TESTING OF AIR-FLOW WINDOWS FOR EVALUATION AND APPLICATION

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ABSTRACT

A description is given of how the performance of air-flow windows was assessed in comparison to a conventional window of good current design. Tests were performed in the University Building Environment and Energy Laboratory which allowed tests quite representative of actual application conditions in a variety of vertical orientations. The "actual application condition" requirement necessitated some approximations to the energy measurements which are not found in guarded hot box or calorimeter kinds of approaches to performance evaluations. The testing technique and required approximations are described. A possible type of solar-residential application is also described briefly.

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A description is given of how the performance of air-flow windows was assessed in comparison to a conventional window of good current design. Tests were performed in the University Building Environment and Energy Laboratory which allowed tests quite representative of actual application conditions in a variety of vertical orientations. The "actual application condition" requirement necessitated some approximations to the energy measurements which are not found in guarded hot box or calorimeter kinds of approaches to performance evaluations. The testing technique and required approximations are described. A possible type of solar-residential application is also described briefly.

NOMENCLATURE

A = Area of window
AF = Air flow correction factor
c_p = Specific heat
f = Function given in Figure 10
h = Heat transfer coefficient
H = See Equations 4 and 5
I = Insolation
$\dot{m}$ = Mass flow rate
q = Heat transfer
RB = See Equation 4
SD = See Equation 4
T = Temperature
U = Overall heat transfer coefficient

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Subscripts

A = Heat flow required with air, across window
B = Heat flow required for make up air exhaust window
eff = Effective
ex = Exhaust
F = From window to room
in = In
o = Outside, vertical
RET = Return
w_{in} = Inside pane
∞ = Outside ambient
1 = From window to room
2 = From window to air flow

INTRODUCTION

a) Description of Operation

The air flow window is an arrangement of a double glazing on the outside, a space through which the air flows and which contains a venetian-type blind, and a single glazing on the inside. Hence it is a triple glazed window with air flow over an enclosed blind.

Air flow can be a variety of modes depending upon the design of the window. For example, commercial designs involve either flow upward or flow downward. In addition, the air can be exhausted to the outside ("exhaust-air window") or it can be returned to the central conditioning system ("return-air window"). Most commercial air flow windows, almost all of these are found in Europe, are of the return-air type with air flow upward.

In order to understand the thermal behavior of the air-flow window, it is helpful to consider the three major environmental conditions to which the windows are exposed: (1) Nightime or overcast skies during daytime, both at low outside temperatures; (2) Daytime with sunshine at low outside temperatures; (3) Time with or without sunshine at high outside temperatures.

1. During nighttime or during daytime with overcast skies at low outside temperatures, warm space

air flows through the window cavity and is discarded directly to the outside in the case of exhaust-air windows, or in the case of return-air windows, the air is returned to the central HVAC apparatus for discharge or reheating. The influence of solar radiation under overcast skies is generally small.

The transmission heat loss from the space to the window is less than for conventional triple glazing as the exhaust air stream gives off some of its heat while flowing through the cavity, resulting in increased temperatures of the inside window surface. The comfort conditions in the space are improved because of higher mean radiant temperatures.

Changes in the air flow through the cavity vary the heat transmission. Heat transmission coefficients as expressed in U-values for conventional windows are not applicable. The energy transfer between the space and the window cavity across the inner glass pane is therefore called the effective U-value (U_{eff}). The energy which is transferred through the inner pane of glass joins the energy carried in the air flowing through the cavity. The energy flow to the outside is a function of the temperature difference between this air and the outside and the air velocity. Figures 1 and 2 show the basic heat flow (outflow from the space is negative).

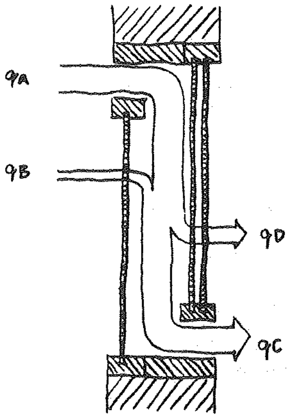

Figure 1. Exhaust-Air Window - Heat loss condition during cold nights or during cold cloudy days.

