

Strategies to Visualize the Cooling Performance of Buildings

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ABSTRACT:

This paper presents a design tool that helps architects understand and resolve the multiple variables involved in determining a building's thermal performance, specifically focusing on cooling performance. Because the issues are so complex, this paper demonstrates a graphic technique that displays the consequences of each individual architectural design decision on the building's thermal performance. This approach is intended for use at the very beginning of the design process, when the building's form is just beginning to be defined. It is so simple and easy to use that an architect can run through dozens of design alternatives in the first hour. The power of the particular technique described here is that it presents a kind of movie, showing dynamically the difference in performance of each successive design revision, telling the architect the magnitude and direction of the changes in thermal performance of each new scheme as it evolves.

1. INTRODUCTION

Architects designing buildings to optimize cooling performance are confronted with an overwhelming number of variables, more even than can be handled by mathematical optimization procedures. There is also no single criterion of success. Therefore the architect's task is inevitably sub-optimization, picking small sets of variables, usually two or three, and trying to optimize their design, then adding another pair of variables and trying to optimize them. The problem is how to know when the performance of a set of variables is optimized. Some aspects of a building's design, for example its cooling performance, can be modeled mathematically. However reporting the results in the form of numerical tables would be ineffective, given the graphic nature of the architect's most effective mode of problem solving. Architects are very good at detecting subtle differences in shapes and forms, and intuiting the causes of these differences. The technique described here builds on these unique aspects of an architect's design experience. With fast computers and sophisticated algorithms, the results of complex mathematical simulations can now be presented as three-dimensional graphic shapes, plotted for every hour of the day and every month of the year. The architect's ability to read and interpret these three-dimensional surfaces is the equivalent of a cardiologist's ability to read and interpret an electrocardiogram, or a radiologist's ability to read a MRI scan. For people with good spatial ability, it is an esoteric but easily learned skill.

2. MEASURES OF COOLING PERFORMANCE

There is no single best measure of improved cooling performance. Is it differences in indoor air temperature, or air conditioner output, or cooling system operating cost, or total building energy consumption, or total building energy cost. While the technique presented here can display the differences in each of these measures of performance, for many designers the plot of Total Energy Cost integrates all these factors in a way that is meaningful to clients and can be compared across buildings of all sizes in all climates. Interestingly it also reflects the value society places on energy conservation because, for example, this tool now incorporates the recent five-tier rate structure introduced in California that penalizes excess consumption above a baseline with energy costs up to three times the baseline rate. Thus architects who are especially concerned about their client's interests, should evaluate the performance of their designs in the light of these strong economic signals.

3. INTERPERTING BUILDING PERFORMANCE

The three dimensional plots of building performance are all laid out on the following format:

