# TECHNOLOGY AND THE STUDIO

## The Building Workshop for for the Solar Decathlon

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### Introduction

The Solar Decathlon provided a national forum for competition among fourteen student teams, each of which designed, built, and operated an 800-square-foot, totally solar-powered home with a home office, and the transportation needs of the home and office. The Decathlon was sponsored by the U.S. Department of Energy, together with the National Renewable Energy Laboratory, the American Institute of Architects EDS, Home Depot and BP Solar. The competition took place on the National Mall in Washington D.C., where each house was constructed and operated from September 18 to October 10, 2002. The competition focused on solar photovoltaic energy production, energy-efficiency, design with climate, thermal comfort, refrigeration efficiency, lighting efficiency, the operation of a home office and transportation using a solar charged electric vehicle.

Professor Michael Garrison of the School of Architecture directed the University of Texas at Austin Solar Decathlon Collaborative team along with Pliny Fisk, co-director of the non-profit Center for Maximum Potential Building Systems in Austin. The graduate student team developed a design using photovoltaic collectors that captured, converted, stored, and used enough solar energy to power an entire household, including the home-based business and the transportation needs of the household and business. The design features a flexible, modular, reusable kit of parts that sits lightly on the land and forms the superstructure around a mobile utility environment.

Our investigations suggest that progressive technologies offer solutions to the serious emerging challenges of energy efficiency and sustainable development and thereby become a strong design shaping force. These progressive technologies integrate photovoltaics; passive solar heating, solar induced ventilation, daylighting, water use efficiency, regenerative waste management, smart energy management systems, and other low-entropy open building systems that contribute to "green" architecture. The application of building systems also included the principles, conventions, standards, applications and restrictions associated with the manufacture and use of existing and emerging construction materials and assemblies and their effect on the environment.

### Design of the Solar Decathlon House

For a house to become a good home it must shelter its inhabitants from the extremes of the outdoor climate to maintain human comfort. A good house must develop the means by which the building exterior or skin can act as the "filter, barrier or switch"—as Norberg-Schulz writes—to maintain comfort conditions throughout the year with as little fossil fuel input as possible. The solar decathlon house is based on the principles of a historical dogtrot house scheme and was designed to be a demonstration of techniques for an energy-efficient and comfortable home. The dogtrot house is so called because of the long open corridor through the center of the house enabling a dog to trot through. The house is square on its site, with the dogtrot corridor running from south to north. The entry to the porch faces south with a long roof overhang that shades the house in summer while acting as a wind-scoop, helping to capture southerly breezes and channel them through the corridor. The living spaces are arranged on both sides of this corridor, with door openings onto the corridor and window openings out of the sides and north wall of the house. When a summer

*Fig. 1. Historical dog-run house, LBJ Ranch.*

breeze sweeps through the central corridor, it creates a low-pressure zone along its path. Simultaneously, the breezes striking the front and sidewalls of the house, finding only small windows to penetrate, create high-pressure zones. The combination of these two pressure conditions, in turn forces an accelerated airflow through the openings in the front and sidewalls of the house. The window openings can be controlled to modulate the velocity and channel the direction of the airflow.

Because summer breezes in Washington D.C. are most active in the morning and late afternoon the dogtrot porch is used during these periods for immediate cooling for ventilation and for "loading" the house with morning coolness that is retained in walls, floors and furniture. Conversely, the evening breezes are used to "flush" the house of heat that accumulates during the afternoon.

The concept of the dogrun house is being combined with the ideals of an open building system. The basic idea of an open building system is the strategy of designing and producing built environments in which the parts making up the whole are given freedom for layout, construction and adaptation. The flexibility of open building reflects the temporary nature of the building in Washington D.C. and the more permanent nature of the house in Austin, TX. Its design is such that its modularity allows for the adaptation of the building according to site.

The house utilizes a B-Line structural steel grid in which building components, such as walls and windows, can be added on to as well as subtracted from in order to accommodate the needs of the household. Under the design process, the house has undergone multiple changes, but has always adhered to its basic conceptual ideas. The building has shifted in position within the structural grid to allow for better interior quality of spaces. And through the use of model making, prototyping and 3D computer modeling, the interior space is taller and more spacious allowing for better ventilation and daylight.

### Mobile Environment

Given the fact that the competition brief for the solar decathlon implied a portable and temporary structure, the design project was intended to show how a mobile environment can be expanded and adapted to a specific site and then modified for the needs of a different site in another climatic zone. In the solar Decathlon Workshop the mobile environment is an Airstream trailer, which contains the kitchen, bathroom and laundry facilities.

