Interim Report, Volume 1

Practical Green Greenhouse Development

A Joint Research and Development Project of

Synergistic Building Technologies

and

Cure Organic Farm

November 1, 2009

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Interim Report, Volume 1

Practical Green Greenhouse Development

Prepared by

Synergistic Building Technologies
and
Cure Organic Farm

Prepared for

The Colorado Department of Agriculture

Under

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N.B. All readers of this interim 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.

1335 Deer Trail Road Boulder, Colorado 80302 USA 303.449.7941 www.SynergisticBT.com

Table of Contents

Section Page

Appendix

Section 1
Introduction

This is a contractually-required interim report on 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. The project was launched by the research team in mid March, 2008 and is scheduled for 18 months. Appendix B of this report lists names and contact information of members of the research team.

Other project deliverables will be a final report detailing information necessary to design, build, and control greenhouses in Colorado-like climates to allow for year-round crop production with minimal carbon footprint. Additionally, a demonstration research and development greenhouse is being constructed, operated, and studied on Cure Organic Farm in Boulder County.

This report covers

- Background of the project and design principles
- Work completed, preliminary findings, and key accomplishments to date;
- Problems encountered and mitigating circumstances; and
- Next steps (with an updated project timeline).

The report is in two parts; this is Volume 1. Volume 2 is a Power Point presentation saved in PDF format. The presentation concentrates on describing the design problems inherent in most greenhouses which limit plant growth in cold months and require substantial quantities of fossil fuel energy to extend their useful growing seasons. It also describes the main design strategies our research team is invoking in the R&D greenhouse in hopes of improving growth and minimizing the use of non-solar energy.

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 cost $3 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.

In short, 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 possible;
- Control the flow of solar flux, both light and heat;
- Control the temperature and flow of air;
- Match the systems of the greenhouse to optimize plant growth.

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 the latter include older mobile homes and conventional greenhouses.

Time constants can be readily determined mathematically even without allowing a building to drift a full 37% of the indoor/outdoor temperature difference. Measuring the change in the time constant of a home is useful in evaluating the consequences of a weatherization job in which a home is air sealed and its walls and ceiling insulated. Frequently the time constant changes from 7 to 10 hours to over 24 hours by virtue of a well-done retrofit of a particularly wasteful home.

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 over heating 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.

The question, then is how to design a greenhouse with a long time constant. The answer is to insulate and add 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 of radiant losses 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/sq ft/degree 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 simpler glazing. (Appendix D 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 solar energy adequate 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. Enhance light and heat gathered by windows with highly reflective light shelves 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.

Make sure that all non-glazed surfaces of the greenhouse's thermal envelop are well insulated (R-20 or more). (Fully 80% of the surface area of the R&D greenhouse is non-glazed and well insulated. The remaining 20% of glazed areas have R values of 10 or more when insulating shutters are closed.)

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 fluxuations in temperature are usually only 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 greenhouse's operation. 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.

We plan to employ this strategy in the greenhouse along with several others.

For many years, the Chinese have successfully employed a technique through which warm air at the top of greenhouses is pulled through pipes to a plenum to which a network of other pipes buried in the soil are connected. The pipes in the soil (off-the-shelf, 4 inch PVC drainage pipes available from building supply merchants) are laced with holes and covered with a water permeable "sock" to prevent the influx of small creatures. The net effect is to move both heat and moisture into the soil—and back from it when needed. Indeed, by varying the fan speed and dampers as a function of the temperature and humidity of the air at the top of the greenhouse and the temperature and moisture content of the soil near the pipes, we plan to "tune" to a useful degree the mass under the greenhouse. The use of heavy perimeter insulation will enhance the ability to control this process.

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 1 and 2).

Figure 1. Stacked blocks form retaining wall. Note rebar hook in top middle.

Figure 2. Half blocks are also available.

As it works out, Boulder Ready Mix, which is only two miles from the construction site of the R&D Greenhouse, is selling us 2 x 2 x 6 foot blocks for $10 apiece (346 pounds per dollar!) Accordingly, a total of 84 of these blocks will be integrated into the foundation and the north wall. In both cases, R-20 insulation is used outside of this mass. The result is lower cost than alternative foundation and structural options, the ability to store a great deal of thermal energy, and increased likelihood of a long lifetime of the structure at modest maintenance expenses. Details of thermal calculations are in Table 2, page 16.

Finally, water is a very useful medium for storing and moving heat. It weights 62.4 pounds per cubic foot , has a specific heat of 1 Btu/lb/F, and, unlike air, lends itself to movement in closed loops where net losses are only frictional. (A useful analogy is the 120 year old cable car system in San Francisco where cable-clinging cars going down hill use gravity to provide energy to aid other cars going up hill.) This helpful property means that a small pump can transfer a good deal more thermal energy per unit of electric energy than can a fan motor moving air in an open loop.

Water can also be used to collect solar energy by the simple addition of India ink. Accordingly, we plan a small-scale experiment as part of the project through which simple collectors fabricated from twinwall polycarbonate are being fitted with plenums at their tops and bottoms, allowing blackened water to be heated by direct beam solar. Two inch polyisocyanurate insulation will be employed behind these simple collectors, yet thermal losses will not be significant since the collectors will be installed inside the greenhouse near the north wall where protection from freezing will not be necessary. Heat from the collectors will be transferred to insulated barrels, also within the greenhouse, either by thermo-siphoning or via small dc pumps depending on the relative arrangement of the collectors and barrels (storage must be above collection for thermo-siphoning to work). Finally, when needed, heat from the barrels will be transferred via heat exchangers to the bottoms of insulated seedling trays, also near the north wall. Suitably controlled, the water thus becomes “smart mass” and delicate seedlings may be kept warmer than are other plants in the greenhouse.

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, 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. 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. The thermostats controlling propane-fired furnaces in the hoop style greenhouses at Cure Organic Farm are set to fire the furnaces at 34F, and doors and side walls are partially opened on hot days to control high temperatures. Watering is also used in summer months not only to provide moisture for growth, but also to supply at least a modicum of evaporative cooling.

We are using a range of strategies for controlling solar flux in the R&D Greenhouse to optimize the environment for photosynthesis and healthy plant growth while controlling thermal losses and gains. Strategies include:

Two light shelves, one on the roof which is fixed; one in front of the south-facing windows that may be manipulated every few weeks as a function of sun elevation. Both are metal painted with high gloss white paint. They function to direct more light into the windows even as the sun approaches the east and west.

