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APPLICATIONS OF DOE-1 TO PASSIVE SOLAR HEATING OF COMMERCIAL BUILDINGS: PRELIMINARY RESULTS

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ABSTRACT

The DOE-1 building energy analysis computer program is being modified to include analysis of passive solar and large thermal mass heating and cooling systems. SUNSPOT is a detailed thermal network computer program developed for direct-gain systems as a reference analysis tool to compare with DOE-1. It was validated by comparison of calculated results with experimental test cell data. A series of runs was then made to determine the sensitivity of solar fraction to type of glazing, location and quantity of mass, and method of computing infrared radiant interchange among inside surfaces.

Simulations using DOE-1 in its present form indicate that the weighting factors used in the program are not satisfactory for large-mass/direct-gain systems. However, it does appear that the weighting factor approach can be retained if an efficient method of determining weighting factors appropriate to passive systems can be developed. Future work will proceed in that direction.

1. INTRODUCTION

The Los Alamos Scientific Laboratory (LASL) and Lawrence Berkeley Laboratory (LBL) are engaged in a joint project to develop analytical and design tools for passive solar and large thermal mass heating and cooling systems in commercial buildings. The initial work at LASL has concentrated on adapting DOE-1 (1), a building energy analysis computer program, to the analysis of large-mass/direct-gain systems. DOE-1 uses the weighting factor approach to approximate heating and cooling loads and room temperatures. Thus the plan was to run DOE-1 in its present form to determine its accuracy in predicting the performance of large-mass/direct-gain systems and to identify changes that are needed to produce an acceptable level of accuracy.

An important requirement for a study of this type is a reliable reference for comparison. In this case, two sources were used. These were experimental data from a direct-gain test cell at LASL and numerical results from SUNSPOT, a detailed thermal network computer code. The work discussed in this paper includes:

- The development of SUNSPOT and its validation.
- Assessment of the accuracy of DOE-1 in its present form for large-mass/direct-gain systems.
- Sensitivity studies using SUNSPOT to determine changes that will be required in DOE-1.
- Plans for future work.

2. PROGRAM SUNSPOT

Program SUNSPOT is an adaptation of PASOLE (2), a LASL-developed thermal network computer program that allows for heat sources and thermal energy storage and has been successfully used for the analysis of several types of passive systems (3). Several changes were made between PASOLE and SUNSPOT so that potentially important effects in direct-gain systems could be analyzed. The most significant changes were the following.

A. The geometry was changed from two to three dimensional so that the effects of mass distribution and geometry could be studied. The glazing, walls, roof, and floor are treated as separate surfaces, each containing one or more nodes. A total of 40 nodes was used in the present analysis.

B. A detailed calculation of the infrared radiant-heat transfer among the inside surfaces was included. Radiative conductances were calculated using a complex matrix procedure (4) and the linearizing approximation

$$4\,\bar{T}^3 (T_I - T_J) \approx (T_I^4 - T_J^4) ,$$

where T_I and T_J are the surface temperatures and $\bar{T} = 0.5\,(T_I + T_J)$.

C. A method for determining the rate of absorption of solar energy by each interior surface was developed. In this method the solar angles and geometry of the structure are used to calculate the fraction of beam and diffuse (sky and ground reflected) radiation striking each surface. Then a matrix solution is carried out for the enclosure, properly accounting for interreflections. The fluxes were assumed to be uniformly distributed over each surface.

D. Radiant interchange between an outside surface and the nighttime sky was calculated using the effective sky temperature approximation of Swinbank (5).

$$T_{sky} = 0.0411\ T_{amb}^{1.5}\quad (^{o}R).$$

The accuracy of SUNSPOT was checked by comparison of temperatures calculated by that model with experimental data taken from a test cell located at LASL. The direct-gain cell is a rectangular structure 5-ft wide, 8-ft deep, and 10-ft high. The south side is double glazed with 1/8-in. Plexiglas. Construction is 2 by 4 frame with fiber glass batts in the cavities and 1 in. of foam insulation on the inside. The cell contains high-density (140 lb/ft^3) concrete blocks that cover the floor and most of the side and back walls. No auxiliary heat or ventilation is provided so the cell undergoes large temperature swings during the diurnal cycle. Infiltration around a small, well-fitted door was calculated using the crack method. A rate of approximately one air change per hour was predicted. A more detailed description of the direct-gain test cell is given in Ref. 6.