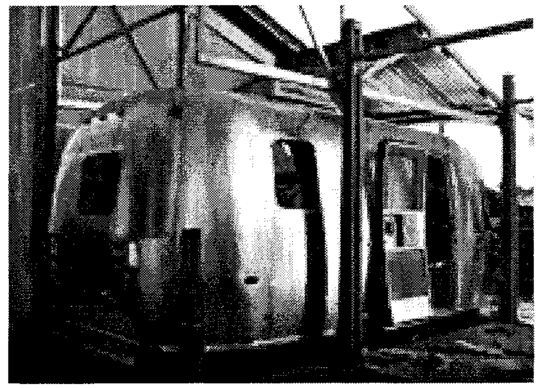

*Fig. 2. A modified 16 foot Bambi Airstream functions as a mobile utility environment.*

An important contribution by the Building Workshop is the recognition that mobile home environments have been notorious in their high use of resources. In our partnership with Airstream, there has been a determined desire to improve this image and to more consciously connect our efforts to the approximately 25% of recreation home clientele who express a desire for more environmentally friendly technology.

In order to provide the remaining functions of the house, a modular and flexible building system will unfold around the Airstream trailer in a dogtrot configuration in response to the site with a flexible orientation to the sun and wind. The Airstream aesthetic is carried through the building, since the streamlined design enhances natural and solar induced ventilation. The modified Airstream will be transported to the National Mall in Washington D.C., where the mobile utility environment and the B-Line structural/utility grid will be unfolded around the Airstream. The grid functions as the platform and superstructure for sustainable building systems. The B-Line open framework developed by CMPBS not only enables high degrees of reuse and reconfiguration to adapt to changing lifestyle needs, but extends the use of materials far better than present short life span building methods. Likewise, the disentanglement of utilities from structure and walls enables controls and utility lines of all types to better evolve with technological advancement.

The idea of isolating the heat and moisture gain from cooking, showering, washing clothes and dishes, etc. within the MUE allows the design to compartmentalize these sources and allow the rest of the living area to remain comfortable. Icynene insulation was installed in the Airstream so that a better buffer against the exterior climate was established. An optional "wrap-a-round" window on the south oriented allows for solar heat gain in colder months.

A standard Airstream has the ability to run from a conventional electric outlet (which is typically provided at campgrounds) or a propane tank (which is usually the option when camping in "primitive area). Both of these power sources damage the environment because they do not rely on current solar energy.

The solar decathlon Airstream generates power through a series of photovoltaic (PV) arrays, which have no emissions. Energy efficient appliances were installed in the modified Airstream, including a specially made energy-efficient Sunfrost D.C. refrigerator, an Equator dishwasher that uses only 4 3/4 gallons per cycle, an Equator combination washer-dryer that uses only 8.27 gallons per cycle, a CookTek induction cook top (1800 watts), a flash-bake oven (900 watts on microwave setting) and a Sun oven solar cooker (solar powered) for the outside solar oven.

In order for the Airstream to be used in a plethora of arrangements in the future the modified Airstream is made with a second door to allow for a passage straight through to another bedroom module that functions as the private side of the dogrun configuration.

This effort is being extended into the materials used to construct the Airsteam and their eco-friendliness to both people and the environment through an understanding of their full life cycle impact. The aluminum walls of the Airstream were removed and Icyene insulation was added to improve thermal performance. The floors

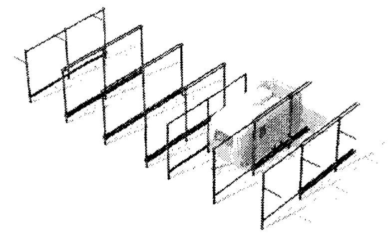

*Fig. 3:.Airstream Trailer as Mobile Utility Unit with B-Line structural columns and Beams*

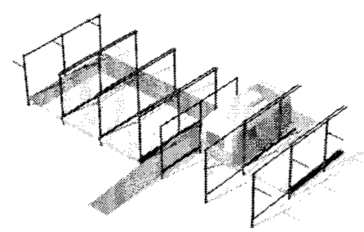

*Fig. 4:.Fly-foam floor foundation with bamboo flooring inside the structure, and bio-composite choice deck outside the structure.*

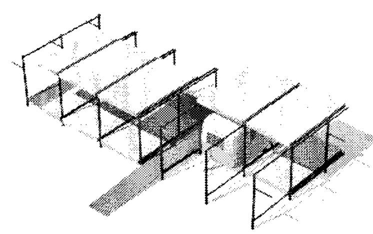

*Fig. 5. Home-Foam Structural Insulated panels used for roofing deck.*

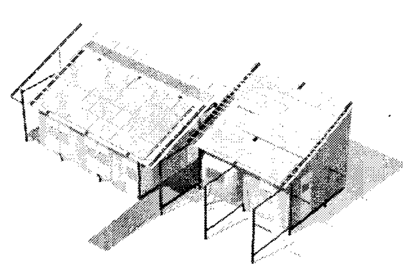

*Fig. 6:. Solar PV panels on metal roofing deck with Hardie board over Structural Insulated Panels for wall infill.*

and the table booth and benches were made from bamboo stained with natural oils. The kitchen cabinets in the Airstream were constructed using a combination of bio-compositie materials.

