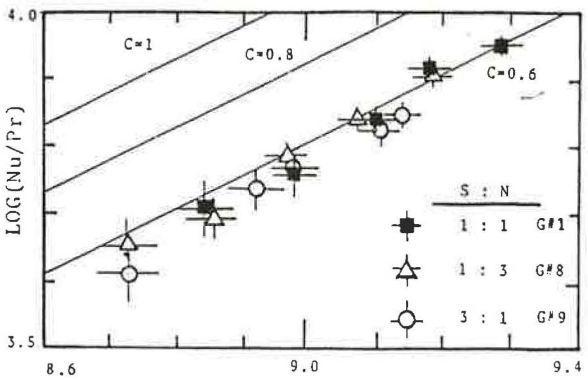

Fig. 7. Correlations between Gr and Nu/Pr for Geometries 1, 8, and 9.

previous works done by Brown and Solvason, Weber, and Grief and Nansteel except that the aperture height ratio and the aperture width ratio seem to have different effects on heat transfer from Weber's results. This inconsistency may be caused by the difference of the geometry of the model or the definition of the room temperature.

For the geometry that has two identical apertures separated vertically, the equivalent single aperture gives consistent results with other geometries. In the case tested in this experiment, dividing an aperture into two apertures at the top and the bottom resulted in 1.75 times the heat transfer for the same temperature difference and the same total aperture area.

The effect of the room volume on the correlation of the heat transfer is very small if the temperatures away from the aperture are used as the room temperatures. This experimental study will be continued in the Solar Energy Section of the Los Alamos National Laboratory.

7. ACKNOWLEDGMENT

The author wishes to thank Dr. J. D. Balcomb and Dr. G. F. Jones of the Los Alamos National Laboratory for their valuable suggestions to this study.

The author also thanks Mr. Lee Dalton, Mr. Burl Ketchum, and Mr. Jose Tafoya for their assitance to the experimental work.

8. REFERENCES

1. W. G. Brown and K. R. Solvason, "Natural Convection Through Rectangular Openings in Partitions, Part I: Vertical Partitions," Int. J. Heat and Mass Transfer 5, 859-868 (1962).

2. M. W. Nansteel and R. Greif, "An Investigation of Natural Convection in Enclosures with Two- and Three-Dimensional Partitions," Int. J. Heat and Mass Transfer 4, 561-571 (1984)

3. D. D. Weber and R. J. Kearney, "Natural Convective Heat Transfer Through an Aperture in Passive Solar Heated Buildings," 5th National Passive Solar Conference, October 19-26, 1980, Amherst, Massachusetts.

4. Matheson Unabridged Gas Data Book; a Compilation of Physical and Thermodynamic Properties of Gases (Matheson Gas Products, East Rutherford, NJ, 1974).

5. J. D. Balcomb and K. Yamaguchi, "Heat Distributiopn by Natural Convection," 8th National Passive Solar Conference, September 5-10, 1983, Santa Fe, New Mexico.

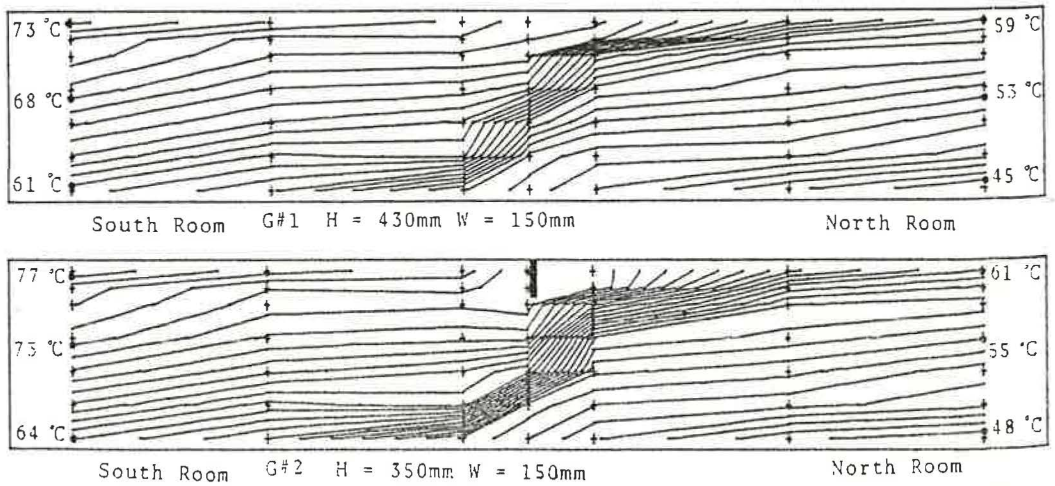

Fig. 8. Isotherms in the vertical plane at the center of the apertures for Geometries 1 and 2.

