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ENERGY SIGNATURES: A PROPOSED NEW DESIGN TOOL

by
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ABSTRACT

Energy Signatures is a proposed new technique for aiding a designer in selecting and sizing passive solar elements on a building. Hourly heat flux profiles for each candidate design element are determined. These profiles are then matched to the hourly energy requirement of the space accounting for weather conditions, internal heat profiles of the space, and the mass characteristics of the building. Simulation analysis techniques are used to determine the Energy Signatures, the load profiles, and check the final result. Least-squares techniques are used to determine the optimum mix of strategies. Examples are given to illustrate development of the method up to the present. Future directions and possibilities are outlined.

INTRODUCTION

A new passive solar design tool, called Energy Signatures, is being developed. This paper constitutes a progress report midway through the project. the approach is similar in concept to the technique called Energy Graphics[1] but extends into important new directions. An energy signature is an hourly profile of heat flux into or out of a space due to a particular component, such as a window, Trombe wall, or sunspace. The signature depends on the orientation and specifications of the component and the building mass characteristics. The key advantage to the energy signature approach is that the hourly profiles take proper account of the full dynamic characteristics of the component being analyzed and of the building. Since buildings are inherently dynamic in their behavior, this accounting is essential if realistic results are to be obtained.

Energy Signatures are calculated individually by simulation for as many time periods and as many building elements as desired. Actual hourly weather data are used. One determines the building heat or cooling requirement profile during the same time periods, also by simulation, assuming a desired internal temperature profile, schedule of internal gains and building mass characteristics. The challenge, then, is to identify the best combination of components from the available options in order to best match the energy requirement profile. This can be done very quickly using a least-squares technique. The procedure is to identify an objective function, which might include comfort, initial cost, and cost of energy, and then minimize this function with respect to the sizes of all available options. Constraints can be imposed using the Lagrangian multiplier technique. This procedure will clearly identify the strategies which will best meet the criteria and the most effective combination of those strategies.

The main purpose of Energy Signatures is to provide a tool which is not only informative, but is also instructive. Many design tools, such as the solar load ratio method or large computer simulation programs, would better be called evaluation tools since they offer no guidance, only results. Energy Signatures will provide the designer with specific quantitative suggestions which identify the most effective strategies and how to blend them to achieve a desired result. The Energy Signatures method has been tried out successfully in several test problems and has produced meaningful answers which would be difficult to determine by other methods. We anticipate that the method will eventually be implemented in a microcomputer environment in which the user, not necessarily understanding the details of the analysis, simply selects candidate strategies and receives advice about the suggested options. The tool can fit into any phase of the design process since the level of detail can increase as the design proceeds and the advice gained by the designer advances from general to the more particular.

Energy Signatures is a project currently underway by the author at SERI and will be further developed and refined in the future.

* On a one year leave of absence from the Los Alamos National Laboratory

CALCULATING ENERGY SIGNATURES

An Energy Signature for a particular design element, such as a Trombe wall or a sunspace, can be calculated from a simple simulation of that element. The objective is to determine an hourly profile of net heat flux into the building, per unit area of the element. As an example, consider a sunspace attached to a building. The solar collection and mass storage characteristics of the sunspace are defined, according to good design practices, and a thermal network model is established. An example of such a model is shown in Figure 1. This sunspace has a massive floor, represented by two nodes, and a 6 inch concrete back wall, also represented by two nodes. Node characteristics are determined using the technique of thermal network reduction[2] to assure that a correct dynamic response will be obtained with a minimum number of nodes.

The simulation can be run with weather and solar inputs for any situation desired. Normally, one would run several cases using weather data typical of different seasons in the location where the building is to be located. An example response is shown for a clear winter day in Denver on Figure 2, showing sunspace and common-wall temperatures. Convection from the sunspace to the attached buildings is permitted when the sunspace temperature is greater than the building temperature, assumed to be fixed at 70°F. This limits the maximum sunspace temperature to 78°F but we note (with a separate simulation) that the maximum temperature would have reached about 110°F without such convection. The doorway convection area is assumed to be 15% of the sunspace glazed area.

