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GREENHOUSE OF THE FUTURE

Final Report

July 3, 1998

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Cal Poly Pomona
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William Korthof
Consuelo Orozoco

Architecture classes:

Regenerative Studies classes:

Principle Investigator

Agriculture Engineering graduate
student

Biology undergraduate
Architecture undergraduate
Engineering undergraduate
Architecture undergraduate

ARC 499 special projects
ARC 303 third design studio
Various seminars and laboratories
RS 400 independent studies

MASTER

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BL
Final

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BUILT FORM (SPRING QUARTER 96)

Early Concept Plan of "Incubator Greenhouse"

Challenges Addressed and Overcome

- computer thermal performance modeling compared to actual pilot structure
- economics and logistics of straw bale construction
- design, approval and construction of straw bale building relying on student labor
- design of photo-voltaic electric system
- design of thermal monitoring and control system

Additional Challenges to be Addressed

- pilot structure thermal performance compared to actual building performance
- adequacy of initial passive thermal control strategies and energy system
- performance and management strategies for agricultural systems

CASE-1 BASECASE

Passive Strategy	Material	Location	
Thermal Storage	Water	Fish Tank	3,485 GAL
	Concrete	Floor	T=4"
	Concrete	Wall	T=1"
Insulation	Straw Bale	Wall	T=17"
Solar Gain	Glazing	Window(south)	285 SF
		Window(north)	16 SF

OUTLINE

RESULT (INDOOR AIR TEMPERATURE)

CASE-2

Passive Strategy	Material	Location	
Thermal Storage	Water	Fish Tank	3,485 GAL
	Concrete	Floor	T=4"
		Wall	T=1"
Insulation	Straw Bale	Wall	T=17"
Solar Gain	Glazing	Window(south)	285
		Window(north)	16
		Roof	681

UTLINE

RESULT (INDOOR AIR TEMPERATURE)

CASE-3

Passive Strategy	Material	Location	
Thermal Storage	Water	Fish Tank	3,485 GAL
	Concrete	Floor	T=4"
		Wall	T=1"
Insulation	Straw Bale	Wall	T=17"
Solar Gain	Glazing	Window(south)	653
		Window(north)	16

OUTLINE

RESULT (INDOOR AIR TEMPERATURE)

Greenhouse Construction

This greenhouse of the future is located at the Center for Regenerative Studies (CRS) at Cal Poly Pomona. The building design was driven by desired environmental conditions. The primary objective was to keep the interior space warm during winter for the breeding of fish and other greenhouse activities, especially in the winter. To do this, we needed a highly insulating envelope. Straw bales provide excellent insulation with an R-value of approximately 50 and also help solve the environmental problems associated with this agricultural "waste product."

All of the walls have rice straw bales except the South elevation, which is composed of a double glazed poly-carbonate clear plastic material that allows sufficient winter sunlight to penetrate into the building. The building will accommodate up to six fish tanks (SAP's) which measure five feet in diameter and height. The water in these fish tanks will absorb heat during the day and release heat to the building interior during the night. The North side of the building receives little direct sunlight, reducing diurnal temperature variation. The lower portion of the North wall is constructed of concrete block. It is anticipated that the compost pile along the exterior of this block wall will transfer additional heat of approximately 1,200 watts during normal decomposition activity -- an amount comparable to a portable electric heater.

The building was framed with six 8 inch-square steel columns. They support glue-lam beams that run the length of the building's eaves on the North and South. In turn, these will support wood-frame trusses running North-South, which will be tied together with the roof surface.

The "skin" of the building has several components. These include a four foot high concrete block wall on the North side, and poly-carbonate sheets on the South side. The remaining wall surfaces, up to ceiling or eaves height, are straw bales encased by cement stucco, exterior and interior. The gables of the East and West ends will consist of cedar siding, matching the adjacent buildings at the CRS. The exposed roof material will consist of standing seam copper or similar material to match the appearance of the CRS building roofs.

This building will require a small amount of electricity to run the water tanks, aeration and lights. Photo-voltaic panels will be installed on the South-facing roof and the electricity will be stored in sealed gell-cell batteries. This will allow the building to be "off the grid." Conventional fire alarm and sprinkler systems will be installed in the greenhouse and linked to the existing buildings.

Initially, bamboo was to be utilized as another sustainable building material. Although it was determined that bamboo would be able to provide more than adequate overall strength for framing and trusses, it would have created significant fabrication challenges. After experimenting with different joints, it was determined that bamboo would be too irregular in size, strength, angle, and shape to be utilized as a framing material. The

effects on the roof surface material (difficulty in providing the desired flat plane) were of particular concern.

