4DPV—PHOTOVOLTAIC SHADING DEVICES AS ARCHITECTURAL TIME PIECES

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INTRODUCTION

The Challenge

Following the first photovoltaic building applications with their characteristic engineered gear attached to roofs and walls without concern for beauty, new building integrated photovoltaic (BIPV) products were introduced. The photovoltaic roof shingle and the solar electric standing seam roofing are two of the most commonly used BIPV building products today.

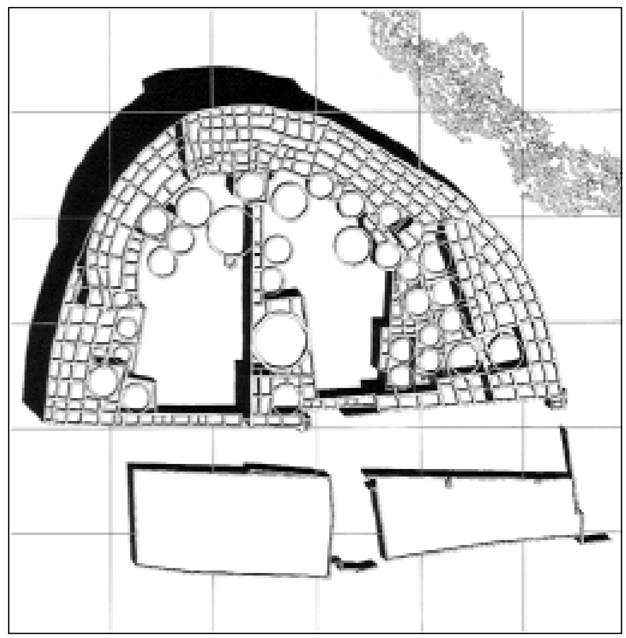
Building Integrated Photovoltaics are often associated with conventional roof forms and traditional house types. While BIPV satisfied the need to pass building codes and zoning requirements without offending a lay person's idea of beautification, this approach left little room for the creative architect to experiment and to innovate.

A challenge for architectural research in this situation is to explore how photovoltaics can be taken from ugly add-ons, via "hidden" BIPV solutions, towards new architectural forms and shapes that could enrich the art and science of building design in response to place and time.

Prior Art

The design of building structures in response to celestial alignments can be traced back through centuries of human creative existence. Recent studies by the Solstice Project indicate that the major buildings of the ancient Chacoan culture of New Mexico reflect solar and lunar cosmology in three separate articulations. The builders of Chaco Canyon would carefully manipulate orientation, internal geometry, and geographic interrelationships in response to the cycles of the sun and moon, see Figure 1 (Sofaer, 1997).

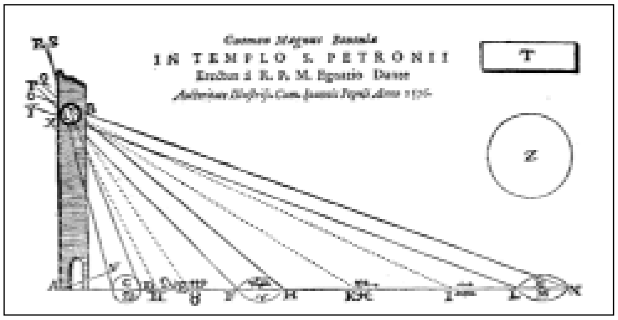
Figure 1: Pueblo Bonito at Chaco Canyon. Plan drawing reproduced from (Morgan, 1994).



Centuries later the great cathedrals in Europe were designed as astronomical observatories. Meridiane were constructed inside the churches in such a fashion that light introduced through a gnomen would indicate the passage of time. Figure 2 shows the sectional relationship of the gnomen to the line on the floor, and the passing of time as the bright spot of light moves along the line, highlighting seasons and religious calendar events.