Overall window area will be relatively modest, but with glazing that has high Vt and SHGC. Modest window areas limit thermal losses; high transmission and extra flux from light shelves increases solar flux flowing to the inside of the greenhouse.

Insulating shutters automated to button up the thermal envelope on cold nights enable the use of low cost glazing and its accompanying high Vt and SHGC. Both shutter systems are equipped with highly reflective but Low E surfaces. When fully open, the swinging shutters in the roof tend to direct light downward to the earth and plants below. Both shutter systems can be manipulated to reflect solar flux back outside to the degree desired. This helps to control for overheating in summer. The shutters also play a key role in expediting a brief mid-winter freeze required for pest control by opening at night and closing during the day.

With the exception of the soil and plants themselves, most surfaces on the inside of the greenhouse are of highly-reflective gloss white. Thus most of the flux which falls on them will be reflected until the flux is absorbed by soil and plants.

We plan to experiment with varying the color of the paint used on the inside of some of the 40 concrete blocks on the north wall to study trade offs in increasing solar flux reflected onto plants and the soil (achievable by high gloss white paint) and increasing the solar flux absorbed by the wall (achievable by using darker paint).

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 owing 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. The system for moving air from the peak of the greenhouse to the soil underneath requires use of a multi-speed fan in a squirrel-cage housing. Further, sometimes fan power is necessary on hot muggy 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.

Separating the fan from the medium allows for more efficient use of the fan for ventilation and flexibility of cooling options. Both the fan and medium will use exterior moveable insulation so they can effectively be 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.

Controlling Systems to Optimize Plant Growth

In the subsection on thermal mass, we touched on the issue of treating seedlings differently from other plants in the discussion of using “smart mass” in the form of hot water heated by simple in-greenhouse solar arrays to keep seedling temperature above predetermined levels. This is one of many systems that must be manipulated in coordination with each other to optimize plant growth.

Controls for opening and closing dampers, actuating fans, blowers, and water pumps for evaporative cooling must be coordinated with weather conditions and the degree of opening of the shutters. This will be a matter of considerable analysis and likely much tinkering in the case of the R&D greenhouse, which will use a variety of sensors and manual controls for all operations except for the shutters, which will have both manual and automatic controls when the greenhouse is constructed. The idea is to learn as much as we can about optimizing the configurations of the systems in the R&D greenhouse as a function of weather conditions in order to optimize plant growth. Proposed phase 2 work will include further automating of all systems.

Section 3
Work Completed, Preliminary Findings, and Key Accomplishments

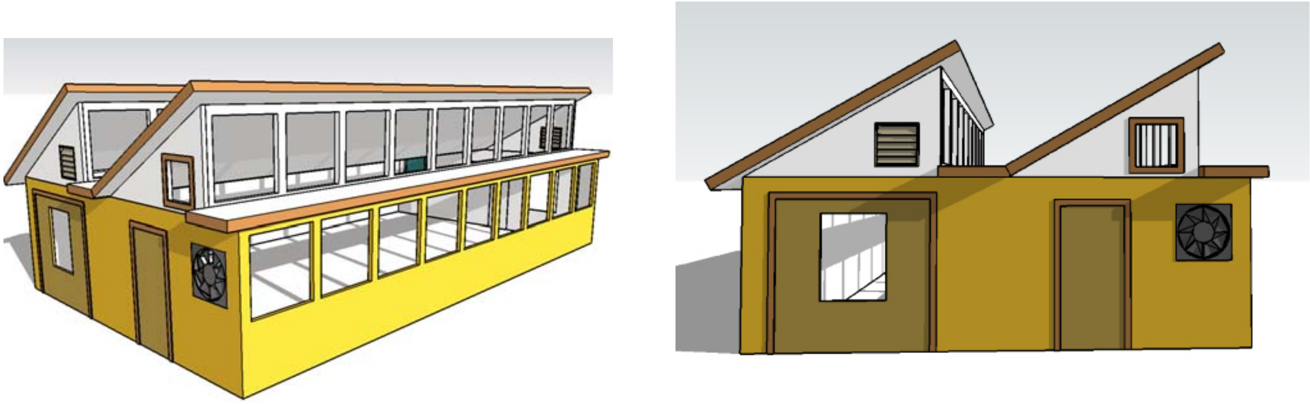
Design Work and Prototype Development

The principles discussed in Section 2 were applied to the design and research work that has been accomplished over the period covered by this report. The result is a set of drawings that have been submitted to Boulder County building officials to secure a building permit, the design, development, and testing of prototypes of two insulating shutter systems and associated controls, an analysis of energy performance of the structure, identification of suppliers and costing of building materials and components, and site preparation.

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 and 4.



Figures 3 and 4 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 painted high-gloss 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, necessitating 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

A reproduction of the full set of plans submitted to the Boulder County Building Department is included in Appendix A. 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's roughly 20 x 50 feet with most glazing facing due south.

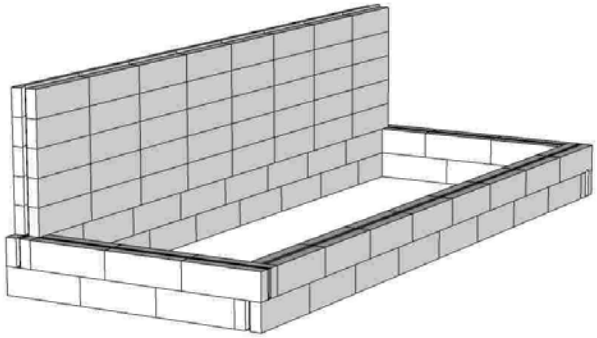
Figures 5 and 6 show the southwest and southeast elevations.

Figure 6. SE elevation.

Figure 5. 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.

The gross surface area is 2367 square feet of which 200 square feet are doors and 455 square feet are windows.

Figures 7 shows foundation and north wall details while Figure 8 includes the wall framing.