### Building Materials

Materials selection and specification for any project, especially one as unique and demanding as the Solar Decathlon, requires a great deal of deliberation. By intentionally placing an emphasis on the environmental, health, and performance of materials for our project we knew there would be many difficult decisions to make. The question quickly became, how would we know what products and materials were appropriate for our design intentions?

The answer, for the University of Texas, Austin team at least, was to develop a set of criteria that would guide the entire process of materials selection, specification, design, and installation. By clearly identifying our goals and priorities we were able to identify, specify, and obtain the products and materials necessary to meet our design and environmental objectives. Our materials selection criteria were expressed through two tools, Guideline Specifications outlining our environmental goals for the project and a Materials Selection Matrix.

Guideline Specification established general goals for the project including:

1. Use resources efficiently:
   a. Select materials that use resources efficiently.
   b. Use construction practices that achieve the most efficient use of resources and materials.
   c. Recycle or reuse job site waste.
   d. Select recycled content materials.
   e. Select materials that can be recycled.
2. Avoid scarce, irreplaceable, or endangered recourses.
   a. Select materials from abundant, well-managed resources.
   b. Select materials that are replaceable, renewable, or can be replenished.
   c. Select materials that minimize damage to natural habitats.
3. Use durable materials:
   a. Select materials with the longest usable life.
   b. Select materials that can be re-used.
   c. Select materials with least burdensome maintenance requirements.
4. Create spaces that are healthy for occupants:
   a. Select low/non-toxic products and materials.
   b. Select materials without toxic maintenance requirements.
   c. Develop heating, ventilation, and cooling strategies that will provide fresh air and will not trap water or pollutants.
5. Use energy efficiently:
   a. Select materials with low embodied energy.
   b. Select materials that save energy during building operations.
   c. Use locally available materials
6. Use water efficiently:
   a. Use construction practices that achieve the most efficient use of water.
   b. Select water-conserving appliances and equipment.

The Materials Selection Matrix evaluated each material using the specification of each material against the following criteria:

Carbon sink potential
Lightweight
Modular/Moveable/Easy Assembly
Efficient
Non-toxic
Recycled/Recyclable
Aesthetically Pleasing
Innovation
Durable
Donated
Biodegradeable
Local

Materials selection criteria such as "use resources efficiently," "create spaces that are healthy for occupants," and "select materials that generate the least amount of pollution" are becoming increasingly more common in today's environmentally aware design world. However, as the Solar Decathlon focuses primarily on engineering issues related to energy efficiency, we felt that the

*Fig. 7. Moveable foundation pads and leveling screws for the transformable structure.*

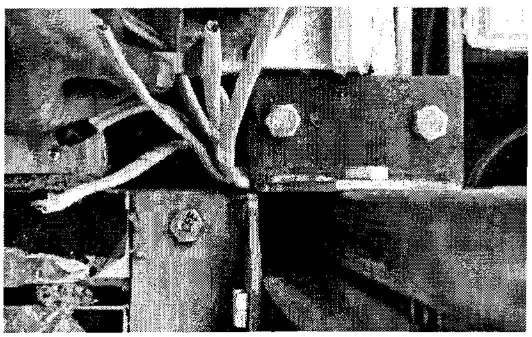

*Fig 8. Structural columns and beam also function as conduits for electrical and plumbing systems in the open grid system*

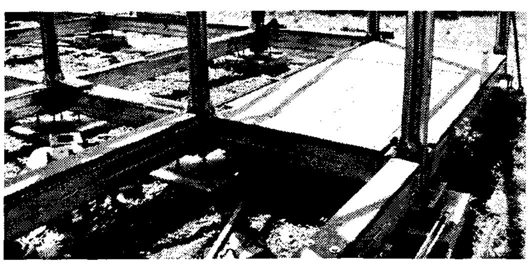

*Fig. 9. Beams and columns serve as a utility grid and to support the floor inserts*

