LA-UR -85-1046

[illegible]

LA-UR--85-1046

DE85 009624

TITLE: PERFORMANCE ANALYSIS OF MIXED PASSIVE SOLAR HEATING SYSTEMS

AUTHOR(S): W. O. Wray and E. D. Best

SUBMITTED TO: Solar Buildings: Realities for Today, Trends for Tomorrow
Washington, D.C.
March 18-20, 1985

Los Alamos

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

PERFORMANCE ANALYSIS OF MIXED PASSIVE SOLAR HEATING SYSTEMS*

W. O. Wray and E. D. Best
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

ABSTRACT

Two passive solar heating systems serving a single thermal zone interact with one another in a manner that tends to improve the overall performance of the mixture. Previously existing simple design analysis methods do not account for these interactions and therefore tend to underestimate performance. However, for the special case of mixed direct gain/unvented Trombe wall systems, a solar load ratio (SLR) analysis that credits the direct gain component with part of the inner surface of the Trombe wall for thermal storage yields good agreement with the results of detailed thermal network calculations. The success of this procedure is a major step toward development of a generalized SLR method for mixed systems.

INTRODUCTION

Existing tools for design analysis of mixed passive solar heating systems do not consider interactions between the systems involved. The standard DOE approach is to calculate the performance of each system acting independently and area weight the results based on the sizes of the solar apertures.[1] Alternately, a related technique developed for the US Navy[2] employs an area weighted average of certain input system parameters. The mixture is treated as a single system, and performance is calculated using the averaged parameters. This approach is easier to apply than the standard method because only one system needs to be analyzed, but, here, too, interactions are neglected.

In this paper we discuss the various situations in which interactions between south-facing systems serving a single thermal zone may affect the performance of the mixture. In particular, the nature of direct gain interactions with unvented Trombe walls is explored using a detailed thermal network computer program called SUNMIX,[3] a derivative of PASOLE.[4] The SUNMIX results are compared with predictions from the simple design analysis procedures described in the preceding paragraph. This comparison shows that system interactions can significantly improve the performance of the mixture under certain conditions. The interaction mechanism that produces this improvement is the sharing of thermal storage media between systems that deliver heat to the interior at different times of the day.

In order to include the effect of shared thermal storage in simple design analysis calculations, it was necessary to develop an expression for the effective heat capacity (EHC) of direct gain buildings, as described in the section so labeled. Furthermore, generalized solar load ratio (SLR) correlations for direct gain buildings were required to do calculations involving shared mass in mixed systems. The generalized correlations include parameters that depend on the EHC of the system, thereby providing the needed flexibility.

The generalized SLR correlations are applied to the analysis of direct gain/Trombe wall mixtures in the section covering shared mass. The method proves successful and verifies our contention that thermal mass sharing is the predominant interaction between systems operating out of phase. The paper ends with a summary.

SYSTEM INTERACTIONS

Possible Mixtures and Mechanisms

The system types for which SLR correlations are available include direct gain, vented and unvented Trombe walls, water walls, sunspaces with either masonry or insulated common walls, simple radiant panels, and thermosiphoning air panels (TAPs). Any of these systems may be combined, but those that deliver heat out of phase with one another are the best candidates for mixing. Direct gain systems, radiant panels, and TAPs all deliver heat approximately in phase with the sun, thermal storage mass within the building shell produces some spreading of the solar pulse by reducing peak heat delivery to the room air at midday and giving up stored heat to the room after the sun has set. Water walls also operate in phase with the sun but spread the solar pulse much more effectively than direct gain buildings because the storage medium is interposed between the absorbing surface and the room air. Convection currents within the containers cause the water temperature to rise almost isothermally so that heat delivery to the room is tempered primarily by the heat capacity of the water.

Unvented Trombe walls, on the other hand, induce a phase lag that depends on the thermal diffusivity of the wall material and its thickness. Transmission of the solar pulse to the room air is delayed

*Work performed under the auspices of the US Department of Energy, Office of Solar Heat Technologies.

by thermal conduction through the wall. Thermal conduction is a much slower process than convection and spreads or broadens the solar pulse more effectively. Thus, for an unvented Trombe wall, the inside surface of the wall reaches its maximum temperature 4 to 8 hours after the peak solar flux and continues to deliver heat to the building interior through the night and well into the early morning hours. Thicker walls yield longer phase lags and broader heating pulses.