Simulations were run for periods in February [illegible] May using solar insolation and dry-bulb temperature data measured at the test cell. Comparisons of calculated and measured values of the globe temperature are shown in Figs. 1 and 2. Agreement is quite good. Earlier runs that did not include infrared radiation from the outside surfaces to the nighttime sky did not give as good agreement between sunset and sunrise.

These comparisons should not be considered a comp[illegible] validation of SUNSPOT because they are limited to a single structure. However, the good agreement for this rather severe case (large glass area, heavy mass, and large temperature changes) does indicate that SUNSPOT can be used with some confidence to predict the effects of various parameters on the performance of direct-gain passive systems.

3. SENSITIVITY STUDIES

A series of simulations was made using SUNSPOT to determine the sensitivity of the performance of a passive solar building to a variety of effects. These sensitivity studies will guide the modification of DOE-1 for passive systems. A structure having dimensions of 37.4 by 37.4 by 8.0 ft, with double glazing covering the south wall, was chosen as the baseline case. The

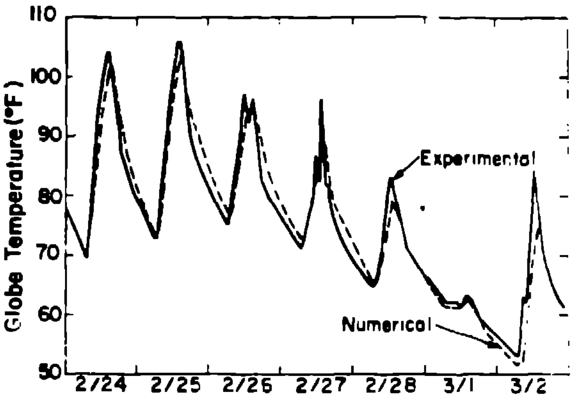

Fig. 1. Comparison of numerical and experimental test cell results (2/24/78-3/2/78).

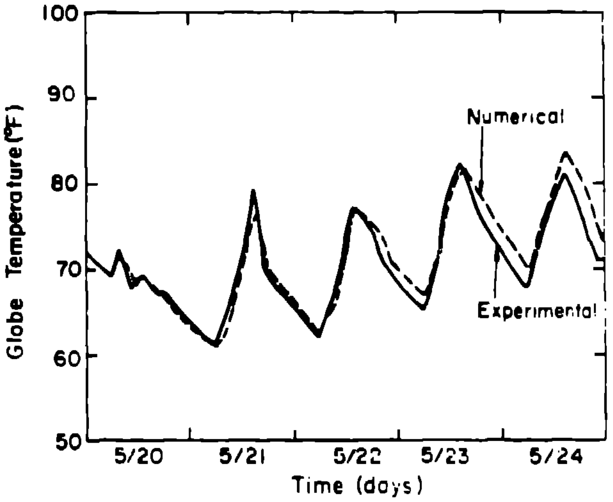

Fig. 2. Comparison of numerical and experimental test cell results (5/20/78-5/24/78).

infiltration rate was 1/2 air change per hour. The weather data used was that of the 1972-73 heating season for Los Alamos, New Mexico. The walls and floor were constructed of 4-in.-thick concrete block (ρ = 120.0 lb/ft^3, C_p = 0.2 Btu/lb-^{o}F, k = 0.47 Btu/h-ft-^{o}F) and R-15 insulation on the outside. The ceiling was of frame construction with R-15 insulation. The inside air temperature range was 65-75^{o}F. Results for the baseline case are shown in Table I. The most significant result is the solar fraction defined as $Q_{abs}/(Q_{abs} + Q_{aux})$ where Q_{abs} is the rate at which solar energy passes through the glazing and is absorbed, and Q_{aux} is the auxiliary heating required.