#3831

NATURAL CONVECTION AIRFLOW MEASUREMENT AND THEORY*

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ABSTRACT

Natural convection is a major mechanism for heat distribution in many passive solar buildings, especially those with sunspaces. To better understand this mechanism, observations of air velocities and temperatures have been made in 13 different houses that encompass a wide variety of one- and two-story geometries. This paper extends previous reports. Results from one house are described in detail, and some generalizations are drawn from the large additional mass of data taken. A simple mathematical model is presented that describes the general nature of airflow and energy flow through an aperture.

1. INTRODUCTION

A series of experiments was initiated in 1981 to determine the nature of natural convection airflow, heat distribution, and stratification in passive solar buildings. The first one and one-half years' work was summarized at the 8th Passive Conference.[1] The scope of our experiments has been extended to include not only velocity and temperature profile scans near midday in doorways but now includes half-hourly data averages recorded over a several-day period. The objective is to study a variety of convection geometries. Each building monitored has a different relationship between the solar collection space, which is a south-side sunspace or central atrium, and the house. Five houses are two-story geometries, six incorporate other types of level change, three have a fan-forced (hybrid) element, and four have special vents or ducts, all in various arrangements.

The experiments are intended to be of a scoping nature in order to identify general airflow and stratification characteristics. Because the observations have been made in occupied houses, they are necessarily limited, and the data are usually less than desired, both in quantity and quality. However, general observations are possible that are very useful to understanding the nature of the phenomena and also for planning more controllable experiments.

The large volume of data taken precludes a complete description and presentation in this short paper. Instead, selected results are given with a more comprehensive Los Alamos report to follow.

2. BEA ALLEN SUNSPACE RETROFIT

This small masonry house is located in a 6000 DD climate in the mountains near Albuquerque. The 1979 retrofit, which also included adding insulation to the outside of walls and roof, has improved house comfort and reduced winter propane used for heating by 75% comparing 4 years prior to the modifications to 4 years after. The 35-ft sunspace addition extends 9 ft out from the south side of the house. The south wall contains 217 ft^2 of double glazing at a 60° tilt (projected area = 188 ft^2). The common wall is 8-in. masonry with several fixed windows, two small operable windows, and a 78-in. by 32.5-in. door opening. Data taken in March are shown in Fig. 1. Even though the sunspace contains considerable mass, the large glazing area results in 40°F sunspace temperature swings on sunny days. This leads to a major convective exchange through the doorway, heating the house and causing 10°F swings in the south house rooms and 7°F swings in the north room. A vertical doorway velocity profile measured at 13:20 on March 21 is shown in Fig. 2. The flow profiles are integrated to obtain minimum and maximum volumetric flow rates of 453 cfm and 600 cfm through the door top half and 435 and 567 cfm returning to the sunspace through the door bottom half. The

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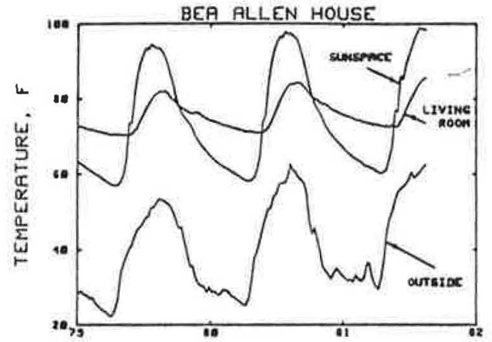

Fig. 1. Temperature histories in the Bea Allen house. Room air temperatures are measured 60 in. above the floor.