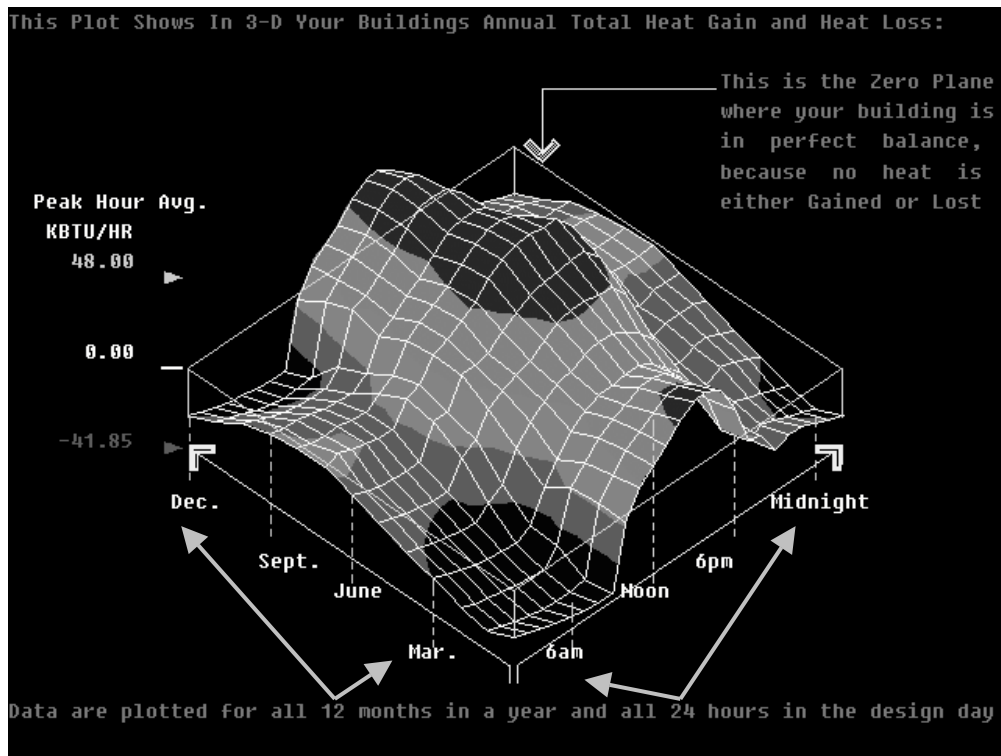


Figure 1: How to Read the Three Dimensional Plots: All 12 months of the year are plotted up along the left side, and all 24 hours of the day are plotted up along the right side of the figure. Positive values are shown above the zero plane, and negative values below it. All the plots are normalized so it is essential to read the values shown on the scale on the left side, because every plot has different values.

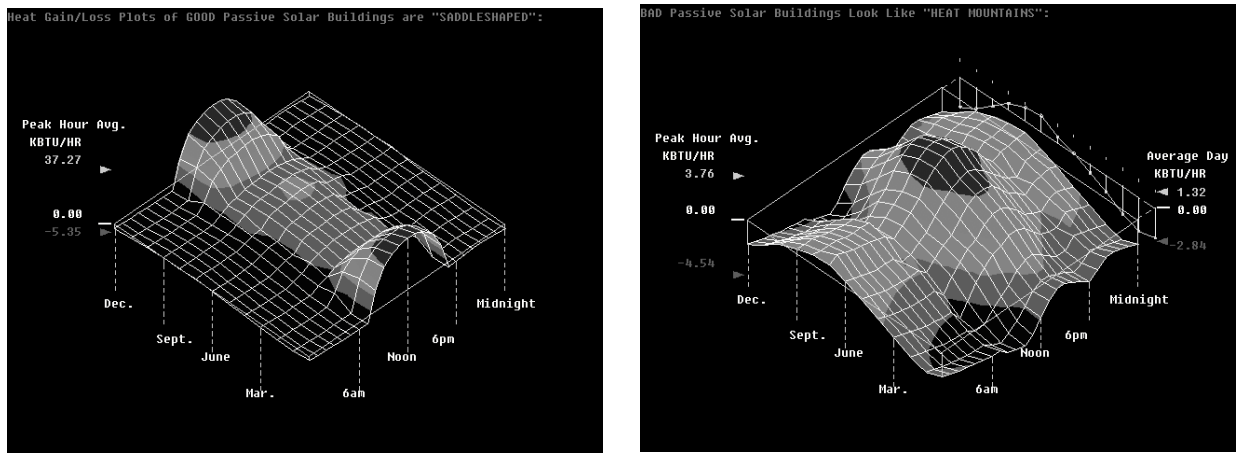


Figure 2: Good vs. Bad Buildings: Saddle Shape vs. Heat Mountain Plots: The best passive solar buildings will have “saddle” shaped plots (left) which means that most of the heat gain is collected in the winter when it is most needed, and in summer there is very little heat gain when it is a liability. The worst buildings have “heat mountain” plots, which means that most of the heat gain occurs in the afternoon in summer, and in winter the heat gain never gets above the zero plane which means this building is losing heat all for all 24 hours of the day.