The effects of infrared radiation among inside surfaces, the distribution of solar energy over the inside surfaces, and mass and its location were investigated. Because these studies are for a single geometrical configuration and

TABLE I

RESULTS FOR THE BASELINE CASE

Month	Degree Days	Q_{aux} (MBtu)	Q_{abs} (MBtu)	Solar Fraction
Sep	209	0	8.62	1.0
Oct	506	2.52	5.91	0.70
Nov	1032	6.90	5.70	0.45
Dec	1144	8.65	5.11	0.37
Jan	1202	8.49	6.07	0.42
Feb	982	6.01	6.16	0.51
Mar	980	5.05	7.35	0.59
Apr	759	2.02	9.39	0.82
May	366	0.55	9.23	0.94
Total	7180	40.19	63.54	

Seasonal solar fraction = 0.61.

weather data for a particular location, they are not universally applicable to all passive solar systems. However, they do give an indication of the importance of these effects in DOE-1 and indicate the kind of changes that will be required in that program.

3.1 Infrared Radiation Among Inside Surfaces

The effect of detailed calculation of infrared radiation exchange among the inside surfaces vs the use of a combined film coefficient for the inside surfaces was examined first. DOE-1 and most other building simulation codes use a combined convective and radiative coefficient $h = h_c + h_r$. This approach has been acceptable for applications in which all surface temperatures are close to the air temperature, but might be expected to give poorer results if some surfaces are at temperatures significantly different from the air temperature (i.e., surfaces receiving solar radiation or cool glass surfaces). These effects were examined by setting the radiative conductances in SUNSPOT equal to zero and increasing the inside convective coefficients by h_r = 0.86 Btu/h-ft^2-^{o}F (see Ref. 7). In Table II, these results are compared using the detailed calculation of the radiant exchange between surfaces.

TABLE II

SOLAR FRACTIONS FOR DETAILED VS APPROXIMATE CALCULATION OF INFRARED RADIATION AMONG INSIDE SURFACES - BASELINE CONDITIONS

Simulation Period	Detailed	Approximate
1/1/73-1/31/73	0.429	0.416
3/1/73-3/31/73	0.602	0.584
9/1/72-5/31/73	0.613	0.598

The solar fraction is slightly lower using the approximate method. However, the differences are relatively small, considering the probable overall accuracy of this type of calculation. Because there does not appear to be any way to incorporate detailed calculations of the inside surface infrared radiation exchange in DOE-1 without significantly increasing the computation time, the present approximate method will be retained. Some improvement may be achieved by adjusting the value of h_r. A value of 0.60 rather than 0.86 gave very good agreement for the conditions considered here. Additional studies will be carried out to determine whether better values of h_r (as a function of the system parameters) can be found.

3.2 Distribution of Solar Energy on Inside Surfaces

Because DOE-1 does not include a calculation of the amount of energy absorbed by each surface, the effect of the distribution of solar energy on the inside surfaces was studied by running a series of cases with both diffuse and clear glazings. In the case of a clear glazing, a large fraction of the solar energy is absorbed by the floor. The diffuse glazing results in a much more uniform distribution of solar energy. Results for a series of cases run with both clear and diffuse glazing and nonuniform mass distributions are given in Table III. The most important conclusion is that the differences are small in all cases. The results also indicate that the condition giving the highest solar fraction is a uniform distribution of radiation over the massive surfaces. For the first case shown in Table III, the mass is concentrated in the floor so that the clear glazing gives better performance. The case of a massless floor and relatively heavy walls shows the opposite effect. The case of equally massive floor and walls shows approximately equal performance for the clear and diffuse glazings.

TABLE III

THE EFFECT OF THE DISTRIBUTION OF SOLAR ENERGY OVER THE INSIDE SURFACES

Weight (lb/ft^2)		Solar Fraction	
Floor	Walls	Clear Glazing	Diffuse Glazing
40	0	0.599	0.595
0	40	0.573	0.576
40	40	0.613	0.612

It should be noted that these results are affected by the simplification used in SUNSPOT of uniformly distributing radiation absorbed by one section of a surface over the entire surface. This assumption has the effect of making the solar radiation distribution appear more uniform than is actually the case. Nevertheless, it appears that detailed accounting of absorption by each surface may not be necessary.