Construction Progress Summary

We were anxious to get started on the construction, and finally started work after seasonal rain showers settled down. The saturated soil around the site made it hard to excavate. Instead of digging trenches for our footings, we had to take the ground down to the same level and back-fill with gravel. The foundation preparation was painstakingly difficult and time consuming. First, we had to decide on the proper slab drainage. A floor drain was out of the question because we would have had to tie into the gray water system. We decided to slope the slab out the door. After calculating out the curb height, we had to set the batter boards and strings using a transit. The transit was used to set the top of the form work, and later helped with the columns. It was a difficult process which took up valuable time, adjusting and re-adjusting. Confirming that we had all the components of rebar and anchor bolts was critical before we could proceed. We poured in two phases: individual column footings, and the rest of the footing -- curb and slab. The first pour we did by ourselves. Column base templates were made to hold the anchor bolts and dammed around them. We mixed our own concrete with a 1:3:3 ratio. For the large pour, a Cal Poly facilities crew guided the process, and the concrete was supplied by a local company who pumped it into the forms. We began at 6 a.m. on the pour date and finished around 5 p.m. We had intended to pour the figure-eight footing as our first phase, but it worked out this way instead.

With the foundation under our belt, the actual building was underway because of our group effort. The next step was to get ready for the straw bale wall raising with sill plates and the door frame. We had a wonderful couple from Arizona, Matts Myhrman and Judy Knox, give us a workshop on straw bale methods. They started with an open lecture and slide show showing the many possibilities and applications of straw bales. The following day was dedicated to training a team of students in the fundamentals of building technique. They would show us slides of each step of the process and then take us to the site for a demonstration. We learned the proper techniques to notch and shape bales. The bales required rebar pins to make the structure monolithic, which required trust in one's assistants. Matts and Judy stressed the process as a community effort and gave us insight on how to organize the volunteers that would attend our bale raising the following day. We had to make sure that the walls went up straight and correct, and that the door frame was square and tied together properly. After the walls were up, the holes had to be stuffed with straw, and an additional mixture of mud and straw was applied to create a flatter surface. It was amazing to work with such a non-uniform material and produce a uniform structure.

It was unfortunate that we could not get the concrete block wall finished to commence with the bale raising. We had no experience in masonry and decided after the fact to sub-contracted out the block wall. The wall is now finished, as well as the form work for the concrete shelf that will support the bales on the North wall. Construction is continuing over the summer with a smaller staff, but the building is anticipated to be finished by the

end of the summer. This will facilitate monitoring the building during the entire upcoming heating season.

Although we did not finish the building in the limited time allotted, the group of students involved worked well with the given situation. Because of other academic demands and deadlines, students did not have the means to work 40 hours a week on the greenhouse project alone. Most students involved did not have previous hands-on experience, and with rain delays, the process seemed to drag on longer than expected. Nevertheless, greenhouse construction is scheduled to be complete before the beginning of the 1998-99 heating season in October of 1998.

Cost

The final construction costs are still currently being determined. Since all thermal gains in the greenhouse will come from passive solar heat from the composting process and solar photo-voltaic, the operating cost for the building will be very low. On the other hand, the cost of construction materials and labor are more expensive than for the more common light-weight, fossil-fuel-heated greenhouses. When the cost of fuel is low, there are strong economic incentives to build, as is the common practice. The course, however, is not sustainable in the long run.

BUILDING CONSTRUCTION

Construction Documents Approved By:

- **Office of the State Architect**
- **Office of the State Fire Marshal**
- **Campus Plan Checking Office**