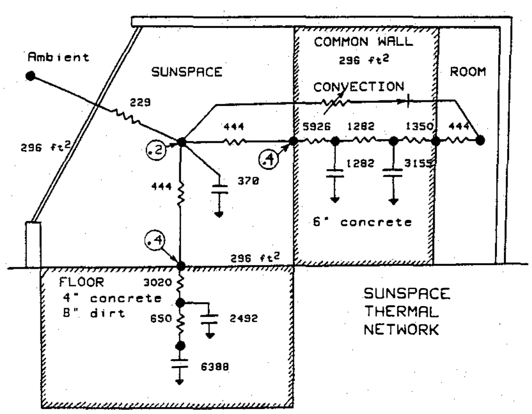

Fig. 1. Thermal network of an attached sunspace. Numbers shown refer to a 40 ft. sunspace length corresponding to a 400 ft^2 floor area; however, results are reported per unit of glazing area. Conductances between nodes are shown in Btu/h-°F. Heat capacities at nodes are shown in Btu/°F. Numbers in circles refer to allocation of transmitted solar gains.

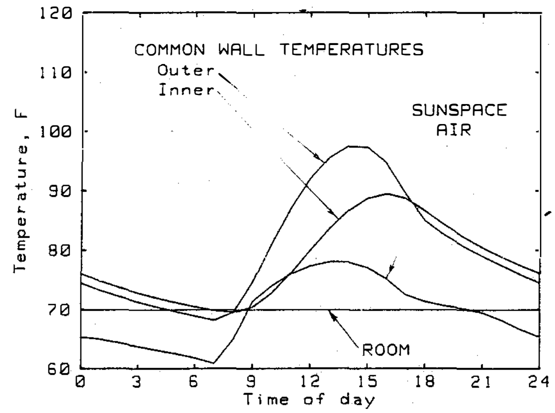

Fig. 2. Simulation results for an attached sunspace in Denver on a clear January day with 26.9°F average ambient temperature. Convection is allowed when the sunspace temperature exceeds the room temperature.

The desired result is the net heat flow into the building. This is the Energy Signature and is shown in Figure 3. The units are Btu/h per ft^2 of sunspace aperture area. The area under the profile is 782 Btu/ft^2 which is comprised of 561 Btu/ft^2 by convection and 221 Btu/ft^2 by conduction through the common wall. An Energy Signature contains valuable information directly valuable to the designer. It indicates, for example that the sunspace is primarily a daytime heater but that moderate common wall temperatures in the range of 68 to 88°F are obtained greatly increasing the comfort of the adjacent room in the evening. The overall efficiency of the sunspace on this clear day is 36%, obtained by comparison with the incident solar energy of 2138 Btu/ft^2. At this stage, the

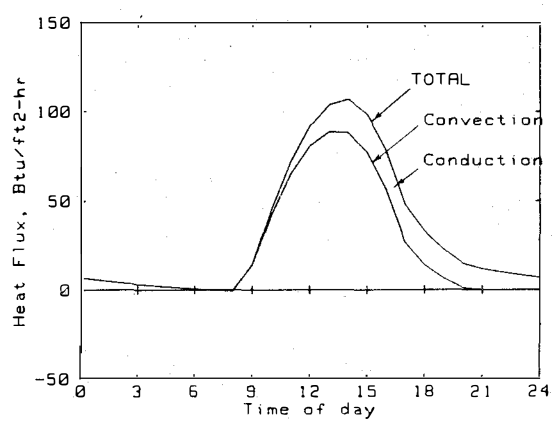

Fig. 3. Sunspace Energy Signature showing the dominant role of convection compared to conduction through the common wall.

designer can try various sunspace design parameter changes to study their effects quickly, without the time or complexity of a full building simulation. The resulting signatures can be saved in a computer file for later use.

Energy Signatures have been obtained in similar fashion for direct gain and Trombe wall situations, as shown in Figure 4. In each case, the building temperature is assumed to be fixed at 70°F. For the direct gain case, the building diurnal heat capacity is 67 Btu per ft^2 of window area, characteristic of an 8 inch exterior concrete block wall, plus sheetrock partitions and furniture. The components of the direct gain signature are shown in Figure 5, which indicates the energy due to directly heated lightweight objects (380 Btu or 26.3% of the transmitted solar radiation), the energy transferred into the room air from storage (1065 Btu/ft^2) and the energy lost back out the window to the outside (517 Btu/ft^2) for a net gain of 928 Btu/ft^2 corresponding to a total efficiency of 47 %.