SOLAR-5 calculates hourly performance for the full year using hourly TMY2 climate data. It generates these 3-D plots of building performance with hours of the day along the right-hand axis, and months of the year along the left-hand axis. The units are given in KBTU/hr heat gain and loss, or KBTUH Output of Heating or Cooling equipment, Air Changes per Hour, KWHr, and Dollars Cost for Electricity or Gas and Total Energy.

4. SOFTWARE:

The program used in this paper is the latest version of Solar-5, a text based command driven whole-building energy design tool that runs in a window partition. Among the features it contains is Morph, that creates a kind of ‘movie’ showing how the performance of any variable changes continuously between one design scheme to another. HEED, the windows version of Solar-5, offers many other features, but does not include the Morph option used to illustrate this paper. Both Solar-5 and HEED can be downloaded at no cost from UCLA's Energy Design Tool Web Page (www.aud.ucla.edu/energy-design-tools).

5. RIGHT BRAIN THINKING:

Designers tend to be right-brain thinkers, which means they are extremely sophisticated at grasping complex information visually, rather than in the form of numbers or text. SOLAR-5 already produces many other kinds of three-dimensional graphic plots showing how the building performs for each hour of each month of the year. Designers can quickly learn to recognize very subtle differences in the shape of these plots and to correlate these differences in performance with differences in the building’s design.

Morph adds the new dimension of time/motion to help designers to see these differences in performance between any two successive designs and to understand intuitively whether the building’s performance is getting better or worse.

6. UNDERSTANDING COMPLEX COOLING CONCEPTS

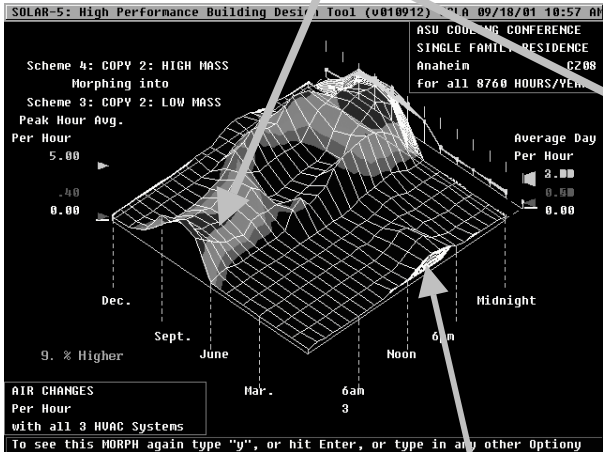
Improving a building’s cooling performance is not simply a function of adding more insulation or more thermal mass, although all these help, but only up to a point. There are many variables that sometimes help and sometimes harm, such as the rate of air change, the size of windows, the ratio of surface area to volume. This model accommodates hundreds of design variables, however many of which will be fixed by criteria other than cooling efficiency. For example the building’s orientation might be constrained by its orientation to the street, not necessarily the optimum solar orientation. A building’s floor area and the size and location of much of its glazing might be fixed by programmatic needs. Thus cooling performance might be degraded by many issues beyond the designers immediate control. Adding still further to the difficulty of this problem is the fact that many design variables interact with each other in complex ways.

Here are two examples that are instructive of the power and precision of this technique:

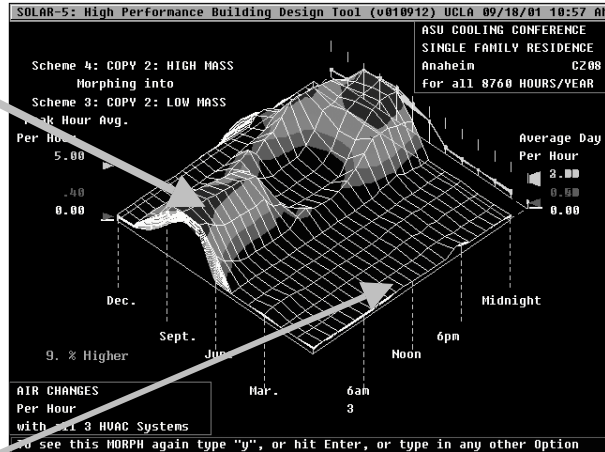
1. air changes vs. thermal mass
2. glazing performance vs. window shading

There are no universal right answers for any of these interactions. As other variables in the design of the building shift, so too will the “optimum” point in each of these interactions. The advantage of this tool is that a picture of slightly better or worse performance begins to emerge as the constellation of design decisions begins to converge. Unfortunately, these complex and highly dynamic concepts cannot be communicated effectively in the static medium of a written paper (the best way to grasp these concepts is to download this software and follow along, using the following as a kind of script).