Vented Trombe walls and sunspaces deliver two components of heat to the building: (1) the thermocirculation component, which is in phase with the sun, though broadened by thermal storage in the absorbing face of the Trombe wall or in the sunspace mass; (2) the conductive component, which is out of phase as in an unvented Trombe wall. Sunspaces with insulated common walls deliver most of their heat to the living space by thermocirculation, the conductive component being very small. Systems that deliver two heat components will prove to be more difficult to analyze in mixtures because our SLR correlations give only the total heat delivered.

Any of the systems described above may interact by sharing thermal storage mass. However, passive solar systems that operate out of phase with one another are the best choices for mixing because thermal mass sharing is enhanced by the sequential nature of heat delivery to the building. If two systems are operating in phase, the one having less mass available relative to the amount of solar heat stored will borrow mass from the stronger system; the thermal coupling may be radiative or convective. This type of in-phase interaction is always beneficial in terms of performance, i.e., the solar savings fraction (SSF) will always increase, and any overheating that is present will always be diminished. (The SSF is the fraction of the building load, exclusive of the solar aperture, that is met by solar energy.) Nevertheless, even in the presence of these beneficial interactions, mixed systems operating in phase will have a tendency to overheat, particularly at small load collector ratios (LCRs). (The LCR is the ratio of the building load coefficient, exclusive of the solar aperture, to the aperture area.) Even in situations for which overheating is not a problem, in-phase heat delivery is far less efficient than heat delivery that is spread more uniformly over time.

The best mixtures for effective mass sharing include Trombe walls, water walls, or sunspaces, used in combination with radiant panels, TAPs, or direct gain apertures. Due to the desire for visual access to the outside, Trombe walls or sunspaces are most commonly found mixed with direct gain systems. We have therefore selected a mixed system with an unvented Trombe wall and a direct gain aperture for initial consideration.

Unvented Trombe Wall Combined With Direct Gain

A series of SUNMIX calculations were performed on a building with a mixture of unvented Trombe wall and direct gain systems. The simulated building, located in Albuquerque, New Mexico, had an LCR of 24. The unvented Trombe wall was double glazed, 12 in. thick, and made of high-density concrete. The direct gain system was also double glazed and had, for thermal storage, a 2-in.-thick layer of high-density concrete with a surface area 6 times the size of the glazed aperture. The ratio of mass area to glazing area is denoted A_m/A_g. SUNMIX calculations were performed for mixtures with Trombe wall fractions ranging from 0 to 1 and the SSF was plotted for each case. Additionally, the DOE and Navy mixing algorithms were applied to the two systems over the same range of Trombe wall fractions. The results are presented in Fig. 1. Note that there is no significant difference between the DOE and Navy procedures and that both simple methods underpredict the performance of the mixture as given by SUNMIX. In this case, the best performance is obtained at a Trombe wall fraction of zero because the direct gain system is the stronger of the two.

Another case was examined in which the relative strengths of the two systems in the mixture were reversed. The Trombe wall thickness was increased to 18 in. and the direct gain A_m/A_g ratio was reduced to 3. After performing the same set of calculations reported for the original mixture, the results presented in Fig. 2 were obtained. Again, we see little difference between DOE and Navy mixing procedures and a still greater discrepancy between the simple methods and SUNMIX calculations. For this particular mixture, the optimum Trombe wall fraction is about 0.7 and SUNMIX indicates that the actual SSF is about 7 percentage points higher than predicted by SLR analysis. Note that existing SLR analysis techniques will erroneously predict that the optimum mixture of any two systems is always obtained by dropping the weaker system.

