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IV – DEVELOPMENT OF THE SUNCATCHER PSG

More than twenty-five years ago, SunCatcher Design Group (now SunCatcher Passive Solar Greenhouses) set out to design a "Green" greenhouse that could outperform and outlast all other greenhouses while being able to function independent of fossil fuels and electricity. The evolution of these structures took place in the mountains of western North Carolina. The SunCatcher greenhouse is science-based and was redesigned from the ground up. We used basic physics, biology, and engineering principles to design a greenhouse that captures solar energy utilizing the sun's changing position during the seasons, providing both the heat and light as needed for plant growth during various times of the year.

We meticulously tracked the performance of our prototypes and have designed for the demanding science underlying horticulture and the exact microclimate demands for a successful harvest. The result of our research is a passive solar greenhouse within an extremely energy-efficient shell that works with the seasons and the weather, balancing structural geometry, materials selection, light transmissivity and reflection, heat and heat storage, natural air flow for ventilation and O_2/CO_2 balance to enable year-round production.

In this chapter, we will take you through the evolution of SunCatcher designs and models from their inception in 2001. For each model, we include basic design features and materials used, and include a representative sample of performance data from an approximately similar time period in mid-winter for each model. We indicate their strong and weak points, and list what we've learned with each model that we used in the later designs. You will learn how various components were utilized in early models and how the SunCatcher design evolved as we put the components together. Some of the earlier, lower cost experimental designs did perform unexpectedly well, and may provide you with additional ideas for your own passive solar greenhouse design.

A note about the performance data and statistics included for the different test models

Although the models were tested in different years, we chose the mid-winter period of January 30 to February 14 to compare their performance. We used 20^0 C (32^0 F) as the minimum and 25^0 C (80^0 F) as the maximum interior temperatures in the performance graphs.

In the data tables, the minimum and maximum temperatures represent the lowest and highest temperatures observed in the two-week period (i.e., NOT the average low and high temperatures). Delta-T is the difference between interior and ambient (=outdoor) temperatures; the min/max temperature columns for Delta-T show the smallest and largest difference between indoor/ambient temperatures.

Data were logged every 30 minutes in the Parkway and Laurel Ridge PSGs, and at 15 minute intervals in the other PSGs. Mean Delta-T was calculated from the temperature difference at each logging event averaged over the two-week period.

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Passive Solar Greenhouse at Parkway Elementary School

Deep Gap, NC (36^0 13'56.21" N, 81^0 33'43.03" W; 963m (3,150 ft) asl)

This 'proof of concept' SunCatcher was built in 2002, and replicated a "classic" 1970s passive solar greenhouse. This was our basic design for a well-insulated, low carbon energy input structure using 100% solar heating. This greenhouse provided a baseline to assess performance of future iterations and larger sized PSGs.





Design data

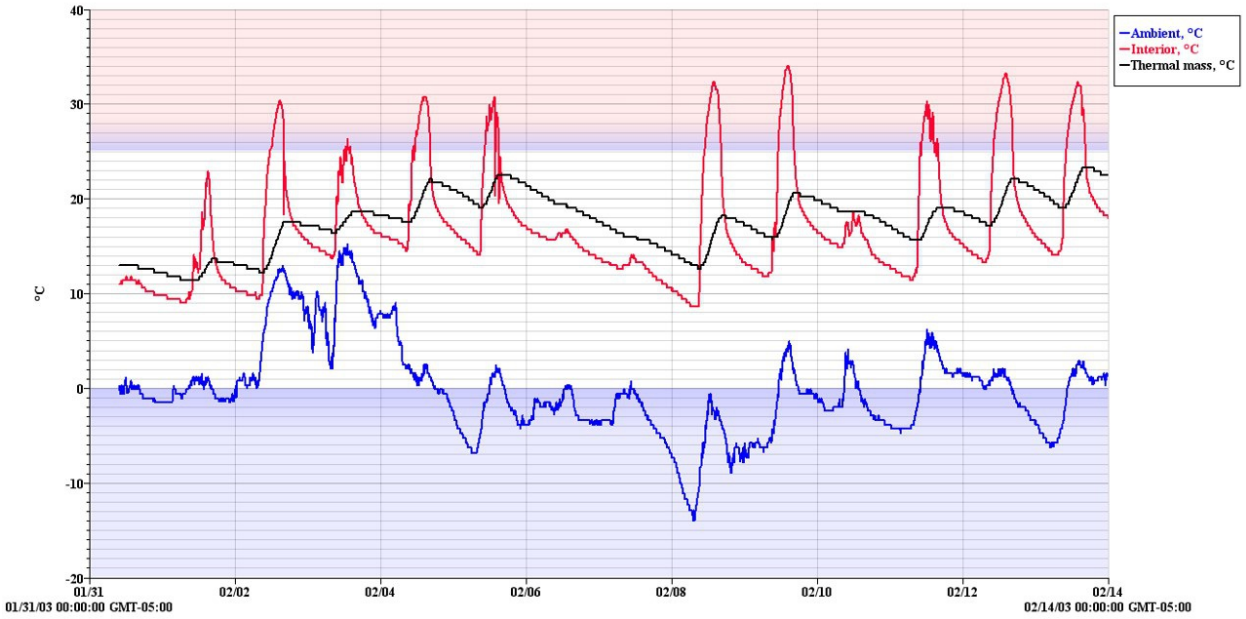
- 12x16 ft, traditional stick building on concrete foundation
- Fiberglass batt insulation, R-17.5 in the north, east and west walls, R-25.5 in the roof, with PE sheeting as vapor barrier.
- Silver colored reflective interior walls and ceiling.
- South facing knee wall and 60^0 (up from horizontal) angled glazing with triple wall polycarbonate (R-2.5).
- Roof up 30^0 from horizontal.
- Thermal mass consisted of 18 55-gallon flat black barrels filled with water (990 gallons).
- Gravel floor.
- Data collected 2003 through 2008.