Notice that the Low Mass home (left) shows air changes falling off in the coolest hours after midnight because the available mass has become fully charged with “coolth”. Note that in the high mass building the mass continues to charge continuously up to sunrise, indicating that there is enough thermal storage.

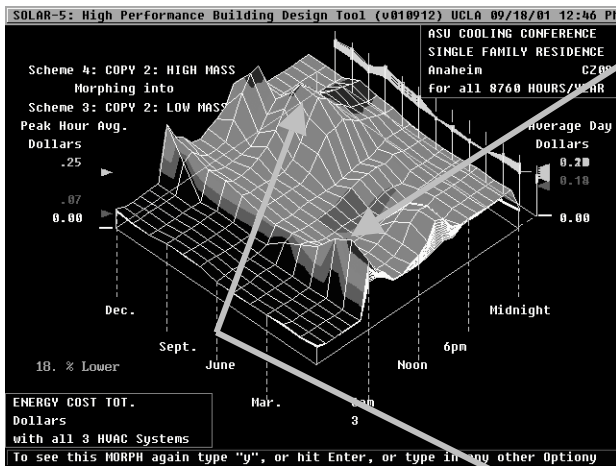


Air Changes: Low Mass Home

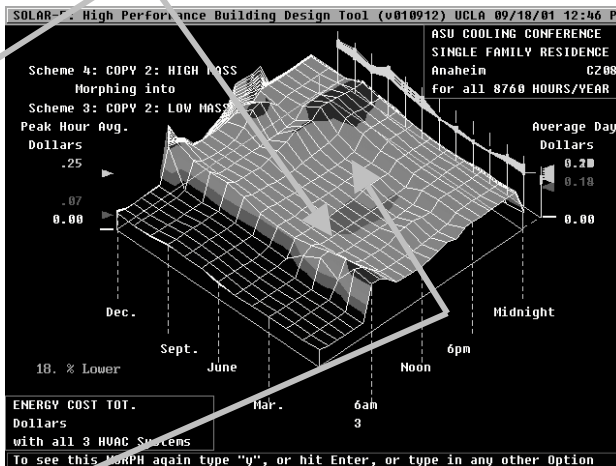


Air Changes: High Mass Home

This shows that on winter afternoons, the Low Mass home must use economizer cycle cooling to prevent overheating. Because the High Mass home (right) has the capacity to absorb this excess solar gain, it does not require ventilation on winter afternoons. It also shows a lower heating energy cost on winter mornings (below).