The enhanced performance of the mixture depicted in Fig. 2 is the result of thermal storage mass sharing. The 18-in. Trombe wall has a long thermal lag time, whereas the direct gain system delivers heat in phase with the sun. Because the direct gain system has little thermal mass of its own and because the inside of the Trombe wall does

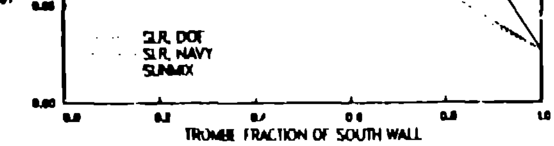

Fig. 1 Comparison of performance results from SUNMIX and SLR methods for 12 in. Trombe wall combined with direct gain system with 2 in.-thick thermal storage mass and A_m/A_g = 6.

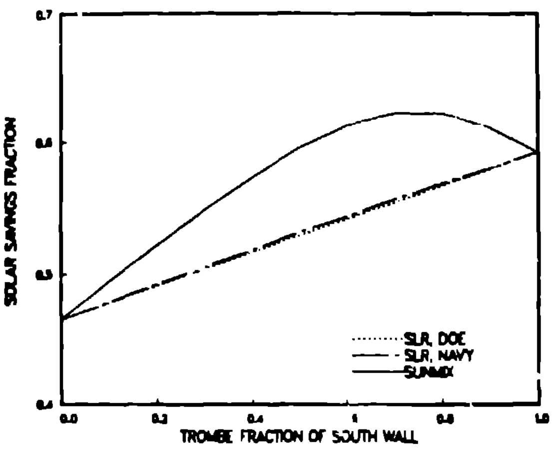

Fig. 2. Comparison of performance results from SUNMIX and SLR method: for 18-in. Trombe wall combined with direct gain system with 2-in.-thick thermal storage mass and $A_m/A_g = 3$.

not receive heat from its outer surface until several hours after the peak of direct gain heating, part of the Trombe wall mass is used for direct gain storage. The increased storage available to the direct gain system strengthens that system and enhances the performance of the mixture. The remainder of this paper deals with procedures for including mass sharing in SLR analysis of mixed systems.

THE EFFECTIVE HEAT CAPACITY OF DIRECT GAIN BUILDINGS

To provide the flexibility needed to account for mass sharing between mixed systems involving direct gain apertures, it was necessary to develop an expression for the EHC of direct gain buildings. The EHC is a single parameter that may be used to characterize a variety of mass configurations and types. As such, the EHC, which has units of Btu/°F ft^2 of solar aperture, provides a measure of the amount of heat that may be stored in the thermal mass of a building during one day and returned to the room air on the same day or on succeeding days at times and rates that lead to improvements in building performance. Improvements in solar thermal performance occur when stored solar energy is delivered to the room air in phase with the building thermal load, thereby reducing auxiliary heating requirements.

An expression for the EHC was developed by fitting a large SUNMIX data base with various functional forms. Four sets of conditions that include buildings located in Albuquerque and Boston at LCRs of 18 and 36 were considered in the investigation. The buildings were double glazed and had no night insulation. Thermal storage mass was located in the floor and north wall and insulated on the outer surface to an R value of 12. (Our results were insensitive to the R value of external insulation for levels of R4 and above.) In each of the 4 sets, 234 cases were considered: 6 values of A_m/A_g (3, 6, 9, 20, 30, and 50), 3 materials (high-density concrete, brick, and pine); and 13 values of the dimensionless thicknesses. (Note: 6 · 3 · 13 = 234 combinations.) The dimensionless thickness, x, is given by

$$x = L \sqrt{\frac{\pi \rho c}{Pk}} \quad . \tag{1}$$

where L is the thickness (ft), ρ is the density (lb/ft^3), c is the specific heat (Btu/lb °F), P is the period (24 h), and k is the thermal conductivity (Btu/ft h °F). The dimensionless thickness is useful because it enables us to characterize the thermal response of various materials with a single set of parameter values.

