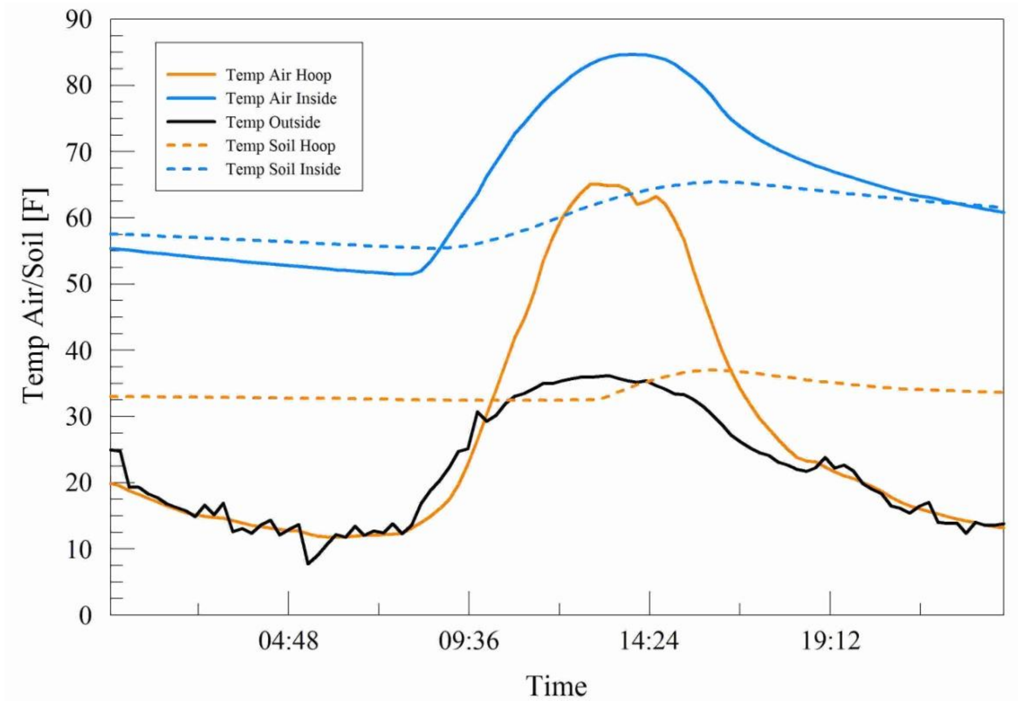

Figure 3-22. Sunny day, low 8F, high 35F, diurnal swing 27F.

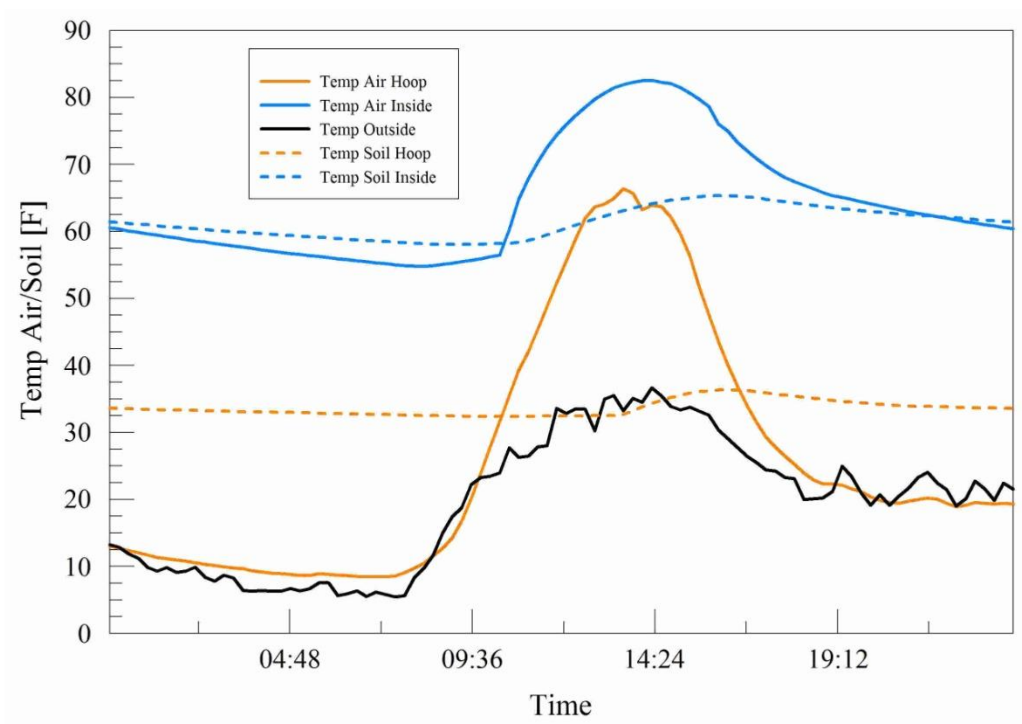

Figure 3-23. Sunny day with snow on ground, low 5F, high 35F, diurnal swing 30F.

Note the key role played by the sun in all cases. The mass of the research greenhouse is successful in storing solar energy and safeguards the soil at an average of 65F, rarely dropping below 60F. The soil in the hoop house is fairly stable as well, but it lives dangerously close to freezing. Overall, in most of December and all of January, the outside air temperature averaged 31F at the greenhouse site, where measurements were at 15 minute intervals (close to 5000 data points over the period.) The research greenhouse averaged 64F over this period with a high of 92F and a low of 48F.

Boulder had a severe cold snap in late January and early February, with temperatures dropping to -18F, the coldest in a dozen years. This allowed the gathering of worse-case circumstances for the research greenhouse.

Figure 3-24 shows greenhouse performance over a five-day period.

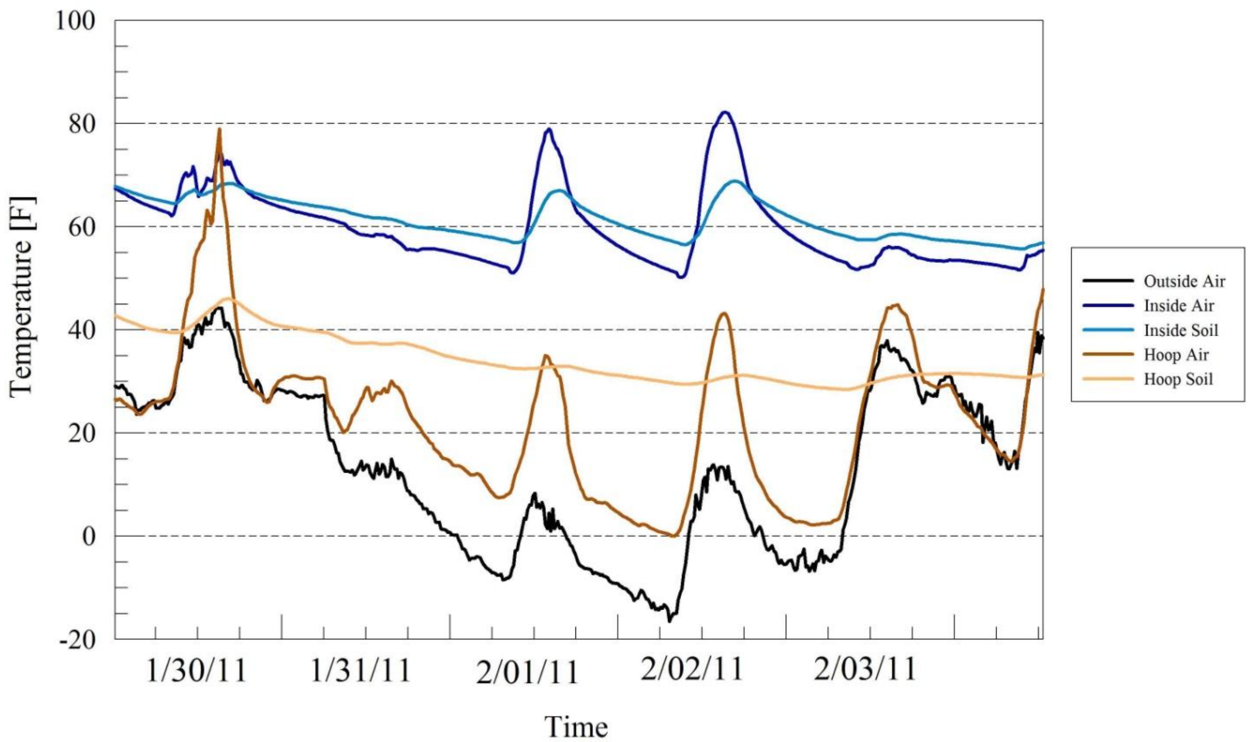

Figure 3-22. Five very cold days, high 44F, low -18F.

Note that the research greenhouse showed modest diurnal swings over this period but never went below 50F, rising to 82F a few hours after the outside air temperature was 18 below zero F. Meanwhile the hoop house air temperature got as low as zero F.

In short, energy wise, the research greenhouse can go to the front of the class.

The following section examines growth performance.

Section 4
Key Findings and Accomplishments: Growth

Planting

A variety of vegetable seeds was planted in the research greenhouse on or just after Thanksgiving day, November 25, 2010. These included two varieties of tomatoes, arugula, radishes, cucumbers, summer squash, basil, eggplant, sweet peppers, mellons, carrots, rainbow chard, and salad mix. A diagram of seeds planted in each section of the greenhouse along with "days from planting to harvest" information from seed suppliers is shown in Figure 4-1.

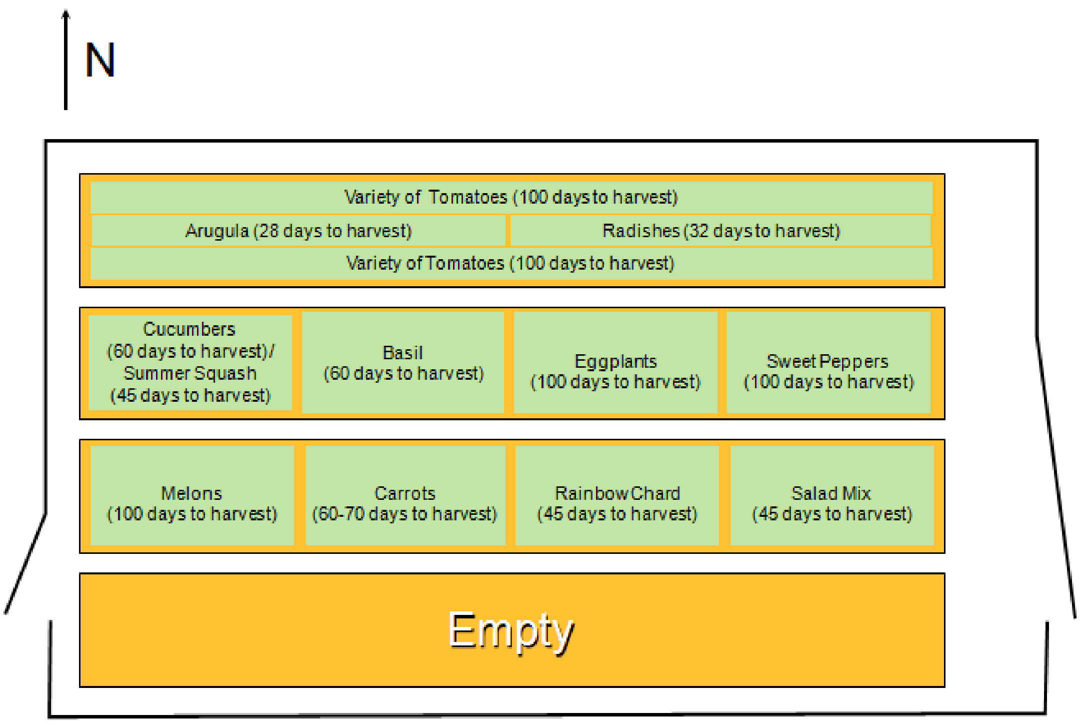

Figure 4-1. Planting chart. The empty space was left to facilitate maintenance and movements of tools, sensors, and equipment.

Tracking growth

Anne Cure, owner of the Cure Organic Farm, expressed amazement at the speed at which sprouts emerged and plants grew. "I've never seen faster growth, even under optimal conditions and the longest days of the year in June," she observed.

Figures 4-2 through 4-4 show photos of plant growth as a function of days after seeds were planted.

Figure 4-2. Ten days after seeding.

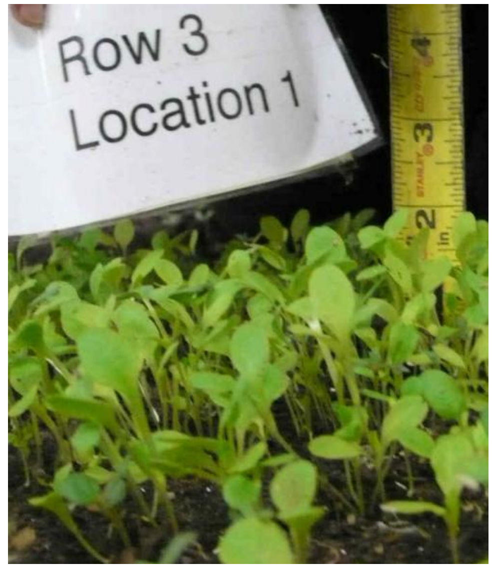

Figure 4-3. Measuring plants 10 days after seeding.