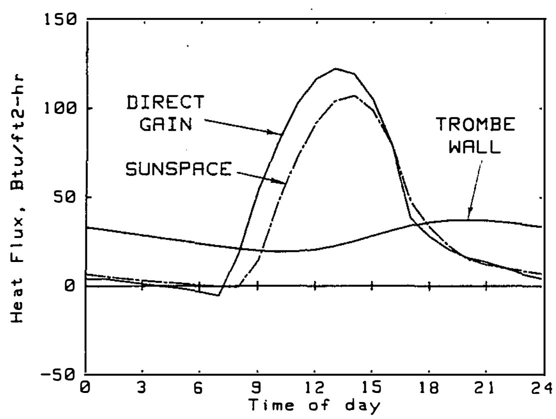

Fig. 4. Energy Signatures of direct gain, sunspace and Trombe wall options. Integrals are 928 Btu/ft^2, and 677 Btu/ft^2 respectively. Room temperature is held constant.

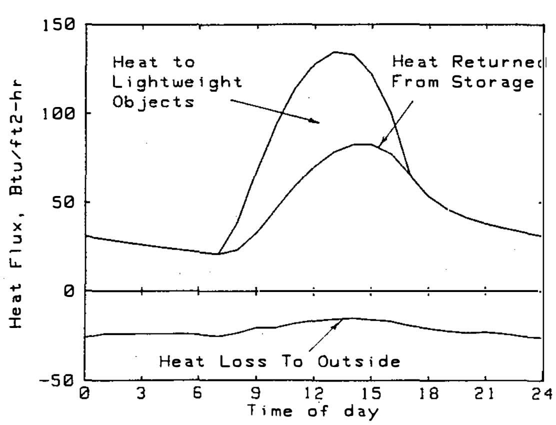

Fig. 5. Components of direct gain heat flux. The sum of the top curve and the heat loss curve is the Energy Signature. Room temperature is held constant.

Figure 4 shows the signatures for direct gain, sunspace, and Trombe wall co-plotted to show differences and similarities. The Trombe wall is 12 inch concrete with a selective exterior surface and no venting. All systems are double glazed. Although the direct gain and sunspace signatures appear very similar, note that the energy delivery to the space is primarily radiant in the direct gain case and primarily heated air in the sunspace case.

ROOM TEMPERATURE VARIATIONS

Up to this point, we have considered the room temperature to be fixed, whereas in practice, the room temperature in a passive building often rises during the day and decreases at night. The effect on the energy signature can be pronounced as shown in Figure 6, which shows the temperatures in a direct gain space. In this case, it was necessary to specify the size of glazing compared to the building loss coefficient, whereas this was not necessary before. For the simulation of Figure 6, the load collector ratio is 22.2 Btu/F°-day per ft^2 of glazing, a rather extreme value representing a direct gain glazing area of about 20% of the floor area. While this is clearly too large a value and would lead to excessive temperature swings and other detrimental effects, it does represent a reasonable upper bound. The corresponding Energy Signature is shown in Figure 7, co-plotted with the previous direct gain signature. These two signatures represent

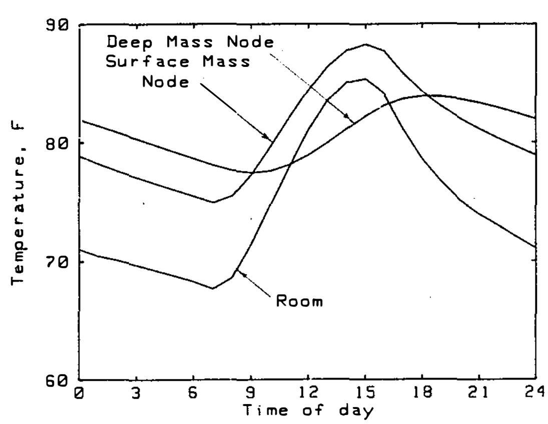

Fig. 6. Simulation results for an overglazed direct gain building showing room and mass temperatures. Direct gain area is 296 ft^2 and building total loss coefficient is 423 Btu/h-°F. No internal gains.