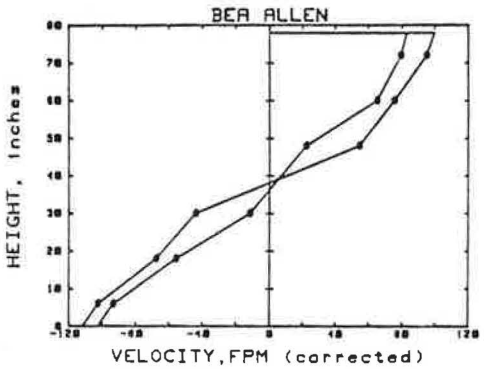

Fig. 2. Doorway velocity profiles measured at 13:20 on March 21, 1984 (Day 81). Maxima and minima of anemometer needle swings are observed and plotted. Each point is the average of two readings at different horizontal locations (1/4 and 3/4 points).

net flow is, therefore, bounded between 114 cfm outward and 165 cfm inward. Because this brackets zero, it is reasonable to assume that no net infiltration airflow passes between these spaces. With this assumption, the best estimate is 513 cfm of airflow in each direction. The mixed mean temperature of each flow stream is calculated based on a velocity-weighted average of the temperature profile shown in Fig. 3 to obtain 93.2°F for the upper half and 75.8°F for the lower half. The corresponding convective energy exchange is 7415 Btu/h (air density is 0.058 lb/ft^3).

An elementary theory can be developed, based on the Bernoulli equation, which leads to a good first-order explanation of the observed conditions. The pressure integral around the path shown dotted in Fig. 4 gives a driving pressure difference of

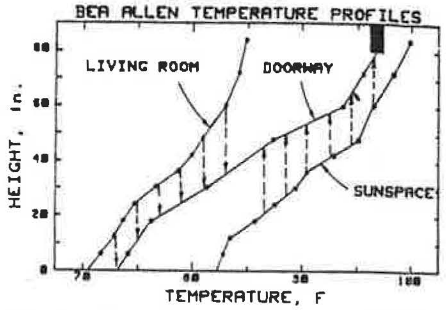

Fig. 3. Temperature profiles at 13:20 on March 21, measured in each room and in the doorway. Dotted arrows show the vertical displacements implied if streamlines are isotherms.

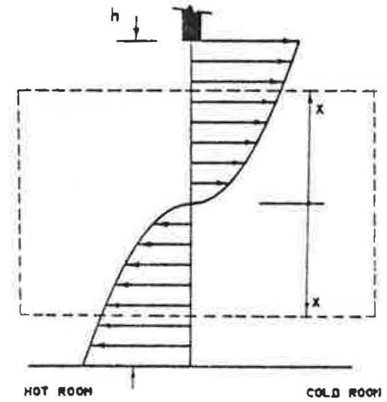

Fig. 4. Sketch showing geometry for analyses. Door height is h, distance from centerline is x.

$$\Delta P = -2\ \Delta\rho\ x \quad ,$$

where x is measured up or down from middoor and $\Delta\rho$ is the difference in air density of the two air columns on either side of the door. This pressure rise is balanced by two velocity head losses around the loop.

$$\Delta P = -2\ \Delta\rho\ x = 2(1/2\ \rho v^2/g_o) \quad ,$$

where v is the local velocity in the doorway and g_o is the gravitational constant 115,800 ft/min^2. Because the pressure is constant to first order, the density difference can be related to ΔT, the room-to-room temperature difference: $\Delta\rho/\rho = -\Delta T/T_o$, where T_o is the absolute temperature, assumed to be 540°R. Solving for velocity,

$$v = \sqrt{g_o/T_o}\ \sqrt{2\ \Delta T\ x}$$

$$v = 14.65\ \sqrt{2\ \Delta T\ x} \quad , \text{ ft/min.} \qquad (1)$$

If ΔT is independent of height, this can be integrated to yield the volumetric flow rate in each direction, V,

$$V = (2/3)wC\ \sqrt{2g_o(h/2)^3\ \Delta T/T_o}$$

$$V = 2.98\ w\ \sqrt{h^3\ \Delta T} \quad , \text{ cfm,} \qquad (2)$$

where w is the door width, ft; h is the door height, ft; and C is the discharge coefficient,[2] taken to be 0.611, which accounts for contraction of the flow streamlines as they pass through the doorway. The energy flow, Q, can now be calculated

$$Q = V\Delta T_d\ \rho c$$

$$Q = 3.22(ADR)(\Delta T_d/\Delta T)w\ \sqrt{(h\Delta T)^3}, \text{ Btu/h} \quad , \qquad (3)$$

where ρ is the air density (0.075 lb/ft^3 at sea level), c is the heat capacity of air (0.24 Btu/lb°F), ADR is the air density ratio (air density/sea level air density), and ΔT_d is the difference in the mixed mean temperatures of the upper and lower air streams.