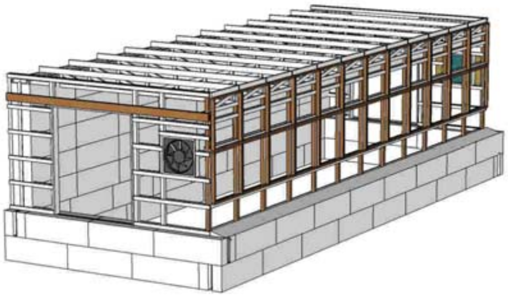
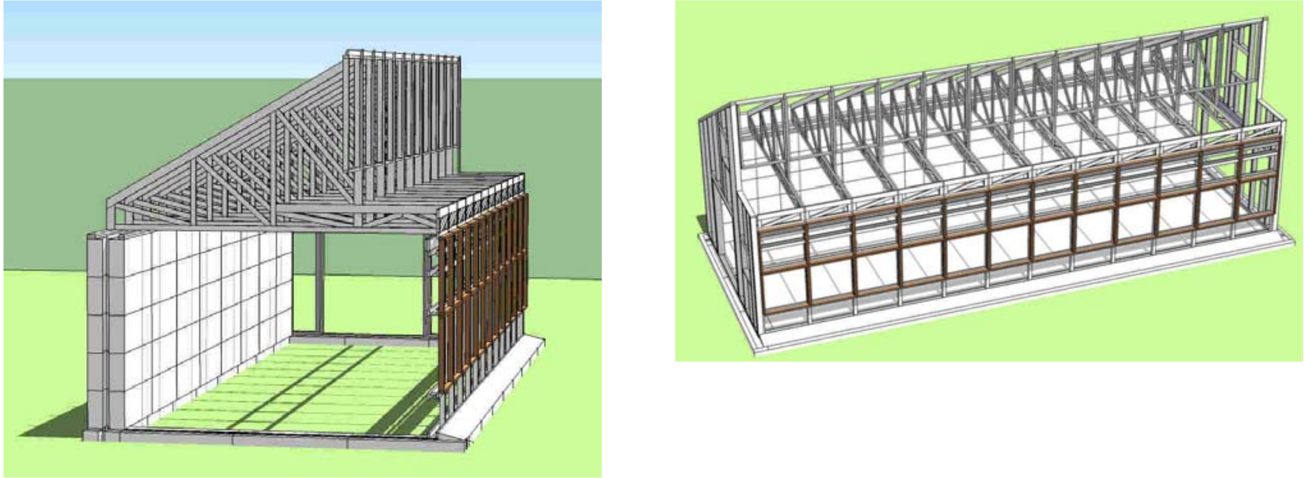


Figure 8. Foundation and wall framing.

Figure 7. Foundation and north wall blocks. These will have 4 inches of Styrofoam Blue Board™ (R = 20) covered by Hardy board or equivalent on the outside.

Note that the foundation blocks are interwoven while the north wall blocks are stacked. A reinforced concrete footer 30 inches wide and 12 inches deep with be poured under the foundation walls.

Figures 9 and 10 show 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 9 and 10. Prefabricated trusses on 48 inch centers.

Each window on the roof will be a nominal 4 feet by 6 feet and be divided into two clear single-glazed units. A single shutter consisting of two-inch thick polyisocyanurate insulating board stock bordered by a U channel of white PVC will be hinged at the top of the window frame allowing the shutter to be swung between the window frame immediately behind the glazing trough 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. A PVC “U” shaped channel surrounds the perimeter of the polyisocyanurate shutter panel. The channel stock provides strength and a clean surface to press against the urethane foam-filled 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 polyiso are made of low emissivity aluminum sheet which has good thermal and reflective properties, especially in the infrared.

The shutters are opened and closed by a dc gear motor that drives a 3/8 inch steel 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 Delrin nut attached to a sliding hinge mechanism at the bottom of the shutter rides the screw and thereby manipulates the shutter. Single pole double throw 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 11 and 12 show a proof-of-concept initial laboratory prototype of the swinging shutter.

Figure 11. This lab prototype allowed the far end of the drive shaft to move through an arc of its own.

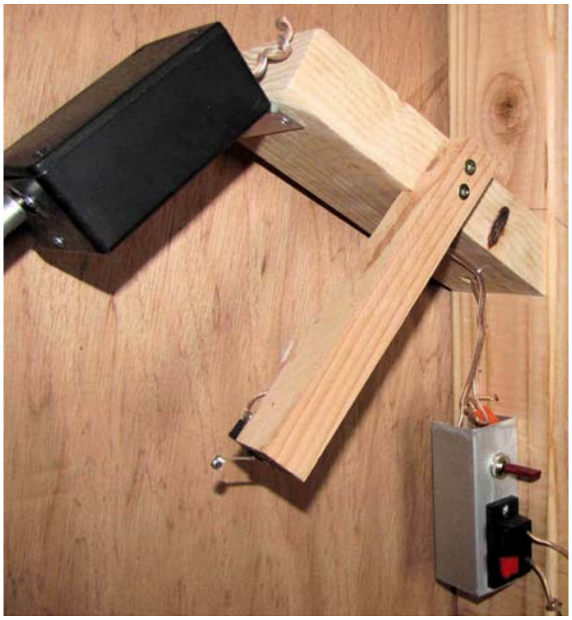


Figure 12. The short 2 x 4 simulates the slope of the roof. The gear motor is in a protective box. The “fully open” limit switch has a small roller that engages the shutter. The reversing switch (with the red handle) is fed by 12 Vdc. The motor draws about 8 watts.

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 uses a right-angle drive to rotate 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 fully open and fully closed positions of the shutter.

A 15.5 square foot prototype was fabricated and is presently being tested in SBT’s fenestration testing lab for U value when open and shut (Figures 13 and 14.)

Figure 13. Completed prototype in shop with shutter half way closed; a smiling engineer, Gary Cler.