Performance observations

The Parkway SunCatcher was the first design and for this reason we took an exceptional amount of data over six years to analyze its performance and discover any defects in its design to inform future models. We carried out a number of experiments (with/without a night-time curtain, ventilation, plant growth, ...), in the process making a number of unexpected discoveries:

1. Vents on the bottom and top of the East and West walls were insufficient for good ventilation.
2. The angle of the glazing and roof was thought optimal for charging the thermal mass, but did not enable sufficient sunlight for good plant growth.
3. In summer, the angle of the glazing allowed in sufficient light for plant growth without causing overheating, as most sunlight reflected off the glazing. As a result, the interior temperature was only a few degrees above ambient temperatures during the summer period.

4. Silver-colored walls improved reflectivity.
5. By happenstance, we discovered how to use a unique venting scheme to enhance CO_2 availability before noon when it's coldest outside and heat is needed inside (so ventilation is not practical). All vents were closed at the end of the day to capture and store CO_2 released by the plants' respiration, providing higher than ambient levels of CO_2 in the mornings for increased plant growth. After opening the vents, CO_2 levels remained at ambient for the remainder of the day until shortly before sunset when vents were closed.
6. A silver-colored trap hung inside the south-facing glazing was used sometimes at night to help reduce heat loss through the glazing at night.



Temperature performance and statistical analysis, January 30 to February 14, 2003.

	Minimum ^{0}C	Maximum ^{0}C	Mean ^{0}C	SD ^{0}C
Ambient +1m	-14.10	15.23	-0.16	4.94
Interior +1m	8.63	34.01	16.93	5.95
Thermal mass	11.38	23.24	11.38	3.01
Delta T	4.64	35.30	16.98	5.83

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Newton-Conover High School PSG

Newton, NC (35040'41.65"N, 81013'32.10"W, 373m (900 ft) asl)

This greenhouse was a passive solar greenhouse built in the more moderate climate of the western Piedmont of North Carolina as a vocational education project teaching construction, solar/alternative energy, agriculture, data collection, and business. It was constructed by the high school's students in 2009 using SIPS panels (Eco-Panels, Inc. of Mocksville, NC).



Design data

- 18x46 ft, largest model to date.
- Concrete slab floor.
- A larger aperture to allow more sunlight into the structure, but with a lower knee wall.
- Triple-walled polycarbonate glazing at a 60^0 angle.
- Window vents in the knee wall and vertically above the angled glazing for ventilation.
- North roof at 45^0-angle from horizontal to better reflect light down onto plants in winter, minimizing plant phototropism.
- A unique experimental venting system using fans to pull in ambient cold winter air through 6-inch PVC underground pipes for pre-warming before entering the greenhouse; these pipes were closed when not used in the summer.



Underground pipes entered the greenhouse along the south facing bottom vents; they were fitted with white PVC elbows to prevent things falling into the pipes.

Performance observations

- Automated vents and fans would increase overall performance and CO_2 levels naturally, while solar thermal intake vents would be a better alternative to preheat incoming air entering the SunCatcher.
- The greenhouse project was a school initiative for which Carroll provided design services. Changes in teachers made consistent management of the PSG problematic as there was no

overlap between them to explain how to manage a PSG as it is different from a standard greenhouse.

- Data may have been collected, but were not shared with SunCatcher Greenhouses; so, we cannot provide a performance graph or statistics. The only anecdotal evidence of its performance is from teachers reporting that plants grew from seed to maturity three to five weeks faster than expected (see the photo below).
- The upper vents were not used, as it was difficult to open and close them as needed given their height and location. Moreover, it was also deemed too risky for students doing this task, and the timing for opening and closing the vents did not match with school hours.



Tomatoes in the Newton-Cover PSG grew and ripened mid-winter faster than they would in the summer outside.

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Laurel Ridge SunCatcher Passive Solar Greenhouse

Laurel Springs, NC ($36^0$22'17.16" N, $81^0$15'45.32" W, 1000m (3300 ft) asl)



The Laurel Ridge PSG replicated the proof of concept of the Parkway PSG at a larger scale with higher quality materials and potential performance; it includes all of the positive Parkway PSG features as well as changes from lessons learned. Built in 2012 with volunteer labor, it served as both a research and demonstration model using different materials and construction methods, in addition to gaining experience with operating and managing the greenhouse for crop production year-round. The structural insulated panels (SIPs) are easy and quick to assemble on-site, providing a much tighter structure than stick-built structures. This SunCatcher is a part of a year-round food production system for the camp and conference center.

Design data

- 24x12 ft using Eco-Panels SIPs
- The long East-West axis is oriented at 15^0 east of due south.
- 60^0 angle glazing, with roof at 30^0-angle from horizontal.
- Windows in the south knee wall and on top of angled glazing for ventilation. Thermal mass of 20 55-gallon barrels filled with water (1,100 gallons) double stacked along the back wall; bottom ones were painted flat black, the top ones alternating a flat blue and red to better reflect photo-synthetically active light from the back of the structure towards the plants to reduce phototropism.
- White interior walls and ceiling.
- Concrete tile flooring.

It was designed to store more heat than needed to improve venting without the use of fans. Even on cold winter days, fresh air could be introduced through the knee-wall vents while excess

humid air was exhausted through the vents on top of the glazing. This provided higher levels of CO_2 for photosynthesis while reducing humidity-related plant diseases. Major vents in the back (north) wall were kept open from late spring through early fall for cooling.