Figure 4-4. 54 days after seeding.

In order to track growth as a function of relevant variables, we measured plant height in inches at least once per week and took a digital photo of each class of plants. (An example is shown in Figure 4-3.) We then plotted the resulting data as a function of the lowest air temperature in the greenhouse each day and daily illumination for each class of plants. Figures 5-5 through 5-14 show the results by plant type. In order, they show the growth of arugula, carrots and melons, chard, cucumber, eggplant and basil, radish, salad mix, summer squash, sweet pepper, and tomato.

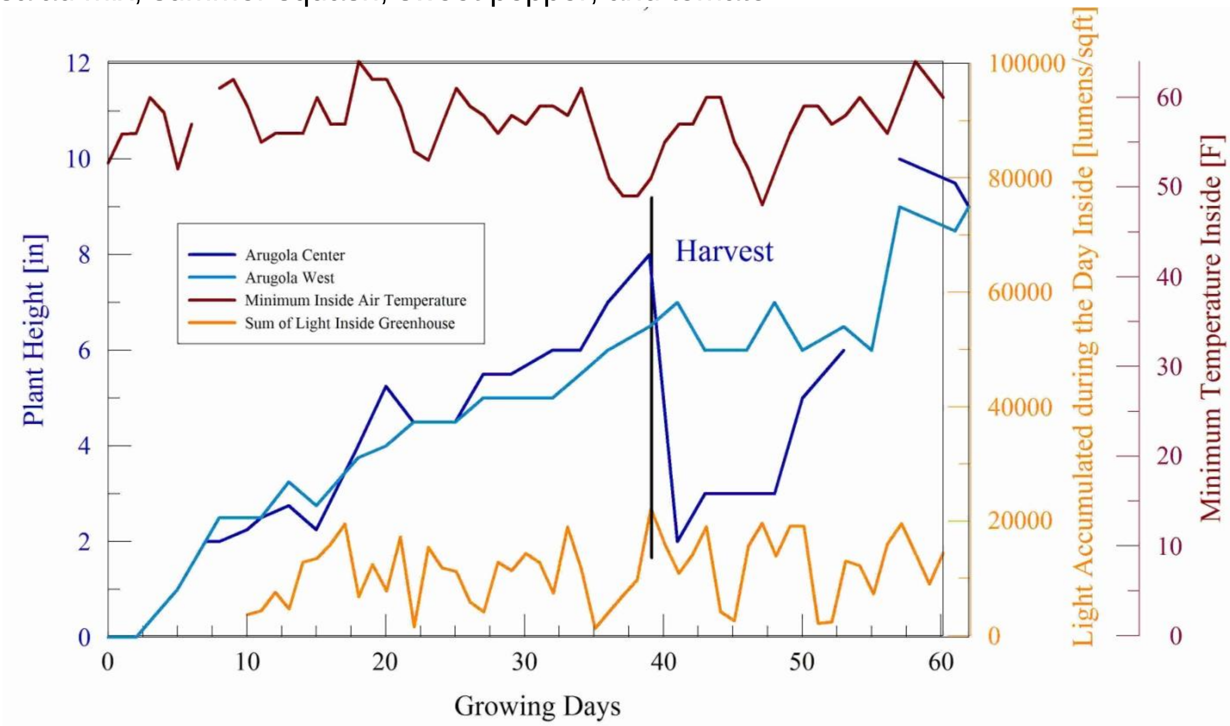

Figure 4-5. Arugula growth.

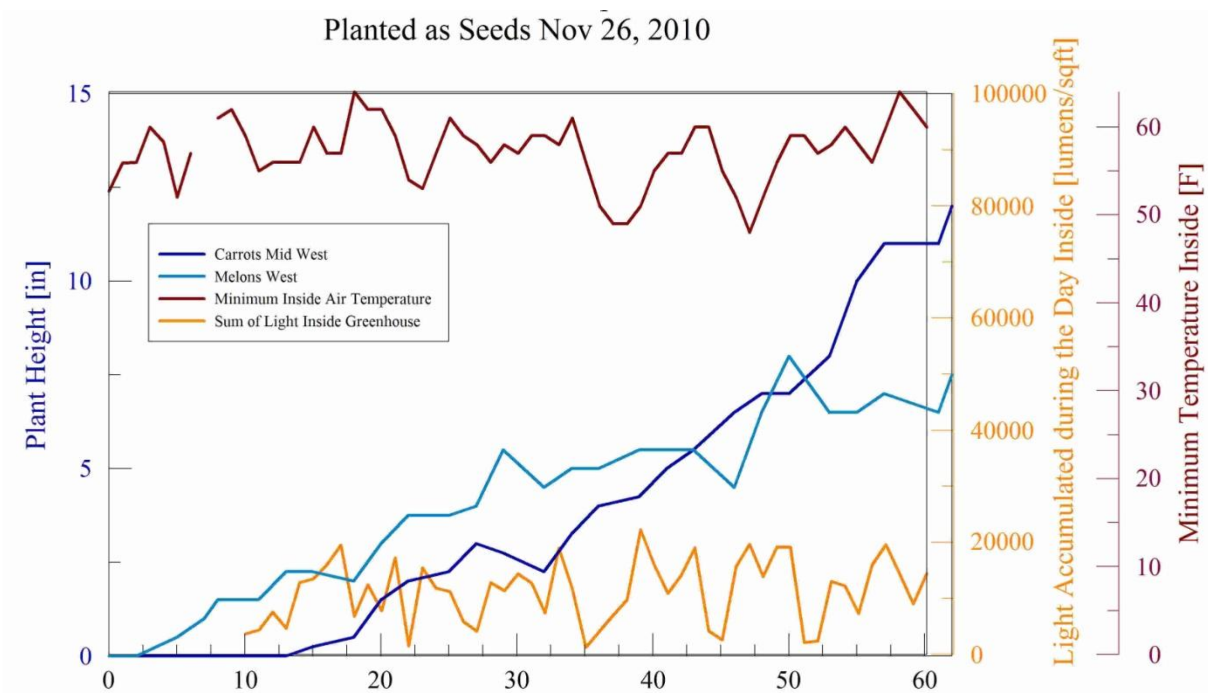

Figure 4-6. Carrots and melons growth.

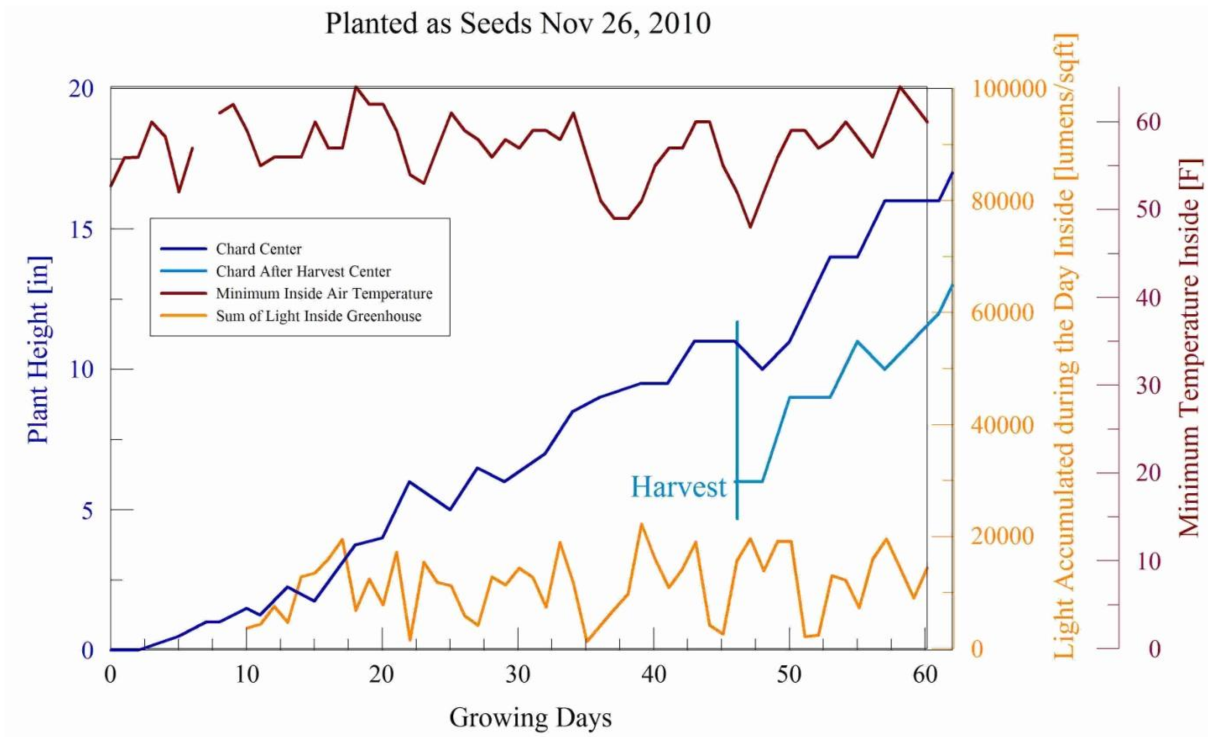

Figure 4-7. Chard growth.

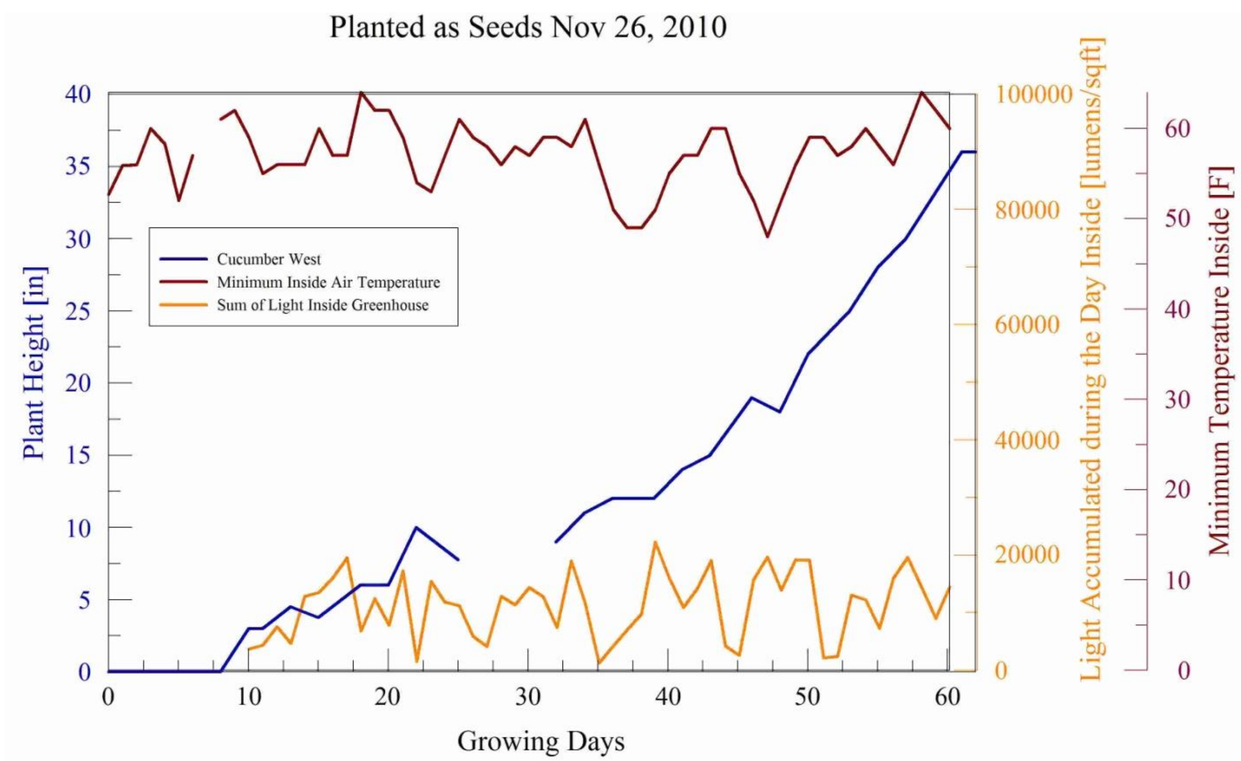

Figure 4-8. Cucumber growth.