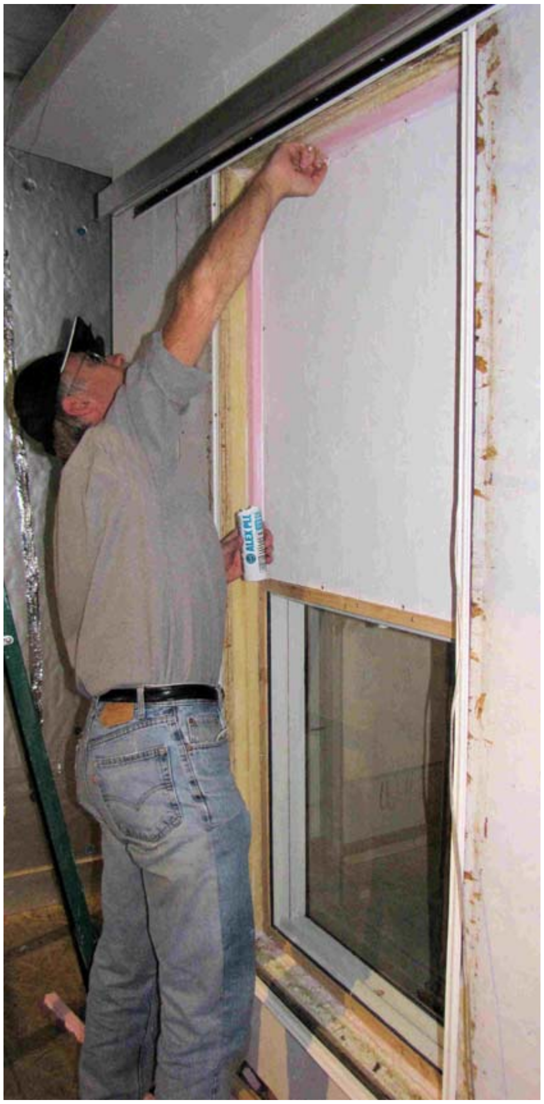


Figure 14. System being installed (and air sealed) in window testing lab, shutter in pocket.

Shutter Controller

We have designed and tested components of a controller to enable both the automatic and manual control of the 24 shutters on the facility. We have on hand electronic controller boards that were designed for the automatic operation of SBT's exterior insulating shutters. Two of these are being integrated into a master controller, one to automatically control the set of swinging shutters on the greenhouse roof; the other to control the pocket shutters on the south wall. These boards use the output of sensors that measure both outdoor temperature and sunlight falling on a south-facing horizontal surface close to the bank of shutters to determine the appropriate circumstances in which shutters should be opened or closed in order to optimize plant growth and energy efficiency.

With the greenhouse master controller, the output of the boards will be wired to trip an "all open" relay or an "all closed" relay. Either action will put 12 Vdc onto a buss with plus-to-minus or minus-to-plus as appropriate to drive gear motors connected to it clockwise or counter-clockwise. The pair of wires from each shutter motor will be connected to its own "auto/manual" switch. If in the auto mode, the shutter motor will be connected to the buss, where it and other shutter motors in the auto mode will be supplied with voltage from the buss when controllers call for shutters to be open or closed. If in the manual mode, each shutter motor will be disconnected from the auto buss and be operable by a reversing switch whose center position is off. Shutters in the manual mode will be able to be fully opened or closed via the manual switch or be stopped anywhere in between as desired. This will allow for testing various combinations of shutter operating configurations to study effects on light levels, energy, and growth.

LEDs will be employed to indicate the present status of each shutter. The control panel will be set up to correspond to the relative location of each shutter, with an upper row of 12 sets of switches and LEDs corresponding to the roof-mounted swinging shutters and a lower row with switches and LEDs corresponding to the south wall-mounted pocket shutters. The panel will be located close to the center of the greenhouse near the north wall. It will be fully enclosed to protect it from moisture and be powered by a 12 volt battery charged by a small PV array.

Site Preparation

The site chosen for the greenhouse is on the Cure Organic Farm next to a dirt road that has good access to the rest of the farm, including storage areas and a food distribution shed where participants of the community-supported agriculture come to pick up their shares of food each week. The site has excellent solar access and (unlike the other side of the road that is zoned commercial) is zoned agricultural. By state law, this means that structures of less than 1000 square feet can obtain building permits for a modest fee.

The site is close to an irrigation ditch; the northwest-most corner of the building will be about 23 feet from the ditch. Accordingly, care was taken to examine soil conditions down to seven feet below grade using the services of a soil engineer to examine the hole dug by "Farmer John" Ellis. As of the date of this report, all is well with the building site, but it remains to secure agreement on this issue with the Boulder County building officials charged with issuing building permits.

Figures 15 through 20 illustrate site work and circumstances; Appendix A includes a satellite view of the site.

Figure 15. "Farmer John" Ellis starting hole for soil testing. This same rig will be used for digging trenches for the footer and foundation.

Figure 16. First four foot hole 16 days after digging is completely dry.

Figure 17. Site preparation nearly complete, looking north, dirt road in foreground. The greenhouse will be close to the road with its long (50 foot) axis running east and west (left to right in the photo), its short (20 feet) axis running north and south. The irrigation ditch runs between the trees.

Figure 18. Looking east from the west end of the greenhouse.

Figure 20. Looking west from the east end of the green house.

Figure 19. Looking south from the north end of the greenhouse.

Energy Calculations

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. However, since we are making no provisions for supplying heating energy except from the sun, it is necessary to calculate heat losses of the envelope under various conditions. In particular, what if there’s a sustained period of very little solar gain from the sun in which the temperature is quite cold? Will the greenhouse stay above freezing? See Table 1.

Table 1. Greenhouse hourly energy losses at in/out temp differences of 10F to 70F

Delta T (F)	Hourly heat loss walls and ceiling (Btu/hr)	Hourly heat loss doors (Btu/hr)	Hourly heat loss windows shutters closed (Btu/hr)	Total conductive hourly heat loss (Btu/hr)	Total hourly heat loss (Btu/hr)
10	856	200	455	1511	1662
20	1712	400	909	3021	3324
30	2568	600	1364	4532	4985
40	3424	800	1819	6043	6647
50	4280	1000	2273	7554	8309
60	5136	1200	2728	9064	9971
70	5993	1400	3183	10,575	11,633

The first column of the table shows indoor/outdoor temperature difference in degrees F. Column 2 shows estimated losses due to conduction from the walls and ceiling assuming a net effective R-value of 20. Columns 3 and 4 show estimated losses due to conduction from doors and windows assuming a net effective R-value of 10 (shutters closed). Column 5 sums estimated conductive losses and column 6 includes estimated convective losses (at 10%) to produce total hourly heat losses.

Given these circumstances, if the outside air temperature is zero F and there is no solar gain—and the indoor air temperature of the greenhouse is 70F—hourly energy losses through the envelope of the greenhouse are estimated at 11,633 Btu/hr.

How will this effect indoor air temperature? Even without the massive north wall, the fact that the greenhouse is coupled to deep earth temperature that would be about 20 degrees above freezing (even without thermal charging from heat at the top of the greenhouse) suggests that the greenhouse will not approach freezing. However, let's imagine that the 40 blocks of the north wall are taken into account and that when the cold and cloudy spell hit when the blocks were at 70F. Table 2 shows that even with outdoor air temps at 0F for 90 hours with no solar availably at all, the north wall blocks alone will keep the greenhouse from freezing.