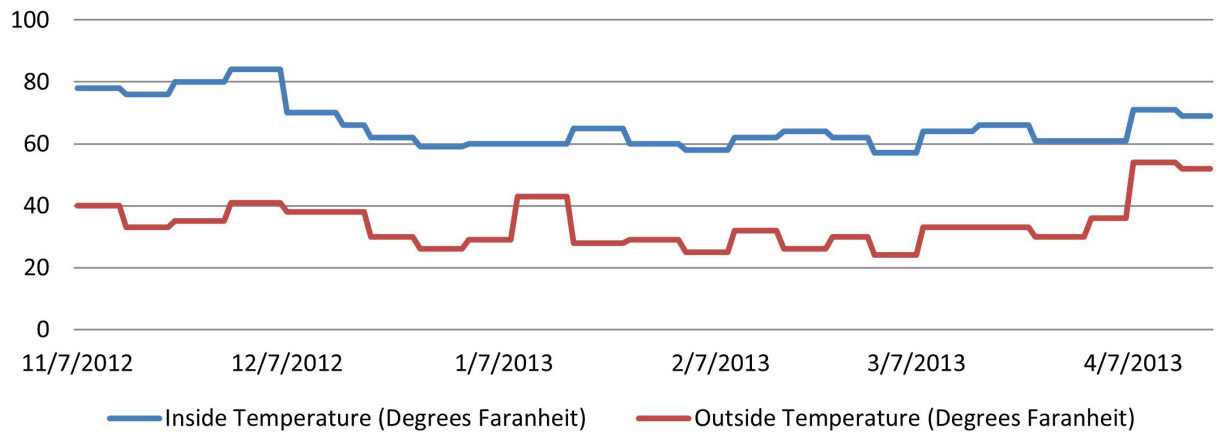
Performance observations

- After several mountain winters the top vents began to leak when it rained or snowed. We redesigned the SunCatcher with larger window vents in the awnings of the East and West walls in future models.
- The 2-to-1 ratio between length and width of this greenhouse provided better light conditions throughout the structure compared to the 16x12 ft Parkway PSG.
- As in the Parkway school PSG, the 30^0-angle of the roof did provide adequate sun exposure to the barrels along the North-wall to charge the thermal mass, but did not provide sufficient light for plant good plant growth. In future models, we changed the pitch of the North roof 45^0 allowing better light reflection from the ceiling toward the plants.

The graph below represents weekly averages of the inside temperature (blue) of the SunCatcher versus the weekly averages of the outside temperature (red). The inside temperatures in November 2012 were higher on average because this SunCatcher did not have someone to open and close vents during the day until December. Once this started, the vents exhausted the excess heat and humidity that built up during sunny days and brought fresh air in for the plants. The Laurel Ridge SunCatcher maintained a +16.7° C ($+30^0$ F) average temperature difference compared with the outside temperature throughout the winter and would perform even better with a shade covering the glazing at night to prevent radiative heat loss.

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Laurel Ridge SunCatcher Performance Winter 2012-2013



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Carolina Mountain SunCatcher

Western North Carolina





Located in the mountains of southwestern North Carolina and built in 2014, this PSG was used for research to provide a performance baseline and standard. It incorporated several improvements over previous SunCatcher models: an easy to assemble SIPs kit; more roof and wall insulation; changing the angle ot the roof 45^0; an automated system to monitor and control the greenhouse from remote locations; and phase-change material instead of water-filled metal barrels as thermal mass. It is a high-quality structure using earth and human friendly, energy efficient materials that are easy to reproduce and quick to assemble on-site. The low energy input system can be powered by off grid technologies if needed.

Design data

- 32x16 ft SIPs construction with R-23 walls and roof.
- Rated for 110-mph winds and large snow loads.
- Concrete slab floor.
- Glazing and roof angles at 60^0 and 45^0 from horizontal, respectively, to reflect more sunlight down on the plants for better light distribution during the short late-Fall to mid-Spring period, limiting phototropism.
- East and west walls have upper vents to exhaust hot, moist, CO_2 depleted air.

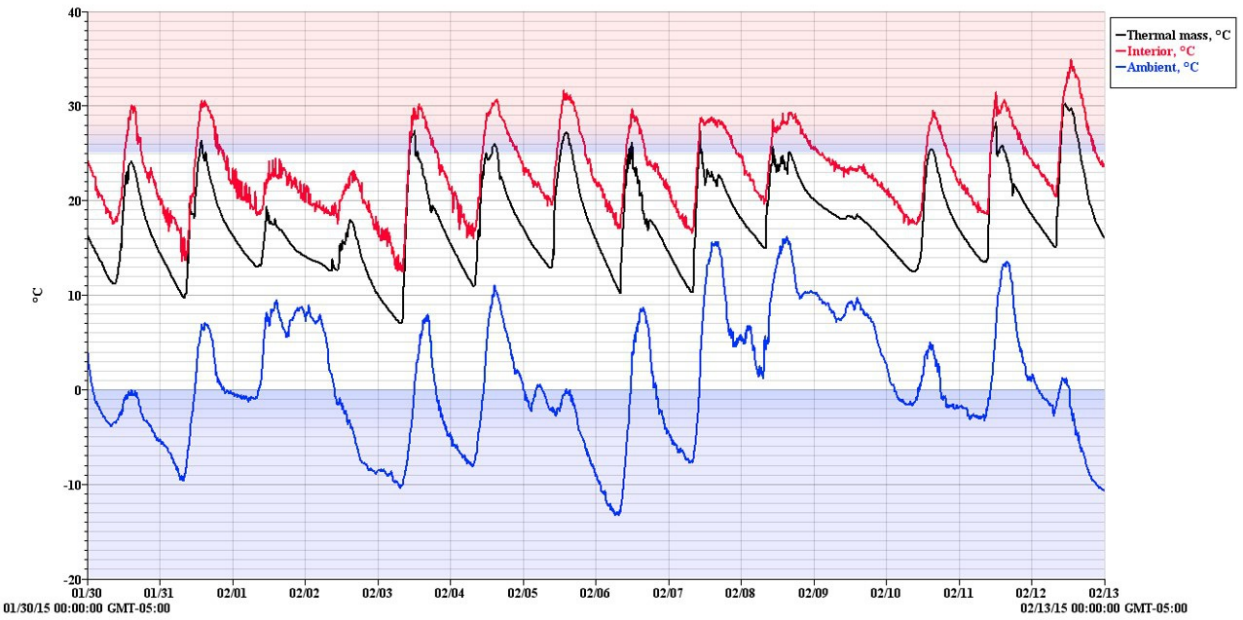
New additions

- Phase Change Material thermal mass embedded into the walls and ceiling, with phase change temperatures set at three different levels: 23^0C, 25^0C, and 29^0C (73^0F - 84^0F).
- A unique venting scheme used automated thermal intake vents and fans (controllable from remote locations) in which the plants themselves are used to increase CO_2 levels above ambient levels. Trapped CO_2 from plant respiration at night ensured higher than ambient levels before noon (when it's coldest outside, and vents remain closed to maintain interior temperature). Once ambient temperatures allow opening of the vents, warm, moist, CO_2

depleted air will be replaced with dry air at ambient CO_2 levels, remaining there for the remainder of the daylight hours until all the vents are closed.