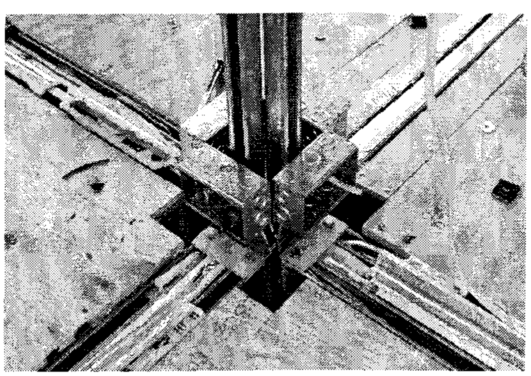

*Fig. 9: B-Line recycled steel columns and beams are bolted together to form an open building system.*

introduction of these criteria was significant. We didn't seek an exhaustive quantitative analysis of potential products and materials, but rather a more qualitative assessment of their suitability to our project's goals and intentions. While fundamentally simple, our Guideline Specifications and Materials Selection Matrix helped to make our intentions more concrete to the general public and ourselves. More importantly, it made environmental and health performance a fundamental part of every discussion we had on products and materials for our Solar Decathlon Entry.

In the end, we have designed and built a house whose environmental performance far exceeds that of a typical new house built today. At the same time, we have assembled a palette of materials that effectively meet the unique demands of our building system and the Solar Decathlon. We've developed a modular and flexible kit of parts that exemplify the best in energy efficiency, durability, healthiness, and efficiency.

**Open Building Systems**

The UTSOA entry is built for change. Gone are nails and glues, cast in place concrete footings and structural welds. In their place are screws, pre-cast fly-ash foundation pads and structural bolts. The major difference between the scenarios is in the connections between parts; the UTSOA entry can come apart and adapt without the destruction of materials.

The key to an adaptable building is the creation of a system that allows for changes and adaptations to occur. Everyone has experienced the frustration that comes when light sockets are not in the right place, HVAC vents that cool the wrong portion of the room and walls that cannot move or expand because of their structural connections. The UTSOA entry addresses this issue by separating the layers of utilities, structure and infill walls. Parts of this system are able to grow or move without disrupting other parts of the building. The entanglement of utilities hidden beneath sheetrock is replaced with utility runs that can be accessed easily without disruption to the walls. These utilities runs have accessible caps in the floor that allow for electrical plugs to move and for HVAC vents to be relocated. In addition, infill wall panels can move independent of structure and the utilities. Thus walls within a building can change to redefine the space plan to suit the changes in family structure. The structure of the house can be added onto or readjusted the same as the utilities or the infill walls. The "once" children's room that was vacated when they went off to college can be deconstructed and added to the living space on another side of the house.

In order to accomplish this complicated system, the UTSOA team was required to rethink traditional methods of construction. The team turned its sights upon building components rather than individual materials. For example, floors were designed to accept either decking materials or insulation and finish materials. These floors were built to be lifted out of place and relocated to another position of the house; the porch can be adapted into added living space with little commotion. Another example is found in the foundation systems. The foundation was designed in pads that sit atop the ground instead of being embedded within it. The result is that columns and footings can move and be relocated to another position within the home. By designing the parts to be interchangeable and to work together with other parts a new way of building was invented.

This new system of parts has embedded within it a set of easily understood rules that allows for anyone to be their own contractor. Occupants can now create new spaces from off the shelf components supplied from their local Home Depot. Thus the equity of the component's cost is retained when one room is deconstructed and added to another part of the home. It is easily conceivable to see a future that when families move from one city to another that their home is packaged along side their belongings. When it arrives to its new location the parts of the original home can be constructed again in a new form that responds to its new climate and site conditions. The University of Texas at Austin's Solar Decathlon entry is a working prototype of this new vision of building. It has already been constructed once in Austin, deconstructed and placed onto trucks and reconstructed in Washington DC. And then deconstructed again and returned to Austin where it was reconstructed yet again.

**Environmental Controls**

In order to make the solar decathlon project work effectively with the sun as its sole power source the issues of environmental controls were divided into five systems:

* Passive solar gain and shading
* Natural and solar induced ventilation
* Daylighting
* Solar hot water heating
* Photovoltaic power

The first three systems are passive, meaning that no electricity or mechanical parts are involved. The last two are active, since they involve the pumping of water and electrical generation via of PV cells. Design decisions were based on calculations, testing of physical models and computer simulations.

**Passive Solar Heating**

Although the Solar Decathlon competition runs from late September to early October in Washington D.C., which has generally mild weather at that time, the project was designed for high performance during cold winter months and hot summer periods in Austin, Texas where it will finally make its home. The goal is to use direct gain to trap solar radiation during the winter days, to store excess heat in a light weight phase change thermal storage material and to have a highly insulative thermal envelope that prevents this heat from escaping during the night.