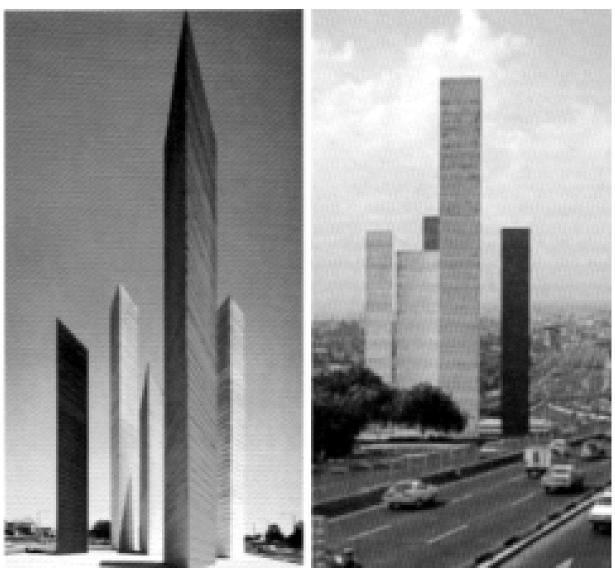
In his design for the Satellite Towers, Mexico's modern master Luis Barragán incorporated celestial alignments in a minimalist, yet powerful way. As one approaches the city from the North, the towers appear as five rectangular slabs with no evident thickness or mass, see Figure 3 (right side).

Figure 2: Meridiana in San Petronio, built by Egnatio Dante. From Riccioli, Almagestum novum, 1:1 (1651), reproduced from (Heilbron, 1999).



Viewed from the South, the towers show their sharp edges as the volumetric massing becomes evident, see Figure 3 (left side).

Figure 3: Torri Satélite, Mexico City (1957), by Luis Barragán, with Mathias Goeritz and the collaboration of Chucho Reyes, reproduced from (Martínez, 1996).



Power of Shade

While the tradition of cosmological expressions in architecture represents an immense source of enrichment and complexity in the perception of space, current trends in the area of building integrated photovoltaic (BIPV) applications do not readily lend themselves to further experimentation and exploration of celestial responses. This research therefore looks beyond the tight, seamless integration of photovoltaics in order to explore PV applications as unique architectural expressions within the overall design aesthetics of a building. In searching for alternatives to conventional BIPV applications, the design of a photovoltaic shading structure was identified as the appropriate vehicle for further exploration.

Since the modern movement in architecture preceded the maturing of photovoltaic technology, there is little or no precedence for PV shading designs. There is, however, a significant volume of work by acclaimed modern architects where shading structures are integrated with the overall architectural design. Le Corbusier and Charles Correa explored the double roof concept in house designs in India, while Paul Rudolph designed roof-shading devices for his Florida houses. In the Far East Ken Yeang designed a house shaded by a white trellis structure, and in the U. S. Southwest the concept of overhead horizontal shading has seen further development by architects like Judith Chaffe and Antoine Predock.

In her Ramada House design for Tucson, Arizona, Judith Chaffe creates a wooden shading structure that hovers above the entire dwelling. The massing of the building volumes resides under the protective umbrella of a “ramada”, thus providing shaded outdoor spaces for the inhabitants on the ground as well as on the roof. The play of light and shade from the Ramada adds to the richness of the design, along with desert vegetation hugging the structure on all sides, see Figure 4.

Figure 4: The Ramada House by Judith Chaffe. Photograph: Author’s collection.

In his Ventana Vista School design, also in Tucson, Arizona, Antoine Predock creates outdoor patios and walkways protected by shading structures assembled from additive sheet metal units. Here the shading devices are conceived of as separate entities that occupy spaces between building volumes while still holding design features integrated with the overall design, see Figure 5.

Figure 5: Ventana Vista Elementary School by Antoine Predock. Photograph: Author's collection.

RESEARCH OBJECTIVES

Design criteria

The following design criteria were established for the development of a PV shading structure for the Skill Center at Yavapai College:

- The structure should provide protection by means of shade for an outdoor circulation space adjacent to classrooms and offices on the top floor of the two-story building.
- The structure should be expressed as a unique architectural element that could enrich and enhance the overall architectural language of the building.
- The structure should produce electric energy to power a hybrid heating, cooling, and ventilation system, in full or in part.
- The geometry of the structure should be developed with the aim of creating dynamic patterns of light and shade in the circulation space below, thus adding a fourth dimension - time - to the perception of architectural space.
- The patterns of light and shade should ideally convey symbols of cultural significance, thus providing a charged visual environment for seasonal events as a way to strengthen the culture of environmental awareness and sensitivity among the members of the college community.

Operational research goals

The operational goals of this research were defined as to provide the detailed design of the above-mentioned shading structure, to see it built as a grid-connected PV array, and to monitor the performance of the structure over a period of one year or more during building operation.

METHODS

Digital 3D models

Digital three-dimensional models of the building were created using the computer program VectorWorks Architect™ by Nemetschek. The 3D model of the shading structure was created on top of the building geometry, which was imported into VectorWorks™ from AutoCAD™ via the DWG file format. Digital models in VectorWorks™ allow for detailed studies of the changing patterns of light and shade on the ground and on the building itself as a result of the geometry of the PV shading device.