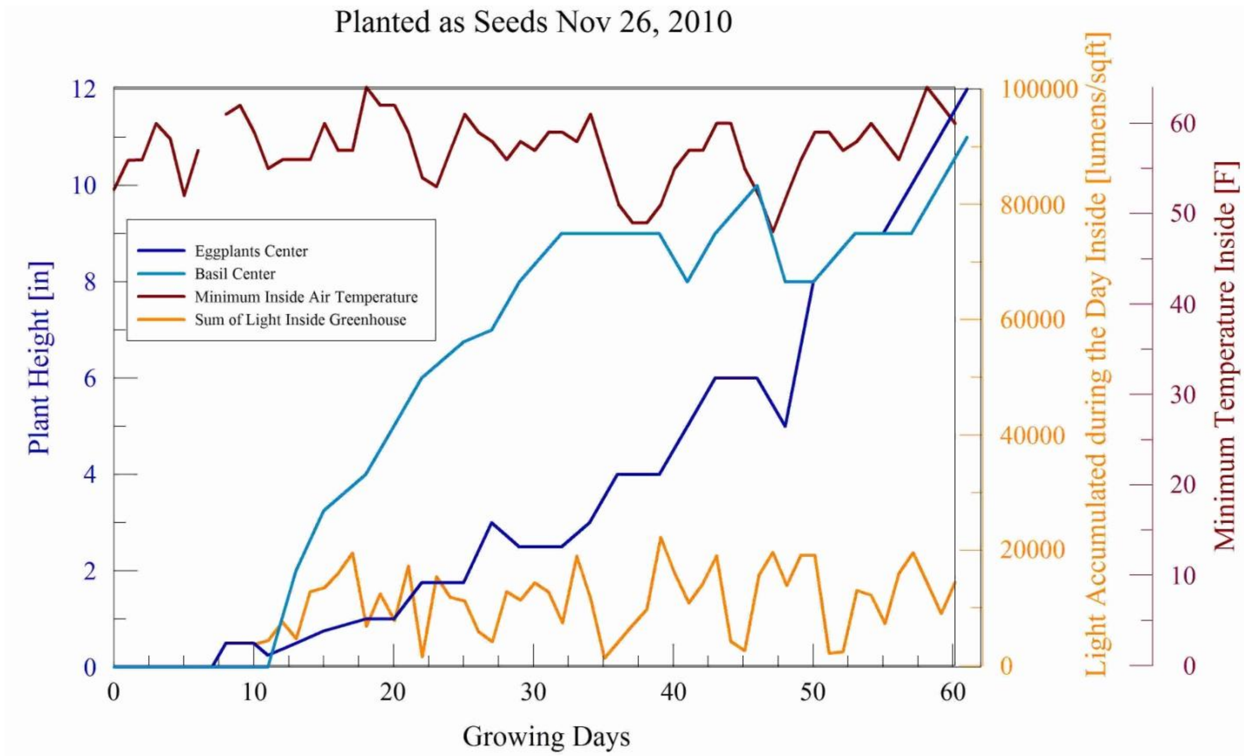

Figure 4-9. Eggplant and basil growth.

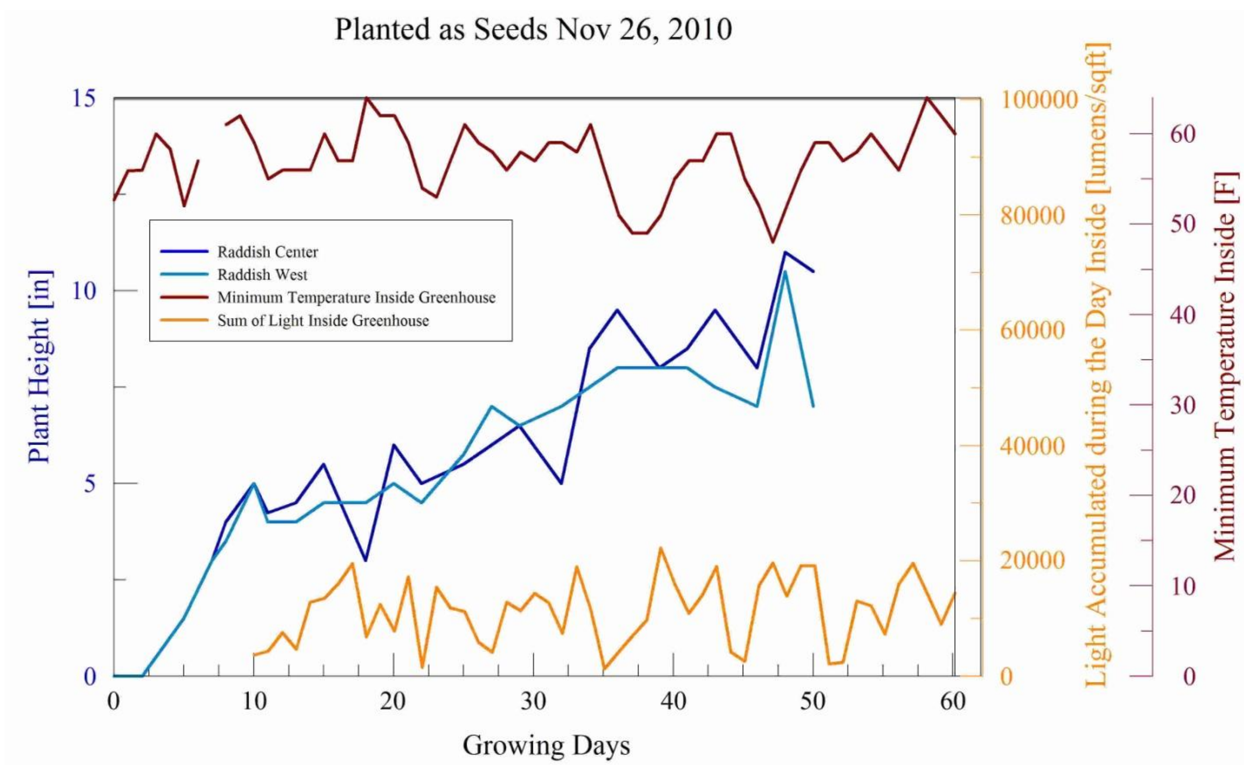

Figure 4-10. Radish growth.

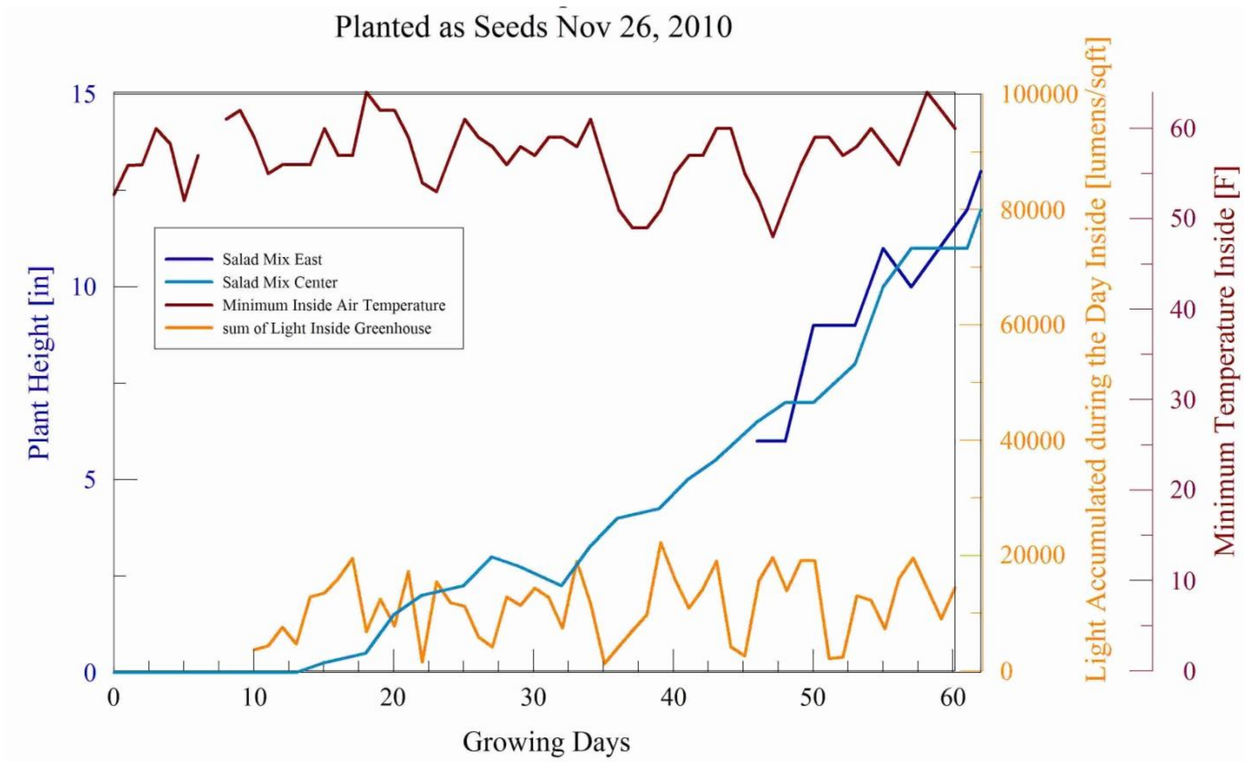

Figure 4-11. Salad mix growth.

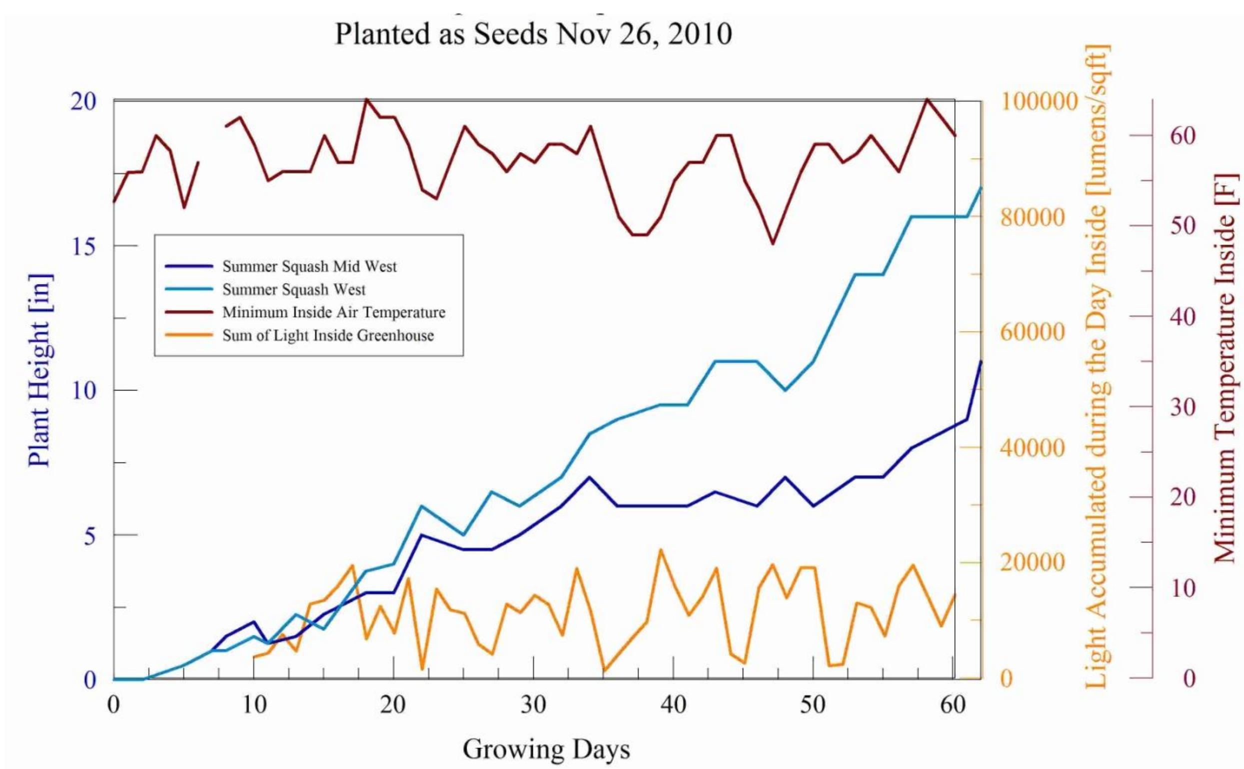

Figure 4-12. Summer squash growth.