Based on Visual DOE-3 simulations passive solar heating was found to be adequate in maintaining comfortable conditions in winter inside the house. An optimum balance point between maximizing heat gain and minimizing afternoon overheating was achieved with a south-facing glazing ratio of 1.2 square feet of glazing per square foot of conditioned floor area. This glazing ratio is calculated to provide up to 72% of the solar heating fraction while minimizing the diurnal temperature swing. A back-up radiant heating system that uses hot water as a radiant heating source is designed to provide the make-up heating required for cool morning periods in

*Fig. 11. Passive Solar Heating through south facing windows.*

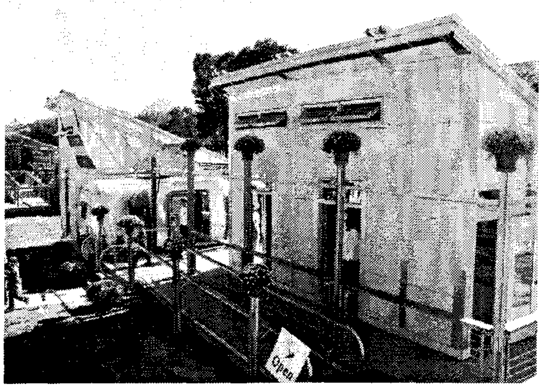

*Fig. 12. North view of UTSOA solar decathlon*

Washington D.C. and in Austin, Texas. Hot water or chilled water in the "ice battery" HVAC unit allows it to function as both a back-up heating or cooling unit.

### Solar Induced Ventilation Cooling

During the heat of the day a ventilated attic space with a PV roof over a radiant barrier shields the house from intense solar radiation. Continuous soffit vents at the eves of the roof overhang vent the attic. The air is exhausted at the peak of the roof using a continuous metal ridge vent. The reflective roof, radiant barrier, the ventilated air buffer and R-30 Structural Insulated Roof panels keep the mean radiant temperature of the ceiling cooler. Broad roof overhangs; a radiant barrier, light exterior colors, and R- 30 Structural Insulated Panels keep the mean radiant temperature of the walls cooler as well. The cooler mean radiant surface temperatures (MRT) and the use of a ceiling fans extend the comfort zone and minimize the need for air conditioning. When there is very little breeze a PV powered "ice-battery" provides back-up cooling and de-humidification.

### Natural Ventilation

In Washington D.C., outdoor conditions are very pleasant for a significant portion of the year. During this time good ventilation will increase comfort inside the building. Ventilation maintains inside temperatures near the outside levels and helps vent heat from solar gain and internal sources to the outside. In addition, the moving air makes higher temperatures feel cooler to occupants.

Cross-ventilation takes advantage of the high and low-pressure areas around the building in order to increase inside air circulation. While interior walls tend to obstruct the movement of air within any home, the same ventilation principles hold true where walls exist. Air will still move from high to low pressure zones, but at a reduced velocity.

In the solar decathlon house, however, the interior partition of the home office actually helps to increase the velocity of the air in the space by creating turbulent air patterns in the room. In general, it can be said that if the wind has to change direction within the room, a larger volume of the space is affected by the airflow, creating higher overall circulation velocities.

The volume of airflow (number of air changes) that passes through a structure is governed by the size of the openings; the greatest number of air changes is obtained when both inlets and outlets are as large as possible. However, the velocity of air movement through the structure is maximized, creating the greatest cooling, when the area of outlets is greater than the area of inlet openings.

Insofar as airflow is concerned, there are two distinguishable types of operable window sash: 1) pivoted or hinged windows (hopper, awning, casement), which exert a deflecting, turning effect on the incoming air current, and, 2) sliding and double-hung windows which operate in the plane of the wall and therefore do not steer incoming flows.

The deflecting ability of vane-type windows employed on the south facing windows of the solar decathlon home are used to direct air streams, which normally flow, along the ceiling to move down into the living zone. A solid, planar sunshade attached to a windward wall deflects the internal airstreams up to the ceiling. This effect was corrected by leaving a gap between the structure and the projection. Downward sloping interior louvers and a Warm Company Venetian blind have a similar control effect to promote good ventilation.

When planning for natural cross ventilation, we were aware that the direction of internal airflow does not always correspond to wind direction. The wind creates areas of high- and low-pressure around a house. High-pressure areas form where wind strikes the building and "backs up." Low-pressure areas occur where velocities are high and eddies form on the downwind side. Air moves into the building through openings in the high-pressure or windward regions and exits at low-pressure or leeward areas. The careful sizing and placement of air inlets and outlets greatly enhanced the cooling effect of this cross ventilation. Generally, the inlets on the windward side of the home are smaller than the outlets on the leeward side for maximum air velocity and optimum cooling. In addition, since inlets that are placed directly opposite each other cause the airflow to only cool objects in the direct path of the airflow and since a greater area may be cooled at lower air speeds if the moving air has to change direction in the room, windows were not placed opposite of each other to promote effective air flow and cooling.