pages 14-21

Building With Straw Lecture and Bale Raising Announcement

page 22

Construction Photos Showing Students Building the Greenhouse

pages 23-32

INCUBATION BUILDING CENTER FOR REGENERATIVE STUDIES CAL POLY POMONA

4105 W. UNIVERSITY DRIVE
POMONA, CA 91768

GENERAL NOTES

1. VERIFY ALL DIMENSIONS, LOCATIONS OF EXISTING UTILITIES, AND CONDITIONS ON THE JOB SITE PRIOR TO THE START OF WORK OR PORTIONS OF THE WORK. NOTIFY THE CONTRACTOR IMMEDIATELY OF ANY VARIATIONS BETWEEN ACTUAL FIELD CONDITIONS AND CONSTRUCTION DOCUMENTS. EXISTING CONDITIONS ARE INDICATED AS A RESULT OF FIELD OBSERVATIONS AND INFORMATION SHOWN ON AVAILABLE RECORDS, AND FIELD CONDITIONS AT TIME OF PREPARATION.
2. ALL MATERIALS AND WORKMANSHIP SHALL COMPLY WITH ALL GOVERNING CODES, ORDINANCES, REGULATIONS AND LAWS.
3. THE DESIGN, FABRIC, AND SAFETY OF ERECTION BRACING, SHORING, TEMPORARY SUPPORTS, AND SCAFFOLDING IS THE SOLE RESPONSIBILITY OF THE CONTRACTOR AND SUBCONTRACTORS.
4. WHERE ANY CONFLICT OCCURS BETWEEN THE REQUIREMENTS OF LAWS, CODES, ORDINANCES, RULES, AND REGULATIONS, THE MOST STRINGENT SHALL GOVERN.
5. IN NO CASE SHALL WORKING DIMENSIONS BE SCALED FROM PLANS, SECTIONS OR DETAILS ON THE DRAWINGS.
6. DETAILS AND/OR TYPICAL SHALL APPLY IN ALL CASES UNLESS SPECIFICALLY INDICATED OTHERWISE.
7. WHERE NO SPECIFIC DETAIL IS SHOWN, THE FINISH OR CONSTRUCTION SHALL BE IDENTICAL OR SIMILAR TO THAT INDICATED FOR LIKE CASES OF CONSTRUCTION.
8. HANDICAPPED COMPLIANCE NOTE:
THESE DOCUMENTS MEET ALL REQUIREMENTS FOR HANDICAPPED ACCESSIBILITY. THE PATH OF TRAVEL TO THE SPACE IS BARRIERS FREE, CONTINUOUS, FIRM AND ACCESSIBLE. TOILET ROOMS ARE PROVIDED.
9. EXIST ALL NEARBY TO PROTECT AND REPAIR/REPLACE ALL EXISTING ELEMENTS TO REMAIN FROM REMOVAL. REPAIR OR REPLACE EXISTING ELEMENTS DAMAGED BY THE EXECUTION OF THIS CONTRACT TO EQUAL OR BETTER CONDITION.
10. DIMENSIONS SHOWN ARE TO STRUCTURAL GRID LINES. FACE OF BRACING AT EXTERIOR WALLS AND FACE OF STUD AT INTERIOR PARTITION WALLS UNLESS NOTED OTHERWISE.
11. INSTALLATION OF THE FIRE SPRINKLER AND FIRE ALARM SYSTEMS ARE "RECEIVED APPROVAL" ITEMS AND SHALL NOT BE STARTED UNTIL PLANS, SPECIFICATIONS AND CALCULATIONS HAVE BEEN SUBMITTED, REVIEWED, APPROVED AND SIGNED BY ARCHITECT AND THE CALIFORNIA SOUTH WEST OFFICE.
12. SPRINKLER ENTIRE INCUBATION BUILDING, COORDINATE ALL SPRINKLER HEAD AND FLOOR LOCATIONS WITH STRUCTURAL, MECHANICAL AND ELECTRICAL. TIME PRIOR TO INSTALLATION, NO STRUCTURAL, MECHANICAL OR ELECTRICAL SHALL BE PENETRATED PRIOR TO WRITTEN PERMISSION OF THE STRUCTURAL ENGINEER.

PROJECT DATA

- APPLICABLE CODES:
- TITLE 24, PART 1 & 2 CCR 1994 UBC WITH CALIFORNIA AMENDMENTS
 - TITLE 24, PART 3 CCR 1994 NEC WITH CALIFORNIA AMENDMENTS
 - TITLE 24, PART 4 CCR 1994 LBC WITH CALIFORNIA AMENDMENTS
 - TITLE 24, PART 5 CCR 1994 UBC WITH CALIFORNIA AMENDMENTS
 - CALIFORNIA FIRE CODE 1994 UBC WITH CALIFORNIA AMENDMENTS
 - TITLE 19, CALIFORNIA CODE OF REGULATIONS (STATE FIRE MARSHAL REGULATIONS)