Additional improvements to enhance the performance of this PSG could include a night time insulating curtain (manual or automated); LED grow lights for short, sometimes overcast winter days; south knee-wall vent inserts or solar thermal intake vents to preheat ambient air entering during cold periods.

Temperature performance and statistical analysis, January 30 to February 13, 2015.



	Minimum ^{0}C	Maximum ^{0}C	Mean ^{0}C	SD ^{0}C
Ambient +1m	-13.32	16.11	6.7	6.58
Interior +1m	12.41	34.92	23.24	4.20
PCM	6.99	30.22	17.70	4.64
Delta T	10.83	38.34	22.98	5.70

Performance observations

As this greenhouse used phase-change material (PCM) rather than water-filled metal barrels, its thermal mass responded differently to changes in temperature and sunlight. The PCM set points were too high for good thermal (especially maximum) temperature regulation, which often exceeded optimal temperatures for plant growth. At the time this greenhouse was built (2015), PCM needed more development before it was ready for the greenhouse thermal storage application.

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Standard hoophouses and experimental models incorporating some PSG design features

Modified Hoophouse at the Sustainable Development Teaching & Research farm

Valle Crucis, NC (36^0 11'37.27" N, 81^0 47'18.75" W, 838m (2750ft asl)





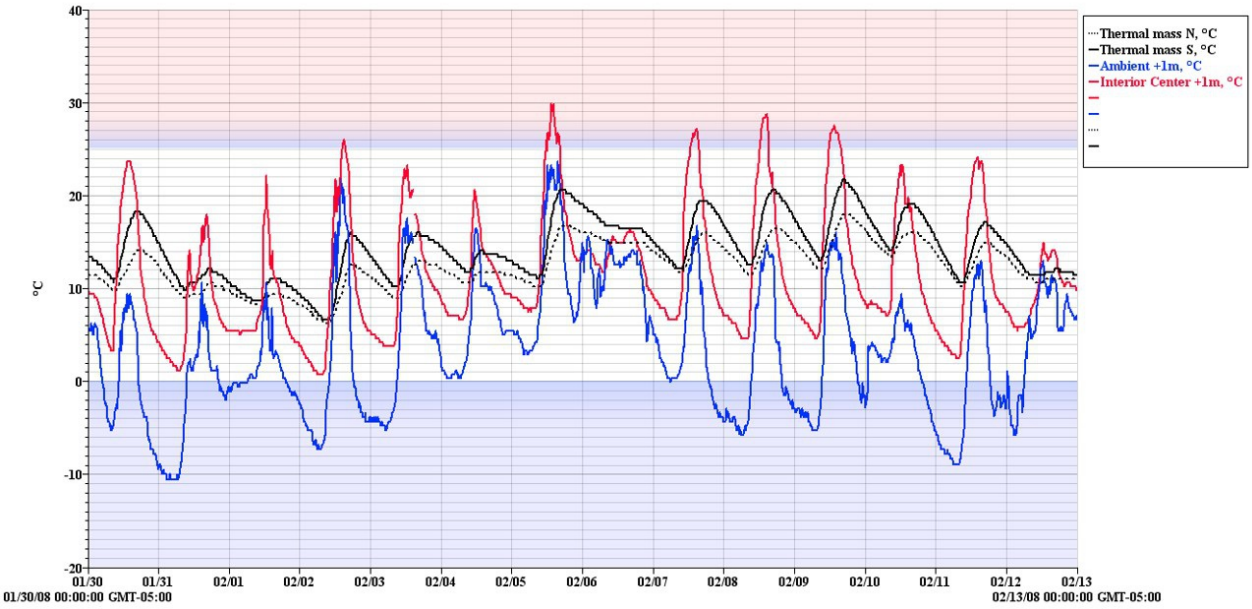


Design data

- Conventional, gothic high tunnel greenhouse oriented with the long axis running in an east-west direction, tilted 15^0 east of due south. The greenhouse was donated, and taken down, moved and rebuilt in 2005.
- 24 x 21 ft., 10 ft. high in center.
- 2 in. PVC pipes set on 4 ft steel pipes pounded 2 ft into the ground.
- End walls of 2x4 in. treated lumber; center posts and roof beam 4x4 in. treated lumber.
- Single layer polyethylene (PE) for end walls and roof.
- North hoop insulated with Reflectix (bubble wrap between layers of aluminum foil).
- 70% shade cloth used during summer on the south half of the hoop.
- 23 55-gallon drums filled with water, painted flat-black. A 300-gallon pallet tank was installed in 2007 to provide irrigation water in winter.
- Single 3x3 ft. fan in west wall, and two 2x2 ft. exhausts in East wall; ceiling fan to distribute warm air downwards during winter period. Vents were closed off with blueboard during the winter period.
- Non-growing floor area covered in heavy duty silver-brown tarp to prevent weed growth.
- Data collection: 2005-2011.