Another way to enhance natural cross ventilation is to shade air inlets, which will lower the temperature of incoming air. A deep south facing overhang assures south facing air inlets are shaded during summer months.
In order to compute the rate of air flow into a space the following formula was used:

$$Q = K\ A\ V$$

where:

Q = the rate of air flow (cu. ft. per hr.)
A = the area of inlets (square feet)
V = wind velocity (mph)
K = a value dependent upon the outlet to inlet relationship where:

| Area of outlet / Area of inlet | K |
|---|---|
| 1:1 | 3150 |
| 2:1 | 4000 |
| 3:1 | 4250 |
| 4:1 | 4350 |
| 5:1 | 4400 |
| 3:4 | 2700 |
| 1:2 | 2000 |
| 1:4 | 1100 |

Rate of Air Flow into a space from *ASHRAE Handbook of Fundamentals*

The window outlet air for the solar decathlon house is two times the inlet area; therefore the K value is 4000. The area of the inlet is 3.5 square feet and the prevailing breeze for this location in summer is normally only 8 mph.

therefore:

$$Q = (4000) \times (3.5) \times 8$$
$$Q = 112{,}000 \text{ CFH}$$

112,000 CFH/2268 cubic feet of interior space equals 50 air changes per hour moving at 566 feet per minute. Air moving at 566 fpm will increase the interior bioclimatic comfort zone of the house interior.

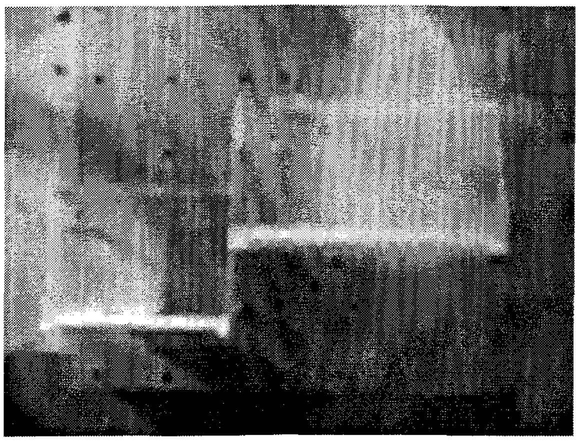

*Fig. 13. View of model from above showing how the natural ventilation was enhanced by the venturi effect achieved with the proper sizing, placement and alignment of windows and vents in the solar decathlon wind tunnel test model.*

*Fig. 14. Day lighting of the solar decathlon interior.*

The project goal is to channel prevailing breezes into the building, increase their velocity so as to maximize the cooling effect, and to ensure that all of the inhabited volume of the spaces has air movement.

Once the window schemes were worked out, the team built a 3/4" scale model and took it to the University of Texas Pickle Research Center wind tunnel facility for testing.

The wind tunnel test confirmed that a 2 to 1 north south ratio of windows worked if the north openings were spread out. High north wall vents were effective, the dogrun was the breeziest part of the house and openings in the east and west walls are essential when the breeze is along an E-W axis.

**Daylighting**

Natural daylighting will be utilized in both the bedroom and living room/office spaces. Daylighting reduces the need for excessive amounts of electrical lighting required to illuminate the space. However, too much daylighting may produce glare and an unacceptable amount of heat gain.

Good daylighting is achieved in the dogtrot design by providing bilateral lighting, (light from two sides) and by providing for large north facing windows. Glare is controlled by shading awnings and by the deep roof overhang along the south elevation. Daylighting shelves attached to the sill of the south facing windows enhance additional daylighting.

Using the Megatron daylight simulator and the rectilinear daylight simulator at the School of Architecture, The University of Texas at Austin, we were able to test the light intensity in various locations within our 3/4" = 1' scale model. Light sensors were affixed at a height of 30" (scaled) above the floor. Wall and ceiling surfaces were an off-white foam core that would imitate the reflection of finish walls and ceiling, and the floor surface was a tan kraft paper that would imitate bamboo flooring. With the daylight fraction method, we were able to convert values into footcandles specifically for a typical overcast Washington D.C. sky.

We found that it was not difficult to achieve the minimum intensity (15 footcandles) of uniform light at the workplane throughout the building during the middle of the day, in fact window shading will be required to reduce some excessive daylighting conditions. Furthermore, with our narrow plan (13.5' deep), the lighting was relatively balanced.