The expression for EHC that gave the minimum average rms (root mean square) error when correlated with the four sets of SUNMIX data is

$$EHC = (A_m/A_g)\left[1 + e^{-0.22(A_m/A_g)}\right] \cdot (0.40 \cdot DHC + 0.27 \cdot HDHC) \quad , \tag{2}$$

where DHC is the diurnal (1-day) heat capacity[5] and HDHC is the hex-diurnal (6-day) heat capacity.* The diurnal heat capacity is the amount of heat that can be stored in the thermal mass of a building, per unit of room air temperature swing, during the first half of a 24-h cycle and returned to the space during the second half of the cycle. Equations and tables for DHC are presented in Ref. 5 and will not be repeated here. The hex-diurnal heat capacity is obtained from the DHC simply by changing the period, P, from 24 h to 6 · 24 = 144 h.

The correlation results for Albuquerque at LCRs of 18 and 36 are presented in Figs. 3 and 4, while those from Boston appear in Figs. 5 and 6. Considering the large, diverse set of data represented in these figures, the correlation between performance and the EHC is quite good.

The EHC given by Eq. (2) is the effective heat capacity per ft^2 of collection aperture. Thus, the first factor in the equation, A_m/A_g, indicates that the EHC increases linearly with the mass-to-glazing-area ratio. However, the second factor imposes a penalty as the area ratio increases. The penalty reflects the ineffectiveness of spreading a fixed volume of mass over increasingly large areas. When mass volume is held constant, large surface areas imply thin layers of mass and, based on inspection of SUNMIX output, thin layers tend to aggravate winter overheating due to their quick response to solar radiation. On the other hand, excessively thick mass layers are ineffective due to the inaccessibility of the deeper layers. The optimum dimensionless thickness is plotted as a function of the dimensionless volume, v, in Fig. 7. The dimensionless volume is

$$v = x \cdot A_m/A_g \quad . \tag{3}$$

*The linear combination of DHC and HDHC in the expression for the EHC was developed by Doug Balcomb of the Los Alamos National Laboratory.

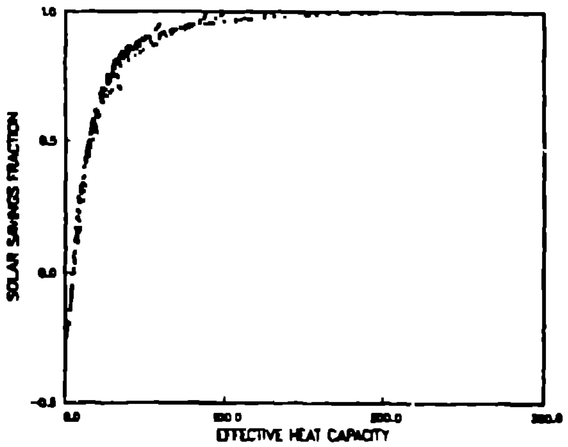

Fig. 3. Solar savings fraction vs effective heat capacity in Albuquerque at LCR = 18.

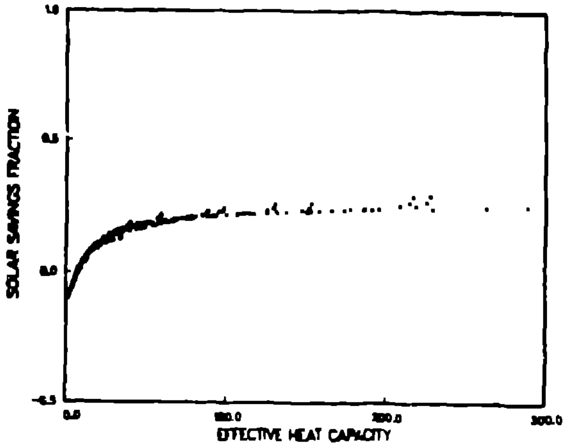

Fig. 6. Solar savings fraction vs effective heat capacity in Boston at LCR = 36.

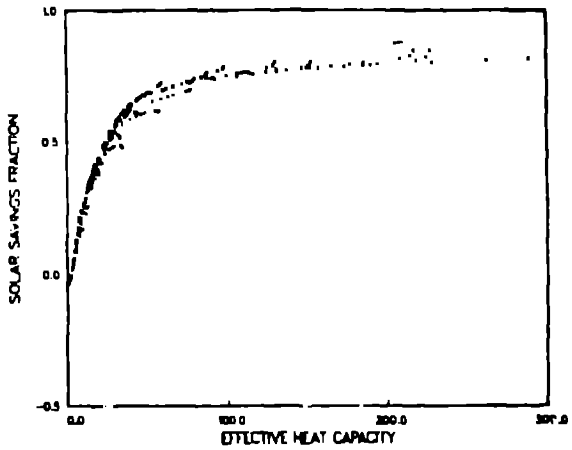

Fig. 4. Solar savings fraction vs effective heat capacity in Albuquerque at LCR = 36.