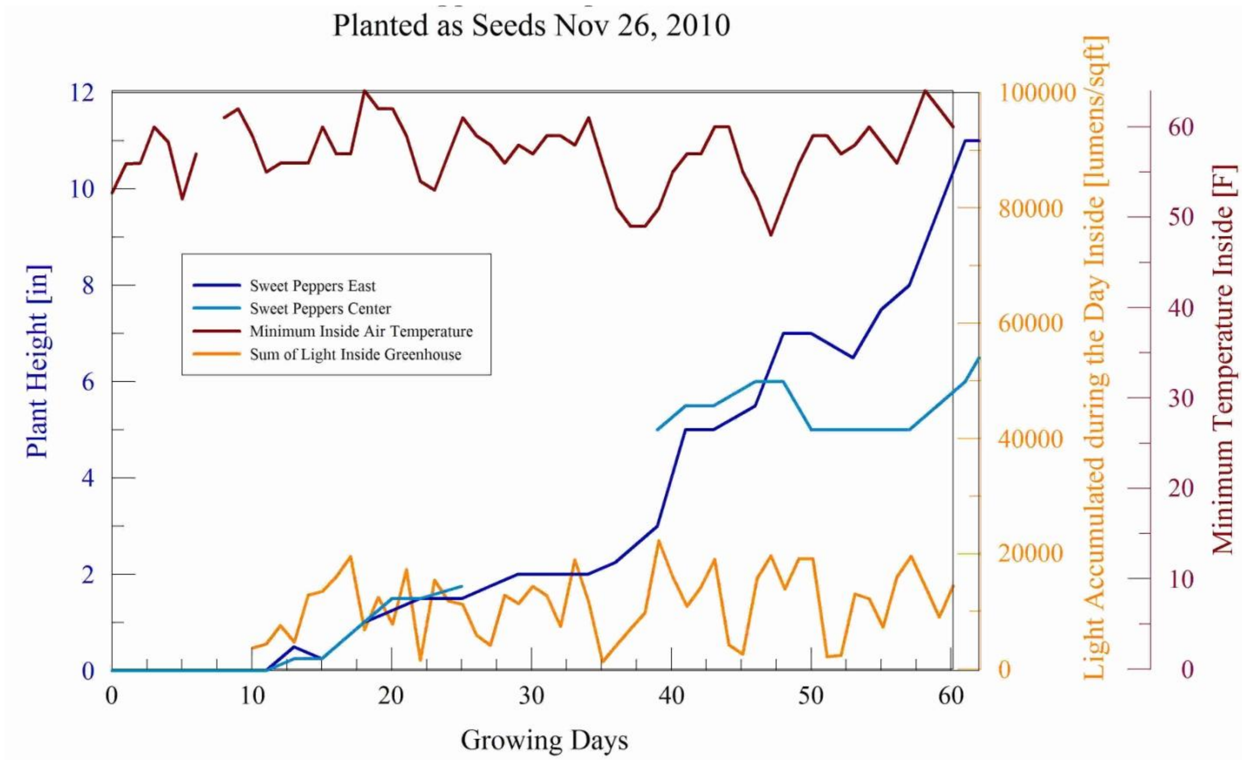

Figure 4-13. Sweet peppers growth.

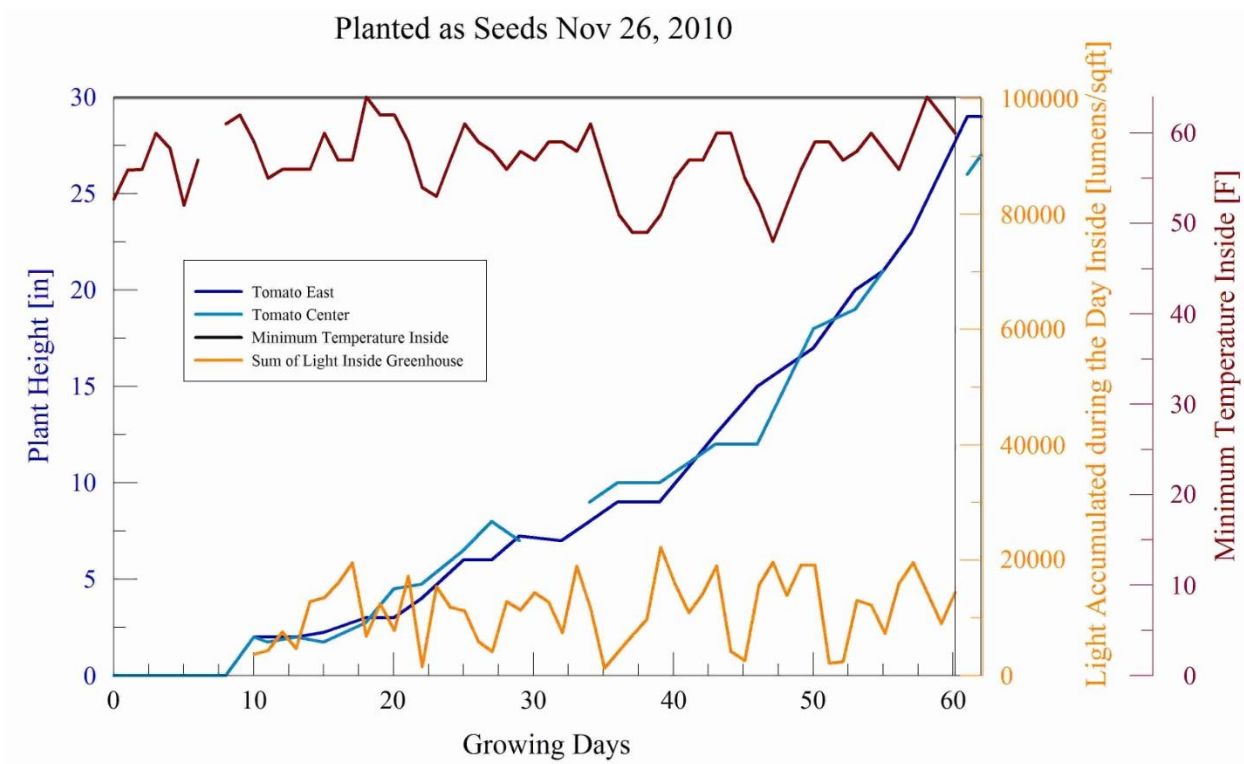

Figure 4-14. Tomato growth.

Section 5
Problems encountered and mitigating circumstances

This was a very ambitious research project that required the development of a number of new techniques for achieving the goal of abundant year-around growth in a practical greenhouse of very modest carbon footprint. As with all research projects, not everything worked as well as we would have liked, but problems suggested solutions, solutions were implemented, and the greenhouse is working extraordinarily well from the points of view of both energy performance and plant growth.

The research project has cost more than we had hoped, in large measure because of delays in launching construction of almost six months due to the building permitting process. The greenhouse is not far from an irrigation ditch and Boulder County building officials were concerned that moisture in the ground close to the proposed building would have deleterious effects on the structure. The situation was resolved by a combination of ensuring that the ditch was indeed 20 or more feet from the building and securing the opinion of a structural engineer that feared issues were not likely to pose a problem at all. Indeed, there have been no problems with this issue at all since the building was completed.

Second, we decided to experiment with a number of different options for insulating shutter designs and ran dozens of tests both in our window testing chamber and in the lab in an effort to ensure that best designs would be implemented in the new greenhouse. These tests took a good deal of valuable time to conduct and analyze. Finally, fabrication of first-off models of both controls and insulating systems are necessarily more expensive than is likely to be the case when design details are finalized and productions tooling can be put into place. In short, research can be costly.

In all events, the very promising findings in greenhouse energy and growing performance flowing from this research lend hope that the extra investment by all parties will yield green dividends in the full sense of the term.

Phase II is in full swing and includes more research in several areas. These include tweaking the cooling and controls systems and measuring results during spring and summer periods. This—and continuing work on designs for the development of a new generation of energy-efficient greenhouses for residential and commercial markets—will be covered in the Phase II final report.

Section 6
Next Steps

In addition to the work documented in this report and further findings that will be the subject of the Phase 2 final report due at the end of the summer of 2011, the team has been active in sharing key project findings with others.

Apropos, Larry Kinney gave a presentation at the 9th Annual Innovations in Agriculture Conference, November 17 and 18, 2009 in Troy, New York. The title of the presentation was “Towards Zero Energy Greenhouses: Insolation, Insulation, Mass, and Smart Controls.”

A 1.5 hour presentation on the project, “Green Greenhouses for Cohousing,” was given at the National Cohousing Conference held in Boulder in June of 2010.

In addition, Larry Weingarten and Larry Kinney presented a good deal about the greenhouse project in general and its insulating shutters in particular at the 2010 Summer Study on Energy Efficiency in Buildings sponsored by the American Council for an Energy Efficient Economy, www.aceee.org. The title of the poster presentation was “Automated Insulating Shutters.”

On February 3, 2011, we presented “Close to Zero Energy Greenhouses that Produce Food all Year Around” at a Clean Energy “Slam” sponsored by a Boulder-based organization engaged in influencing the City’s energy future. Our presentation and those of others are available at www.RenewablesYES.org.

Of course, many people have visited the greenhouse construction site, both individuals and groups representing educational, agricultural, and energy efficiency-related organizations. Such visits will continue.

Promising findings like these lend lots of hope for the future. Phase II work includes designs of several classes of a new generation of greenhouses from small structures that can be attached to homes where they supply both food and heat to large commercial structures that can supply food for communities via grocery stores, farmers’ markets and restaurants.

Advanced controls and more elegant systems for saving energy cost effectively are in the offing.

Appendix A
Analysis of Greenhouse Thermal Response

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Contents by Section

A.1 INTRODUCTION

Background

In 2008-2010, Synergistic Building Technologies (SBT) introduced the concept of heavily-insulated deep-earth coupled greenhouses. A major question is whether passive geothermal and passive solar resources can extend the growing season without supplemental heating.

SBT initiated a construction demo project in Colorado; Dr. Stiles concurrently started an independent modeling project for preliminary design specifications. Early data from the demo project and the modeling indicates a promising collaboration for future research and development.

Why Model?

Goal: A specification tool for standardized greenhouse designs that can be deployed in different localities.

How to Get There?

- Quantify the relative contributions of deep-earth coupling and solar gain in heating, cooling, and maintenance of interior temperature.
- Benchmark the impact of window area: Light requirements of given crops vs energy performance
- Evaluate the impact of size of structure on energy performance; what are the upper limits and why?
- Evaluate how different materials, layer thicknesses, etc impact energy performance; seek the minimum-built structure.
- Predict energy performance of the design in different locations; emphasize the role of available sunlight.

Overview of the Model

- A thermal equivalent circuit model of intermediate complexity and precision; the best approach would be finite-element modeling, which would require substantial resources to set up and operate.
- Uses an industry-standard convention for defining thermal time constant for sections of a building.
- Whole-building thermal response is assumed to be a linear superposition of the different pathways for heat to travel into and out of the building.
- The present model features customizations of other investigators' basic theory to adapt it to greenhouses.

Greenhouse Design

- A "reference" solar greenhouse design was adopted based on current industry best practices.
- The design was modified to incorporate a model of deep-earth temperature as input to greenhouse using better foundation insulation than is usually found in greenhouses.
- Work to date has resulted in the first spreadsheet implementation of the theory.
- SBT's demo has out-performed the current best practices for solar greenhouses.

Research Topics Investigated to Date Using This Model

- Preliminary assessment of how much non-window envelope insulation is needed, and minimal storage mass to moderate extreme winter swings in interior temperature.

- Quantify the contributions of deep-earth coupling and solar gains to interior temperature of the reference design.

- Check to make sure that operable insulating shutters contribute to maintenance of interior temperature.

- Evaluate how increasing the thermal storage mass beyond best-practices recommendations moderates temperature swings.

Results are summarized in Section A.5

A.2 REFERENCE GREENHOUSE DESIGN

National Sustainable Agriculture Information Service (NSAIS)
http://attra.ncat.org/attra-pub/solar-gh.html#heat
Alward, Ron, and Andy Shapiro. 1981. Low-Cost Passive Solar Greenhouses.
National Center for Appropriate Technology, Butte, MT. 173 p.
NSAIS recommendations:
• 45-60° north roof slope.
• vertical north wall for stacking heat storage.
• 45° south roof glazing.
• vertical kneewall.
• part of end walls glazed for additional light