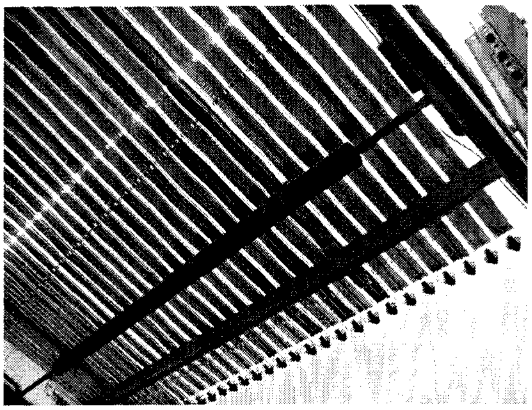

*Fig. 15. Evacuated tube solar hot water heater.*

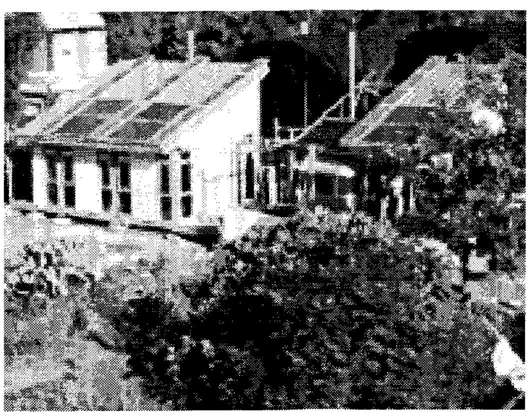

*Fig. 16. Solar PV system-15 Roof mounted BP solar Photovoltaic Panels and 6 Roof mounted ASE solar Photovoltaic Panels. UTSOA solar decathlon house in Austin, Texas.*

**Solar Water Heating**

The solar decathlon project employs a 50-gallon batch solar water system manufactured by Thermo Technologies. The direct pump system uses an electric circulating pump to move heat from the 30-tube manifold solar collector to the storage tank. This means that the system is free from the constraint of placing the collector below the tank as required for thermosiphon flow. The pump can move heat from the collectors on the roof to the storage tank on the south deck. Good sense still calls for minimal length of pipe run for efficiency.

A differential controller turns the circulating pump on or off as required. There are two sensors, one at the outlet of the collectors, and the other at the bottom of the tank. They signal the controller to turn the pump on when the collector outlet is 20°F warmer than the bottom of the tank. It shuts off when the temperature differential is reduced to 5°F. The philosophy behind this design is that the cost of heating your collectors with hot water from you tank is low cost freeze protection if only required occasionally. These systems are commonly used in the Sunbelt, and only where freezing is a rare occasion. The annual total BTU's collected per square meter (10 tubes) equals 3,602,086 for Washington D.C., and the annual total BTU's collected per square meter for Austin, Texas equals 4,625,681.

**Photovoltaic (PV) power system**

One of the main active solar components for the solar decathlon house is the Photovoltaic (PV) power system. Solar PV, along with wind and biomass, has emerged as one of the best renewable energy generation technologies in the market today. To meet the power needs of the solar decathlon's modern home-office, solar PVs form an integral part of the design.

The solar decathlon home is a stand-alone PV power system. This means that the house does not have any connection to the power utility grid. A more common use of solar PV 's are grid-connected systems, which supplement or backup their PV power with a connection to the electric grid. Stand-alone systems are more challenging to design since they leave no room for breakdowns and usually need more PV modules and a large battery bank. When there is a stretch of cloudy days (dark days), the PV array will produce at greatly reduced efficiency; as a result the battery bank will discharge to supply the home's power needs. It is under these conditions that grid-connected systems can draw from the grid.

A stand-alone system, on the other hand, has to have a battery bank that services a certain number of dark days. In conventional practice, the economic optimum is designed for 2 dark days. If the dark period continues beyond two days, backup systems like diesel generators are used. Since the solar decathlon prohibits the use of any non-renewable source of energy our system was designed for 3

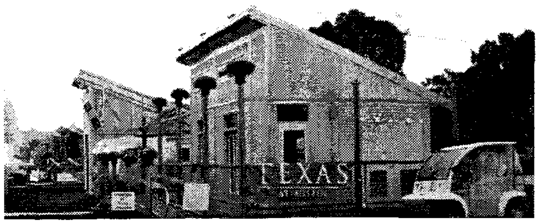


*Fig. 17 . Ford Electric Think Car adjacent to the UTSOA solar decathlon*

dark days. It is important to know that this does not imply that the battery bank will discharge entirely if there are three moderately cloudy days. PV modules continue to produce power from natural ambient light although at greatly reduced efficiency and so the batteries will receive some charge.