Digital images were created for each hour of a typical day for each month of the year. The images were then animated in the non-linear digital video editing program Final Cut Express™ for analysis of the dynamic effects on each typical day. Changes and adaptations were made to the geometry of the PV array in order to meet the specific design criteria described above. Various PV panel tilt angles were analyzed in VectorWorks™ for their impact on the shading patterns.

Computer simulations

An un-official version 1.4 of Energy-10™ was used to simulate the predicted electric output from the PV array and to analyze the interaction of the array with the utility grid as well as the response to the hour-by-hour loads on the building. Energy-10™ was developed with funding from the U.S. Department of Energy (DOE) under the direction of Dr. Dough Balcomb at the National Renewable Energy Laboratory (NREL). Version 1.4 of the program had an integrated TRNSYS module that performed the PV output calculations. A location specific weather file for Cottonwood, Arizona was developed in WeatherMaker™, to be used for the Energy-10™ simulations (Lerum, 2003). Separate runs were performed in order to test each of various tilt angles.

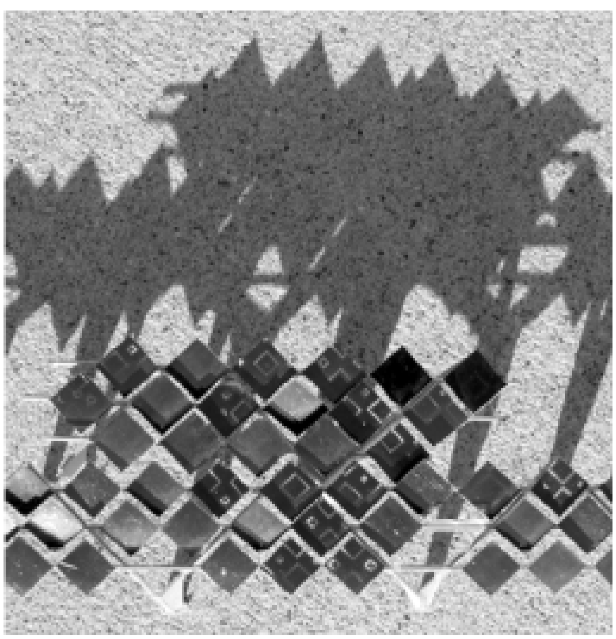
SIMULATION RESULTS

Configuration

Explorations in digital and physical models led to a decision to use square PV panels measuring 3 feet by 3 feet. Each panel would be assembled from two 21Wp modules. The PV array would be assembled from a total of 166 panels arranged in seven rows. The total peak performance of the initial design was estimated as approximately 7 kWp.

Each row of panels is mounted diagonally on a rod, allowing for seasonal change in the tilt angle. The decision to mount the square panels on a diagonal was based on model experiments where minimum self-shading and maximum variety in the shade patterns were explored as design goals, see Figure 6.

Figure 6: Early exploration of dynamic shading patterns from PV panels mounted diagonally. Model and photograph by the author.



Shading patterns

Digital images of the changing shading patterns were produced from perspective views in VectorWorks™. Of more than one hundred images, four are reproduced here. Apart from the dynamism of the play of light and shade, the particular geometry of the shading structure also produced images of symbolic significance. These symbols show up on specific times as explained in the captions below, see Figure 7, Figure 8, Figure 9, and Figure 10.

The four images included above indicate that the PV array is not only providing sufficient shade. There is an additional element of symbolism produced by the PV panels mounted above the main circulation space. Apart from the ever-changing abstract patterns of light and shade, there are images of significant symbolic value that show up on specific dates important to the solar calendar.

Figure 7: Perspective looking towards the East. A mountain range shows up on the north wall at noon at winter solstice, December 21st.

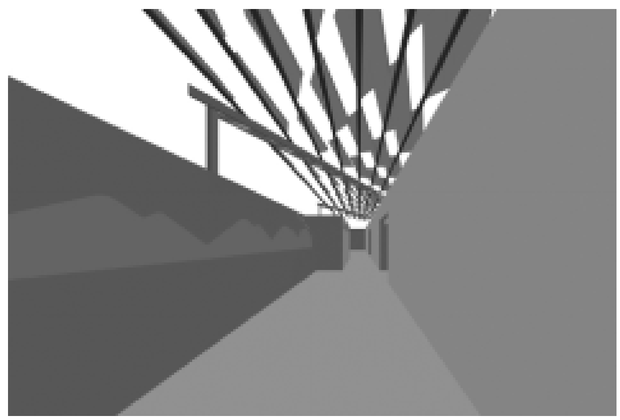


Figure 8: Sun rays on the north wall at noon at Equinox, March 21st and September 21st. This biannual event corresponds to what the ancient peoples of the Southwest identified as the "middle of time".