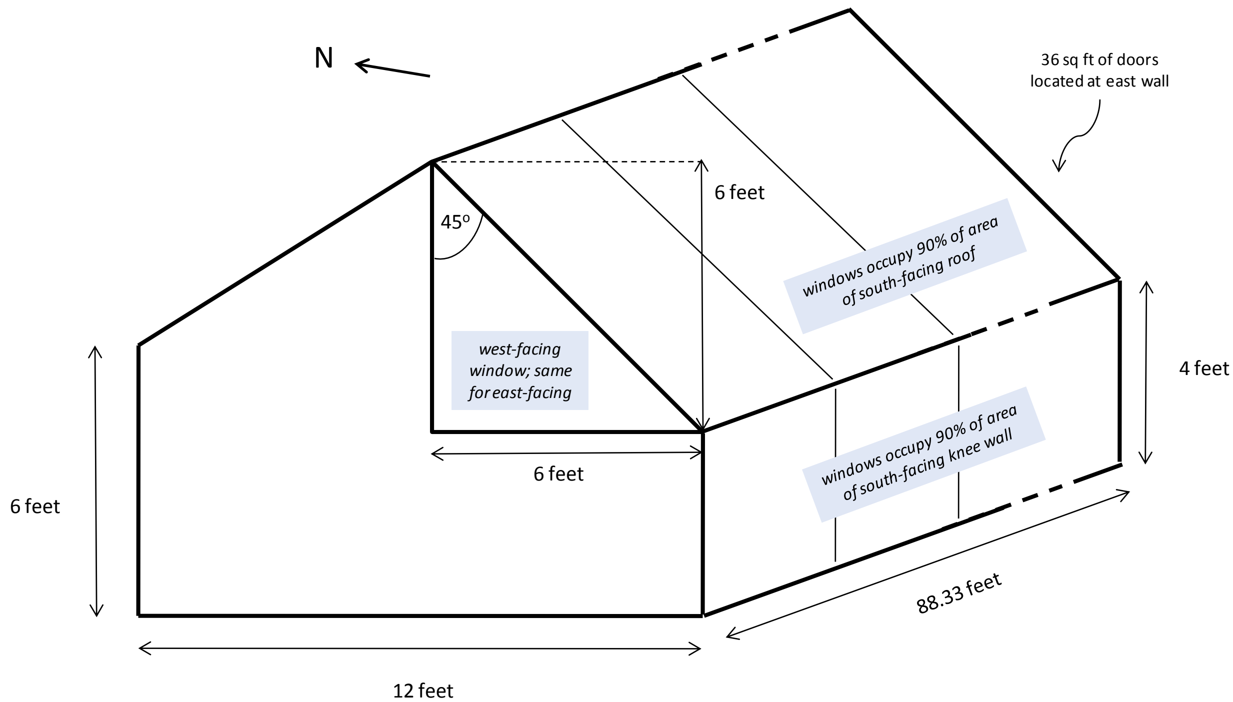
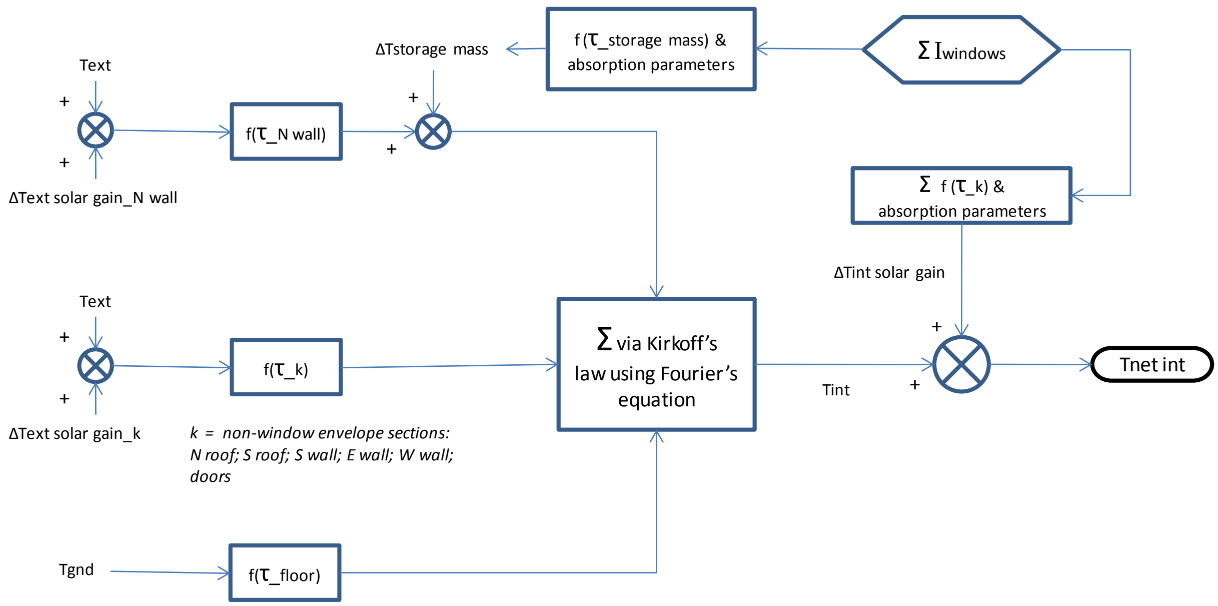


Figure A2.1 The reference greenhouse design as modeled

3 SUMMARY GRAPHIC OF THERMAL PATHWAYS & THE MODEL



LEGEND

Text = exterior dry bulb ambient air temperature
ΔText solar gain_k = increment of exterior temperature of the kth envelope section due to insolation
f(τ_k) = a function of the time constant (τ) of the thermal mass of the kth envelope section; "absorption parameters" are for calculation of interior solar heat gain of the section
Σ Iwindows = sum of solar gains (Btu/hr) due to irradiance through all of the windows
ΔTstorage mass = contribution of interior solar gain absorbed and released by storage mass at north wall
Tgnd = "deep earth" temperature computed at a nominal depth of 4 feet below grade
Tint = interior air temperature including gains through non-window areas of the envelope
ΔTint solar gain = total contribution of interior solar gains excluding storage mass contributions
Tnet int = net interior air temperature; output of the model

Figure A3.1 Flowchart and definition of key terms of the model

A.**4 COMPONENTS OF THE MODEL**

4.1 Model is based on:

Milo E. Hoffman and Moshe Feldman, "Calculation of the Thermal Response of Buildings by the Total Thermal Time Constant Method" Building and Environment Vol. 16 No. 2 pp 71-85 1981

(referred to hereafter as "H&F")

Intermediate approach between simple degree-day calculations and finite-element analysis

DOE & CANMET simulations are much more comprehensive but underlying assumptions are often not readily discernable and do not always provide results in convenient formats

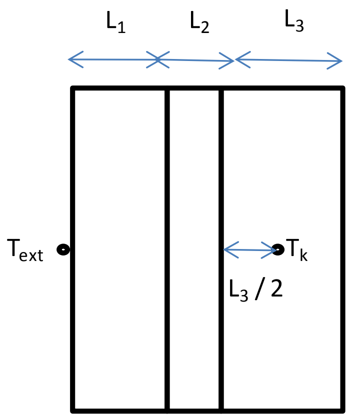
Several modifications of H&F's original formulations to adapt them to greenhouses

Customized calculations allow for customized analysis of results

This is an ongoing work in progress

4.2 H&F's Conventions for Thermal Response of Building Envelope Components

A building is assumed to be composed of a number of different thermal branches between the interior and exterior. Each branch has an area and is comprised of the same order, composition, and thickness of layers.
Each branch has its own thermal time constant. The value of the time constant is computed up to the most internal layer of the heat flow path represented by the branch. As an example of the convention applied to a three-layered heat flow path,



Nomenclature

R_o thermal resistance at an outside surface of the heat flow path
hr ft^2 ^{o}F / Btu
L_x thickness of the xth layer in the heat flow path (x = 1,2,3)
ft
T_k , T_{ext} interior and exterior temperatures
respectively, at designated locations
K_x heat conductivity of the xth layer
(Btu x <thickness> / hr ft^2 ^{o}F)
ρ_x density of the xth layer
lb / ft^3
c_x constant-volume heat capacity of the xth layer
Btu / lb ^{o}F

Figure 4.2.1 Conventions for modeling a section of building envelope as a thermal branch in a network

Define the total time constant of the heat flow path shown above, τ, as a sum of time constants of its constituent layers according to the following convention:

$$\tau = \left(R_o + \frac{1}{2}\frac{L_1}{K_1}\right) L_1\rho_1 c_1 + \left(R_o + \frac{L_1}{K_1} + \frac{1}{2}\frac{L_2}{K_2}\right) L_2\rho_2 c_2 + \left(R_o + \frac{L_1}{K_1} + \frac{L_2}{K_2} + \frac{1}{2}\frac{L_3}{K_3}\right) L_3\rho_3 c_3$$

Eqn (4.2.1)

- The time constant of each layer is taken as a function of the heat conductivity to half its thickness
- For each consecutive layer, the conductivities of the layers between it and the outside are cumulative
- According to the units defined above, the time constant has units of hours

The solution of the differential equation for a thermal branch network defines the transient response of a section of the building's envelope. Let the heat flow path described above be designated as the kth path of a given building (lower case <u>k</u> to distinguish it from heat conductivity, <u>K</u>). Define the total time constant of the kth path as τ_k. The temperature at the interior layer of the path as shown is then T_k. The thermal response functions of each path are assumed to be linear, stationary, and to obey the principle of superposition.

This section derives approximations that characterize the time-varying change of the internal path temperature, T_k, as a function of changes in T_{ext}. The results are applied to binned meteorological data for purposes of simulation. The next section relates this transient response to the computation of interior temperature of the structure.
The following modification of the diagram shown above introduces equivalent-circuit notation for the thermal path. Note that the exterior surface is assumed to be at the exterior temperature, T_{ext} .

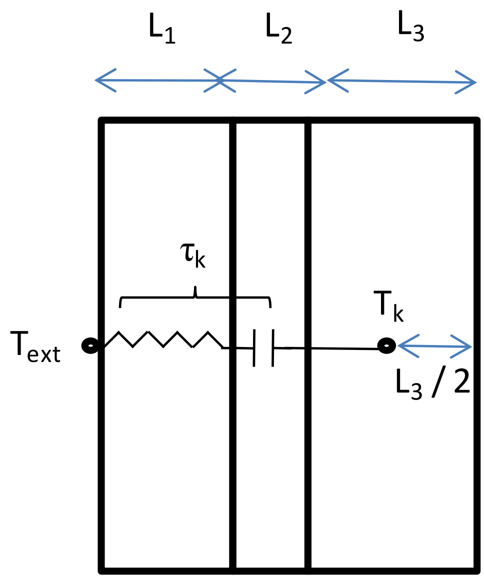


Figure 4.2.2 Details of thermal time constant derivation

This temperature of this section of the building's envelope is derived from Fourier's equation. The laplacian of the temperature field is equal to a factor of density multiplied by specific heat capacity divided by conductivity and multiplied by the time rate of change of the temperature. To simplify notation, let Tk = T in the following equations.

$$\nabla^2 T = \frac{\rho\, c}{K} \frac{\partial T}{\partial t}$$

Eqn (4.2.2)

The situation is simplified by assuming one-dimensional heat flow per section of building envelope and that there are no other thermal sources other than T_{ext}.
Accordingly, with the first round or re-arrangement of terms,

$$\frac{\partial}{\partial x}\left(\frac{K}{\rho\, c} \frac{\partial T}{\partial x}\right) = \frac{\partial T}{\partial t}$$

Eqn (4.2.3)

The units of either side of this equation are ^{o}F/hr.
In the second re-arrangement of terms,

$$\frac{\partial}{\partial x}\left(\frac{\partial T}{\partial \left(x/K\right)}\right) - \rho\, c \frac{\partial T}{\partial t} = 0$$

Eqn (4.2.4)

A linear approximation of the exact differential yields

$$d\left(\frac{\partial T}{\partial\,(x/K)}\right) - \rho\, c\, dx\,\frac{\partial T}{\partial t} = 0$$

Eqn (4.2.5)

The units of (x/K) are identical to those of thermal resistance, hr ft^2 ^oF/Btu. The units of (ρ c dx) are taken as those of thermal "capacitance," Btu/ft^2 ^oF.

Collecting the terms R for thermal resistance and C for thermal capacitance, and adopting a finite-difference approximation,

$$\frac{T_{ext} - T_k}{R} - C\,\frac{d\,T}{d\,t} = 0$$

Eqn (4.2.6)

The value of the product RC is to be understood as being equivalent to the thermal time constant τ_k as developed by the convention associated with Figure 4.2.2. The next re-arrangement of terms gives the following ordinary first-order differential equation:

$$T_k + \tau_k\,\frac{d\,T_k}{d\,t} = T_{ext}$$

Eqn (4.2.7)

The solution to this differential equation is the familiar exponential growth relationship, obtained by integration of the following form:

$$\tau_k \int \frac{1}{T_{ext} - T_k}\, d\,T_k = \int d\,t$$

Eqn (4.2.8)

Substituting variable u = (T_{ext} - T_k) and noting that du / dT_k = -1, the general solution is

$$-\tau_k \ln(T_{ext} - T_k) = t + A$$

Eqn (4.2.9)

where A is a constant to be evaluated based on initial conditions.

The solution will be cast in a form that is convenient for working with binned meteorological data. This data will be treated as a time series of step functions of T_{ext} that "drive" the system. An elementary approach will be based on the following graphic.

