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# A Transient Heat and Mass Transfer Model of Residential Attics Used to Simulate Radiant Barrier Retrofits, Part II: Validation and Simulations

*A computer program was developed and used to implement the model described on Part I of this paper. The program used an iterative process to predict temperatures and heat fluxes using linear algebra principles. The results from the program were compared to experimental data collected during a three-year period. The model simulated different conditions such as variations in attic ventilation, variations in attic ceiling insulation, and different radiant barrier orientations for summer and winter seasons. It was observed that the model predicted with an error of less than ten percent for most cases. This paper presents model results for nonradiant barrier cases as well as cases for radiant barriers installed horizontally on top of the attic floor (HRB) and for radiant barriers stapled to the attic rafters (TRB). Savings produced by radiant barriers and sensitivity analyses are also presented. The model results supported the experimental trend that emissivity was the single most significant parameter that affected the performance of radiant barriers.*

## Model Validation

The model was compared to experimental data collected during a three-year period. Details of the experimentation procedures and more comparisons between experimental and simulated results are available in Medina (1992) and Medina et al. (1992). Figure 1 depicts ceiling heat flux results from tests corresponding to the summer of 1990.

In all figures the heavy solid line corresponds to the data while the solid line corresponds to the model predictions. In all comparisons presented herein, the attic insulation had a nominal resistance value of 3.35 $m^2K/W$ (R-19). Figure 2 shows the retrofit case (installing a Horizontal Radiant Barrier—HRB—to the attic floor of one of the test houses) corresponding to Fig. 1. Figure 3 shows a comparison between model results and experimental data from tests which were carried out during the summer of 1991. The radiant barrier was installed in the Truss Radiant Barriers (TRB) configuration. The TRB configuration consisted of installing the radiant barrier against the rafters which support the attic deck and roof.

Figures 4 and 5 show comparisons of ceiling heat fluxes from data gathered during the winter of 1990–1991. Figure 5 shows the radiant barrier case for the same period as Fig. 4. As shown in the figures, the predictions were in good agreement with the data during both the peak and off-peak times. The cumulative difference between data and predictions was less than ten percent for summer simulations and less than 12 percent for winter simulations (most of them to within less than ten percent).

In all of the comparisons between model predictions with experimental data it was observed that the model did not accurately predict ceiling heat fluxes during the first hours of simulation. The reason is found in the nature of Eqs. (2) and (3) of Part I of this paper. The response factors handle the energy storage in building components by using a combination of present and historical predictions of surface temperatures ($Tsi$ and $Tso$). Since during the first few hours of simulations, not enough surface temperature predictions are stored, the model lacks accuracy.

The radiant barrier emissivity used in the simulations was estimated using the following relation:

$$\epsilon_{RB} = \epsilon_{aluminum} \% A_{aluminum} + \epsilon_{perforation} \% A_{perforation} .$$

$$\epsilon_{RB} = 0.05(0.95) + 0.90(0.05) = 0.0925 \qquad (1)$$

The term $A_{perforation}$ is included because radiant barriers are perforated to allow moisture migration across the barriers. The emissivity used for the perforated part is that of the attic insulation (0.90). In this paper, only a few figures are presented to demonstrate the accuracy of the model; however, the model predicted well in many other situations (i.e., different insulation levels, different attic geometry, various house locations and orientations, different attic airflow, and flow patterns). Further results and discussions are found in Medina (1992). The model was sensitive to attic airflow variations, it predicted reasonably well when different values of insulation were used, and it produced accurate results in the post-retrofit (radiant barrier case) when either the horizontal or truss radiant barriers were used. In addition, the model predicted the moisture transfer. Whenever moisture transfer was not accounted for, the model did not accurately predict off peak time heat fluxes such as early mornings and nights (Medina, 1992). As stated previously, the model compared to experimental data to within an error of less than ten percent. This degree of accuracy provided reliable estimates of savings produced by the radiant barriers for seasonal or year-long simulations under a variety of situations for different weather conditions and geographic locations.