This theory, while much oversimplified, yields results surprisingly close to observations. The square-root dependence of velocity on height in Eq. (1) has been observed in careful measurements done in a confined 1/5 scale box and also in many simple doorway situations observed in this project. The flow given in Eq. (2) is predicted to be

$$V = (2.98)(2.87)\ \sqrt{(6.5)^3(13.5)}$$

$$V = 520 \text{ cfm} \quad ,$$

for the Bea Allen case, in good agreement with the observation of 513 cfm. The value of $\Delta T_d/\Delta T$ observed is 17.4°F/13.5°F = 1.29 and ADR = 0.77 so that

$$Q = 4.15(ADR)w\ \sqrt{(h\Delta T)^3}$$

$$Q = 7538 \text{ Btu/h} \quad ,$$

also in reasonable agreement with the observed value of 7415 Btu/h.

Energy flows reported by Weber[3] (referenced to sea level) are correlated by:

$$Q = 4.6\ w\ \sqrt{(h\Delta T)^3} \quad ;$$

however, more recent Los Alamos similitude experiments done at 1/5 scale in Freon[5] 12 indicate that the 4.6 constant should be about 3.9. The above theory gives a constant of 4.15, which is somewhere in between.

One problem with using the theory outlined above is the dependence of energy flow in Eq. (3) on the ratio $\Delta T_d/\Delta T$. This ratio is not presently predictable. It does imply that stratification is beneficial to energy transfer.

Temperature profiles measured in each room and in the doorway of the Bea Allen house are shown in Fig. 3. The important observation is that doorway temperatures are not simply a horizontal translation of the corresponding room temperatures. If we assume that neither significant heat transfer nor mixing take place along a streamline, these temperature profiles imply vertical displacements of the air streamlines, as shown by the arrows in Fig. 3. These displacements are roughly 14 in. downward for the cold stream and 18 in. upward for the hot stream. These displacements have a major effect on $\Delta T_d/\Delta T$. Smoke streams are observed to be very nearly horizontal in the doorway and not particularly turbulent. Based on these observations, we can speculate about the nature of the convective exchange as follows (see Fig. 5):

a. Flow from the cold room drops about 14 in. as it approaches the door and levels off, crowding out the bottom 14 in. of air in the room. After passing through the door, the cold streams, being colder than any air in the sunspace, quickly fans out, dropping to fill a cool pool about 12 in. deep near the floor.

b. Flow from the hot room elevates about 18 in. as it approaches the door and levels off as it passes through the door. The flow then quickly turns upward, being warmer than any air in the cold room.

c. This implies that there are three pockets of air not directly involved in the convective exchange: (1) a thin layer near the floor of the cold room, (2) the air in the hot room above the level corresponding to a horizontal plane 18 in. below the door height, and (3) a layer in the cold room extending from 14 in. above the door midplane nearly to the ceiling. No hot pocket is observed at the ceiling of the cold room; presumably this air is quickly drawn off into boundary layers dropping down the cooler walls.

Having calibrated the doorway at one point in time, the energy exchange at other times

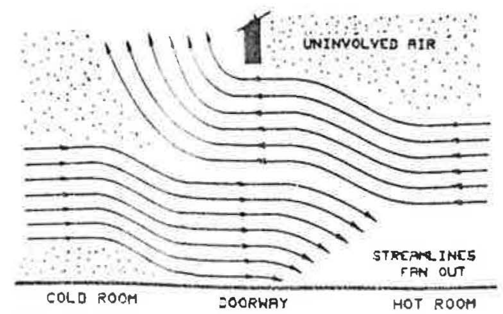

Fig. 5. Speculation of streamline character, based on temperature profiles, assuming streamlines are isothermal.

can be inferred by assuming that the energy exchange is proportional to the product of velocity and ΔT_d.

A plot of the convected energy is shown in Fig. 6. The daily total is 48,770 Btu.

Solar radiation measured in the plane of the sunspace glazing, is plotted on Fig. 6 as a dashed line. Note that the doorway convection ceases about 2 hours after sundown.

The integral of the solar radiation curve is 2340 Btu/ft^2. If we ignore shading, the energy incident on the sunspace glass is 217 x 2340 = 507,800 Btu, implying that the doorway convection is only 9.6% of the incident solar. The sunspace seems convection limited and might perform better if the doorway were larger. Our guideline calls for 10% of the projected area or 18.8 ft^2, which is very close to the door area of 18.7 ft^2. This indicates that the guideline may be too small.