The energy balance of the window becomes increasingly negative with increasing air flow. The reduction in the amount of heat transmitted through the inner window pane is less than the heat content of the air which is discarded to the outside by the exhaust-air window. This reduction of heat transmission is also less than the energy loss in the cavity as indicated by the temperature drop between the space air and the returned air of the return-air window.

2. During daytime with sunshine at low outside temperatures, the warm space air flows through the window cavity and is influenced by solar radiation primarily through the secondary reaction of the glass and window frame being heated by radiation. Refer to Figures 3 and 4 (heat loss condition) and Figures 5 and 6 (heat gain condition).

Heat transmission through the system because of the inside/outside temperature difference is strongly counteracted by shading devices located in the window cavity which act as solar absorbers in the air stream. Windows which have no direct solar radiation exposure operate under conditions similar to those described for fully overcast, daytime skies.

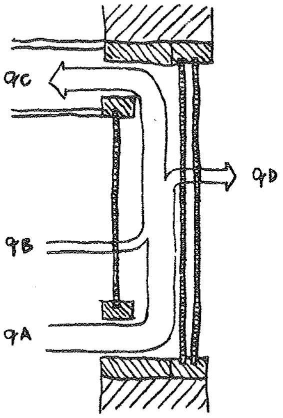

Figure 2. Return-Air Window - Heat loss condition during cold nights or during cold cloudy days.

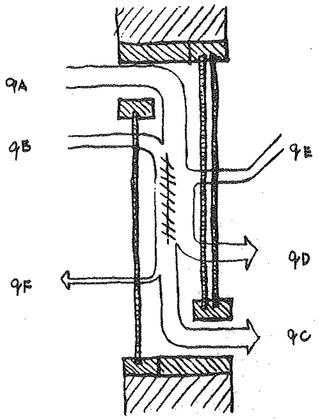

Figure 3. Exhaust-Air Window - Heat loss condition during cold sunny days.

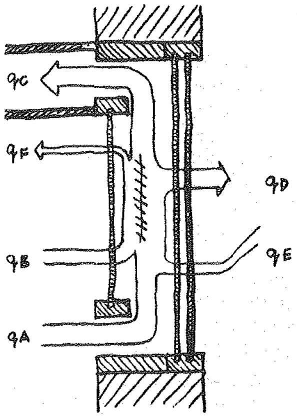

Figure 4. Return-Air Window - Heat loss condition during cold sunny days.

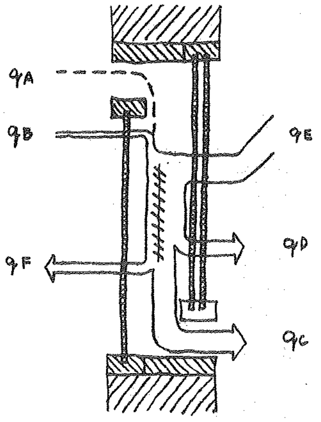

Figure 5. Exhaust-Air Window - Heat gain condition during cold sunny days.

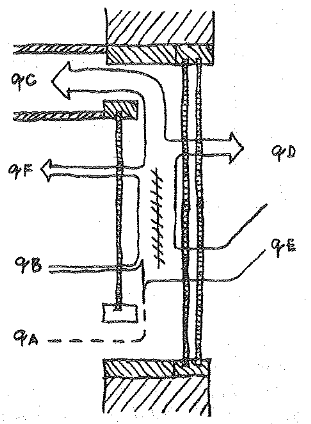

Figure 6. Return-Air Window - Heat gain condition during cold sunny days.

Sun angles at clear winter day conditions are typically low and considerable heating through south-facing windows can occur. A shading device in the window cavity can control this heating. It can block or redirect solar radiation to thermal storage areas and may enhance daylight conditions. The shading device can diffuse daylight and/or direct it deeper into the space.

3. During times with or without sunshine at high outside temperatures, the thermal behavior of air-flow windows is similar to the just-described conditions of positive energy balance, but with positive flow components only. Heat is generally not needed in any part of the building and is not desired for storage.