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Temperature performance and statical analysis, January 30 to February 13, 2008



	Minimum ^{0}C	Maximum ^{0}C	Mean ^{0}C	SD ^{0}C
Ambient +1m	-0.18	13.81	7.01	4.43
Interior +1m	5.67	23.83	12.28	4.71
Thermal mass S	-1.15	20.96	4.73	4.82
Thermal mass N	4.34	21.99	11.27	4.06
Delta T	0.73	25.95	13.19	5.20

Performance observations

- The PE cover was replaced after two years, as PVC pipes leach chlorine which degrades polyethylene, especially on the end wall hoops. When replacing the cover in 2007, we taped the tops of the PVC pipes on the south-side with aluminum tape so that there would not be direct contact (it was not a problem on the north side as the Reflectix prevented direct contact).
- Initially, a second row of barrels was placed in the center of the structure, the main plant bed being located along the south glazing; plants close to the plastic cover experienced freeze damage during the winter. The plant bed was moved to the center before replacing the PE in 2007, and barrels were placed along the south and west side (see picture) – crops thrived there and produced well during the subsequent winters.
- The shape of the greenhouse was not ideal for good solar collection in winter and causing overheating in summer; shade cloth was installed during summers to reduce overheating.

- During the Winter and early Spring, air and thermal mass temperatures on the north side of the greenhouse stayed several degrees warmer than the south half, as the insulation minimized radiative heat loss.
- Plywood was placed on the barrels on the North side for trays to germinate seeds in early Spring (warmer!), but once germinated they would experience phototropism if not moved toward the south side.
- High humidity levels were problematic in the winter, as moisture would condensate on the greenhouse cover on very cold nights.

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Hybrid PSG at Sustainable Development Teaching & Research farm

Valle Crucis, NC (36^0 11'36.63" N, 81^0 47'15.14" W, 838m (2750 ft) asl)

Another SunCatcher, experimenting with materials and design, was the hybrid hoop model. It was a half-hoop structure with 60^0 angled south-facing glazing for increased winter solar gain, and included all the same design features as the modified hoop greenhouse as well as insulated east and west end walls. It was built in Summer/Fall 2006 for a comparative research MS thesis (Duus, 2007) together with the A-frame PSG (following) and Parkway PSG.

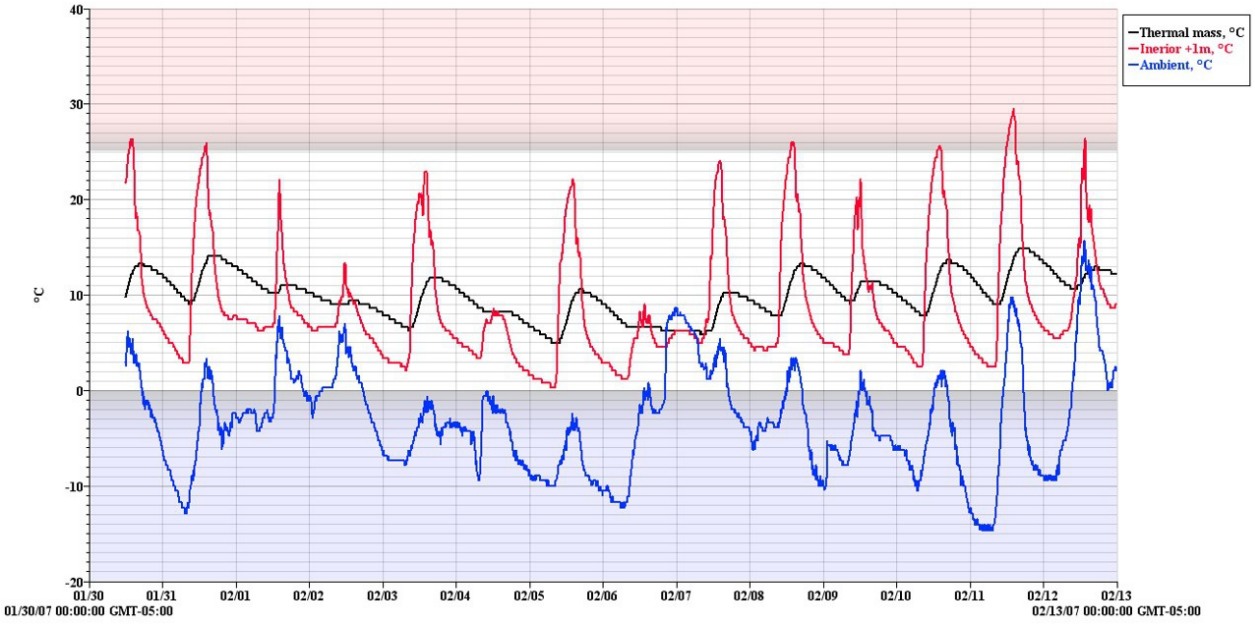






Design data

- Half-hoop with 60^o south-facing glazing.
- Oriented with the long side running in an east-west direction.
- Size: 16x12 ft., 6.8 ft. high.
- Three rows of stacked 6 in. wide cinder block mounded with soil on the north and half the east and west sides; gaps sealed with spray foam.
- North hoop made of 1 in. PVC pipes; main structure used 4x4 in. and 2x4 in. treated lumber.
- Single layer 6 mil polyethylene IR greenhouse plastic, with the North hoop, East and West walls insulated with Reflectix aluminum-bubble- aluminum wrap.
- 7 vertical 55-gallon barrels in the back and 4 horizontal barrels in the front, painted flat black and filled with water (605 gallons).
- Data collected during the winter of 2006-2007.



Temperature performance and statistical analysis, January 30 to February 13, 2007.

	Minimum ^{0}C	Maximum ^{0}C	Mean ^{0}C	SD ^{0}C
Ambient +1m	-14.73	15.62	-3.19	5.53
Interior +1m	0.29	29.50	8.88	6.40
Thermal mass	4.99	14.85	9.99	2.31
Delta-T	-2.84	27.01	12.10	5.44

Performance observations

- This was one of two experimental PSGs with the same foot print as the Parkway PSG but using minimal, cheaper materials and simpler construction methods.
- The greenhouse was an average of 12^{0}C (21.6^{0}F) warmer than the ambient temperature, and the thermal mass smoothed out day/night swings well. The interior temperature never dropped below zero during the testing period.
- Despite the minimal material, the design provided strong passive gains.