Other observations in the Bea Allen house are as follows:

a. Velocities measured 6 in. below the door top (x = 33 in.) correlate well with $\sqrt{\Delta T}$, as shown in Fig. 7. These 84 data points are taken over a period of 13 days; each represents the average of 300 points sampled over 1/2 hour. The best-fit to $v = K\sqrt{\Delta T}$ is K = 20.3. We expect K = 14.65 $\sqrt{5.5}$ = 34.3, based on Eq. (1). The ratio is 22.8/34.3 = 0.63. We note that a fundamental assumption in the theory is that the velocity is horizontally uniform at the value v and that energy losses through the doorway are negligible. Inclusion of a nonuniform horizontal velocity and losses tend to reduce the theoretical value of K and bring it more in line with the observed value. In any case, one would expect to see a smaller-than-theoretical value of K in practice.

b. A hybrid element was installed in the house consisting of a fan that pulls 1031 cfm of air from the sunspace, discharging it into a downstairs room on the north side of the house, hoping to transfer heat to the downstairs room. This is a notable failure. Not only does this airstream fail to heat the downstairs room to any significant degree, but the return path for this air is via the same doorway referred to previously. This clearly inhibits the natural exchange through the door, reducing K to about 15. Temperature rises in the upstairs are notably less on days when the fan is operated. (Previous data presented were obtained when the fan was off.)

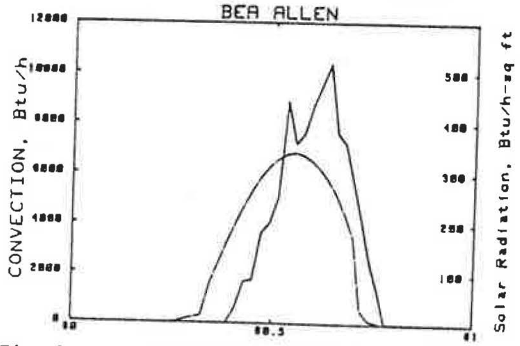

Fig. 6. Energy convected through doorway on March 20, 1984.

c. Heat flow conducted through the common masonry wall to the house is small, accounting for only about 10.4 Btu/ft^2 per day.

d. Temperatures measured on the inside surface of the sunspace double glazing (using a thermocouple fastened to the window with clear tape) show 64°F temperature swings compared with 40°F temperature swings in the greenhouse air. The glass is about 9°F colder than the room air at night and 15°F warmer during the midday peak.

e. Stratification in the 10-ft-high sunspace is about 14°F during the midday peak and 2°F at night.

3. GENERALIZATIONS FOR OTHER HOUSES

Similar observations have been made for the other houses monitored, but limitations of space prohibit a full description here. Although it is somewhat risky and difficult to draw general conclusions from the observations, we have attempted this where a general trend seems clear.

3.1. Velocity vs. ΔT Correlations

Correlations such as the one shown in Fig. 7 have been made using data taken in five houses. Each case shows a reasonably consistent relationship between velocity, measured near the top of the door, and room-to-room ΔT. The correlation constant. K, in the relation $v = K\sqrt{\Delta T}$, has been determined by least squares for each data set. The values obtained are given in Table I. In all cases, the ΔT measurements are made at the same level in the two adjacent rooms at a height near mid-door.

These values seem quite consistent. A value of K of about 20 to 22 is observed for a single doorway without a level change from room to room. The 11-in. level change in the Ed Balcomb house seems to have significantly increased K; however, an extreme case of level change as in the Doug Balcomb house

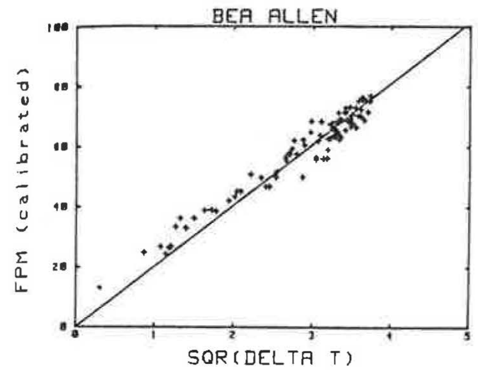

Fig. 7. Velocities measured 4 in. from the top of the doorway connecting the sunspace to the living room in the Bea Allen house. The temperature difference (ΔT) is between air temperatures measured 60 in. above the floor.

does not produce quite so large an effect. For the multiple doorways in the two-story interconnected space of La Vereda, K is much greater, presumably due to the large increase in effective height (this geometry involves five doors and a hallway and is not easily analyzed). These results lend confidence to our expectation that airflow can be predicted, even in complex geometries, provided temperatures are known.