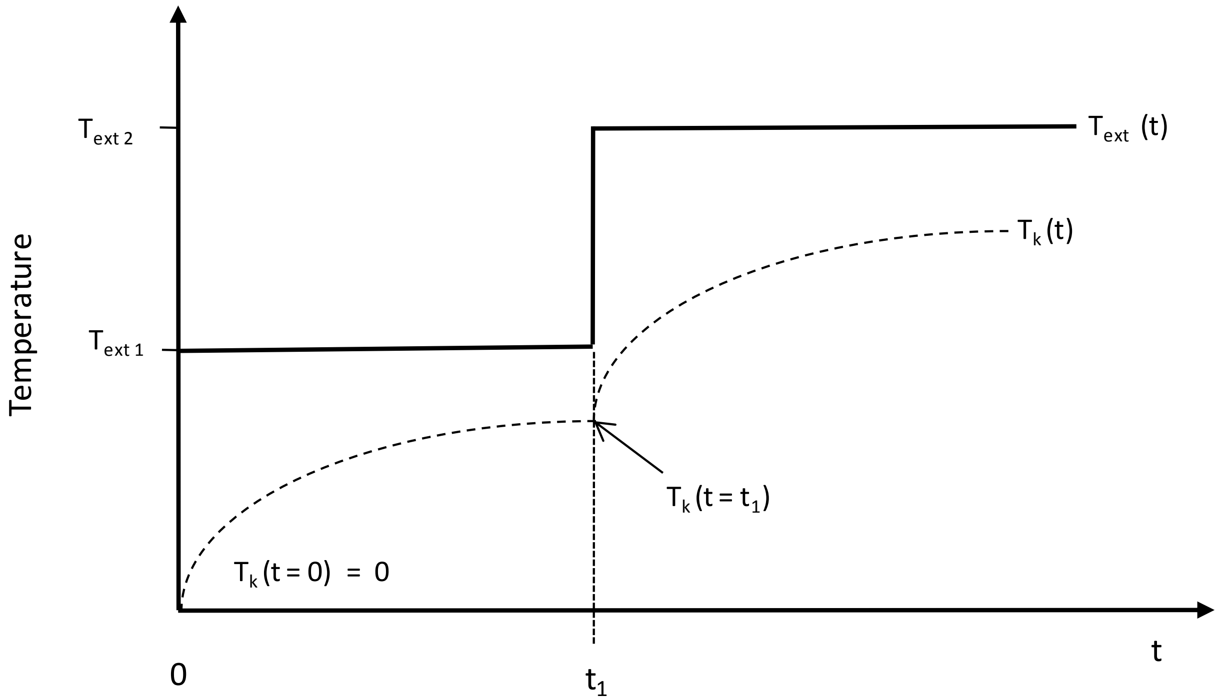


Figure A4.2.3 Convention for the time variable in transient responses

The plot shows the two temperature functions of interest, T_{ext} and T_k, as functions of time. At $t < 0$, both temperatures start out at zero. This arrangement illustrates the basic exponential growth process. Namely, a sudden transition of T_{ext} to a value $T_{ext\,1}$ at $t = 0$ initiates exponential growth of T_k.

At a time $t = t_1$, T_{ext} step-changes to a different value, $T_{ext\,2}$. Because heat energy cannot leave the thermal mass instantaneously, T_k must start exponentially changing from its value at $T_k(t = t_1)$.

Table 4.2.1 lists a set of interpretations for key variables in Eqn (4.2.9) that are convenient for describing the functions shown in Figure 4.2.3.

Table 4.2.1 Time variable interpretations

Variable in Eqn (4.2.9)	Interpretation
T_{ext}	Source temperature, equal to the value of T_{ext} at the step change
t	Time *elapsed* since the step change in T_{ext}

In the time interval $0 \le t < t_1$, source temperature $T_{ext} = T_{ext\,1}$ at the step change, and the time elapsed since the step change is simply $(t – 0) = t$. $T_k(t = 0) = 0$, and the solution for <u>A</u> in Eqn (4.2.9) becomes

$$A = -\tau_k \ln(T_{ext\,1})$$

Eqn (4.2.10)

and the solution to Eqn (4.2.7) becomes

$$T_k(t) = T_{ext\,1}\left(1 - \exp\left(-t/\tau_k\right)\right), \quad 0 \le t < t_1$$

Eqn (4.2.11)

The conventions listed in Table 4.2.1 are better illustrated in the time interval $t_1 < t$. The source temperature at the step change is now $T_{ext} = T_{ext\ 2}$. The time elapsed since the step change is now ($\underline{t - t_1}$). The value of T_k at the step change is found by direct solution of Eqn (4.2.9) at $t = t_1$ and will be designated as $T_k(t_1)$. The solution for $\underline{A}$ in Eqn (4.2.9) becomes

$$A = -\tau_k \ln\left(T_{ext\ 2} - T_k(t_1)\right)$$

Eqn (4.2.12)

giving the solution to Eqn (4.2.7) as

$$T_k(t) = T_{ext\ 2} + [\,T_k(t_1) - T_{ext\ 2}\,]\, exp\left(\frac{-(t - t_1)}{\tau_k}\right), \quad t_1 \le t$$

Eqn (4.2.13)

These solutions check with the observations that for $t_1 >> \tau_k$, $T_k(t_1) \approx T_{ext\ 1}$, and that for $(t - t_1) >> \tau_k$, $T_k(t) \approx T_{ext\ 2}$.

The solution offered by Eqn (4.2.13) may be generalized to any time of step change t_i if the time-series of values of T_{ext} are known and if the value of $T_k(t_i)$ at the time of the step change is known.

4.3 Kirkoff's Law Using Fourier's Equation for Computation of Interior Air Temperature

The time-varying internal temperature of a section of building envelope has been defined as $T_k(t)$in the previous section. This section derives an expression for the contribution of $T_k(t)$ to the interior temperature, $T_{int}(t)$, of the whole building in the absence of other inputs.

Returning to the example of the three-layered section in Figure 4.2.2, the problem is one of computing $T_{int}(t)$ under the conditions shown in Figure 4.3.1.

Fourier's equation may now be re-visited. By H&F's convention, the density term ρ of Eqn. 4.2.5 vanishes for the last half of the most interior layer of the building section (it is assumed to be mass-less). This removes the time-varying term for temperature T from the equation. The units of (x/K) remain those of thermal resistance (hr ft^2 ^oF/Btu).

The remaining terms of Eqn. 4.2.5 thus reduce to $(T_k - T_{int})/R_k$. This is the thermal "current" exchanged between the building section and the interior of the whole building.

The model now invokes Kirchoff's current law: The sum of the thermal currents entering and leaving the common "node" at T_{int} must be equal to zero. Before quantifying that sum, note that the ratio of temperature to thermal resistance has units of (Btu/hr)/ft^2. *Total power* through the k^{th} section of building envelope is found by multiplying the quantity $[(T_k - T_{int})/R_k]$ by its total interior surface area, A_k (ft^2).

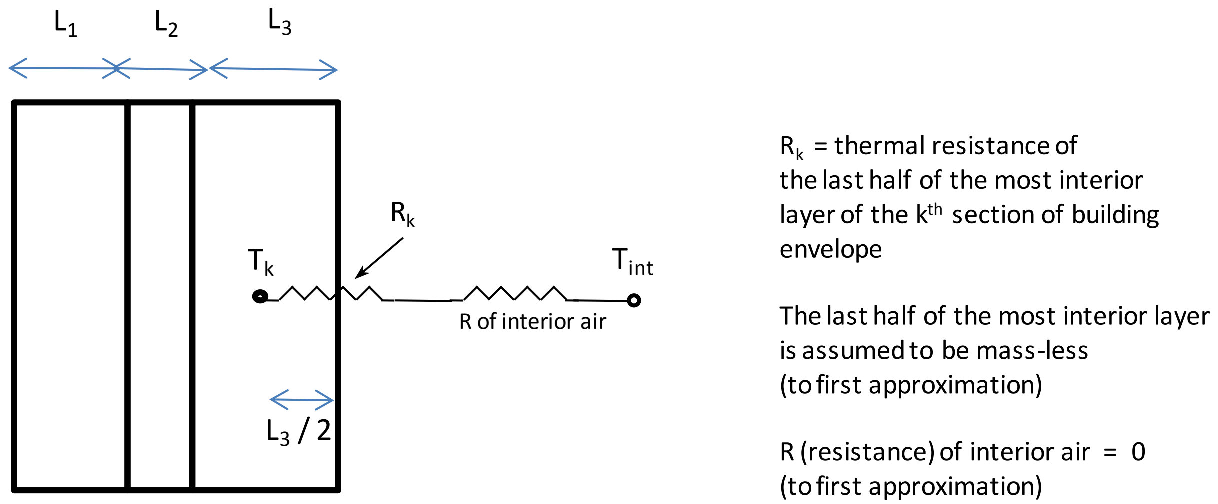


Figure 4.3.1 Conventions for the relationship between section interior temperature and indoor air temperature

Kirchoff's relationship then becomes:

$$\sum_k \left[\frac{T_k(t) - T_{int}(t)}{R_k} \; A_k \right] = 0$$

Eqn (4.3.1)

The model stipulates that T_{int} must be the same for each term of this series, giving the final result for interior temperature of the whole building:

$$T_{int}(t) = \frac{\sum_k \frac{A_k}{R_k} T_k(t)}{\sum_k \frac{A_k}{R_k}}$$

Eqn (4.3.2)

where $T_k(t)$ was developed in the previous section.

4.4 Ground Temperature Model

- "Deep earth" temperature was taken from an approximation commonly used for first-order analysis
- This ground temperature, Tgnd, acts through the foundation of the structure in the same way that Text acts outside and through the envelope as shown in Figures 4.2.2 and 4.3.1
- A 6" thick concrete slab was assumed for the foundation of the "reference" greenhouse (this should be replaced by a model of loose moist soil for the next iteration)

Source: CBD-180. Ground Temperatures, G.P. Williams, L.W. Gold July 1976
http://irc.nrc-cnrc.gc.ca/pubs/cbd/cbd180_e.html

$$T(x,t) = \overline{T} + A \exp\left[-x\sqrt{\frac{\pi}{\alpha t_o}}\right] \cos\left[\frac{2\pi t}{t_o} - x\sqrt{\frac{\pi}{\alpha t_o}}\right]$$

Eqn (4.4.1)

T(x,t) = ground temperature as a function of depth below surface (x) and time (t)
T bar = average annual temperature
A = peak temp minus Tbar (= Tbar minus min temp); the annual "half temperature" excursion
α = soil thermal diffusivity term (K/Cv)
to = term of period over the year

The values adopted for the model are as follows:

Table 4.4.1

Variable	Value	Units & Notes
T bar	40	deg F; per TMY3 data ADK Regional
A	30	deg F; per TMY3 data ADK Regional
α	0.0125	avg of wet clay & sand (typical upstate NY conditions)
To	365	Days
X	4	Feet

4.5 Calculation of Insolation on Exterior Surfaces
This calculation uses the conventions introduced in:
M. Stiles and W. Marzano, "Open Source Calculations of Insolation on Photovoltaic Arrays" Energy Engineering Vol 107 No. 3, 31-50, 2010
Key features:

- Uses TMY3 hourly data for the central Adirondack (NY) region
- Computes total insolation (Btu/hr/ft^2) on a surface of a given orientation (direct beam, diffuse, ground-reflected)
- Assume that all wavelengths are converted to thermal energy at the greenhouse's surfaces
- Used to compute hourly incident insolation at walls and windows

4.6 Exterior Solar Gain
H&F's model uses a variation of the concept of the "sol-air temperature" (ASHRAE Fundamentals 2005, Ch. 30 "Nonresidential Cooling and Heating Load Calculations," pg. 30.22). Heat balance at an exterior sunlit surface gives the heat flux into the surface q/A (in Btu/hr ft^2)as

$$q/A = \alpha I + h_o(T_{ext} - T_s) - \varepsilon\Delta r$$

Eqn (4.6.1)

where

α = absorptance of surface for solar radiation
I = total solar radiation incident on surface, Btu/hr ft^2
h_o = coefficient of heat transfer by long-wave radiation and convection at outer surface; typical value 3 Btu/hr ft^2 ^oF
T_{ext} = exterior air temperature, ^oF
T_s = surface temperature, ^oF
ε = hemispherical emittance of surface
Δr = difference between long-wave radiation incident on surface from sky and surroundings and radiation emitted by blackbody at exterior air temperature, Btu/hr ft^2

Express the rate of heat transfer in terms of an equivalent sol-air temperature, $T_{sol\text{-}air}$, at the external surface,

$$q/A = h_o(T_{ext} - T_{sol\text{-}air}) \quad \text{Eqn (4.6.2)}$$

Combining the last two equations gives

$$T_{sol-air} = T_{ext} + \frac{\propto I}{h_o} - \frac{\epsilon\,\Delta\, r}{h_o} \quad \text{Eqn (4.6.3)}$$

ASHRAE's convention is that the contribution of long-wave radiation from the sky is negligible for vertical surfaces, i.e. $\varepsilon\Delta r = 0$ for vertical walls. To a first approximation it will also be assumed to be negligible for the sloping north roof (which doesn't receive sunlight for much of the year anyway).
The goal is to compute the value of the exterior temperature of the kth surface, T_{sk}. The quantity T_{sk} will then replace the quantity T_{ext} in Figure 4.2.2. All other aspects of the derivation remain the same for computation of the inner temperature of the section of the envelope, T_k. Similarly, the contribution of T_k to the building's interior temperature remains the same as in Section 4.3.
H&F's model defines the net exterior surface temperature as

$$T_{sk} = T_{ext} + \Delta\text{Text solar gain\_k} \quad \text{Eqn (4.6.4)}$$

Their convention for the increment of the kth surface's temperature due to solar radiation is:

$$\Delta T_{ext\ solar\ gain\_k}(t) = \frac{\alpha_k\ \Delta I_{sk}}{h_o + \left({}^{1}\!/_{R_s}\right)\ \exp\left(-\Delta t/\tau_k\right)} \quad \text{Eqn (4.6.5)}$$

The total time constant of the kth section of the building, τ_k, is defined in Section 4.2. ΔI_{sk} is a step change in incident solar irradiance and follows Section 4.2's conventions for step changes in inputs: Δt is the time since the last step change in I_{sk}. Step changes in solar irradiance and exterior temperature are assumed to occur simultaneously.
R_s is an adjustment factor that reconciles time-varying external surface temperature with the thermo-physical properties of a section of building. H&F define R_s as the ratio of the building section's heat capacity *per unit area of external surface* and its time constant.