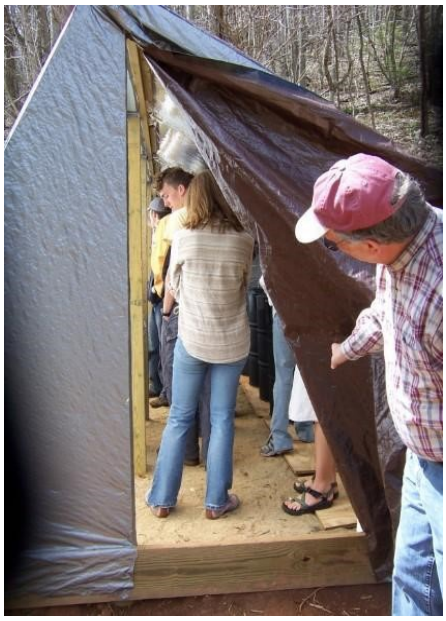
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A-frame PSG at Maverick Farms, Valle Crucis, NC

(36^0 10'49.46" N, 81^0 46'45.75" W, 910m (2986 ft) asl)







Design data

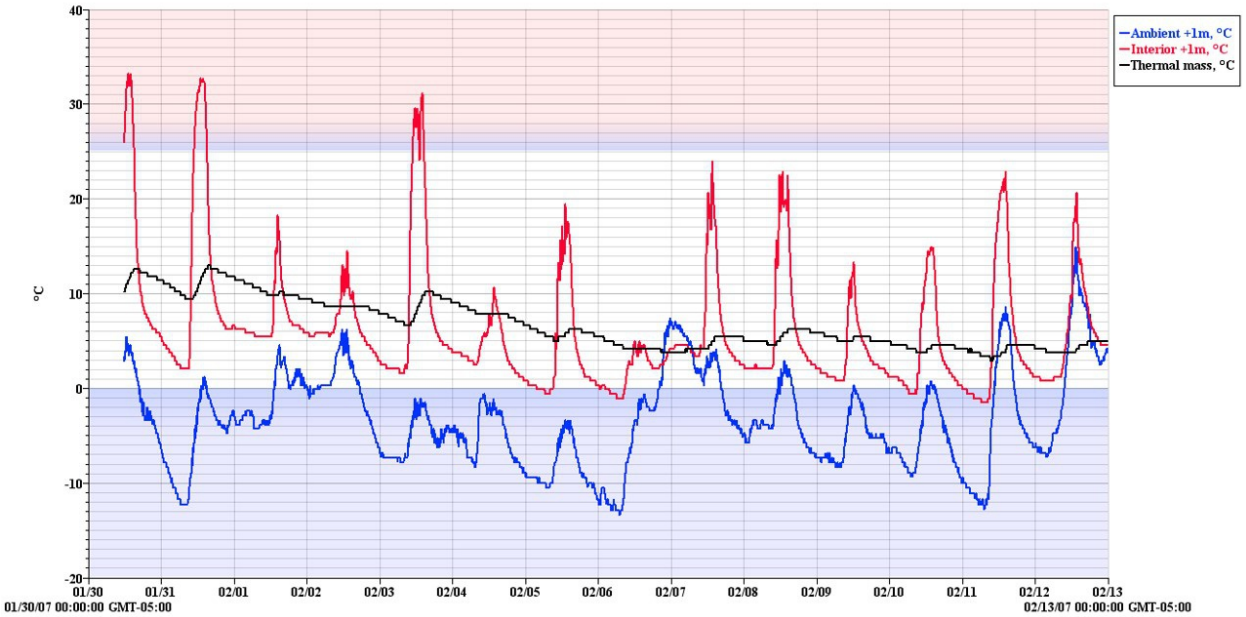
- Built by students in the Passive Solar Greenhouse Design and Construction class in Spring 2006.
- 16x12 ft, 7 ft. high.
- Low-cost tarp construction.
- Night-time flap to cover south facing glazing at night.
- South facing glazing of 5 mm. twin-wall Solex corrugated polyethylene panels at a 60^0 angle.
- 7 vertical 55-gallon barrels in the back and 4 horizontal barrels in the front, painted flat black and filled with water (605 gallons).
- Main structure of 4x4 in., 2x4 in. and 2x6 in. treated lumber
- Roof and side panels made of 0.5 in. OSB
- East, West and North walls insulated with 0.25 in. blue board (R- 5) and 0.25 in.Thermax board (R=5).
- Heavy duty 10 mil silver/brown tarp for roof and side panels, and as curtain over the glazing.
- Data collection: 2006-2008.

Performance observations

- Corrugated polyethylene glazing is milky-white, limiting light penetration; it has a low R-value.
- Lower light levels impacted plant growth as well as thermal performance.
- Maintained a lower average temperature difference between interior and ambient (9.2^0 C / 16.6^0 F) than the hybrid hoop PSG. In part. This may have been due to the farmer not always opening and closing the tarp covering the glazing in time (or sometimes not at all).

- Interior temperature exceeded 30^0 C (86^0 F) on several days, and night-time temperatures dropped below freezing on very cold nights.

Temperature performance and statistical analysis, January 30 to February 13, 2007.