Table 2. Contribution of north wall thermal mass to freeze prevention

Mass (Btu/F/Block)	North wall blocks	North wall mass (Btu/F)	North wall mass @ 38F over freezing	Hours of storage @ 70 indoor/ outdoor delta t
691	40	27,640	1,050,320	90

This result is comforting since such worse-case weather conditions have never occurred in Boulder. It remains to document actual energy and growth performance versus actual weather conditions under various scenarios of control settings on the R&D greenhouse.

Section 4
Problems encountered and mitigating circumstances

As mentioned above, there have been delays in the building permitting process owing to the proximity of the greenhouse to the irrigation ditch. The team is trying hard to accommodate the requests of the Boulder County building officials, who in spite of the downturn in the economy are busy with a large influx of homeowners seeking permits for energy-saving retrofits. We are cautiously optimistic that we'll have a permit by the first of November, at which point we plan to break ground and work fast.

The more serious problem stems from inadequate funding to accomplish as much as we would like on the project. We mistakenly assumed that the grant would be for the $100,000 we proposed, but when the team found that only $50,000 was available for R&D projects such as this one, we decided to tighten our belts and proceed with the project nonetheless. This has meant that most of the design and research work accomplished so far has been *pro bono publico* to ensure that there are adequate funds available for greenhouse materials and professional labor. (Indeed, much labor for building the greenhouse will be from volunteers.) As a consequence, we have already more than exceeded the $33,000 match seven months into the 18 month project and so far have billed the Department for only $12.5K of the $50K grant.

In spite of modest funding for an admittedly ambitious research project, the team's enthusiasm for the job is unabated. Indeed, the analyses we have conducted that have resulted in the design and prototype developments described in Section 3 of this report have further fueled our excitement that we're engaged in something of potentially great consequence. However, in order to fully explore, mine, and document the very rich data we believe will flow from the R&D greenhouse, a good deal more of analytical equipment and professional labor will be required than is provided for in the present grant. Accordingly, the team is applying for a Phase 2 grant on the project through the current open solicitation for the Department of Agriculture's ACRE program.

If funded, we will be able to develop better analytical tools, harvest a lot more practical wisdom, and share it more broadly.

Section 5
Next Steps

As indicated in Sections 3 and 4, our paperwork for securing a building permit has not yet yielded one, but we are hopeful that we will have it in hand by early November. In the meanwhile, we are pressing on with the testing and manufacturing of the insulating shutters and ordering other specialty parts like the trusses that are being manufactured off site. Delays have put off the projected ready-for-operation date from Thanksgiving to mid December, but this should have no effect on our being able to complete the tasks associated with the current grant and produce final deliverables by August of 2010.

Our contract with the Department of Agriculture identifies the following subtasks:

a. Reviewing greenhouse design and developing a set of working drawings;
b. Designing instrumentation and controls;
c. Fabrication of subsystems and greenhouse;
d. Installation of instrumentation and controls;
e. Calibration of instrumentation and refining protocols;
f. Planting, gathering data and undertaking any corrections;
g. Analyzing data; and
h. Drafting a final report

Table 3 lists subtasks, shows completion percentage as of the date of this interim report, and indicates expected dates for completion.

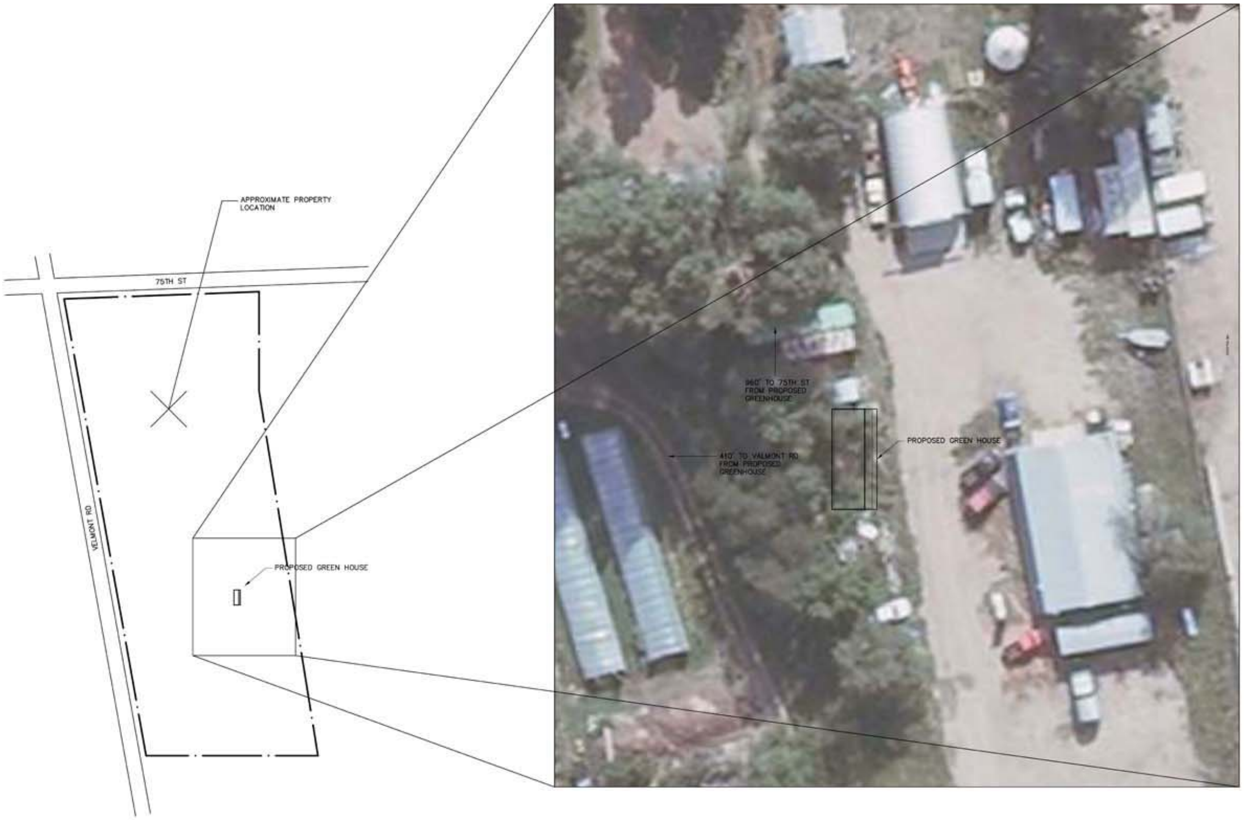
Task 3. Project Timing

Task	Description	% Complete	Date complete
a	Review design and develop drawings	100	October 2009
b	Design instrumentation and controls	90	March 2010
c	Fabricate subsystems and greenhouse	20	January 2010
d	Install instruments and controls	0	January 2010
e	Calibrate instruments and refine protocols	10	March 2010
f	Plant, gather data, undertake corrections	0	August 2010
g	Analyze data	10	August 2010
h	Draft final report	10	August 2010