If there are n layers in the building section, the heat capacity per unit area is taken as ($L_1\rho_1c_1$ + $L_2\rho_2c_2$ + … + $L_n\rho_nc_n$) where L is the thermal path length (ft), ρ is density (lb/ft^3), and c is specific heat capacity (Btu/lb ^{o}F). The time constant is as defined in Section 4.2.

H&F's exponential term in Eqn (4.6.5) was omitted in the present simulations for the following reasons:

- The principal building sections under consideration are the walls and roof. Their time constants were found to be on the order of tens of hours or longer (see Addendum). The insolation data used for the present simulations is supplied in hourly bins. For any given hour, the exponential term in Eqn. (4.6.5) does not change by much from unity.

- Calculations of ($1/R_s$) from the information supplied in the Appendix show it to be an order of magnitude smaller than the ASHRAE-supplied value of h_o = 3 Btu/hr ft^2 ^{o}F.

The increment of the kth surface's temperature due to solar radiation was thus defined as:

$$\Delta T_{ext\ solar\ gain\_k}(t) = \frac{\alpha_k\ I_{sk}\ (t)}{h_o}$$

Eqn (4.6.6)

where I_{sk} (t) is interpreted as the solar irradiance on the kth exterior surface for a given hourly time bin. The step function introduced in Eqn(4.6.6) is thus one of a change from the absence of solar irradiance.

The contribution of wind to surface temperature of a building section was not modeled. This may tend to overestimate the computed value of surface temperature.

4.7 Insolation Through Windows

Insolation to the interior through a window in Btu/hr, is taken as Itlt * A * SHGC * LF, where:
Itlt is irradiance on tilted surface as described in Section 4.5
LF = "loss factor," taken as solar absorptance of the window (AHSRAE Ch 30 Nonresidential Cooling & Heating Load Calcs Eqn. 21). LF = 0.85 per Ch. 31 Fig. 18
A = area of window
SHGC = Solar Heat Gain Coefficient (from AHSRAE Fundamentals 2005 Ch 31 Fenestration Table 13). For 1/4" clear single pane glass, the average SHGC over range of incidence angles is ~ 0.6; hemispherical diffuse value ~ 0.7; total SHGC for greenhouse calculations = 0.65

- This is a gross simplification of heat transfer through fenestration.

- The interior solar gain at any given hour is the sum of input through all windows, denoted as ΣIwindows in Figure 3.1

- Automated window shutters diminish night-time envelope losses; when the shutters are closed, the simulation changes the R value of fenestration and sets the SHGC to 0.

- Fenestration Shutter Schedule:

Table 4.7.1 Fenestration Julian Dates

	From	To	Calendar Dates
Early Year	1	120	Jan 1 - Apr 30
Late Year	274	365	Oct 1 - Dec 31

Table 4.7.2 Fenestration Closure Schedule (military time)

	From	To
a.m.	00:00	8:00
p.m.	18:00	24:00

4.8 Interior Solar Heat Gain and Interior Temperature

H&F modeled interior solar heat gain as an increment in interior temperature. The solar heat gain increment acts as an exponentially time-varying quantity through the various sections of the building envelope between the interior and exterior.

H&F's basic proposition is that each interior section of a building's envelope contributes an increment in interior air temperature as it absorbs interior solar heat gain. This follows from their assumption that all of heat transfers are independent of each other and add linearly.

For the kth section of envelope, the equilibrium increment in interior temperature is the total interior solar heat gain (in Btu/hr) divided by Ak/Rk,tot where Ak is section area and Rk,tot is the total thermal resistance between interior and exterior (note the units resolve to temperature). Total thermal resistance is taken to be:

$$R_{k,tot} = R_{oi} + (\Sigma R)_k + R_{oe}$$

Eqn (4.8.1)

Where Roi, Roe are the reciprocals of the interior and exterior surface conductances to air, respectively, and (ΣR)k is the sum of the total thermal resistances of the layers in the envelope section.

Note the difference between (ΣR)k and Rk as defined in Section 4.3. (ΣR)k is simply the sum of each layer's thickness multiplied by its thermal resistivity (expressed in R per unit thickness).

The following additional conventions were introduced to H&F's in order to model the reference greenhouse:

- The fraction of interior insolation that is absorbed by the thermal storage mass is subtracted from the total entering through the windows.

- It is assumed that the fraction of the remaining interior insolation incident on each section of the building's envelope is equal to that section's fraction of the total interior area. For example, the roof has an interior face area of 600.92 square feet, which is 26% of the total interior face area. 26% of the available interior insolation is thus assumed to be incident on this section of the envelope.

- The quantity of insolation incident on a given section of envelope is multiplied by that section's absorptance. This factor was found to be an empirical approximation and is a matter of ongoing research.

Combining these conventions with H&F's formulation, let the asymptotic interior solar heat gain of the kth section of envelope be defined as:

$$\Delta\text{Tint solar gain\_k} = \frac{\sum Iwindows \;\; x \;\; {}^{A_k}/_{\sum A_k} \;\; x \;\; solar\ absorptance_{\_k}}{{}^{A_k}/_{R_{tot\_k}}}$$

Eqn (4.8.2)

The time-varying value at a time t is then given as:

ΔTint_int solar gain_k (t) = ΔTint solar gain_k (t) + [(ΔTint_int solar gain_k (t1) - ΔTint solar gain_k (t)) x exp(- (t-t1) / τk)]

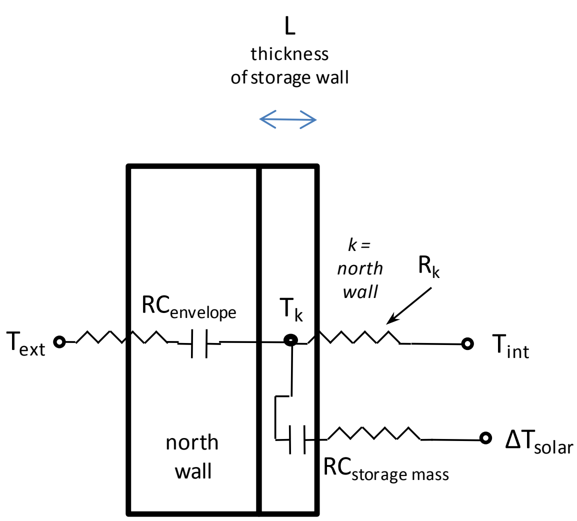
Eqn (4.8.3)

where the time variables t, t1 follow the conventions described in Section 4.2. The total increment in interior air temperature is then taken as the sum of all the ΔTint_int solar gain_k .

4.9 Storage Mass Solar Gain

The formulation presented here is a variation of H&F's model of heat gain at a surface due to insolation. The original H&F model assumes that all of the solar irradiance admitted through the windows directly heats the interior air mass. In the present model, a portion of the interior solar irradiance is absorbed and stored by the north wall's mass.

The internal temperature of the north wall will be a function of both exterior insolation through the envelope (via Eqn (4.6.6)) and interior insolation via the storage mass. The conventions for computing temperature changes in the storage mass are explained in the following figure.



R_k = thermal resistance of the interior half of the thermal storage mass; same as for the most interior layer of the north wall

$RC_{envelope}$ = time constant of the portion of the north wall excluding the thermal storage mass

$RC_{storage\ mass}$ = time constant of the portion of the storage mass that absorbs and releases heat from solar irradiance admitted through the windows

ΔT_{solar} = increment in temperature of T_k due to an increment of solar irradiance admitted through the windows

Figure 4.9.1 Thermal storage mass model

Note that this model places the internal temperature node, Tk, for the entire north wall assembly at the center of the thermal storage mass. The thermal model of the storage mass thus incorporates the conventions for Tint delineated in Sections 4.2 and 4.3.
Referring to Figure 4.9.1,

$RC_{storage\ mass}$ = [(1/heat transfer coefficient at interior surface[1]) + ($R_{storage\ mass}$/2)] x
thickness of storage wall x storage mass density x storage mass specific heat

Eqn (4.9.1)

$R_{storage\ mass} = 2\ R_{k\ =\ north\ wall}$

Eqn (4.9.2)

ΔT_{solar} = [(insolation through windows, Btu/hr) ÷ (storage mass face area / R_k)] x
(% interior solar irradiance absorbed by storage mass) x (solar absorptance of storage mass)

Eqn (4.9.3)

In the last equation, the insolation through windows is defined in Section 4.7. The percentage of interior solar irradiance absorbed by the storage mass is taken simply as the fraction of the total interior surface area (including the floor) occupied by its face area. The solar absorptance of the blackened storage mass is taken as 0.9.
Two time-varying temperatures sum at the T_k node shown in the figure. One is due to T_{ext} acting through $RC_{envelope}$ as described in Sections 4.2 and 4.6. The other term $\Delta T_{storage\ mass}$ is an incremental change to the first term. $\Delta T_{storage\ mass}$ at a time t is then given as:

$$\Delta T_{storage\ mass}(t) = \Delta T_{solar}(t) + [\Delta T_{storage\ mass}(t_1) - \Delta T_{solar}(t)] \exp(-(t - t_1) / RC_{storage\ mass})$$

Eqn (4.9.4)

where the conventions for the time variables are defined in Section 4.2.

A.5 SELECTED RESULTS

5.1 *Preliminary assessment of how much non-window envelope insulation is needed with minimal storage mass to moderate extreme winter swings in interior temperature*

Early results show that envelope insulation of R20 to R25, combined with a 4" thick masonry storage mass at the north wall, moderates interior temperature swings. This will be designated the "minimal configuration" for a greenhouse design.

5.2 *Quantify the contributions of deep-earth coupling and solar gains to interior temperature of the reference design*

Given the minimal configuration, the average daily exterior and interior temperatures were computed using only (a) exterior temperature and (b) deep earth temperature as input to the greenhouse through the floor. These calculations excluded all other sources including exterior solar gains. The results are plotted in Figure 5.2.1:

[1] Typical R value for interior surface heat transfer is 0.68, see http://www.p1m.com/rv.htm

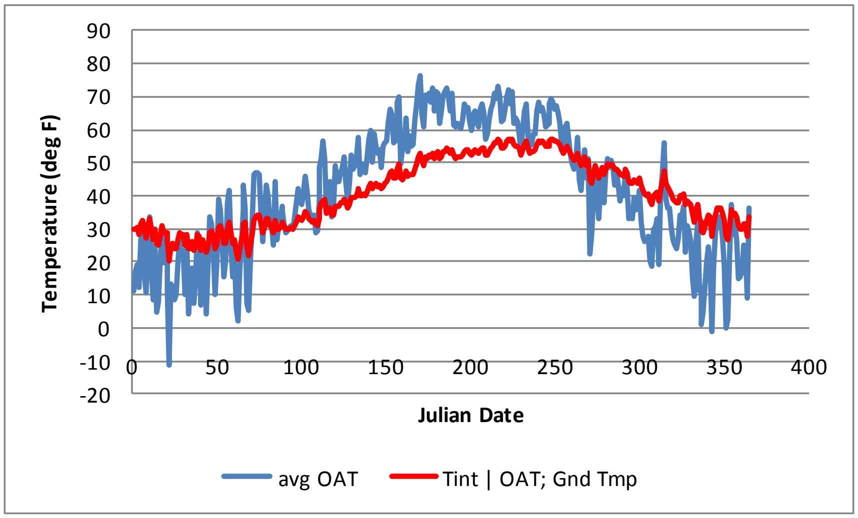


Figure 5.2.1 Exterior and interior daily temperatures, deep-earth coupling and operable shutters only; OAT = outdoor dry bulb air temperature; Julian date 1 is January 1, 365 is December 31

It is seen that average interior temperature falls near or below freezing for a significant portion of the heating season. Coupling the structure to deep earth temperature alone is insufficient for maintaining interior temperatures suitable for crop growth. This is attributable to the presence of large areas of fenestration, which lowers the overall R-value of the structure. This suggests that the minimum configuration of greenhouse will require additional heating sources in regions where there is very little available sunlight.