	Minimum ^{0}C	Maximum ^{0}C	Mean ^{0}C	SD ^{0}C
Ambient +1m	-13.46	14.85	-3.12	5.13
Interior +1m	-1.51	33.17	6.04	6.58
Thermal mass	2.89	12.93	6.65	2.61
Delta-T	-3.29	34.16	9.17	5.86

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Modified Hoophouse at the Sustainable Development Teaching & Research farm, Fleetwood, NC

(36^0 19’09.75” N, 81^0 29’59.81” W, 975m (3200 ft) asl)







Design data

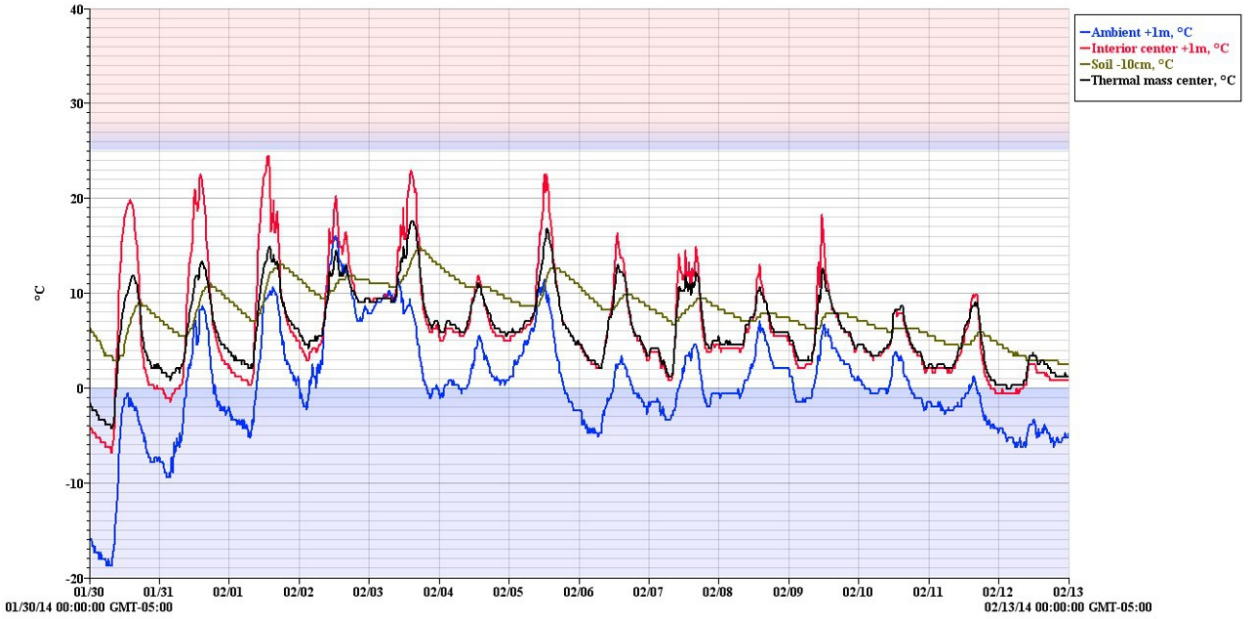
- Clearspan gothic-style Pro Solar Star high tunnel kit, 35'W x 48'L, 16 ft high in center, constructed in 2012
- East-West main axis, tilted 15^0 east of due south.
- Structure was adapted to the slope – 8 ft high south wall with drop-down curtain, and 4 ft high north wall finished with 0.5-inch plywood.
- Single layer 6 mil woven PE greenhouse plastic for the roof and drop-down curtain on the south wall.
- North hoop insulated with 4 mm Reflectix silver mylar-bubble-mylar wrap (R=4) before installing the PE cover.
- End walls of 10 mil woven polyethylene with 3 zippers.
- 64 55-gallon metal barrels painted flat black filled with water, 22 in the center, 24 along the north wall, and 18 placed along the south wall (3,200 gallons)
- Two 300-gallon pallet tanks to collect rainwater from installed gutters along the south roof to use for watering crops.
- Two 4x4 ft. louvers outfitted with automatic vent openers were placed in the top center of the East and West walls.

Performance observations

- The mylar Tekfoil disintegrated within one year, and was replaced with white/silver Microfoil (aluminum foil covered foam) insulation. Note: The aluminum-faced Tekfoil used in the Valle Crucis modified hoophouse was still in excellent condition (with some wear-and-tear) after 15 years (initial installation in 2005).
- Despite the large thermal mass, the greenhouse was not always able to maintain adequate growing temperatures due to the much larger internal volume of the structure.

- The drop in temperature in the morning of January 30 was due to a failure of the drop-down curtain mounting due to heavy wind gusts during the night associated with a strong cold front moving through the area. The brackets holding the rolling tube winding up the cords were installed as per instructions, but should have been installed the other way up. The zig-zag anti-billowing rope was insufficient to prevent billowing with the strong wind gusts, and were replaced by 1x4 in. wooden slats.
- The roof-angle was not ideal for maximum solar gain during the winter months.
- Thermal mass and interior temperature in the north side of the greenhouse were several degrees warmer than in the south and center. It was good for germinating seeds in early Spring, but once sprouted, needed to be placed on top of the center and south rows of barrels to prevent leggy seedlings.

Temperature performance and statistical analysis, January 30 to February 13, 2013



	Minimum ^{0}C	Maximum ^{0}C	Mean ^{0}C	SD ^{0}C
Ambient +1m	-18.76	16.00	0.75	5.60
Interior +1 m	-6.68	24.40	6.89	5.77
Thermal mass (center row)	-4.33	17.52	6.48	3.90
Soil -10cm	2.89	14.85	8.58	2.49
Delta T	-0.79	21.39	6.11	3.53

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OWNER DESIGNED AND BUILD PSG

Cattle Panel Passive Solar Greenhouse

Sugar Grove, NC (36^0 14'44.70" N, 81^0 49'12.11" W, 817m (2696 ft) asl)

This PSG started out as a COVID project in 2021 by den Biggelaar, to test the long-held idea to use bend cattle panels for this purpose. The basic frame was put together in Spring, and used as a pole bean trellis during the summer; the greenhouse was finished after their harvest. Several modifications have been made since to improve its performance.