The PV array, which will cover most of the roof area above the bedroom and Airstream roof area of the house, supplies power that will be routed through Schottky diodes, lighting arrestors and charge controllers to a battery bank. The PV array will be mounted on the two roofs of the house both of which will be inclined at an angle of 20 degrees to the horizontal and will be facing due south. All the electric loads in the home will be supplied from the battery bank. This ensures that each load receives a steady power supply irrespective of weather conditions and time of day. Most of the loads in the house run on alternating current (AC). Only the refrigerator, custom-made by Sunfrost, will use direct current (DC). Power from the batteries will go through two Trace SW4024 Inverters that will convert the DC input into a sine wave AC output to service all the loads in the house except the refrigerator. The power will then flow through an AC panel-board that consists of breakers for each circuit and one main circuit breaker (MCB). The office, Airstream, solar car, and bedroom are each on separate circuits.

**Load Analysis**

The PV power system was sized after a detailed load analysis. The type of current drawn by each load (AC or DC), its power consumption and the number of estimated average hours of daily use were tabulated. This information allowed us to calculate the average total energy (in Watt-Hrs) that would be needed to run the house each day. Solar radiation data for Washington, DC and Austin, Texas along with the specifications of our PV module types were used in conjunction with the load analysis to estimate the number of PV modules we would need. We estimated a peak power consumption of 7,988 watts with and average watt-hours per day of 12,766. For economic reasons we settled on a 3.6KW. The retail costs of PV panels are currently in the range of $6.00 per watt thus, a 3.6KW system would retail for $21,800 and a 7.9KW would be $47,400. We believed that it was important to demonstrate that solar PV system be affordable so we used the 3.6KW System. This system requires only one Trace Controller and Inverter to operate vs a dual system required for a larger PV system and was therefore more affordable as well. During the competition we found the 3.6KW system adequate if we managed the load and did not utilize every appliance and charge the car at the same time.

We are using a hybrid of BP Solar 275U modules and ASE-300-DG/50 Modules. Our calculations project the need for 25 BP275U modules (75 watts each at peak power) and 6 ASE-300-DG/50 (300 watts each at peak power). We are using such a hybrid for two reasons. Firstly, it showcases two different technologies. The BP 275U are among the most efficient modules on the market today. This module uses the tried and tested mono-crystalline silicon technology. The ASE panels are highly reputed, efficient and easy to install multi-crystalline silicon modules. Secondly, since the Solar Decathlon is also about shrewd financial management, it was economically optimal for us to use this hybrid system.

The system is designed to output 24V DC to the inverters and the DC refrigerator load. Hence we needed 4 Trojan L-16 6V batteries to attain this voltage. Our load analysis revealed that we needed a capacity of 1,197 Ah (accounting for 3 dark days) to power the system, which requires us to employ 16-20 batteries.

**Transportation Analysis**

The electric car provided to each team for the "Getting Around" competition is the Ford Th!nk Neighbor. The competition organizers recommend that each team charge their car with excess energy generated by their PV system and then analyze how much mileage they will get out of their car. We have included the car in our load analysis in order to ensure that the PV system is sized to produce enough electricity to power the car for 60 miles each week. For each full 8-hour charging, the car has a range of 30 miles. The load analysis accounts for a full 8 hour charging for 2 days/week, which would allow the car to be driven for 60 miles. In designing the PV system we account for inefficiencies and errors by adding a safety factor to the load analysis. Normally, all the assumed inefficiencies do not materialize, causing the PV system to be slightly over-designed. Hence, in all likelihood, the system would produce excess power that could be used to charge the car, enabling our team to add more than 60 miles per week to our mileage credit.

## Conclusion

In conclusion the solar decathlon workshop has been helpful in teaching the solar decathletes about how energy intensive different daily activities are and how energy efficiency and energy independence may be achieved. The decathlon workshop has allowed the students to design, test and demonstrate that market-ready technologies exist that can meet the energy requirements of our daily activities while providing a beautiful structure in which to live and work.

The Solar Decathlon competition grounds building design knowledge in action and immediate experience. In this way decathletes are able to evaluate the actual performance of design decisions and re-establish the continuity and inter-relationship between the process of conceiving, making and using buildings emphasizing the importance of making and thinking at the same time.

Through observation, and post-occupancy data collection along with comparisons to values derived by model studies, computer simulations and calculations, decathletes have an opportunity to assess the performance of green building systems and to better understand and describe the variety of ways occupants actually experience an environmentally responsive building. This level of understanding is especially potent in the forum of the Solar Decathlon in which disciplinary knowledge and interdisciplinary understanding take place.

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