If the energy pick-up in the space is close to or more than the cooling capacity at minimum fresh air requirements (including internal heat gains), then the exhaust-air window is more energy efficient than the return-air window (Figures 7 and 8). All or nearly all of the air from the interior spaces is dumped to the outside. This is also true for air-flow requirements which are considerably larger than the minimum, as energy recovery in cooling systems is not efficient at small temperature differences.

Virtually all of these windows in existence have been applied to office buildings in Europe. Only recently has their application in the United States occurred. Needless to say, these windows involve a premium first cost compared to the typical single or double glazed windows used here in commercial projects. The air flow window's possible performance benefits over its conventional counterparts have yet to be demonstrated. Also, there are several possible variations on the basic air-flow design that may be appropriate for sun-tempering (passive/active) residential solar applications.

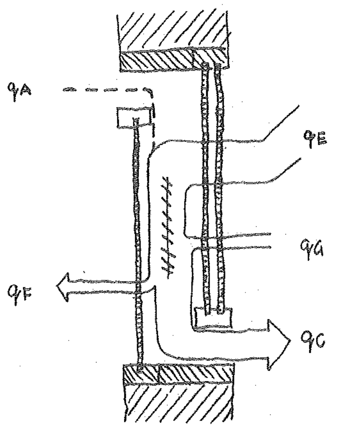

Figure 7. Exhaust-Air Window - Heat gain condition during warm sunny days.

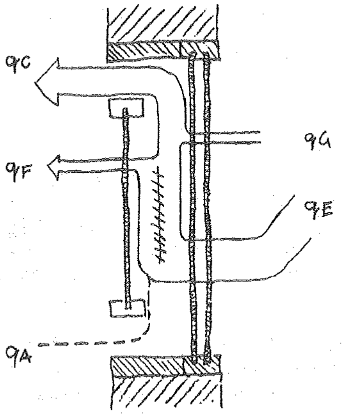

Figure 8. Return-Air Window - Heat gain condition during warm sunny days.

b) Previous Performance Studies

Studies in the open literature of the air-flow window are quite limited. One of the most quantitative is a Swedish investigation of basic performance information (1)* Results from a two-year study were reported, including heat transfer, glazing temperatures, transmitted solar energy and air velocity information. Comparisons to more conventional systems were mentioned, but not specifically delineated. A qualitative evaluation of the cooling function of exhaust air windows has been given by Chapman (2).

One of the few studies of the comparison between exhaust air windows with conventional windows in the open literature was performed by a Finnish firm,

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* Refers to literature cited in References section.

Ekono (3). Details of application in one of the company's office buildings were given, as was some performance information. Yearly heating savings for the use of their windows, compared to 2-pane windows with venetian blinds between the panes, ranged from almost 30% with 100% recirculation, to about 10% with no recirculation. Sufficient details were not included to generalize these results to other locations and climates.

c) The Present Work

In mid-1979 the University of Utah entered into a contract with Lawrence Berkeley Laboratory to evaluate the air-flow window concept. A basic aspect of this program has been the side-by-side comparison of various air-flow windows with a conventional double-glazed window with thermal break frame and conventional venetian blinds inside. Both types of windows have been operated simultaneously while energy flows have been inferred from various measurements. This paper gives a description of this program and the testing details. As a final aspect, the application of these types of windows to a HUD-solar-initiative house (not part of the Lawrence Berkeley Laboratory program) is touched upon.

EXPERIMENTAL PROCEDURE

a) BEE Lab

A key dimension to the testing program is a unique facility at the University called the Building Environment and Energy Laboratory (BEE Lab.) This facility, actually a test rig, is a 20 ft x 20 ft x 10 ft high (6.1 m x 6.1 m x 3.05 m high) steel frame box elevated from the ground approximately 3 ft (1 m) on a rotatable crane base. Rotation of the BEE Lab on its base allows for easy changes of up to 360° of orientation.

The bulk of the thermal envelope of the BEE Lab consists of polyurethane panels 6 in (15.24 cm) thick, with a 12 in (30.48 cm) thick glass fiber insulated floor. The polyurethane panels are attached by a bolt/clip arrangement so that they can easily be rearranged for evaluation of virtually any kind of components pertinent to a building's skin. A double-doored entry way is used to cut down on infiltration losses.