OCCUPANCY SEPARATION REQUIREMENTS

A3 - B2	NONE
B2 - B1	1 HOUR
B1 - A3	1 HOUR

DESCRIPTION	PHASE I FACILITY COURSE COMMONS LECTURE/RESEARCH	PHASE II FACILITY LECTURE BUILDING	PHASE III FACILITY RESEARCH BUILDING
OCCUPANCY CLASSIFICATION	MIXED A-3, B-3, B-1	B-3	B-3
CONSTRUCTION	TYPE V-N	TYPE V-N	TYPE V-N
FIRE SPRINKLERS	YES	YES	YES
TOTAL OCCUPANT LOAD	189	77	77
NUMBER OF STORIES	14-0"	ONE	ONE
HEIGHT OF BUILDING	29'-0"	29'-0"	29'-0"
FLOOR AREA (GROSS) :			
A3	0.970 SF		
B2	1.000 SF	2,646 SF	
B1	2.000 SF		
TOTAL FLOOR AREA (GROSS)	12.970 SF		
TOTAL BUILDING AREA	25.940 SF		
ADDITIONAL AREA SUMMARY CALCULATED ON THE BASIS OF THE VILLAGE CENTER (INCLUDING THE NEW ACADEMIC FACILITY) AS A SINGLE BUILDING.			
CURSE LEVELS			
OCCUPANCY	A3	B2	B1
BASIC ALLOWABLE AREA	6,000	8,000	6,000
INCREASE FOR SPRINKLERS (CODE)	17,250	17,250	17,250
DESIGN AREA	6,970	1,000	2,410
MIXED OCCUPANCY	6,970	1,000	2,410
CALCULATION	17,250	17,250	17,250
	6,970 + 0.000 + 0.000 = 6,970		
SECOND LEVEL			
BASIC ALLOWABLE AREA	6,000	8,000	6,000
INCREASE FOR SPRINKLERS (CODE)	17,250	17,250	17,250
DESIGN AREA	6,970	1,000	2,410
MIXED OCCUPANCY	6,970	1,000	2,410
CALCULATION	17,250	17,250	17,250
	6,970 + 0.000 + 0.000 = 6,970		
MULTI-STORY INCREASE	N/A	N/A	N/A
	24,000	24,000	24,000
TOTAL BLDG.	17,250	17,250	17,250
	2,646 + 1,976 + 2,509 = 7,131		

DIRECTORY

ARCHITECT
BROOKS CAVIN, III
CLARKSON ENVIRONMENTAL DESIGN GROUP, INC.
488 NORTH BROADWAY, SUITE 300
CLARKSON, CA 95711
TEL (925) 685-2996 FAX (925) 685-4262

STRUCTURAL ENGINEER
JEFFREY L. VAN DYKE, P.E.
1841 W. 18th STREET, SUITE 3
LAKELAND, CA 91706-2000
TEL (925) 932-5070 FAX (925) 932-5070

PROJECT LOCATION / SCOPE

THE CENTER FOR REGENERATIVE STUDIES IS A 16-ACRE AREA OF LAND ON THE CAMPUS OF THE CALIFORNIA STATE POLYTECHNIC UNIVERSITY AT POMONA, CALIFORNIA, LOCATED JUST SOUTH OF TEMPLE AVENUE. IT IS A PORTION OF THE UNIVERSITY'S "VILLAGE" DEVELOPMENT, A 200-ACRE AREA OF CONVEYED LAND THAT IS TO BE DEVOTED TO EDUCATION AND RESEARCH IN THE SUSTAINABLE USE OF RESOURCES.

THE CENTER FOR REGENERATIVE STUDIES IS BEING BUILT IN SEVERAL PHASES. PHASE I AND II ARE COMPLETED AND OCCUPIED. THESE DOCUMENTS REPRESENT THE SITE IMPROVEMENTS AND STRUCTURE FOR THE INCUBATION BUILDING ONLY.

THE BUILDING CONSTRUCTION FOR THE INCUBATION BUILDING TOTALS APPROXIMATELY 714 SQUARE FEET OF NEW ASSEMBLY AREA.

THE STRUCTURE WILL BE STEEL TUBE COLUMNS WITH GLULAM BEAMS AND PREMANUFACTURED ROOF TRUSSES WITH SIPR ORIENTED STRAND BOARD DECKING AND COPPER ROOFING. THE EAST, WEST AND THE UPPER PORTION OF THE NORTH WALLS ARE STUCCO CLAD SIMILAR TO THE LOWER PORTION OF THE NORTH WALL IS CONCRETE MASONRY. THE SOUTH WALL IS TO BE CLAD WITH ALUMINUM CLAD ON GABLE.