In addition to this work, the team has begun to share early project findings with others. Apropos, Larry Kinney has been invited to give a presentation at the 9th Annual Innovations in Agriculture Conference, November 17 and 18, in Troy, New York. The conference is sponsored by the New York State Energy Research and Development Authority, http://www.nyserda.org/InnovationsInAgriculture/default.asp. The working title of the presentation is "Towards Zero Energy Greenhouses: Insolation, Insulation, Mass, & Smart Controls." In addition, we have submitted a proposal to present a juried paper at the 2010 Summer Study on Energy Efficiency in Buildings sponsored by the American Council for an Energy Efficient Economy, www.aceee.org. An abstract for the paper, "Innovations in Green Greenhouse Design," is reproduced in Appendix C.

Appendix A
Project Drawings

This appendix consists of reproductions of the permit set of architectural drawings of the greenhouse dated September 17, 2009. They were prepared by Brian Crawford of Bryan Bowen Architects.



VICINITY MAP 2 A0
SCALE: 3/8 = 1'-0"

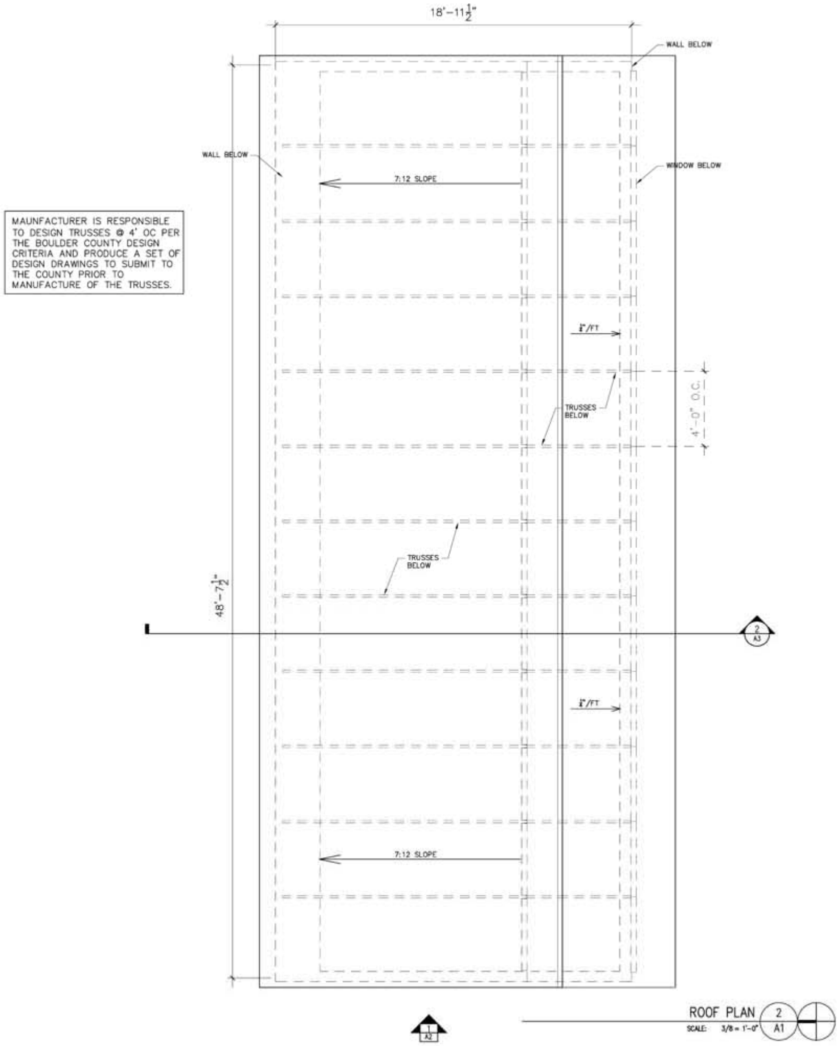
PARTIAL SITE PLAN 1 A0
SCALE: 3/8 = 1'-0"