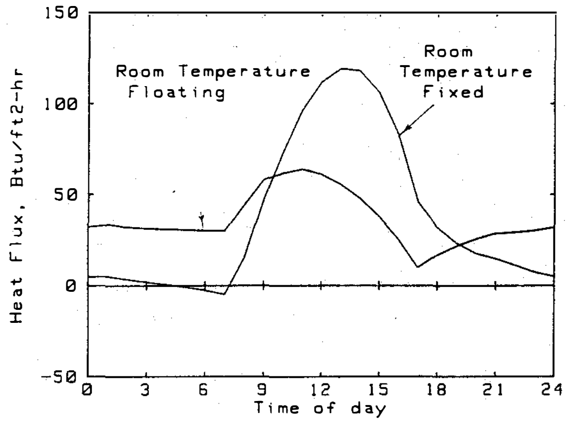

Fig. 7. Direct gain Energy Signature computed with fixed room temperature compared with signature computed with overglazed system and floating room temperature. Integrals are 928 Btu/ft^2 and 868 Btu/ft^2 respectively.

a reasonable range of possible cases, depending on the actual building inside temperature variation.

USE OF ENERGY SIGNATURES

We propose that a designer would amass a file of Energy Signatures representing different design elements, different orientations, different element parameters, different seasons and different types of day in each season (sunny, cloudy, etc.). These signatures represent a "kit of options" that the designer may select. The next step is to determine the nature of the building load profile. This can be determined by simulation. The basic inputs required are weather data, the desired hourly room temperature profile, building hourly internal gains and building characteristics including loss coefficient and mass storage elements. A simulation is performed, assuming no passive solar elements are present. This yields an hourly profile of load.

One can then compare the profile of building energy requirement against the various strategies available, represented by their Energy Signatures, and identify the strategy or mix of strategies which will best match. If the energy profile match could be made to be exact, then the actual building temperature would match the desired profile, but generally this is not possible and a method for identifying a set of strategies which will be optimum, based on some defined criteria, is needed.

SELECTING STRATEGIES

A method has been developed for identifying an optimum set of strategies. The criteria used for optimization is that the integral of the square of the deviation of the resulting auxiliary energy should be a minimum. The rationale for this is partially mathematical (it leads to simple answers) and partly physical (it leads to small excursions in auxiliary heat and tends to minimize discomfort). The important point to stress is that the procedure leads to specific numerical recommendations for the best size of each strategy. Since the procedure is very fast to implement, even on a microcomputer, the process if identifying favorable strategies can proceed very quickly. An example using the profiles developed earlier will help to illustrate the procedure and its flexibility in the hands of a designer. In all these cases, a constraint was applied forcing the total auxiliary heat to be zero. This causes the average building temperature to equal the desired average building temperature, a reasonable design goal for a Denver residence on a clear winter day.

A load profile was generated for a 1500 ft^2 medium weight building in Denver, based on a night setback of 5^{o}F and an internal gain profile representative of a residential application. Trials were then made to determine the best mix of several pairs of strategies. Invariably, the Trombe wall was selected as the dominant strategy with a small amount of direct gain or sunspace. The following pairings were indicated:

With fixed room temp.	TW - 271 ft^2 DG - 34 ft^2
With floating room temp.	TW - 285 ft^2 DG - 172 ft^2

The difference between these is the choice of direct gain signature used (see Figure 7). These bound the possible result. The indicated size of Trombe wall does not change much between the two. The indicated area of direct gain should be closer to the smaller value since the direct gain area is small and the resulting room temperature swing will be small). At this point, the designer would probably select the direct gain area based on architectural considerations rather than performance. The result for a combination of Trombe wall and sunspace is very similar, due to the similarity between the direct gain and sunspace signature. Again, a choice would be dictated based on architectural considerations.

In order to check the result, a full building simulation was run with 250 ft^2 of Trombe wall and 50 ft^2 of direct gain. A six-node simulation was used with 300 ft^2 of mass wall in addition to sheetrock and furniture mass. The result is shown in Figure 8 showing a reasonably comfortable building operating without auxiliary heat on a clear winter day.