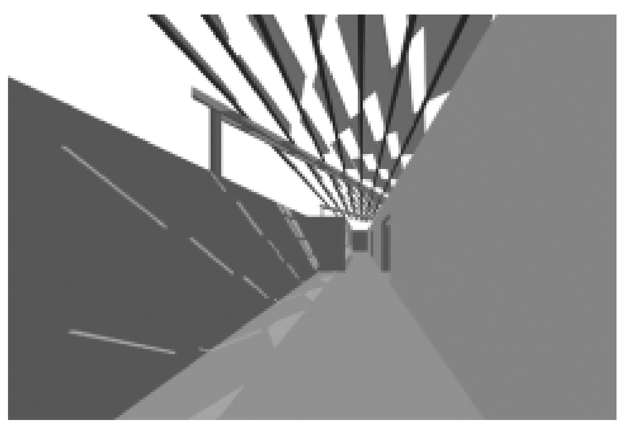


Figure 9: On March 21st and September 21st the sun leaves a mark on a west facing wall as it sets due west.

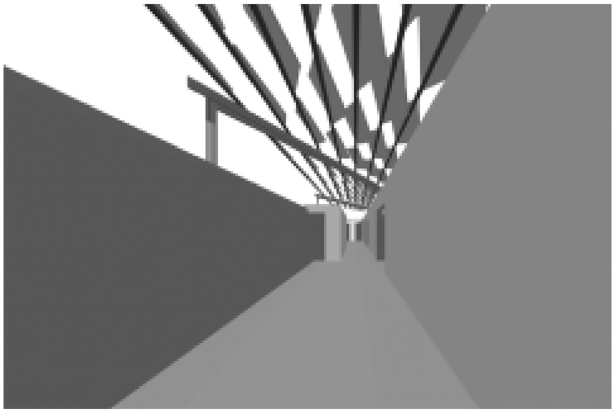
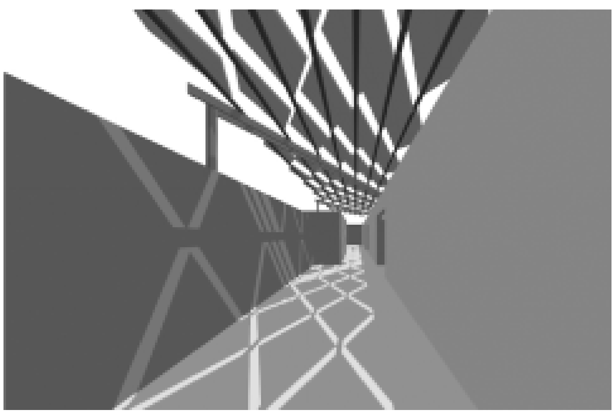


Figure 10: At noon on summer solstice the pattern of the Diamondback rattlesnake appears on the floor of the main circulation space. The snake enjoy the protective shade of the PV array temporarily for an hour or so, then it vanishes, not to show up again until June 21st next year.



The mountain range, the suns rays, and the Diamondback rattlesnake are icons intrinsic to the Sonoran desert environment. These symbols are reinforced and revitalized by the design of the shading structure as a timepiece.

PV output

The PV output was simulated in Energy-10™ version 1.4 for three different tilt angles (fixed all year) as well as the combination of a 23 degrees summer tilt and a 47 degrees winter tilt, see Figure 11. The results indicate that there is an estimated 3% increase in the predicted annual output, in kWh, achieved by changing the tilt from 47 degrees to 23 degrees on March 21st and switching back to 47

Figure 11: Monthly values of annual electric output from the PV array with various tilt angles.