Energy Cost Total: Low Mass Home

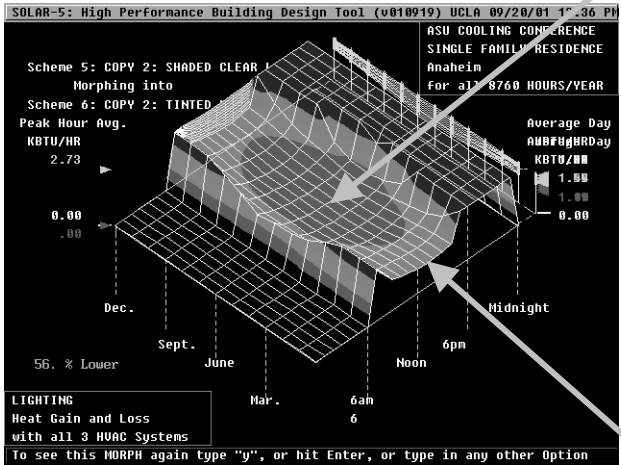


Energy Cost Total: High Mass Home

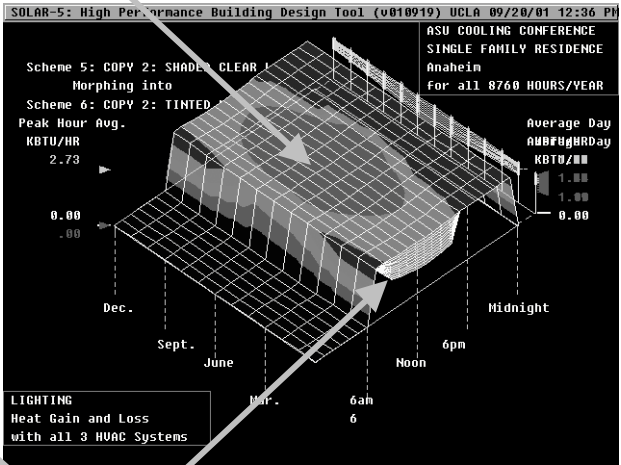
Notice that in the Low Mass home (left), air conditioning costs peak on summer afternoons because there was not enough interior thermal mass to store the coolth collected the night before. The High Mass home (right) shows only a much smaller peak, both in overall height and total number of hours.

Figure 3: Air Changes vs. Thermal Mass: One of the most complex interactions that occur in the design of a passively cooled building is the relationship between internal mass and ventilation air. How much mass is too much or too little for the given building in the given climate? This example starts with Scheme 2, the Energy Efficient home. It is copied into two new schemes and only the thermal mass is changed: Scheme 3 is Low Mass, with gypsum board walls and wood floors, while Scheme 4 is High Mass, with slab floor and half the walls changed to concrete block. These pairs of images show how one scheme morphs into the other, revealing subtle differences.

Notice that the plot of Lighting energy shows that Shaded Clear windows (left) bring effective daylighting into the interior. The Tinted Unshaded window (right) shows virtually no savings from daylighting, meaning that artificial lights must burn day and night.

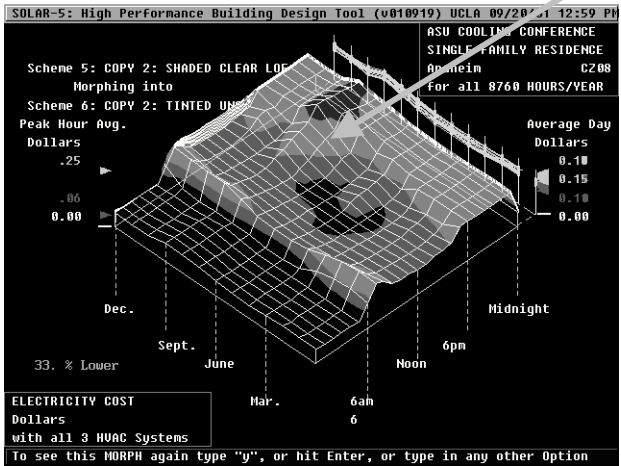


Lighting: Clear Shaded Glazing

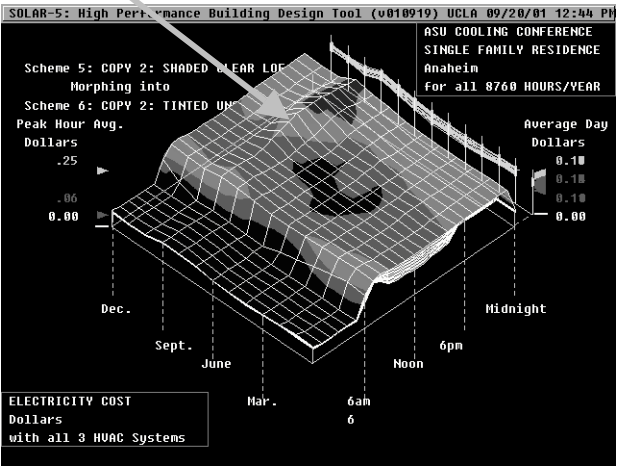


Lighting: Tinted Unshaded Glazing

This shows that the pattern in the improvement of Lighting energy, essentially matches the Electrical Cost savings of using clear shaded (left) compared to tinted unshaded Low-E glazing (right). The Electricity Costs (below) show that energy savings come primarily from lights, plus the reduction in heat gain which must be removed by ventilation or air conditioning. Other plots will show savings in Furnace Fuel and Fan Power costs.