## Savings Produced by Radiant Barrier Retrofits

After the validation of the model, it was the objective to apply its results to a variety of case scenarios. Cooling and heating season simulations are presented for cases which in-

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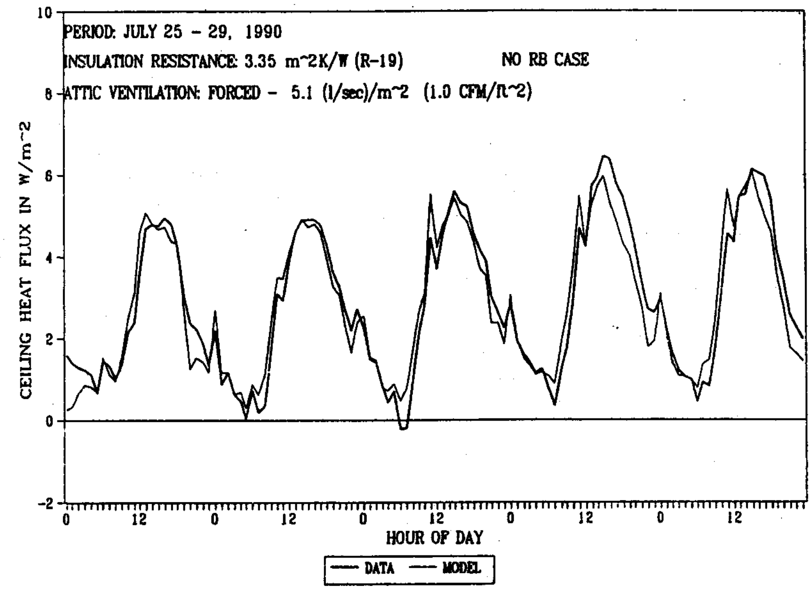


Fig. 1 Model results: ceiling heat fluxes (base case, insulation resistance: 3.35 m²K/W, R-19; with attic airflow rate: 5.1 (l/sec)/m², 1.0 CFM/ft²)

clude different levels of insulation and different radiant barrier orientations. The simulations were driven by weather tapes from Typical Meteorological Year (TMY) data from the National Oceanic and Atmospheric Administration (NOAA). Figure 6 presents the yearly performance of a HRB for Austin, TX. The ventilation rate was 5.1 (l/sec)/m$^2$ of attic floor (1.0 CFM/ft$^2$) and the insulation level had a resistance value of 3.35 m$^2$K/W (R-19). The indoor temperatures were chosen representative of usual residential patterns. The total cooling load savings in a typical year for this city was estimated as 3.14 kWh/m$^2$-year (996 Btu/ft$^2$-year) and the yearly heating load savings was 0.08 kWh/m$^2$-year (24.52 Btu/ft$^2$-year).

The bars in the figure represent monthly ceiling load and the numbers above the bars represent ceiling heat flow percent reduction produced by the radiant barriers as defined by

$$\%\text{Reduction} = \frac{\int_{\text{test period}} q''_{\text{control}}\, dt - \int_{\text{test period}} q''_{\text{retrofit}}\, dt}{\int_{\text{test period}} q''_{\text{control}}\, dt} \qquad (2)$$

where $q''_{\text{control}}$ refers to ceiling heat flux from the control attic and $q''_{\text{retrofit}}$ refers to ceiling heat flux from the retrofit attic. For example, the savings produced in the month of July (31.8 percent ceiling heat flow reduction) translated to a savings of 0.58 kWh/m$^2$-mo (183.13 Btu/ft$^2$-mo). The percent reductions observed in the figure during the summer months (June, July, and August) were in good agreement with those which were recorded in the experiments. Heating season savings were lower as expected. Winter seasons in this part of the country are short and mild. The performance of the TRB is very similar to that