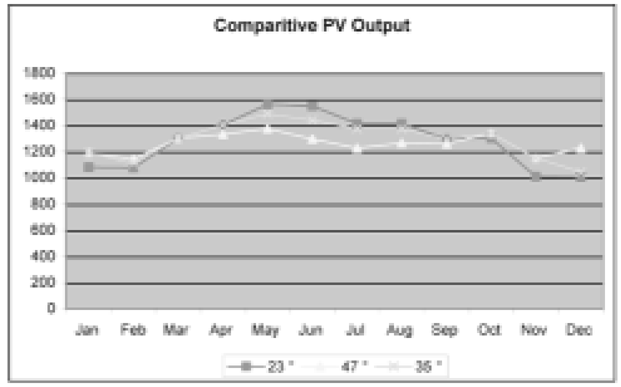
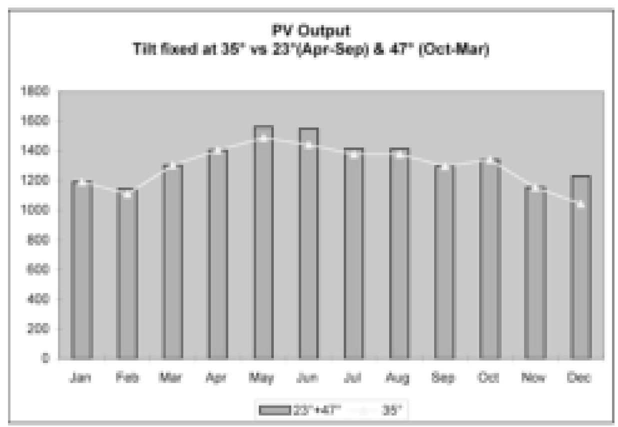


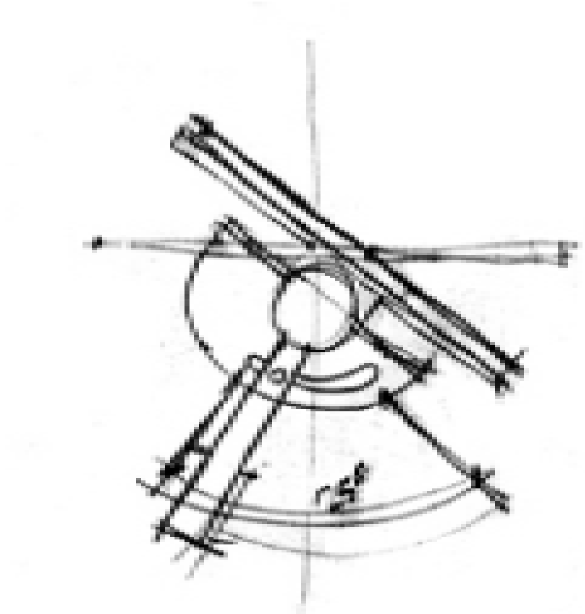
Figure 12: Monthly values of annual predicted electric output from the PV array with panels fixed at a 35 degrees tilt angle (line) and panels at 23 degree tilt during the summer half and 47 degrees tilt during the winter half of the year (bars).

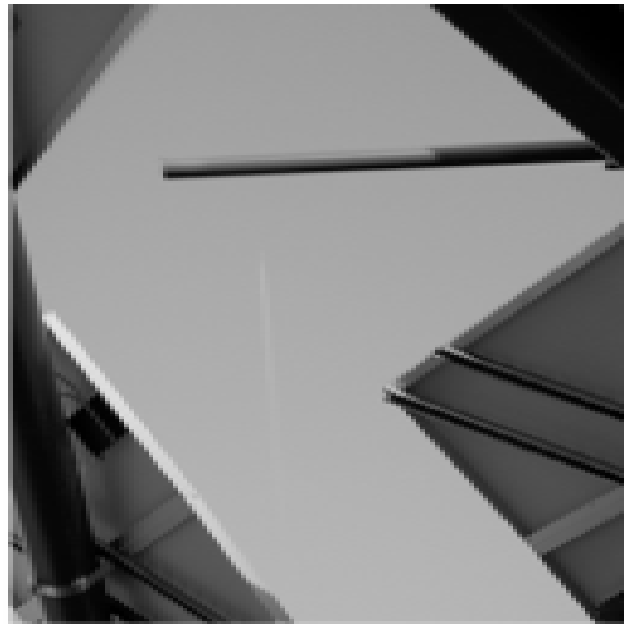


degrees on September 21st. The increase is mainly due to improved efficiency in May, June (23 degrees tilt angle) and December (47 degrees tilt angle), see Figure 12.

An increase in the annual PV output of 3% may seem too small to justify a biannual tracking mechanism, but it was still decided that the design should allow for a change in the tilt to be implemented two times a year – at the "middle of time". A tilt lever design was developed to allow for manual changing of the tilt, see Figure 13. Each year on March 21st and September 21st, at solar noon, a community event would take place where students, faculty, staff, and other members of the community would gather to change the tilt of the panels in celebration of the passing of time.