3.3 Mass and Its Distribution

The results of the parametric study of mass and its distribution are presented graphically in Fig. 3. Note that the solar fraction increases with increasing total mass, but the curve is nearly flat for heat capacities greater than about 40,000 Btu/°F. This corresponds to wall and floor thicknesses of 8 in. and is consistent with the results of Ref. 6.

The results plotted in Fig. 3 also show that structures of equal mass but different mass distribution give different results, with the more uniform mass distributions yielding higher solar fractions. This indicates that room weighting factors depending only on total (or average) mass may not be sufficiently accurate, but may have to be computed for each structure to properly reflect the mass distribution.

4. ASSESSMENT OF DOE-1 APPLICABILITY

Finally, runs were made with DOE-1 in its present form to determine which aspects of the calculation will need revision. DOE-1 is not designed for systems with very large masses, nor can it rigorously account for infrared radiation exchange among the inside surfaces, distribution of solar energy over the inside surfaces, or the effect of mass and its distribution. Determination of heating/cooling loads and inside air temperature by DOE-1 may be considered a three-step process.

A. The heat fluxes at the inside surfaces are computed using wall response factors. These factors are calculated for each wall as a function of its density, thickness, thermal properties, and the combined heat transfer coefficient on the inside surface. Application of this procedure to heavier walls should cause no difficulty.

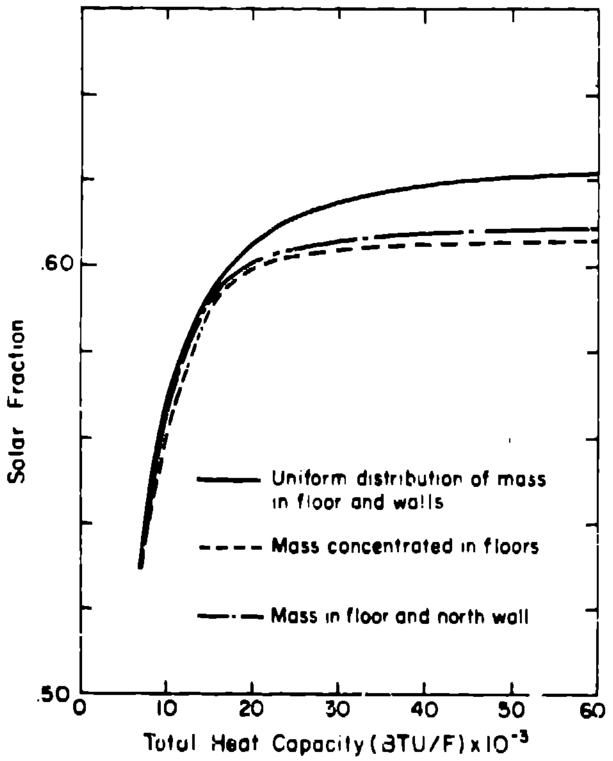

Fig. 3. Effect of mass and mass distribution on solar fraction.

B. Room weighting factors are then used to convert the wall heat fluxes, solar inputs, and other energy generation rates into heating and cooling loads. These weighting factors are tabulated coefficients taken from Ref. 7. There are three sets available corresponding to light, medium, and heavy construction. Heavy construction corresponds to 130 lb/ft^2 of floor, which is significantly lighter than many large-mass passive systems. This part of the procedure may be adaptable to large mass systems if an efficient method can be found for generating room weighting factors at an appropriate level of detail.

C. The preceding calculations are performed based on a fixed inside air temperature. If the actual heating and cooling rates supplied to the space differ from the loads found in Step B., the air temperature will vary. This variation is computed using air temperature weighting factors that are also characteristic of light, medium, or heavy construction. New values will also be required for these coefficients.

Results of a simulation of the test cell for the time period 2/24/78-3/2/78 are shown in Fig. 4. The air temperatures are compared with those computed by SUNSPOT. The trends are similar, but the values predicted by DOE-1 are much higher.