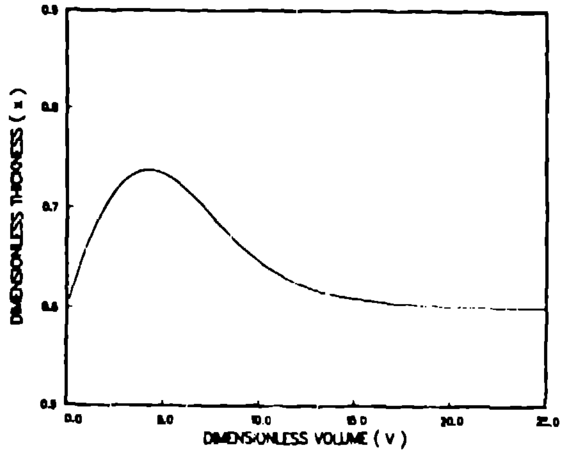

Fig. 7. The optimum dimensionless thickness as a function of dimensionless volume.

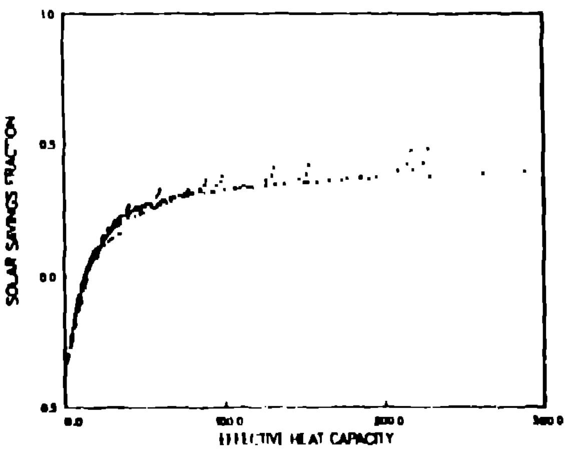

Fig. 5. Solar savings fraction vs effective heat capacity in Boston at LCR = 18.

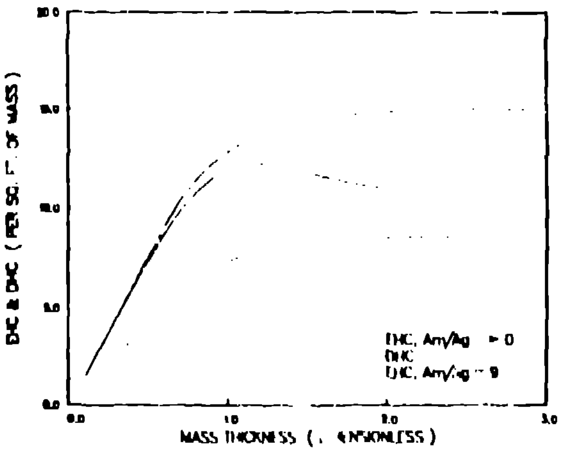

Fig. 8. Comparison of effective heat capacity and diurnal heat capacity at two mass to glazing area ratios.

Note that the optimum dimensionless thickness of 0.73 occurs at a dimensionless volume of about 4. Moreover, the full range of optimal values of x is only 0.6 to 0.73, making it an easy matter to select a mass thickness that will perform well. The thicknesses corresponding to the optimal range of x are given below for our three reference materials.

Material	x = 0.6	x = 0.73
Concrete	3.6 in.	4.5 in.
Brick	2.6 in.	3.2 in.
Pine	1.4 in.	1.7 in.