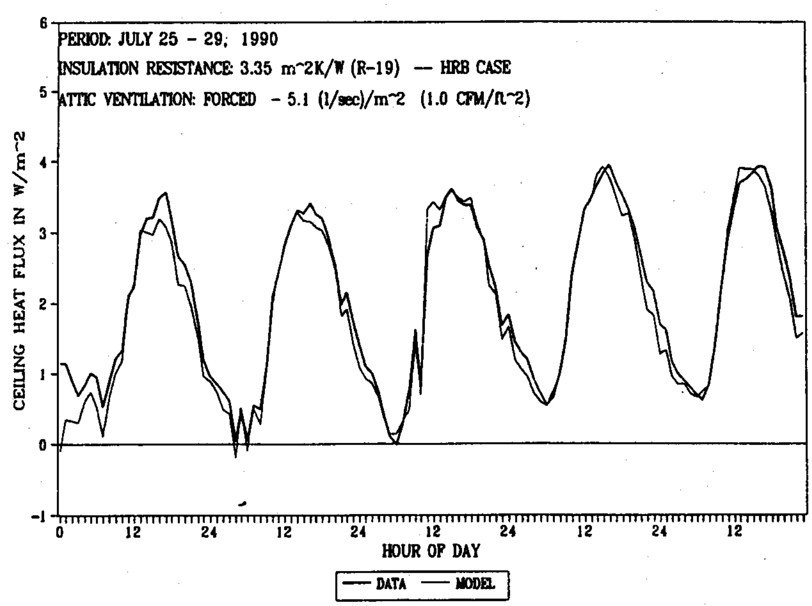


Fig. 2 Model results: ceiling heat fluxes (HRB case, insulation resistance: 3.35 m²K/W, R-19; with attic airflow rate: 5.1 (l/sec)/m², 1.0 CFM/ft²)

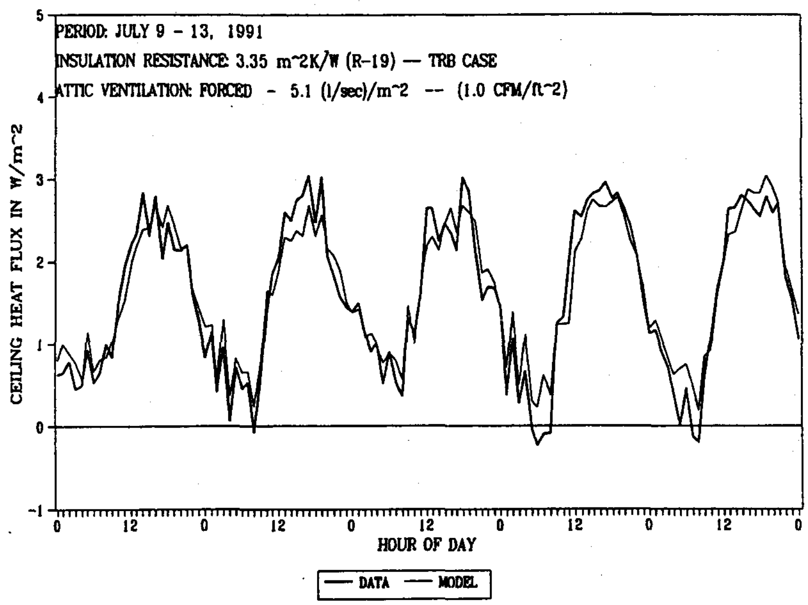


Fig. 3 Model results: ceiling heat fluxes (TRB case, insulation resistance: 3.35 m²K/W, R-19; with attic airflow rate: 5.1 (l/sec)/m², 1.0 CFM/ft²)

of the HRB. It has been shown experimentally that the HRB outperforms the TRB by reducing the ceiling heat flux by an extra one to five percentage points (Medina, 1992). The model results supported this trend. One reason for the better performance of the HRB over the TRB is that when the TRB is stapled to the roof rafters, the end-gables are left uncovered. This physical situation was also simulated by the model. Simulations for TRB retrofits are shown in Fig. 7.

Table 1 summarizes the amount of ceiling heat load savings for three kinds of insulation levels in reference to their corresponding base (no RB) cases. On can conclude that as the existing ceiling insulation levels increase, the savings produced by applying radiant barriers decrease. In addition, and as expected, most savings from the installation of the barriers are realized during the hottest months of the year.

## Sensitivity Analyses

Several of the parameters which affect the performance of a radiant barrier were investigated. The model showed that radiant barrier emissivity was the single parameter which affected its performance the most. The emissivity of radiant barriers does not change easily due to temperature or moisture changes. However, the emissivity of radiant barriers changes due to dust and contaminant accumulation on its surface, especially in the case of a HRB. Dust accumulation on radiant barrier surfaces is a major concern because dust accumulation makes the emissivity of radiant barriers increase. Dust accumulates because it travels with the air that ventilates the attics. Dust size and quantity accumulated, therefore, will depend on the location of the building. Other contaminants such as pollen and dry weeds, are