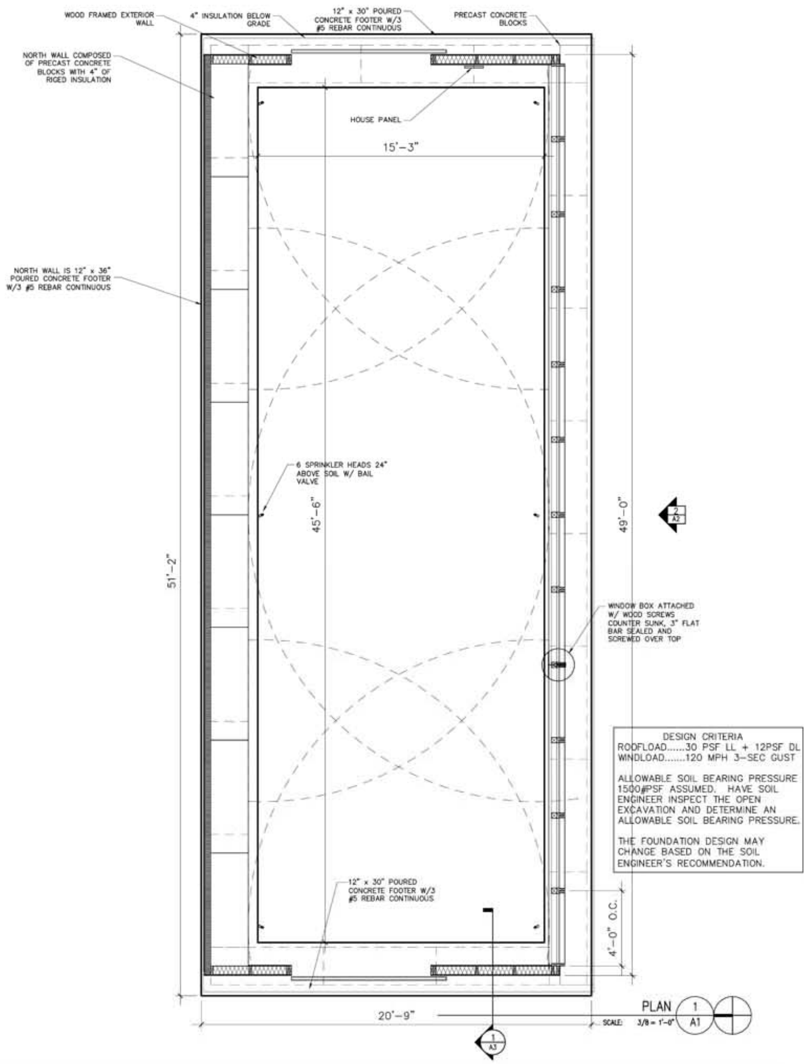
bb:a CURE ORGANIC FARM TEST GREENHOUSE

Permit Set
2009 Sept 17th

bryanbowenarchitects
1510 zamia avenue #103 boulder, colorado
t. 303.443.3629 f. 303.443.2039

Sheet A0





bb:a

CURE ORGANIC FARM TEST GREENHOUSE

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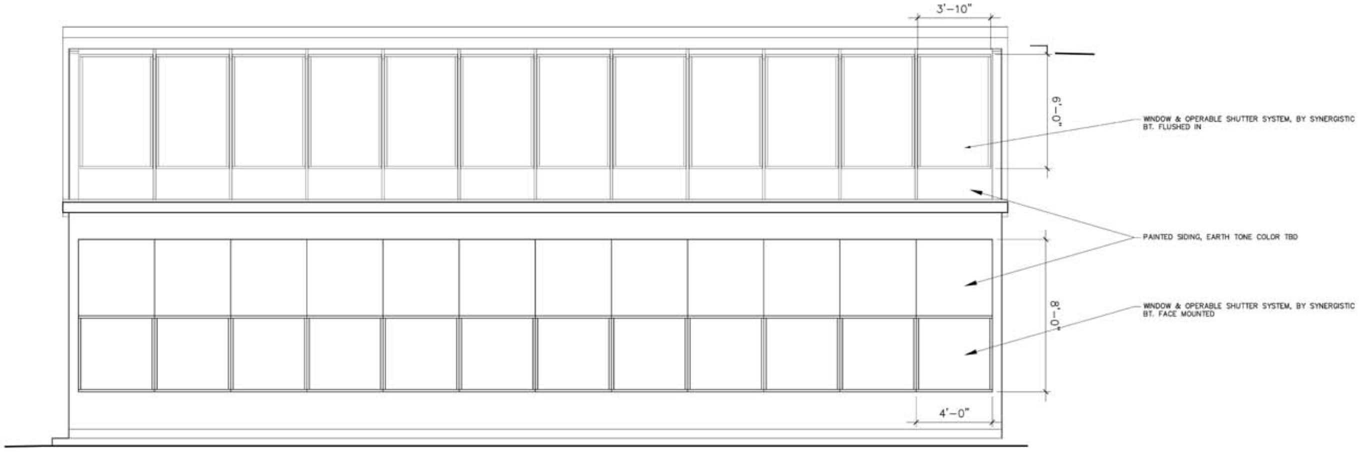
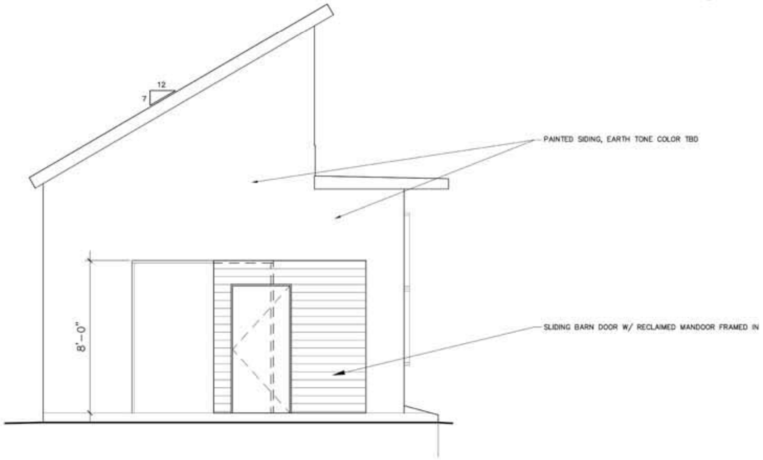
1510 zamia avenue #103 boulder, colorado
t. 303.443.3629 f. 303.443.2039

Sheet A1



SOUTH ELEVATION 2/A2
SCALE: 3/8 = 1'-0"



WEST ELEVATION 1/A2
SCALE: 3/8 = 1'-0"