The third factor in Eq. (2) indicates that the performance of direct gain buildings depends on long-term thermal storage, up to 6 days, as well as on the predominant 1-day cycle. The long-term storage effect is represented in Fig. 8, where the EHC per ft^2 of mass surface is compared with the DHC for two values of the area ratio, A_m/A_g, over a range of x from 0.0 to 3.0. The middle curve, which exhibits a maximum, is the DHC. The upper curve is the EHC taken to the limit as the area ratio approaches zero. Note from the upper curve that the EHC, unlike the DHC, does not decrease beyond a certain value of x. Each increment in thickness will yield an improvement in performance at a fixed area ratio, although returns diminish rapidly beyond an x of about 1.5. Furthermore, the limiting value of the EHC at small area ratios is about 15% greater than the maximum value of the DHC, because the long-term storage effects are included.

The lowest curve in Fig. 8 is the EHC per unit of mass surface area at an area ratio of 9. Note that the general character of the curve is the same as the uppermost but that the area ratio penalty has dropped the effectiveness of a square foot of mass considerably.

Use of the EHC in generalized direct gain performance correlations is discussed in the next section.

GENERALIZED DIRECT GAIN PERFORMANCE CORRELATIONS

Performance correlations developed for the US Navy[6] have the following form:

$$SHF = 1 - e^{-F \cdot SLR} , \qquad (4)$$

where SHF is the monthly solar heating fraction and SLR is the monthly solar load ratio defined by

$$SLR = \frac{S/DD}{LCR + G} \qquad (5)$$

where S is the amount of solar radiation absorbed per ft^2 of aperture per month, LCR is the load collector ratio, and DD is the monthly heating degree days for the period of interest. The remaining variables, F and G, are correlation parameters called the scale factor and the effective aperture conductance, respectively. The solar heating fraction is the fraction of the total building load, including the collection aperture, that is met by solar energy. (All results presented in this paper will be in terms of the more familiar solar savings fraction.)

The SLR correlations for direct gain buildings, in the form of Eq. (5), were generalized by relating F and G to EHC and the steady state aperture conductance, U_c, as follows:

$$G = G(U_c, EHC) , \qquad (6)$$

$$F = F(EHC, G) . \qquad (7)$$

The functions currently in use for Eqs. (6) and (7) are complex and subject to revisions, we therefore choose not to present them in this paper. However, the utility of the equations is obvious. Instead of being forced to rely on a limited set of correlations for direct gain buildings, we are able to analyze any system for which we know the steady state aperture conductance and the effective heat capacity; both of these quantities can be easily calculated from the characteristics of the design. Equations (6) and (7) therefore provide the flexibility needed to analyze shared thermal mass in mixed systems as demonstrated in the next section.

SHARED THERMAL MASS IN DIRECT GAIN/TROMBE WALL MIXTURES

A third type of SLR mixed-system calculation was performed on the two direct gain/Trombe wall systems described in Section 2. The initial performance results obtained for those systems were presented in Figs. 1 and 2. For the new set of calculations, the Navy SLR mixing procedure was applied as before except that the direct gain system was credited with part of the Trombe wall mass adjacent to the inner surface. Credits of 1 through 6 in. were tested for each mixture and in both cases the closest agreement with SUNMIX calculations was obtained with a 4-in. contribution. The results are presented in Figs. 9 and 10, which show that the shared mass SLR mixing algorithm provides an accurate representation of Trombe wall/direct gain interactions as modeled by SUNMIX.

Despite the encouraging results shown in Figs. 7 and 8, many questions remain unanswered. How will the mass sharing interaction be affected as the thickness of the Trombe wall is decreased, ultimately to 4 in. or less? What effect will thermocirculation vents, either in Trombe walls or in sunspaces with masonry common walls, have on the performance when these systems are mixed with direct gain? How will water walls, radiant panels, and TAPs interact with one another or with other system types? All of these questions must be addressed before a generalized SLR-type design procedure for mixed systems can be provided.