THIS BUILDING WILL NOT BE CONNECTED TO THE ELECTRIC, WATER OR SEWER SYSTEMS EXCEPT AS REQUIRED BY FIRE ALARM AND SPRINKLER SYSTEMS.

THE BUILDING WILL BE TYPE V-N.
THE OCCUPANCY WILL BE B-3.

VICINITY MAP

LOCATION MAP

SHEET INDEX

- 1 - TITLE SHEET
- 2 - SITE PLAN
- 3 - LAYOUT PLAN
- 4 - PLANS
- 5 - BUILDING ELEVATIONS
- 6 - NORTH/SOUTH SECTION
- 7 - EAST/WEST SECTION
- 8 - DETAILS

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ARCHITECT
BROOKS CAVIN, III
C-8044

CONSULTANT

DRAWER

CENTER FOR REGENERATIVE STUDIES
CALIFORNIA STATE POLYTECHNIC UNIVERSITY POMONA
POMONA, CALIFORNIA 91768
(909) 860-5155

INCUBATION BUILDING
CENTER FOR REGENERATIVE STUDIES

TITLE SHEET

NO.	REVISIONS	SCALE: NTS
1	SEPT 29, 1993	BRANN CH
2	OCT 22, 1993	CHECKED: B.C.H.
		DATE: JUL 29, 1997

SHEET
A-1
OF 8 SHEETS

④ NORTH ELEVATION

③ SOUTH ELEVATION

② EAST ELEVATION

WEST ELEVATION

⑧ NORTH ELEVATION

⑦ SOUTH ELEVATION

WEST ELEVATION

⑥ EAST ELEVATION

① EAST / WEST SECTION
SCALE 1/4" = 1'-0"

DATE 12/15/1997
BY *[Signature]*
DWG. 1130149

ARCHITECT BROOKS CAVIN, II C-8004	CONSULTANT	OWNER CENTER FOR REGENERATIVE STUDIES CALIFORNIA STATE POLYTECHNIC UNIVERSITY POMONA POMONA, CALIFORNIA 91768 (909) 860-5555	INCUBATION BUILDING CENTER FOR REGENERATIVE STUDIES	EAST / WEST SECTION	SECTION 10-00	
					NO.	REVISION
					1	12/15/1997
					2	01/17/1998
					SCALE 3/4" = 1'-0"	
					SHEET	
					A-7	
					DATE JUL 17 1997	
				OF 8 SHEETS

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OFFICE OF REGISTRATION SERVICES
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College of Environmental Design at Cal Poly Pomona
Center for Regenerative Studies and the Department of Architecture

BUILDING WITH STRAW

A Public Lecture on the
**History and Technology of
Building with Straw Bales**

by Leading Authorities
**Matts Myhrman and
Judy Knox**

Thursday, May 14, 1998 at 7:30 pm
College of Environmental Design (Building 7) Gallery

Details will be presented regarding the Bale Raising for
the new CRS Incubator Building to be held at CRS from
8:00 am to 5:00 pm on Saturday, May 16, 1998

Greenhouse Of The Future Test Module

Summary

For purposes of examining the thermal benefits of housing aquaculture tanks, an insulated passive-solar-gain test module was designed, built and monitored at the Center for Regenerative Studies at California State Polytechnic University, Pomona. The target water temperature was 30 degrees C, which is the optimal culture temperature for most tilapia strains. The test module contains one five-foot diameter water tank. This compares with six five-foot diameter water tanks in the full-scale "Greenhouse of the Future." Solar-5, a thermal modeling computer program developed by the University of California at Los Angeles Architecture Department, was used for optimizing the design for the least nighttime heat loss and greatest daytime heat gain during winter. A secondary design objective was to moderate summer heat gain. Solar radiation and air and water temperatures were logged every ten minutes from December 13, 1997 to June 13, 1998. Using a night insulation cover, the indoor air and water stabilized at mean temperatures of 29.0 degrees C and 29.2 degrees C, respectively. This was in spite of unusually low insolation rates. Regression analyses indicated that ambient air temperatures at the site explain greater than 80 percent of the nighttime temperature variations in the housed tank water. The regression equations showed that the test module heat loss coefficient based on water tank energy losses agreed closely with the calculated value. These results suggest that:

- 1) aqua-culture tank water can be maintained near the 30 degrees C target temperature for tilapia year-round in sunny, low-elevation, southern California locations by housing the tanks in passive solar buildings constructed of common and inexpensive materials, and
- 2) the thermal performance of this type of structure can be predicted for locations where average temperatures and insolation rates are known and wind speeds are moderate.