3.2. Energy Flow

Measured energy flow values vary widely, depending on conditions. Although most cases seemed to follow intuitive prediction, there were two surprises, described below:

a. A small attached sunspace (Steve Scheu house) is connected to the house with 3.5 ft^2 of operable vents at the ceiling level above a 19.1 ft^2 door opening. Detailed measurements performed with the vents open and the vents closed show a 16% increase in airflow with the vents open but an insignificant change in energy flow. The sunspace temperature does increase by 3°F when the vents are closed, but there is a subtle shift in sunspace stratification resulting in nearly identical energy transport. In this case, the aperture size is already quite adequate (28% of projected glazing area), and an increase in area has little effect. It appears that the comfort issue may be far more critical in determining the placement and sizing of convection apertures than the issue of energy exchange.

b. The complex multi-level geometry of the Jim Young residence includes both doorways and window openings connecting the house to the sunspace plus three underfloor circular ducts that provide a return air path from the uppermost level of the house to the sunspace. As expected, opening the ducts significantly increases air and energy transport, partly because ground contact of the ducts cools the return air, helping to pump additional flow. However, closing the windows with the ducts open, which reduces the aperture area from 47.2 ft^2 to 19.8 ft^2, actually increases the energy transport by 16%, although the air exchange decreases by 51%. The reason for this peculiar result is that the airflow through the windows tends to mix the air in the sunspace, reducing stratification and, therefore, reducing the ratio $\Delta T_d/\Delta T$. This more than compensates for the increased airflow. Significantly, sunspace comfort is greatly improved with the windows open (emphatic comment by house occupant working in the sunspace during the experiment). Also, the owners close off the ducts at night to avoid cold drafts.

We predict that the most difficult part of estimating energy transport will not be in predicting airflow, which depends weakly on ΔT and not at all on stratification, but in predicting ΔT_d, which depends strongly on stratification.

In several of the houses studied, convection is two-stage. That is, heat is first convected from a sunspace to a living space and then convected through a single doorway to a more remote room, often a bedroom or bathroom. This seems to work well; the observed ΔT values are reasonable (2-3°F) and the remote rooms are kept comfortable. The cyclical nature of the living space temperatures (7°F temperature swing) seems to enhance the second-stage convection.

3.3. Stratification

The most general statement that can be made is that stratification (0.5 to 1.2°F/ft) is observed in every case where there is significant zone-to-zone convection through apertures. The evidence strongly suggests that convective exchange and stratification are strongly linked, although the physical reasons are not yet completely clear.

In some, but not all cases, a single closed-off room will not stratify, that is, the air mixes. This usually happens at night when a sunspace is bounded on the south side by a cold glass surface and on the north side by a warm mass wall surface. Strong boundary layer flows are observed, and temperatures in the core of air in the center of the room are nearly uniform and in some cases slightly cooler at the top. In the daytime, however, the inner glass surface becomes much warmer than the room air, due to solar energy absorption, and boundary layer flows rise along both surfaces.

TABLE I

VELOCITY CORRELATION CONSTANT, K, ft/min °F-1/2

K	Aperture	Situation
20.3	Single Doorway	Bea Allen house. Floors at same level.
31.5	Multiple Doorways	La Vereda Model 4 (see Ref. 1). Measurements made in the upper doorway. Air return path to the greenhouse is through doorways at a midlevel and at a lower level.
24.0	Single Doorway	Doug Balcomb house. Measurements are made in an upstairs doorway leading off a balcony at the top of a two-story greenhouse.
27.6	Single Doorway	Ed Balcomb house. Measurements are made in a door leading from a central atrium. There is an 11-in. step up from the atrium to the adjacent room. Other doors leading from the atrium have no step up.
22	Multiple Apertures	Jim Young house. Measurements are made in a window opening between a sunspace and the living room. The house is built on a south-sloping hill and there are several level changes. The living room floor is 45 in. above the sunspace floor. The major flow path is not through the window but through two doorways in series.

In one case a stratified sunspace was observed to mix during the day when the door connecting to the house was closed (Steve Scheu house). In another case this did not occur (Doug Balcomb house); it is postulated that mixing did not occur in the second situation because of a small convective exchange with massive cool surfaces surrounding a staircase located in the sunspace.