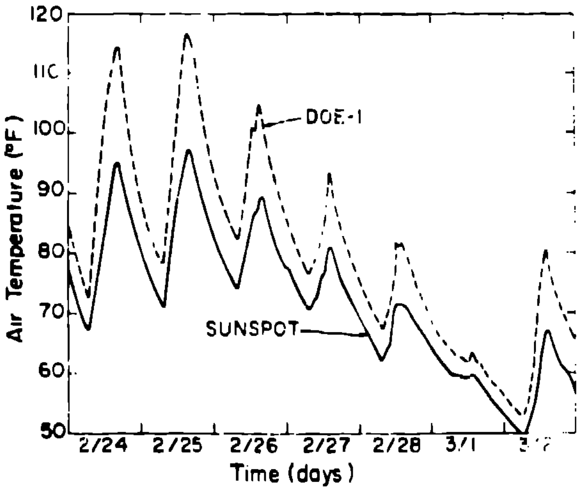

Fig. 4. Comparison of test cell temperatures predicted by DOE-1 and SUNSPOT.

Additional runs were made in an attempt to isolate those procedures in DOE-1 that must be altered. First, a case was run for the test cell geometry holding the inside air temperature at 83°F and eliminating the solar input. This eliminates the use of the room weighting factors for solar energy and the air temperature weighting factors. For this case, comparison of the heating/cooling loads calculated by DOE-1 and SUNSPOT shows good agreement (see Fig. 5).

The next step was the addition of the solar energy input. In this case, the agreement between results calculated by the two computer programs was less satisfactory. This is not surprising because the room weighting factors for solar energy were those for "heavy" construction, which is much lighter than the case considered here. Additional numerical experiments designed specifically to test the air temperature weighting factors show that those now available in DOE-1 are also unsatisfactory.

5. CONCLUSIONS

Based on the studies carried out using SUNSPOT and the preliminary runs made with DOE-1, the following conclusions have been drawn.

- The approximate method of accounting for infrared radiation exchange among inside surfaces by using a combined convective and radiative coefficient will be retained. Studies will be carried out to determine the best values of h_r as a function of system parameters.

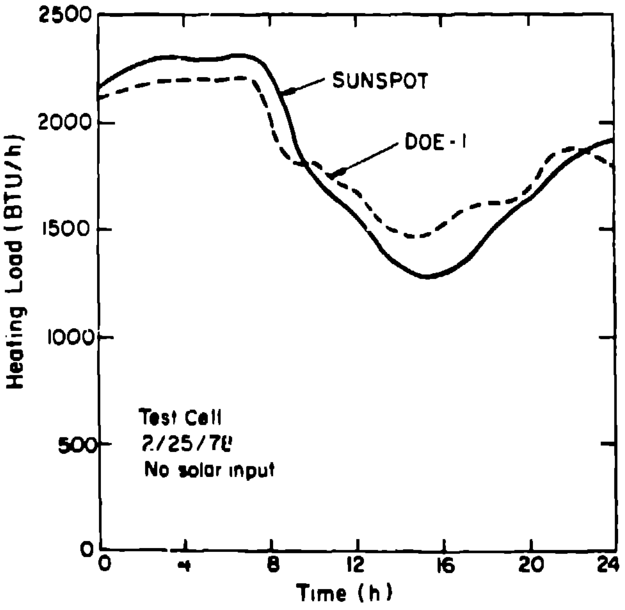

Fig. 5. Comparison of heating/cooling loads predicted by DOE-1 and SUNSPOT with no insolation.

- The method of accounting for solar radiation as an energy input released to the room air over a period controlled by the room weighting factors will be retained. It will be necessary to determine the appropriate weighting factors as a function of system parameters.
- A study of room weighting factors and air temperature weighting factors will proceed to determine an efficient method of generating coefficients suitable for large-mass/direct-gain passive system analysis.

6. ACKNOWLEDGMENTS

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PASOLE and Version 1 of SUNSPOT were developed by Group Q-11 at LASL. They also supplied the experimental data from the test cell. The development of Version 2 of SUNSPOT used in this work was a joint project between Groups Q-11 and WX-4 at LASL.

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