5.3 *Check to make sure that operable insulating shutters contribute to maintenance of interior temperature*

The coldest day of the year in the data set used for the model was March 3. The following figure shows the hourly interior temperature trend with and without the shutters:

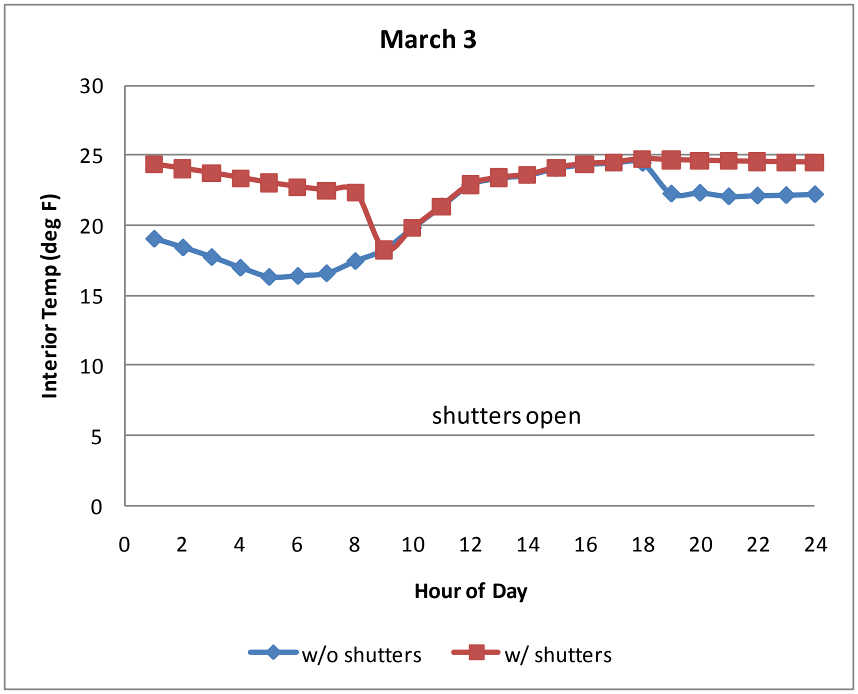


Figure 5.3.1 Impact of operable shutters on interior temperature

The shutters improve interior temperature by several degrees for the minimum configuration of greenhouse. This verifies the sensitivity of the model to this important design feature.

5.4 *Evaluate how increasing the thermal storage mass beyond best-practices recommendations moderates temperature swings*

Typical best-practices design does not recommend using more than 4" – 8" of masonry for the storage mass of a solar greenhouse [2]. Recommendations for envelope insulation are not well defined. The following simulations specifically address the combination of minimal insulation levels (R20-R25) with amount of storage mass in ways that the best-practice designs do not. Coldest-day-of-the-year hourly plots are given by Figures 5.4.1 and 5.4.2 for the cases of low storage mass (4" masonry) and of high storage mass (2' poured concrete), respectively.

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[2] http://attra.ncat.org/attra-pub/solar-gh.html#heat

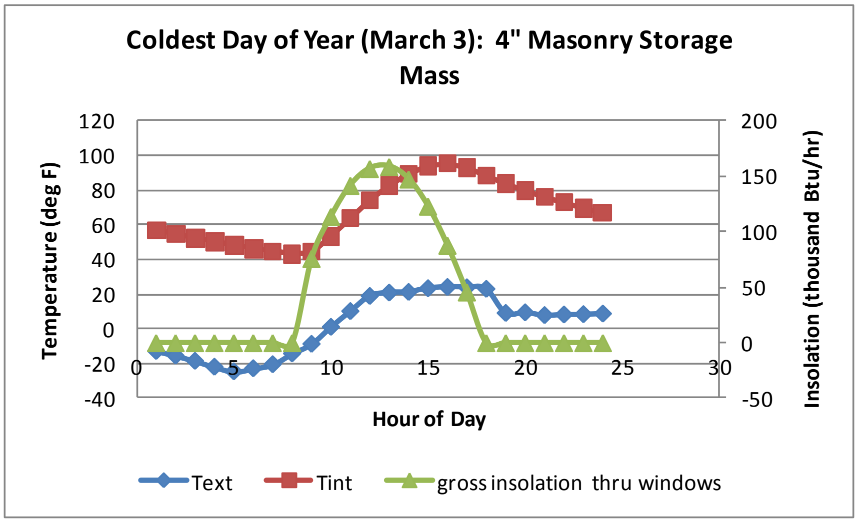

Figure 5.4.1 Low storage mass hourly values

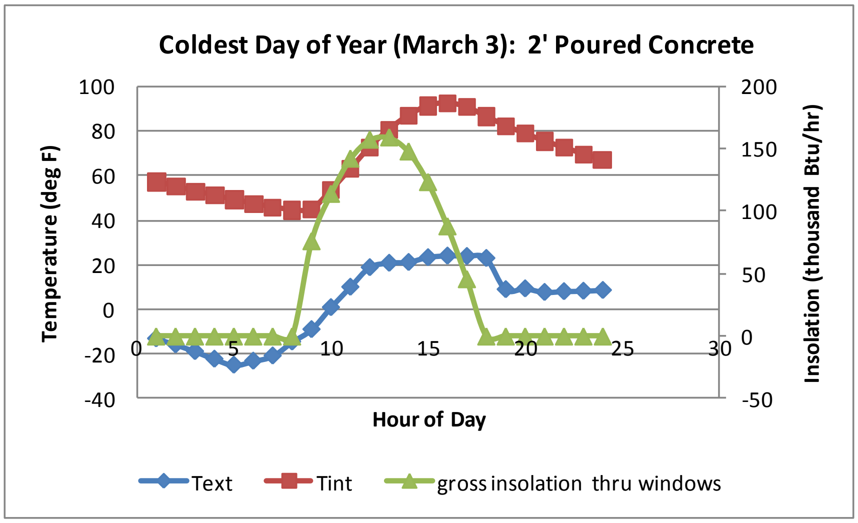

Figure 5.4.2 High storage mass hourly values

The minimum and maximum interior temperatures for the two cases are listed in Table 5.4.1.

Table 5.4.1

	Coldest Day of the Year Interior Temperature (deg F):	
Storage Mass	Minimum	Maximum
4" masonry	43.1	95.1
2' poured concrete	44.4	92.4

The larger thermal mass moderates interior temperature swings under these conditions by several degrees F. This represents a significant amount of energy moderation given the size of the structure and its bulk thermal capacity. It is anticipated that increasing envelope insulation will moderate the model's temperature swings even more.

Frequency histograms of hourly interior and exterior temperatures for the month of February are given in Figures 5.4.3 and 5.4.4.

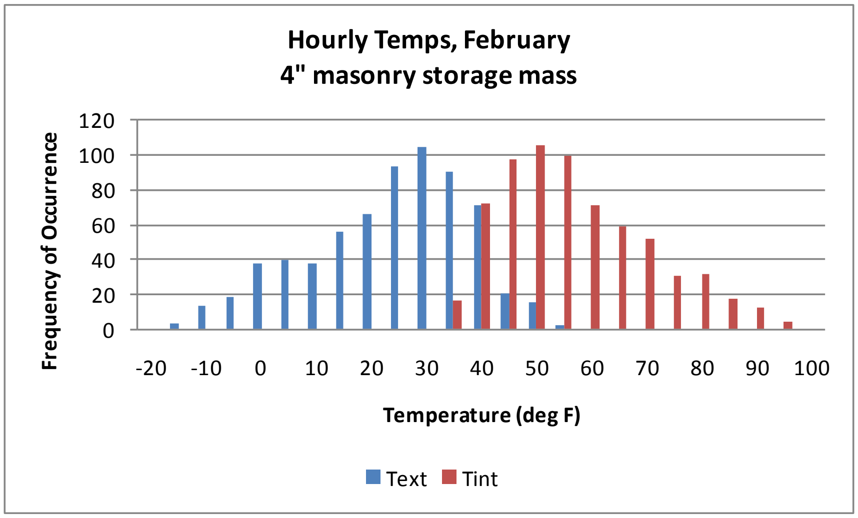

Figure 5.4.3 Exterior and interior February temperatures for low mass case

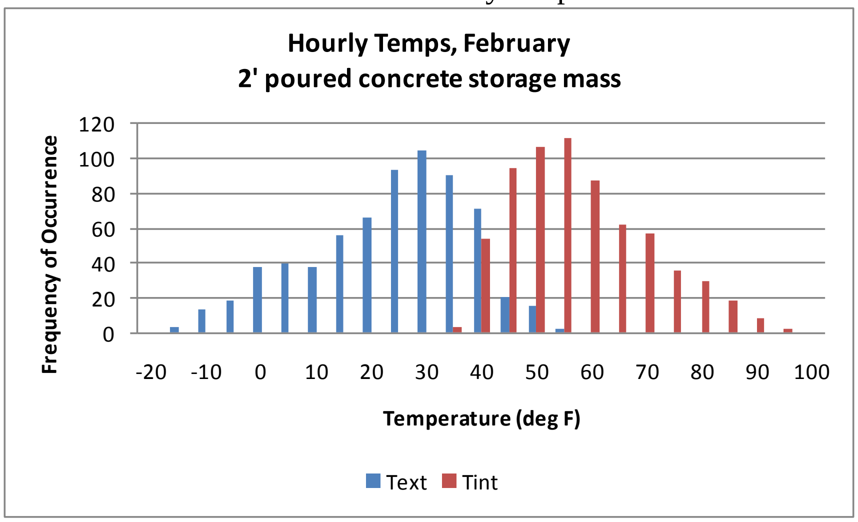

Figure 5.4.4 Exterior and interior February temperatures for high mass case

The high-mass case has a shift in frequency of interior air temperatures away from the 35-40 deg F range to the 55-70 deg F range compared to the low-mass case. These results suggest that even for present best-practice greenhouse design, a modest level of insulation results in good utilization of substantial storage mass. Optimal combinations of envelope insulation and storage mass for a given geographical location may be explored using this simulation model.

A.6 THE FUTURE OF MODELING

- Apply Synergistic Building Technology's design as input parameters to the model
- Refine models of geothermal (deep earth) and solar inputs to the system and calibrate to measured results
- Second generation of software coding, first generation design application
- Track actual performance against modeled
- Interface with whole-facility monitoring

Appendix B
Technical Terms

A handful of technical terms are used throughout this report, particularly as regards fenestration. This appendix gives more information.

A **British Thermal Unit (Btu)** is the energy needed to raise a pound of water a degree Fahrenheit (F). It follows that a million Btus (MBtu) is the energy needed to raise 100,000 pounds 10 degrees F. A MBtu is roughly the energy equivalent of a person year of labor. The table shows the relationship between costs of a MBtu of energy from various energy sources. Note that the most common raw material for generating electricity, coal, costs about a tenth as much as does the finished product.

Fuel	Unit	Btu/Unit	Cost/ Unit	$/MBtu
Coal	Ton	28,000,000	$90	$3.21
Crude Oil	Barrel	6,300,000	$60	$9.52
Heating Oil	Gallon	140,000	$2.60	$18.57
Propane	Gallon	92,000	$1.75	$19.02
Gasoline	Gallon	125,000	$2.60	$20.80
Natural Gas	Therm	100,000	$1.10	$11.00
Electricity	kWh	3,412	$0.110	$32.24

Solar heat gain coefficient (SHGC) is the fraction of solar heat transmitted through a window system (plus absorbed energy that ends up supplying heat inside) with respect to the amount of solar heat that would flow through an unimpeded opening of the same size. It is a dimensionless number that can range between 0 and 1. SHGC's of clear single and double-glazed window systems run from 0.7 to 0.9, whereas windows with spectrally- selective glazings typically run from 0.2 to 0.5.

Visual transmittance (V_t) is the fraction of visible light transmitted through a window system with respect to the amount of visible light that would flow through an unimpeded opening of the same size. It is also a dimensionless number that can range between 0 and 1. V_ts of clear single and double-glazed glass run from 0.8 to 0.9, whereas heavily-tinted glass can have a V_t of 0.1 or even lower. Double-glazed spectrally-selective glass typically runs from 0.4 to 0.7 V_t.

The **conductivity** of window systems, the **U-factor**, is its heat transfer coefficient. It is the measure of choice in rating window systems. The lower the U-factor, the better a window insulates. The U-factor is the reciprocal of R-value and is the rate of heat loss through a window *system* (which counts its frame) measured in Btu per hour per square foot per degree Fahrenheit (Btu/h-ft^2-°F). **U-value** has the same units, but refers to the conductivity through the center of glass only. Unlike the ratings for insulation products, window U-factors and U-values include the effects of indoor and outdoor air films.

Appendix C
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Marc Plinke gathered and analyzed the performance data for Sections 3 and 4 of this report. He is the President of Synergistic Building Technologies. Marc has worked in industry for all of his two-decade long professional career. He worked both in the laboratory developing new products and as a new business developer for several environmental products all of which as still being sold today. Marc is a co-holder of five patents and has given more than 100 presentations worldwide. Marc holds doctorates in engineering from both the University of Karlsruhe in Germany and the University of North Carolina at Chapel Hill. He lives in Boulder with his family in a 1961 house that he and his wife have renovated into a beautiful net zero energy home. Having a net-zero greenhouse and an electric vehicle are next on his dream list.

Michael Stiles wrote Appendix A of this report, an analysis of greenhouse transient response. He is a Senior Energy Specialist for MCW Custom Energy Solutions in Saratoga Springs, New York, the recently incorporated US branch of the Toronto-based MCW Group. His current assignments include a number of self-funding Energy Performance Projects and a pilot chiller plant commissioning project for the Ontario Power Authority. He has enjoyed working with Larry Kinney since 1990 on a wide variety of ground-breaking energy endeavors. He holds three patents in the field of solar energy and has professional experience in fields ranging from biomedical research to science education. He holds a Ph.D. in Biophysics from Syracuse University and is a Certified Energy Manager. Mike lives and works in Saratoga Springs, New York where he can often be found puzzling through obscure mathematics over a pint of Guinness or playing his guitar for the endless river of tourists.