The evaluation of the air-flow window involved the installation of one of these windows adjacent to a conventional double-glazed, thermal-break-frame window. A photograph of this arrangement is shown in Figure 9.

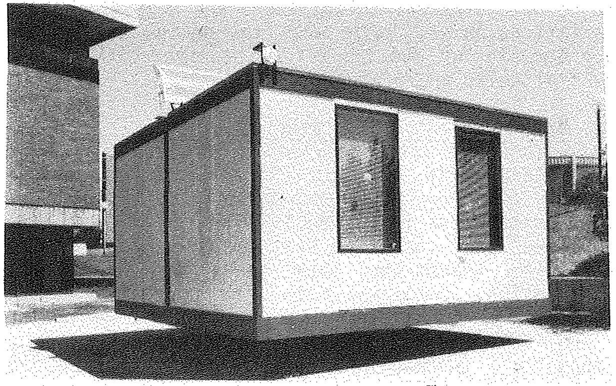

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Figure 9. Photograph of BEE Lab showing reference window (left) and flow window (right).

b) Air-Flow Window Evaluation Technique

Testing of the air-flow window was accomplished with air being forced through the air-flow window from a small centrifugal blower. See Figure 10.

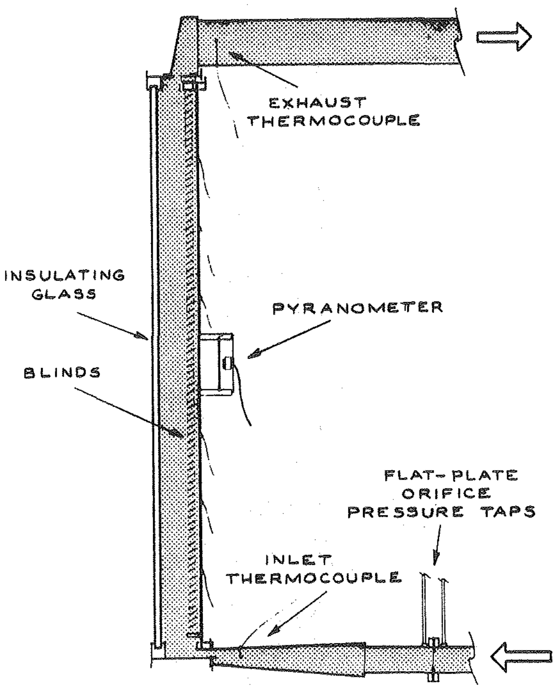

Figure 10. Return Air Window

Air flow was measured with an ASME standard orifice with pressure drop being monitored on a draft gage. Variations in air flow, when desired, were accomplished by an adjustable by-pass following the blower but prior to the orifice. Temperatures were measured at a variety of locations along the air flow path, over the window surface, and in the room and outside. Incident solar flux was measured in the vertical plane with an Eppley model PSP pyranometer. Transmitted solar flux in the vertical plane was measured on the inner pane of the window with a Lycor pyranometer. Because of the non-uniform transmitted radiation pattern due to some settings of the blinds, a translucent diffuser plate was mounted between the glass and the pyranometer, removed from the glass approximately 1 in (2.54 cm). This arrangement was calibrated with the Eppley pyranometer both with and without the diffuser.

Heat flows through each air-flow window were assessed in the following ways. The sensible heat carried with the flow was easily inferred as follows:

$$q_A = |\dot{m}\, c_p\, (T_{in} - T_{ex})| \qquad (1)$$

All of the quantities on the right hand side of equation 1 were measured and logged on time periods varying from 5 minutes to 20 minutes.

How this quantity is interpreted in the energy performance evaluation of the window depends upon the flow type of the window and its operational mode. For example, consider a return air window where 100% of the flow air is returned to the space. In this case, the energy quantity represented by Equation 1 must be added or removed by the HVAC system.