Materials And Methods

The test module faces four degrees east of due South (azimuth = 176). The ground directly to the South is white concrete with an estimated reflectivity of 30%. The module has interior dimensions of 5-foot length x 5-foot width x 6.7-foot height (average floor to ceiling height) enclosing 98 cubic feet of air and 72 cubic feet of water. A 5.2-foot x 5.2-foot x 4-inch hole was dug for the foundation. A 2-inch x 6-inch dual-wall, square lumber frame was constructed, placed in the hole, and anchored in place with sections of 0.5-inch rebar. The interior of the frame is packed with gravel and topped with a layer of sand sandwiched between two layers of 6-mil plastic. The top of the completed foundation is 3.5 inches above ground level. This foundation provides a secure and level footing for wall construction. It also maintains the dry-air space in the gravel bed, thus preserving its insulation value.

The walls are framed with 2-inch x 6-inch lumber with 0.5-inch plywood applied forming the interior wall. The roof is a 2-inch x 6-inch dual wall construction with packed straw for insulation and the top sheet of plywood extending on all sides to form the roof

structure. The roof and ceiling have a slope of 6:12. Eighteen straw bales are stacked against North, East and West sides of the module with packed straw in the gaps where the bales meet the roof. 2-inch x 6-inch lumber posts are anchored to the ground and the roof for bale and roof support. White polyethylene poultry curtain weave is battened to the posts to protect the straw bales from rain. The South wall is glazed with two sheets of greenhouse polyethylene plastic with a 3.5-inch air gap.

Measures were taken to eliminate infiltration and ex-filtration, including caulking and taping all joints, and the installation of a very small, weather-stripped access door which normally remains locked shut. In addition, the interior is lined with 6-mil black agricultural plastic. The ceiling has an additional layer of bubble plastic insulation skinned with aluminum foil on both sides ("Reflectix"). Total roof R-value is calculated to be approximately 9.5 C/Wh (18 hr*F/Btu). North wall straw bales are laid flat and assigned an R-value of 24 C/Wh (45 hr*F/Btu). East and West wall straw bales are stacked on their sides and assigned an R-value of 16 C/Wh (30 hr*F/Btu). A single layer of Reflectix was applied to the exterior of the glazing each night from January 18 to March 22. The calculated mean hourly heat loss rate per-degree Fahrenheit for the test module, with the Reflectix cover on for 15.5 hours each 24-hour period, is 21 Wh/C (40 Btu/hr*F).

Two translucent fiberglass aquaculture tanks were used for the experiment: one inside the test module and one outside (control). Small pumps were used to mix the water in each tank to ensure uniform water temperatures throughout the tanks and to provide satisfactory dissolved oxygen levels for the fish. Formal testing was conducted in five 5-week periods. A 100 percent water change was made at the beginning of each 5-week test session using water of an average temperature of 16 degrees C.

Data

Temperature data were recorded every ten minutes using Hobo thermistor devices manufactured and distributed by Onset Computer Corporation. Two thermistor sensors were placed at a depth of two feet below the water surface: one in the control tank (outdoors) and one in the test module tank. Another sensor was placed next to the tank, but not in contact with it, out of direct sunlight. A fourth sensor was placed in an identical position relative to the tank at the control tank. Data were downloaded into an Excel computer spreadsheet weekly. Total horizontal insolation data was recorded for ten minute intervals at the Center for Regenerative Studies weather station, located about 50 yards away from the experiment site. These data were also downloaded into the Excel computer spreadsheet. These five parameters are presented in Charts 1, 2, and 3.

Results

Weekly temperature means and ranges, together with each week's mean daily total horizontal insolation, are presented in Table 1. The insolation rates were measured at the Center for Regenerative Studies weather station. Test module tank water was heated to an equilibrium temperature within the first five to ten days of each test period in direct relation to South vertical incident insolation and ambient air temperatures.

In test runs 2 and 3, where night insulation was used, test module water leveled out at a mean temperature of about 29.2 degrees C and test module air next to the tank leveled out at a mean temperature of about 29.0 degrees C. In test runs 1, 4, and 5, where night insulation was *not* used, test module water temperature leveled out at about 27.1 degrees C and test module air temperature next to the tank leveled out at about 25.7 degrees C. As expected, daily temperature fluctuations were somewhat greater in winter than in spring and summer months. Seasonal mean ambient and control tank temperatures for the testing periods were, respectively, 12.1 degrees C and 15.0 degrees C for winter, 16.6 degrees C and 19.5 degrees C for spring, and 16.9 degrees C and 17.2 degrees C for summer.