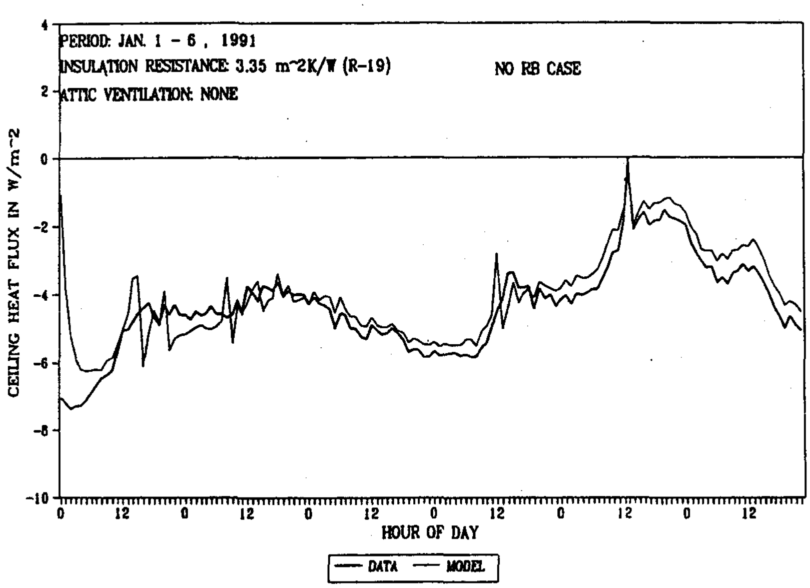


Fig. 4 Model results: ceiling heat fluxes during the heating season (base case, insulation resistance: 3.35 m²K/W; with attic airflow rate: 0 (l/sec)m², 0 CFM/ft²)

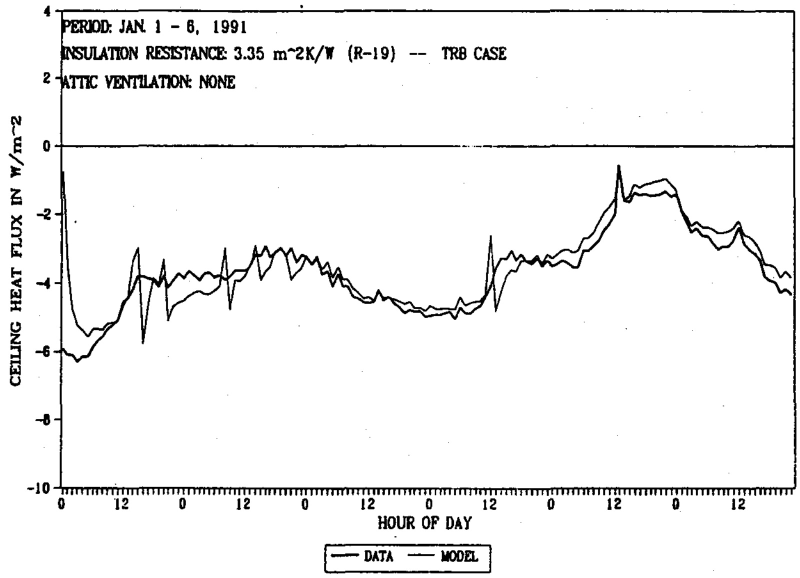


**Fig. 5 Model results: ceiling heat fluxes during the heating season (TRB case, insulation resistance: 3.35 m²K/W, R-19; with attic airflow rate: 0 (l/sec)/m², 0 CFM/ft²)**

treated as dust in the analyses. Figure 8 shows the effect of increasing radiant barrier emissivity.

Cooling season results indicate that the seasonal effectiveness of the radiant barriers drops dramatically as the emissivity increases. Heating season results suggest an improvement in the performance of the radiant barriers. At higher values of emissivity, the cumulative amount of energy which escaped from the conditioned space was lower because more energy was admitted into the conditioned space during the sunny periods. Therefore, the heating seasonal effectiveness of the radiant barriers increased with an increase in emissivity. Other parameters such as roof absorptivity, attic ventilation flow rate, and roof slope had only second order effects. According to the model, once a ventilation flowrate of 0.5 (1/sec)/m² (0.1 CFM/ft²) had been achieved, extra ventilation had no effect on the performance of the radiant barrier. This result is supported by experimental data.