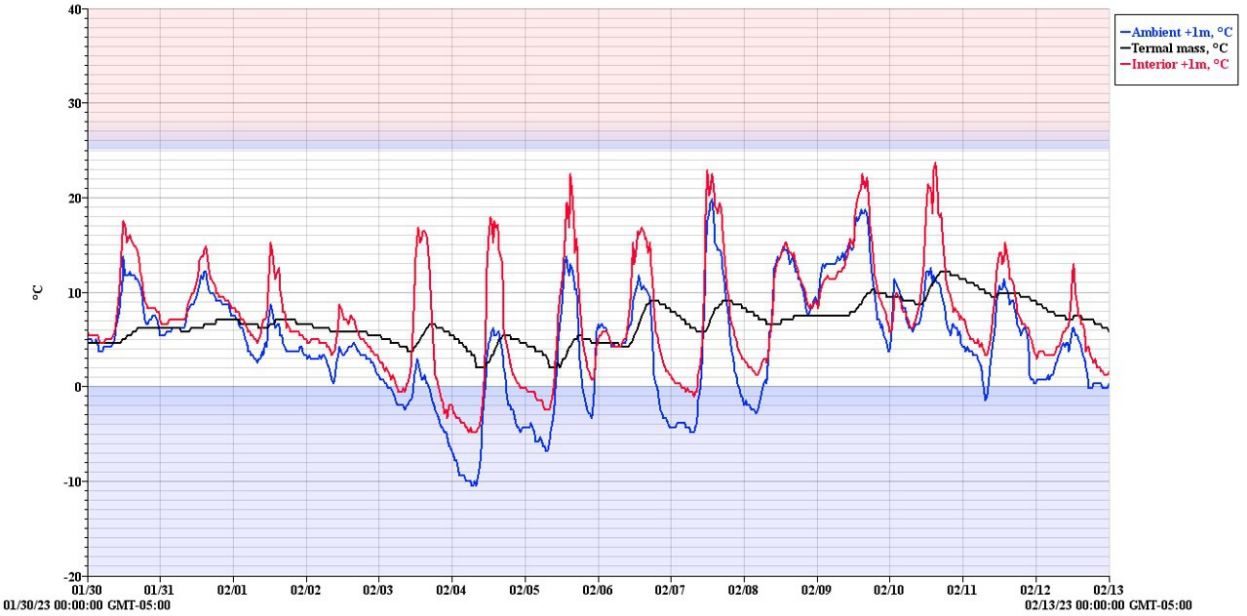


Design data

- 8x8 ft. footprint.
- Two cattle panels side-by-side, bend in a 4x6x6 ft. shape to form knee wall, glazing and roof.
- 2x4 in., 1x4 in. and 2x6 in. severe weather lumber; used some treated 2x8 in. pieces on the north side along the bottom.
- 4 in. cinder blocks on the west and south side to level the structure.
- 3/8 in. untreated plywood, water-sealed and painted.
- 4x6 ft. double-wall polycarbonate panels as windows on east and west side, attached with aluminum U-profiles to the structure.
- Double layer 6 mil polyethylene greenhouse cover.
- ¾ in. blueboard foam insulation for the roof, covered with old corrugated cardboard (to limit sun degradation of the foam) (foam and cardboard are sandwiched between the polyethylene cover).
- 0.5 in. blueboard insulation (R3.2) for the walls.
- Vent with automatic vent opener in the north wall; one automatic 16x6 in. basement vent in lower East wall.
- 2 flat-black 55-gallon barrels with water as thermal mass along the north wall.
- Brown/silver heavy duty tarp as curtain along the inside angled glazing.

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Temperature performance and statistical analysis, January 30 to February 13, 2023.



	Minimum ^{0}C	Maximum ^{0}C	Mean ^{0}C	SD ^{0}C
Ambient +1m	-10.56	19.81	4.48	5.95
Interior +1m	-4.82	23.63	7.33	5.85
Thermal mass	2.03	12.16	6.75	2.03
Delta-T	-1.99	15.71	2.89	2.69

Performance observations

- The cattle panel greenhouse has performed better than expected; in the 2022-23 winter, potted rosemary and lemon grass survived with only minor freeze damage on some leaves. On very cold nights, interior temperatures dipped below freezing for a short time, but recovered rapidly once the sun hit the structure (its sub-optimal location with hills and trees on east and south sides limits direct sun until 10:30am).
- Thermal performance (see graph and statistics below for the Jan 30 to Feb 14, 2022 period) shows that adequate temperatures were maintained during this period. However, the thermal mass sensor was rather erratic; data was gathered using Hobo H8 loggers and sensors, some of the latter being more than 10 years old. Using sensors in liquid or the soil also degrades them faster, giving less accurate results; for that reason, no soil temperature data could be retrieved in 2023 and 2024 due to defective sensors.
- Given shape and size, door placement is not ideal for easy access to open and close the curtain daily. So, the curtain is down 24 hours a day both in winter (to reduce radiative heat loss at night) and summer (to prevent overheating) but there is still sufficient light entering through the knee wall and side windows for crop growth. In winter 2024, a crop of lettuce (with a

lightweight Remay cover) did not get any freeze damage even when early morning temperature on several days in January dropped to -17/-18^{0}C (1^{0}F).

- Placement of the barrels in the northwest corner is not ideal as, with the glazing curtain down, no direct sunlight hits the barrels. Placement along the south knee wall would have been better to improve heat storage diminishing day/night temperature swings (changed to South glazing in 2025). Also, to place the barrels level on the slight slope of the land, the boards under the barrels were put on top of the cinderblock in the NW corner. As snow that accumulated there melted in January 2025, the cinder blocks sank leaving a 2 in. gap for cold air to enter the structure.
- As this greenhouse was an experimental and temporary structure as proof of concept of using cattle panels, den Biggelaar did not invest in a solid foundation, better insulation, and lumber to build it. The greenhouse could also easily be made longer by adding cattle panels; bending the panels in a 3x5x8 ft. shape would allow for a greater width while still giving enough height to place barrels along the south knee wall. And, of course, using treated lumber of appropriate dimensions (scarce in 2021 due to COVID) would make for a more durable structure.