Table 1: Weekly Temperature Means and Ranges and Total Horizontal Insolation

TEST RUN 1: No Night Insulation					
	Ambient Air mean, range (degrees C)	Inside Air mean, range (degrees C)	Outside Water mean, range (degrees C)	Inside Water mean, range (degrees C)	Total Horizontal Insolation (W/sq.m.)
Dec. 13-19	12.7, 5 - 23	23.6, 17.5 - 32	14.1, 10 - 17.5	22.6, 16 - 27.5	3322
Dec. 20-27	8.9, 1 - 21	25.7, 22 - 32	13.2, 9.5 - 16.5	27.2, 23 - 32	4786
Dec. 28-Jan. 3	14.3, 7 - 25	28.5, 26 - 32	16.9, 12 - 21	30, 26 - 32.5	2890
Jan. 4-10	9.9, 2 - 18	24, 22 - 32	12.7, 11 - 15.5	25.2, 23.5 - 27.5	2303
Jan. 11-17	13.3, 7.5 - 21	24, 22 - 31.5	15.4, 12.5 - 18	24.4, 22.5 - 27	2636

TEST RUN 2: With Night Insulation					
	Ambient Air mean, range (degrees C)	Inside Air mean, range (degrees C)	Outside Water mean, range (degrees C)	Inside Water mean, range (degrees C)	Total Insolation (W/sq.m.)
Jan. 18-24	11.8, 5 - 21	24.8, 18 - 33	no data	23.8, 15 - 31.5	no data
Jan. 25-31	12.7, 6 - 25	31.2, 28 - 36	16.3, 13 - 20	31.8, 29.5 - 34	3202
Feb. 1-7	11.3, 4 - 21	26, 23 - 32	13.5, 10 - 16.5	27.3, 25.5 - 30	1954
Feb. 8-14	12, 5 - 21	26.6, 22 - 32.5	15.2, 12 - 18	27, 24 - 29	3193
Feb. 15-21	10.6, 4 - 18.5	27.4, 24 - 33	14.5, 11 - 18	28.4, 26 - 31	4250

TEST RUN 3: With Night Insulation					
	Ambient Air mean, range (degrees C)	Inside Air mean, range (degrees C)	Outside Water mean, range (degrees C)	Inside Water mean, range (degrees C)	Total Insolation (W/sq.m.)
Feb. 22-28	12, 5 - 25	29.9, 16 - 32	15.4, 11.5 - 21.5	—	4184
Mar. 1-7	12.9, 7.5 - 26	22.9, 20 - 28	17, 14 - 22.5	23, 9 - 26	4050
Mar. 8-14	15.6, 6 - 29	29.8, 23 - 34.5	19.8, 14 - 25	29.1, 24 - 33	5489
Mar. 15-21	15.8, 8 - 27.5	30.2, 27.5 - 34.5	19.5, 16.5 - 23.5	29.9, 27.5 - 32.5	4466
Mar. 22-27	15.2, 7.5 - 29.5	30.7, 27.5 - 36.5	19.6, 14.5 - 26	30.5, 27.5 - 33	3193

TEST RUN 4: No Night Insulation

	Ambient Air mean, range (degrees C)	Inside Air mean, range (degrees C)	Outside Water mean, range (degrees C)	Inside Water mean, range (degrees C)	Total Insolation (W/sq.m.)
Mar. 28- Apr. 4	9.7, 3 - 19	19.5, 16 - 25	no data	17.9, 15.5 - 19.5	3481
Apr. 5-11	13.4, 6 - 25.5	23.2, 19 - 27	no data	21.8, 18.5 - 25	5258
Apr. 12-18	12.6, 3.5 - 22	24.3, 22 - 28	15, 11.5 - 20	no data	5919
Apr. 19-25	18.3, 10 - 35.5	28.1, 25 - 33	—, 15 - 26	28.6, 25 - 30	5664
Apr. 26-May 2	18.5, 7.5 - 32	29, 26 - 32	21, 15.5 - 26	29.2, 27 - 31	6605
May 3-9	16.4, 10 - 22	27.3, 24.5 - 30.5	17.7, 14.5 - 22	28, 26 - 30.5	3419