bb:a | CURE ORGANIC FARM TEST GREENHOUSE | Permit Set
2009 Sept 17th | bryanbowenarchitects
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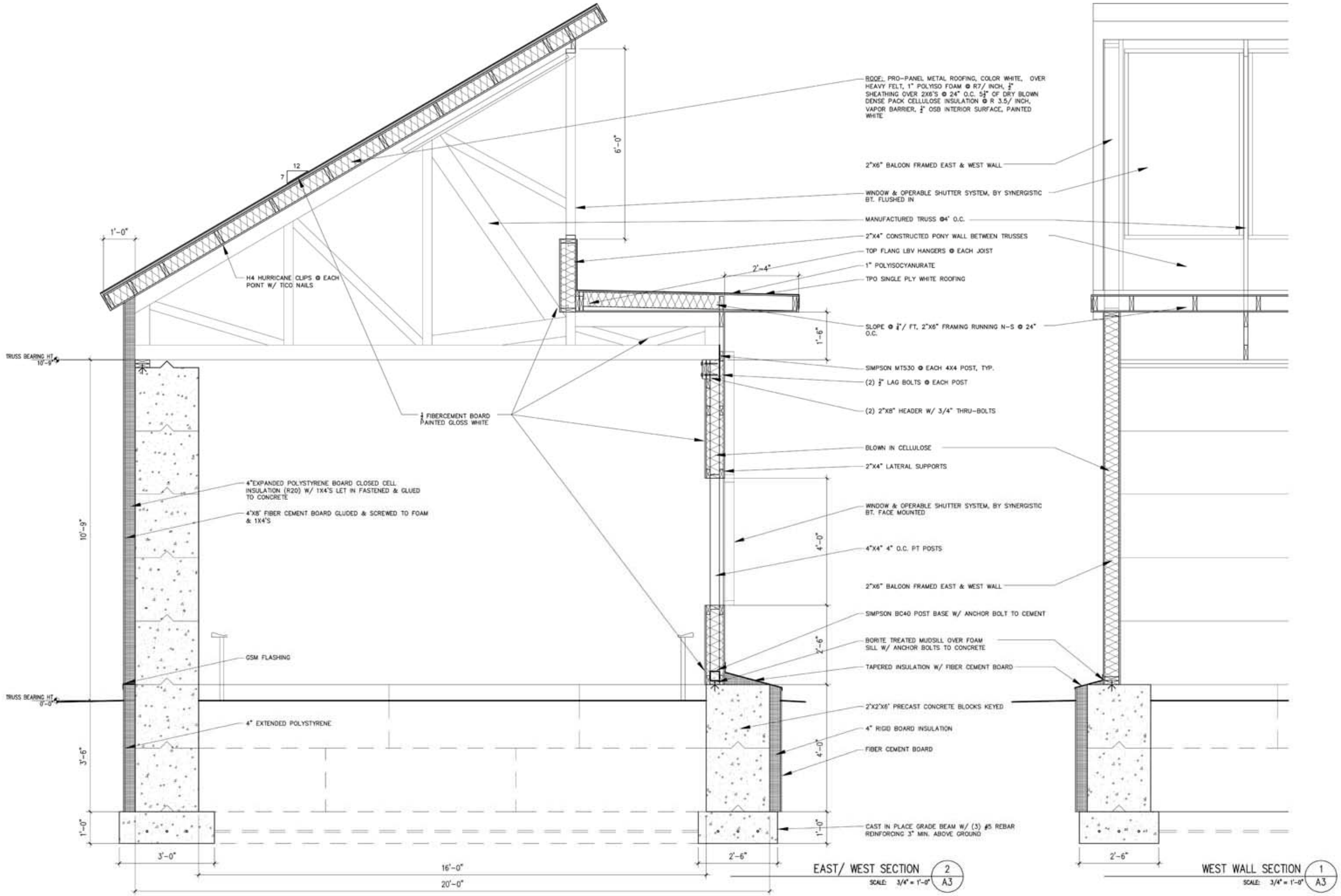

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Permit Set
2009 Sept 17th

bryanbowenarchitects
1510 zamia avenue #103
t. 303.443.3629
boulder, colorado
f. 303.443.2039

Sheet A3

Appendix B
Greenhouse Research Team Contact Info

Todd Bergeson, President
Xcel Outsourcing
5500 Central Avenue #100
Boulder, CO 80301
303-501-8250
Email: toddb@xceloutsourcing.com
www.xceloutsourcing.com

Bryan Bowen, Principal
Bryan Bowen Architects, P.C.
1510 Zamia Ave # 103
Boulder, CO 80304
303-443-3629 (V)
720-318-8746 (C)
Email: bryan@bryanbowenarchitects.com
www.bryanbowenarchitects.com

Brian Crawford
Bryan Bowen Architects, P.C.
1510 Zamia Ave # 103
Boulder, CO 80304
303-443-3629 (V)
303-947-5689 (C)
crawford@bryanbowenarchitects.com

Gerald (Gary) Cler
SBT Vice President of Engineering
622 Parkview Mountain Drive
Windsor, CO 80550
Cell: 970-674-8728
Email: GaryC@SynergisticBT.com

Wyncia Clute, Esq
SBT Chief Administrative Officer
1335 Deer Trail Road
Boulder, CO 80302
Voice: 303-449-7941
Cell: 303-579-7537
Email: WynciaC@SynertisticBT.com

Anne Cure
Cure Organic Farm
7416 Valmont Rd
Boulder, CO 80301
(303) 666-6397
Email: cureorganicfarm@yahoo.com

John Ellis
Farmer John's
3889 75th Street
Boulder, CO 80301
Voice: 303-440-0750
Cell: 303-931-9540
Email: farmerjohns@wildblue.net

Mark Jackson
P. O. Box 20533
Boulder, CO 20533
303-502-0575
fixitmark@gmail.com

Larry Kinney
SBT President
1335 Deer Trail Road
Boulder, CO 80302
Voice: 303-449-7941
Cell: 303-579-1439
Email: LarryK@SynergisticBT.com

Marco Chung-Shu Lam
The Mandala Community Center
2516 Broadway
Boulder, Colorado 80304
voice: 303-444-2357
cell: 303-359-1161
Email: pranafarmer@gmail.com
www.boulderacupuncture.net

Larry Weingarten
SBT Design Engineer
P.O. Box 928
Monterey, CA 93942
Voice: 831-484-7077
Cell: 831-402-0490
Email: LarryW@SynergisticBT.com
Packages & physical address:
279 San Benancio Road, Salinas, CA
93908

Appendix C

Abstract for 2010 ACEEE Summer Study on Energy Efficiency in Buildings

Panel 11, Sustainable Communities: Systems Integration

Innovations in Green Greenhouse Design

A key element of successful sustainable communities is the ability to grow wholesome food locally all year around. In many climates this necessitates the use of greenhouses, but conventional designs require substantial fossil fuel energy to sustain growth in winter. This paper reports on a research project to develop practical techniques (those that work well, are cost effective, can be implemented by farmers, and are broadly applicable) for enabling greenhouses to continue to produce food during cold months with minimal fossil fuel use. Findings are based on data from a 1000 square foot instrumented R&D greenhouse on a community-supported organic farm in Colorado.

Strategies include raising the effective time constant of a greenhouse by including the mass of the earth within the thermal envelope, increasing the overall R-value of the envelope via fixed and moveable insulation, and storing solar energy when it is plentiful--releasing it to the greenhouse's plants when it is not. It is possible to use a fraction of the window area normally thought critical to grow plants by the use of external and internal reflective surfaces and glazing of high solar heat gain coefficient. This allows for the use of much more insulation than conventional wisdom views as practical. Insulating shutters automated to close when losses exceed solar gains keep nocturnal temperature drifts to a minimum.

Inferences are drawn for the development of truly green greenhouses suitable for residential, community, and commercial use.

Appendix D
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 ($Btu/h\text{-}ft^2\text{-}°F$). **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.