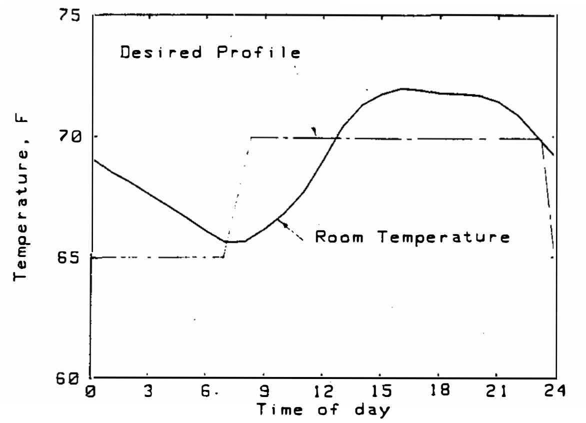

Fig. 8. Full building simulation result for a clear January day with no auxiliary heat. Internal gains are 60000 Btu/day with a residential profile. Solar glazing is 250 ft^2 of TW and 50 ft^2 of direct gain based on Energy Signature method recommendations.

COMMENTS ON THE EXAMPLE

As seen in Figure 8, the simulated room temperature profile is a reasonable approximation to the desired profile. Since the thermostat setup preceeds the sunrise, none of the passive strategies investigated could produce the morning ramp desired. The result obtained is about as good as can be achieved with the strategies employed. The error is small and probably tolerable. If a faster morning pickup is needed, then this might best be done with a small amount of auxiliary heat, starting at about 5 a.m.

The point of this example is to demonstrate that the methodology selected the best pair of strategies in one pass, that is, without iteration. It is true that this answer could have been obtained by conventional simulation by iterating on Trombe wall and direct gain areas until a satisfactory result is obtained. The advantage of the Energy Signatures approach is that selection process is more efficient because it is based on information about the characteristics of the individual strategies available. Simply observing the nature of signatures of the various elements is quite informative itself. The decision process is facilitated by dividing the calculation into stages.

In the example given, the optimization was based on a single clear winter day and no economic criteria were used. The point of the example was only to demonstrate that the method works, not to recommend the resulting design. Such a decision must clearly also take into account many other factors including summer, swing season, and cloudy-day performance, as well as the value of auxiliary heat saved and the cost of the system elements.

FUTURE DIRECTIONS AND POSSIBILITIES

The criteria used for optimization will be extended. The objective function which was minimized in the above example was the mean-square deviation of the hourly energy error. In order to include other considerations, the objective function can easily be expanded to include terms which account for the cost of auxiliary heat and the initial cost of the system elements. Thermal comfort could more accurately be included by using a convolution of the hourly energy error with the building response function. Each term would be weighted by constants indicating its relative importance. The integrals can be calculated over a series of several days representing actual historical weather sequences. Time-of-day weighting functions can also be employed. Several weather sequences can be added together representing different seasons to assure that the optimization process correctly accounts for year-round performance. In this way, the summer cooling penalty of passive heating elements can be included automatically. Natural cooling and daylighting strategies can also be included to the extent that they can be simulated.

A limitation of the method as outlined here is that interactions between systems (which represent non-linear effects) are not properly accounted because the signatures represent the systems individually and we assume that the aggregated response is a superposition of the results of the individual responses. This limitation can be overcome by a two or three step process with the first step being as described above. This process should narrow the selection of strategies to a few which show up reasonably well. The signatures for these elements can then be recalculated using a building modified by addition of a base amount of each element as determined in the first step. These signatures should be determined for an incremental addition of the element, for example, one ft^2 added to the base amount. The design can then be re-optimized using these modified signatures. If the results are very different than for the first step then another iteration may be necessary. This procedure can also account for the fact that the incremental effectiveness of each strategy decreases as the total solar area increases.

The Energy Signatures method can be used either for a whole building, which may be appropriate for a single-family residences, or can be applied on a space-by-space basis to larger buildings. For example, the window sizing on various facades of a building could be chosen individually, assuming no thermal interaction between zones, or interaction factors could be developed to account for thermal transfers between zones if this is permitted.

A longer-range goal is to use the method to help determine optimum building shape, orientation and layout. In this case, constraints would be added to maintain constant building floor area but the length of various facades would be free parameters in the optimization process.

None of the above comments are intended to suggest that the normal design process can or should be replaced by a purely mathematical and automatic process. The designer is always in total control and can select design strategies based on any criteria desired. The Energy Signatures technique is only proposed to help the designer make better informed choices based on information about the performance characteristics of the various design options under consideration in the particular climate where the building is to be located.

The purpose of this project is to explore these possibilities to determine if the proposed method can be an effective design tool. At this stage, the results are promising.

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