SUMMARY

It has been demonstrated that previously existing SLR-based design analysis procedures for mixed systems are inadequate because they neglect certain important interactions, these procedures tend to underpredict the performance of mixed systems and to erroneously suggest that optimal perform

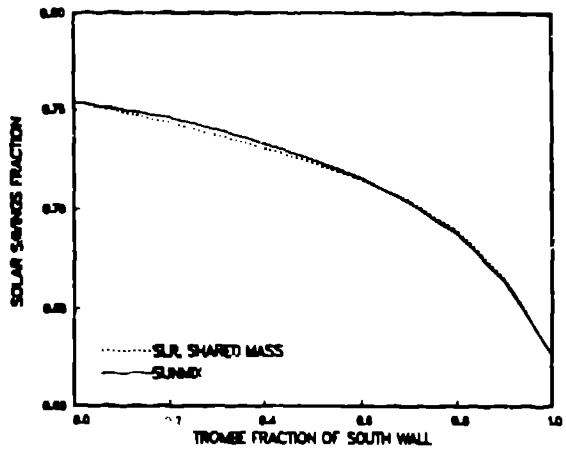

Fig. 9. Comparison of performance results from SUNMIX and shared mass SLR method for 12-in. Trombe wall combined with direct gain system with 2-in.-thick thermal storage mass and $A_m/A_g = 6$.

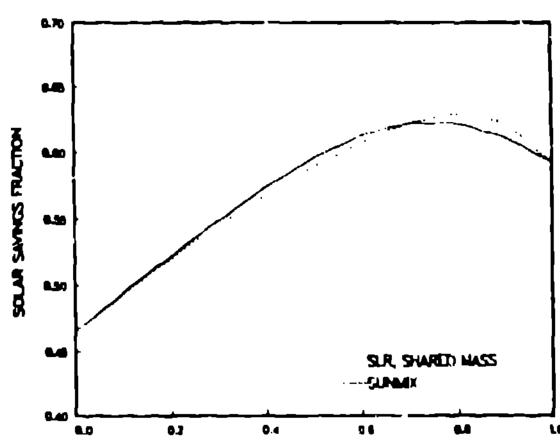

Fig. 10. Comparison of performance results from SUNMIX and shared mass SLR method for 18-in. Trombe wall combined with direct gain system with 2 in.-thick thermal storage mass and A_m/A_g 3.

ance is always obtained by simply eliminating the weaker system.

To provide the tools needed to account for the effect of thermal mass sharing in mixtures involving direct gain systems, an expression for the effective heat capacity of direct gain buildings was developed. The direct gain performance correlations were then generalized by relating the correlation parameters to the effective heat capacity and the steady state aperture conductance. Finally, the generalized performance correlations were used to demonstrate that one can model the effect of mass sharing between unvented Trombe walls and direct gain systems simply by allocating part of the Trombe wall mass to the direct gain system and proceeding with the established SLR analysis method for mixtures.

Although much work remains to be done, the encouraging results presented in this paper indicate that the chosen path is appropriate.

REFERENCES

1. J. D. Balcomb, C. D. Barley, R. D. McFarland, J. E. Perry, Jr., W. O. Wray, and W. S. Knoll, Passive Solar Design Handbook, Volume Two, US Department of Energy, Washington, D.C., 1980, DOE/CS-0127/2, pp. 30-38.

2. W. O. Wray, F. A. Biehl, and C.E. Kosiewicz, "Passive Solar Design Manual for Naval Installations," Los Alamos National Laboratory internal report LA-UR-83-2236.

3. W. O. Wray, C. R. Miles, and C. E. Kosiewicz, "A Passive Solar Retrofit Study for the United States Navy," Los Alamos National Laboratory report LA-9071-MS, p. 6.

4. R. D. McFarland, "PASOLE: A General Simulation Program for Passive Solar Energy," Los Alamos National Laboratory report LA-7433-MS.

5. J. D. Balcomb, C. D. Barley, R. D. McFarland, J. E. Perry, Jr., W. O. Wray, and W. S. Knoll, Passive Solar Design Handbook, Volume Two, US Department of Energy, Washington, D.C., 1980, DOE/CS-0127/2, pp. G1-G6.

6. W. O. Wray and C. R. Miles, "A Passive Solar Design Manual for the United States Navy," Proc. 7th National Passive Solar Conference, American Solar Energy Society, Knoxville, Tennessee, August 30 September 1, 1982, pp. 183-188.