## Conclusions

The model captured the transient effects associated with heat conduction across solid components, as well as the convection (forced or natural, laminar, or turbulent), attic air stratification, and radiation. The energy balances were coupled to mass balance equations which accounted for the air and moisture transfer. In addition, the model accounted for hourly solar loads on the attic exteriors. The model predicted hourly heat fluxes and surface temperature in attic structures. It was shown that the model produced accurate results in both the pre and the post-retrofit (radiant barrier case) cases. The simulations results and the experimental data were in agreement in most cases. The summer ceiling load reductions when using HRBs were in the order of 30–40 percent when the insulation resistance was 3.35 m²K/W (R-19). These results agreed with data gathered during several summers. In addition, the simulations also predicted the

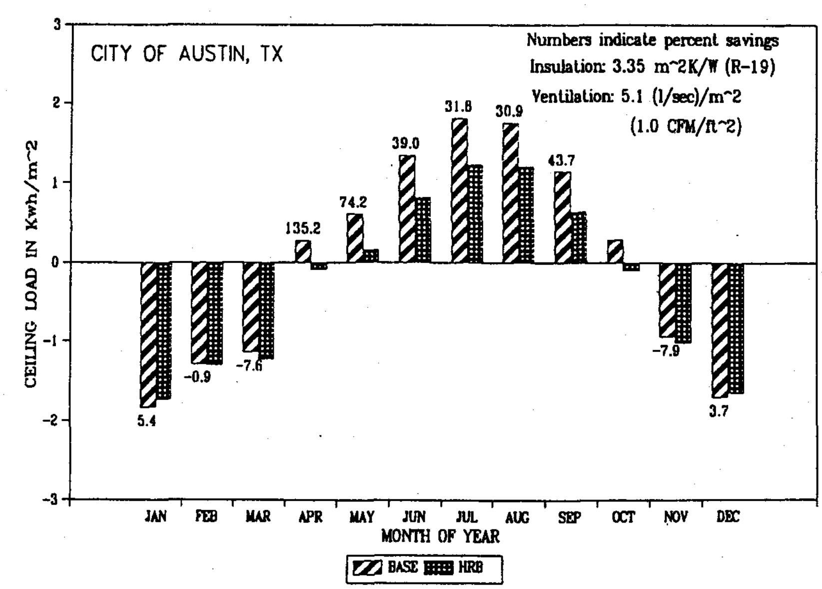


**Fig. 6 Yearly performance of a HRB (insulation resistance: 3.35 m²K/W, R-19; with attic airflow rate: 5.1 (l/sec)m², 1.0 CFM/ft²)**

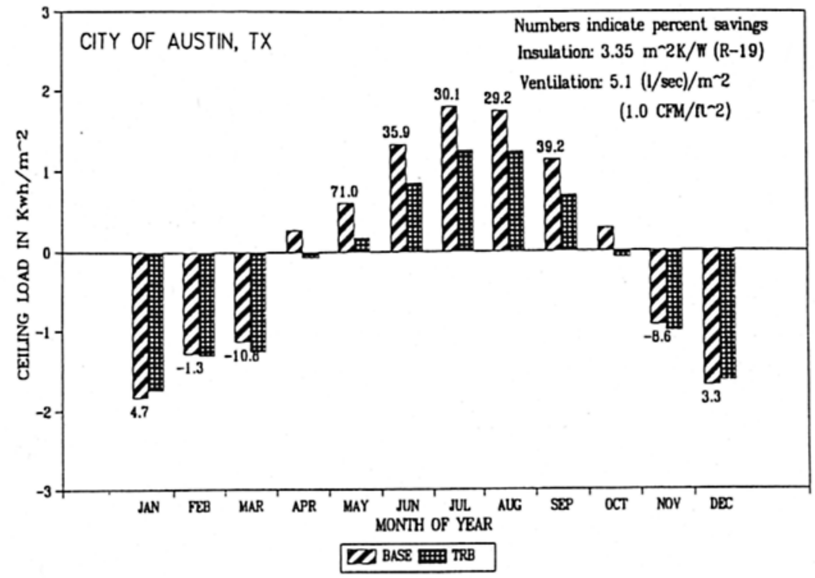


Fig. 7 Yearly performance of a TRB (insulation resistance: 3.35 $m^2K/W$, R-19; with attic airflow rate: 5.1 (l/sec)$m^2$, 1.0 CFM/$ft^2$)