Electrical Costs: Clear Shaded Glazing



Electrical Costs: Tinted Unshaded Glazing

Fig. 4: Clear Shaded Windows vs. Tinted Unshaded Windows. Window glazing represents the most important single element in the thermal performance of homes. Here the north and south windows both use dual panes of 1/4 inch glass, in Scheme 5 (left) both are clear (not Low-E), and in Scheme 6 (right) the inner lite is Low-E coated and the outer lite is SuperGrey High Performance tint. The Morph option clearly shows the comparative energy savings of Scheme 5 (left). Table 1 (below) shows that the clear shaded glazing saves 33% in energy costs compared to the dark gray tint.

Type of Glazing: Two lites of 1/4" glass. In the unshaded windows exterior lite is tinted and the Low-E coating is on #3 surface (LOF Pilkington)	U-Value	Visual Transmittance	Solar Heat Gain Coefficient (SHGC)	Annual Energy Cost Increase	Percent Cost Increase vs. Clear
Clear Float (not Low-E) shaded, vs...	.490	.79	.72	---	---
1. Clear exterior and interior, Low-E unshaded	.330	.74	.67	\$ 102	9%
2. Grey Tint exterior, Low-E interior	.330	.37	.38	\$ 155	13%
3. Bronze Tint exterior, Low-E interior	.330	.45	.45	\$ 129	11%
4. Blue Green Tint exterior, Low-E interior	.330	.62	.45	\$ 56	5%
5. EverGreen High Performance, Low-E	.330	.55	.34	\$ 71	6%
6. SuperGrey High Performance, Low-E	.330	.07	.14	\$ 387	33%

Table 1: Cost Savings of using Clear Shaded Glazing compared to various Tinted Low-E Unshaded Glazings

7. EXAMPLE: ANALYZING THE PERFORMANCE OF LOW-E vs. UNCOATED GLAZING

As an example of the kind of detail possible with this tool, the comparative performance of installing various types of glazing was evaluated. The example Energy Efficient building evaluated using six different Low-E coated windows that were not shaded, and was compared with the performance of an identical dual glazed window that contained clear float glass (not Low-E) and was shaded by a large overhang on the south windows while the north windows were unshaded (Table 1).

The results show (Table 1) in this case that clear properly shaded windows are better than any combination of tinting and low-e coating in unshaded windows. The biggest annual savings occurs with very heavily tinted SuperGrey Glass \$387 per year which amounts to 33% of the heating energy bill. The smallest difference occurs with Blue Green High Performance Low-e glazing, which ironically performs better even than EverGreen glazing which the manufacturer claims offers “exceptional performance values and unsurpassed year-round comfort”. As a footnote, this entire analysis took about 10 minutes using the Morph function and the Compare function.

8. CONCLUSION:

The objective of this paper is to encourage users to experience first hand the speed and convenience of using this tool for designing energy efficient buildings. These examples emphasize cooling issues, but the range of options covers any of the hundreds of design variables that influence a building’s thermal performance.

ACKNOWLEDGEMENTS:

The underlying work on Solar-5 and the development of our other Energy Design Tools was made possible through grants from the UCLA Academic Senate, and the University of California Energy Institute, the US Department of Energy, Southern California Edison, and Southern California Gas. HEED was developed in conjunction with Constructive Technologies Group, under contract to Southern California Edison and funded by the Public Utilities Commission Public Interest Energy Research Program.

REFERENCES:

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SOFTWARE AVAILABILTY: These “morph movies” are produced by the latest version of SOLAR-5, (www.aud.ucla.edu/energy-design-tools).