TEST RUN 5: No Night Insulation

	Ambient Air mean, range (degrees C)	Inside Air mean, range (degrees C)	Outside Water mean, range (degrees C)	Inside Water mean, range (degrees C)	Total Insolation (W/sq.m.)
May 10-16	13.8, 8 - 24.5	20.8, 18.7 - 24.8	15.1, 10 - 20	21.4, 19.5 - 23	4462
May 17-23	17.1, 9.5 - 28	24.9, 21.5 - 28	18.8, 16 - 22.5	25.6, 23 - 27	6532
May 24-30	16.6, 7 - 26	25.5, 23 - 30	17.4, 14 - 21	26.1, 25 - 27	5514
May 31-June 6	17.8, 10 - 28.5	26.6, 25 - 29.5	18.8, 15 - 27	27.2, 25 - 29.5	no data
June 7-13	16.3, 12 - 27	25, 23 - 28.5	15.5, 14.5 - 20	25.4, 25 - 27	3912

Table 2 shows insolation rates for vertical, south-facing surfaces. These rates were derived from total horizontal insolation rates measured at the Center for Regenerative Studies weather station and from Typical Meteorological Year (TMY) figures. The derivation for estimating south-vertical insolation from horizontal insolation was developed by R. D. McFarland of the Los Alamos Scientific Laboratory (Balcomb 1980, 271). McFarland's correlation assumes a ground reflectance of 30 percent.

Table 2: Mean Daily South-Vertical Insolation: Site Measured Compared with Pomona TMY

(W/sq.m.)

	Decemb er	January	February	March	April	May
Site	5660	3970	3982	3731	3224	2283
TMY	4130	4269	4493	4433	3685	2978

Analysis

The thermal mass (translucent water tank) to building volume ratio for the test module is very large, and most of the sunlight entering the test module shines directly on the tank. Given this configuration, the test module is similar to a solar collector and can be analyzed as such. Nightly heat loss measurements from the tank were plotted as a function of the average difference between ambient air temperature and tank water temperature for the same periods to generate a scatter plot. A regression analysis of the scatter plot indicates that 83 % of nighttime heat loss from the water tank is explained by the difference between the ambient air temperature and the tank water temperature (Figure 1). The regression equation indicates a test module overall heat loss coefficient of 19 Wh/C (36 Btu/hr*F), which agrees closely with the calculated figure of 21 Wh/C (40 Btu/hr*F).

Figure 1: Test Module Heat Loss Rate Regression Analysis

Conclusions

In the test periods where the night insulation was used to cover the glazed South face of the structure, the test module maintained mean water temperatures of 29.2 degrees C. This was in spite of unusually low insolation rates. Regression analyses indicated that heat losses were reduced significantly by the application of night insulation. Results suggest that:

- (1) aquaculture tank water can be maintained near the 30 degrees C target temperature for tilapia year-round in sunny, low-elevation, Southern California locations by housing the tanks in passive solar buildings constructed of common and inexpensive materials, and
- (2) the thermal performance of this type of structure can be predicted for locations where average temperatures and insolation rates are known and wind speeds are moderate.

References

Balcomb, J. Douglass, et.al. (1980), Passive Solar Design Handbook; Volume 2: Passive Solar Design Analysis. Prepared for the U. S. Department of Energy, Washington, D. C.

PROTOTYPE MODULE

Prototype Module Photos

pages 41-45

**Thermal Performance Charts Showing Diurnal Temperature
Fluctuations as Recorded Using Prototype Module**

pages 46-48

mm315321.xls

ControlAir
 CntriWatr
 SACWatr
 SACAir

mm531606.xlc

Conclusion

When construction is complete, The Greenhouse Of The Future, at the Center for Regenerative Studies at Cal Poly Pomona, will be utilized as a research tool and as a demonstration of the integration of agricultural systems for reducing environmental impact. Greenhouse construction is scheduled to be complete before the beginning of the 1998-99 heating season in October of 1998.

We expect to incorporate water-based agricultural systems, including integrated aquaculture or hydroponics. Future research with The Greenhouse Of The Future will involve thermal performance recording, including Hobo monitors. These sensors will be used to record inside ambient temperature, humidity, water temperature, and outside temperature. These systems may be developed to utilize and treat reclaimed waste water for both fish and production plants. In the long run, the greenhouse will have the capability of providing a flexible environment for multiple uses in a passive thermally managed design.

Cal Poly Pomona Students Present Incubator Greenhouse at GIS Conference at Orlando, FL, June 1998