Table 1 Monthly savings produced by a HRB under various insulation levels for Austin, TX

| Month of the Year | Ceiling Load Savings kWh/m²mo(Btu/ft²mo) 1.94m²K/W (R-11) | Ceiling Load Savings kWh/m²mo(Btu/ft²-mo) 3.35m²K/W (R-19) | Ceiling Load Savings kWh/m²mo(Btu/ft²-mo) 5.28m²K/W (R-30) |
|---|---|---|---|
| Jan | 0.71 (226.11) | 0.10 (31.52) | -0.07 (-22.40) |
| Feb | 0.39 (123.25) | -0.01 (-3.49) | -0.12 (-37.31) |
| Mar | 0.25 (79.16) | -0.09 (-27.34) | -0.16 (-51.47) |
| Apr | 0.44 (138.58) | 0.27 (85.25) | 0.20 (61.74) |
| May | 0.80 (254.30) | 0.45 (142.59) | 0.32 (102.83) |
| Jun | 1.23 (388.38) | 0.52 (165.66) | 0.38 (121.11) |
| Jul | 1.51 (479.44) | 0.58 (183.13) | 0.42 (134.62) |
| Aug | 1.44 (457.27) | 0.54 (171.78) | 0.40 (126.40) |
| Sep | 1.11 (350.72) | 0.50 (158.54) | 0.37 (115.71) |
| Oct | 0.58 (184.69) | 0.28 (89.09) | 0.20 (64.68) |
| Nov | 0.20 (64.73) | -0.07 (-23.53) | -0.14 (-43.72) |
| Dec | 0.62 (195.37) | 0.06 (20.02) | -0.09 (28.54) |

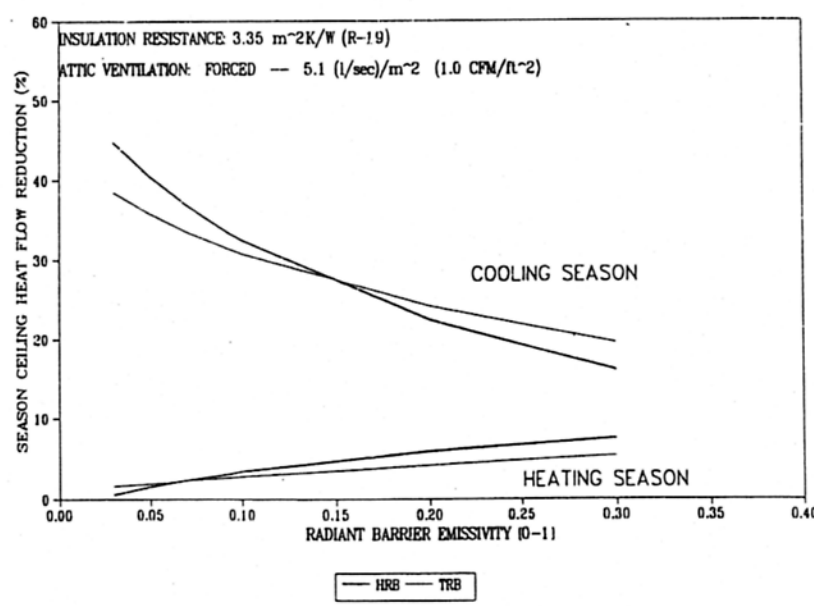


Fig. 8 Radiant barrier performance as a function of radiant barrier emissivity (insulation resistance: 3.35 $m^2K/W$, R-19, with attic airflow rate: 5.1 (l/sec)$m^2$, 1.0 CFM/$ft^2$)

lower (one to five percent) performance of the TRB when compared to the HRB. The relative ceiling heat flux reductions produced by the radiant barriers as a function of insulation resistance were also in agreement with the experimental efforts. That is, the percent reductions were higher if lower insulation values were combined with the radiant barriers. The sensitivity analyses showed that the single most significant parameter that affected the performance of radiant barriers was the barrier emissivity. During the cooling season, the percent of ceiling heat flow reduction dropped approximately 20 percentage points when the emissivity increased from 0.03 to 0.3. Other parameters had only second-order effects on the barrier performance. In addition to simulations and sensitivity analyses, this program could also be integrated with whole-house energy simulations programs.

## References


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