4. CONCLUSIONS

a. Large air and energy exchange rates are observed to occur naturally in passive buildings, often providing the major mechanism for heat distribution.

b. A simple Bernoulli-based model successfully predicts airflow in a single door. No obstacles are seen to extending the model to multiple aperture situations.

c. Aperture velocities correlate reasonably well with $\sqrt{\Delta T}$.

d. Stratification is normally present in multizone convective exchange. Although stratification may decrease comfort in some cases, it tends to enhance energy exchange.

e. Cool air approaching an aperture tends to drop and warm air approaching the aperture from the other side tends to rise.

5. ACKNOWLEDGMENTS

We are grateful to the many people who allowed us to come into their homes to take measurements and to Jim Hedstrom and Lee Dalton for assistance in obtaining and setting up the data acquisition system. We also wish to thank Professor David Otis, Summer Faculty Research Associate at Los Alamos from the University of Wisconsin, for valuable discussions on stratified flow phenomena.

6. REFERENCES

1. J. D. Balcomb and K. Yamaguchi, "Heat Distribution by Natural Convection," Proc. 8th Passive Solar Conf., Santa Fe, New Mexico, September 7-9, 1983, ASES, Boulder, Colorado, pp. 153-158.

2. I. G. Currie, Fundamental Mechanics of Fluids, McGraw-Hill (1974), p. 131.

3. D. D. Weber and R. J. Kearney, "Natural Convection Heat Transfer Through an Aperture in Passive Solar Heated Buildings," Proc. 5th Passive Solar Conf., Amherst, Massachusetts, October 19-26, 1980, ASES, Boulder, Colorado, pp. 1037-1041.

RESEARCH RESULTS: DAYTON POWER AND LIGHT'S ENERGY HOME

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Abstract

Research results from one year of monitoring Dayton Power and Light's Energy Home are presented. Located in Miami County, Ohio, The Energy Home is a traditionally-styled, brick, ranch home on a slab with a total living area of 1,928 square feet. It incorporates high insulation levels (R-25 walls and R-40 ceiling), a passive solar design, an active solar water heating system, a one-line plumbing system and other energy-saving features. Data from the first 12 months of monitoring (September 1, 1981 - August 31, 1982) indicates most items have worked as well as, or better than predicted, but a few have had some unexpected negative results. Graphs of The Home's hourly energy use during DP&L's system peak day in 1982 are shown. Information from the two families that occupied The Home demonstrates the impact lifestyle has on energy consumption and utility system load, especially in the workings of a passive solar home.

1. INTRODUCTION

This report presents the results from one year of monitoring The Dayton Power and Light Company's Energy Home. The Energy Home is located near Tipp City, Ohio, at 7765 Winding Way South. Construction began in February 1981, and was completed in June 1981.

The Energy Home is a traditionally-styled brick ranch house with a total living area of 1928 square feet. It incorporates high insulation levels, an assortment of energy-saving features and a passive solar design to form an attractive energy-efficient home. In addition, The Energy Home has an active solar water heating system.

One of the main objectives of this project has been to determine how well the actual usage of certain energy-saving devices, appliances and construction techniques compares to their performance claims. Information from the first 12 months of monitoring (September 1, 1981 - August 31, 1982) indicates most items have worked as well as or better than predicted, but a few have had some unexpected negative results.

Specifically, The Energy Home's insulation provided the biggest energy savings and proved to be the best investment. This was followed closely by the home's passive solar design and next by its high efficiency gas furnace. These findings were as expected. The surprises were the solar water heater pump and the furnace fan; both used more energy than was initially estimated.

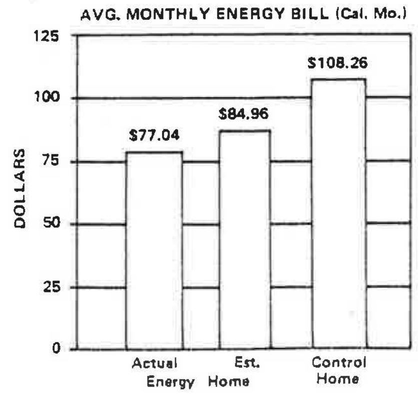

Figure 1: The Energy Home's average calendar month bill for the 12 month study period.

On the whole, The Energy Home's heating systems performed better than expected, especially considering the combination of 7% more heating degree