Figure 13: Tilt lever design by Kenyon Architectural Group (left) facilitates biannual changing of the tilt angle as a community event. Right side: tilt lever as built.





Early estimates of the PV output support the notion that the peak production from the photovoltaic shading structure would match the peak load represented by fans, pumps, and damper motors in a hybrid heating, cooling, and natural ventilation system designed by the author, see Figure 14. Preliminary estimates of the annual electric energy consumption also indicated that the it would require zero net energy to heat, cool, and ventilate the building with this system, provided that the PV array was grid-connected (Lerum, 2003).

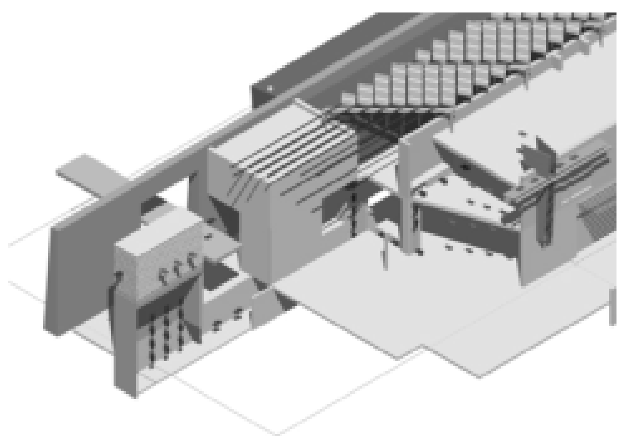
The mechanical systems design was changed during the bid process. The building now incorporates a forced air DX (direct expansion) heating and cooling system with

"packaged units" (heat pumps) on the roof. This change in the mechanical systems design – motivated by short-term economic considerations - eradicated the balance between the environmental control systems and the PV array.

AS BUILT

The building was completed in January 2004. While the installation and fine-tuning of the photovoltaic shading device took longer time to complete, it was operational by early summer 2004. The power peoduction represented by PV shading, as well as

Figure 14: Cut-away isometric diagram explains the integration of the PV shading structure with a hybrid heating, cooling, and ventilation system—as designed by the author.



its interchange with the public electricity grid, will be monitored. Since the power system is still in its start-up phase, it is too early to predict the long-term yield in the power harvested from the sun. Preliminary measurements indicate that the peak power output may reach above 10 kWp.

Figure 15 shows a view of the building from NW with the PV shading structure hovering over the main circulation space behind the massive north-

Figure 15: Views from NW show the photovoltaic shading structure hovering over the building, with patterns of light and shade appearing on the patio walls.

facing wall. Here, in April 2004, the panel tilt angle is still not fine-tuned to its winter position. Even with the panels not exactly in their final position, it is evident that the structure is creating some very characteristic patterns of light and shade on the walls of the main circulation space and patio. The changing configurations of lit and shaded figures are visible through a large opening in the north-facing wall, where one looks into the public patio.

The size of the photovoltaic panels as well as the number of rows of panels were changed during the bid process. The panels are now spaced more openly, but the diagonal mounting and juxtaposition of the panels were kept as designed. Figure

16 shows patterns of light and shade as they appeared in the early afternoon on March 14th. As compared to the simulated images, the play of light and shade on the completed building is more complex, which may lend itself to a multitude of interpretations. One can now imagine the face of a mountain lion apprearing on a west-facing wall (Figure 16, middle section).

The increased complexity is in part attributed to the fact that the slanting wall of the main circulation space is cladded in copper. Once the copper has had enough time to take on a patina, reflec-

Figure 16: Views looking East into the main circulation space and patio on March 14th, 2004.

tions will deminish and the patterns on the walls and the floor will stand out with sharper images.

CONCLUSIONS

With the exception of the zero energy heating and cooling system, all major design criteria, as described above, were met or exceeded. A 10 kWp grid-connected photovoltaic shading structure will provide an annual output of approximately 21,000 kWh, which will reduce the amount of off-site energy required to cool the building. At times the building will be self-sufficient with electric power, and there may be certain time windows where electricity is sold back to the grid. The next year of monitoring the performance of the PV shading structure will allow for a more detailed analysis.

Dynamic patterns of light and shade are created on the floor and walls of the building, marking the passing of time. Images of significant cultural value appear on specific dates, thus providing the backdrop for community events that will help build a culture of environmental awareness among students, faculty, staff, and other members of the community. The photovoltaic shading structure takes on an architectural expression that sets it apart as a unique architectural feature, complementing the overall aesthetic of the Skill Center at Yavapai College.

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