A totally different situation exists for exhaust air operation. If all of the air circulated through the window is dumped to the ambient, a like quantity of ambient air must be conditioned and returned to the space. In this situation, the associated energy quantity is:

$$q_B = |\dot{m}\, c_p\, (T_{in} - T_\infty)| \qquad (2)$$

The energy quantities represented by Equations 1 and 2 depend at least implicitly on the insolation and the overall temperature difference. Examination of these two equations can give some insight into performance of the two types of windows in a variety of operating conditions. Windows of the return-air type where a portion of the air is exhausted will demonstrate a proportion of each of the two energy flow quantities shown above.

Solar energy transmitted directly through the window assembly as short wave length radiation was measured by the Lycor pyranometer. Incident solar energy in almost the same plane was inferred from the Eppley measurement. A transmissivity for the window was easily formed from these two measurements.

Measurement of the combined re-emitted radiation and natural convection from the inside of the window to the room caused considerable problems. Several approaches were attempted and rejected, including the use of a heat flux transducer (heat flows were too low for devices of this type that were available) and an insulated flow box mounted over the window (too much thermal inertia relative to the heat flows here, but see more on this approach in the discussion on the reference window testing). A method was finally adopted where calculations of the radiation and natural convection were used as a function of temperature difference, the latter being between the inner window pane and the room. In particular Newton's Law of Cooling is used

$$q_F = h\, A\, (T_{W_{in}} - T_{in}) \qquad (2)$$

where

$$h = f\, (T_{W_{in}} - T_{in}) \qquad (3)$$

and is shown graphically in Figure 11.

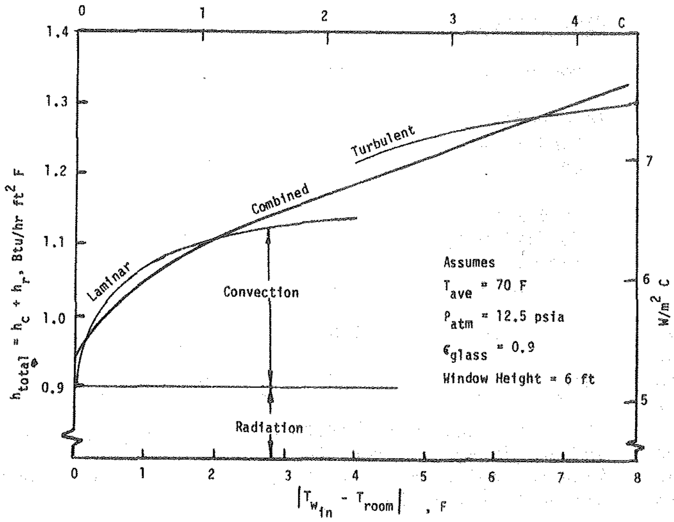

Figure 11. Combined heat transfer correlation used for exchange between inside pane of flow windows and room.

By other approximate means of estimating this heat flow, it was determined that this was reasonably accurate. It is a relatively small overall contribution to the total heat flow in most operating conditions. Its greatest absolute error is found at small temperature differences and is due to inaccuracies in the temperature measurement.

Great concern was held for the accuracy of the use of a thermocouple to measure the glass surface temperature, particularly in periods of high incident solar flux. However, thermocouples were used and were affixed with small amounts of transparent glue. Temperatures registered from this type of installation were checked periodically with a Barnes Instatherm infrared temperature indicator, with very good engineering accuracy.

Temperatures were measured at several locations on the inner pane of the windows and in the room. As would be anticipated, some variation with location was found in each of these groups of measurement. Considerable effort was expended to determine the most reasonable spatial averaging of the various readings.

When the matrix of testing conditions was defined, it was necessary to consider that more than one flow window was to be tested under a variety of weather conditions and orientations. Hence it was not possible to define long term performance on the basis of long term actual data. For this reason it was decided to characterize the flow window parametrically, and then simulate long-term performance with a computer model. The parameters were chosen to be general, somewhat akin to the overall heat transfer coefficient and shading coefficient used to characterize common windows. The basis of the parameters chosen, and their values for particular flow windows, is the subject of another paper (4). However, the form used is as given in Equation 4.

$$q_W = A[(I_o \times RB) + (H_1 \times SD_D \times AF_D) + U_1 \times (T_\infty - T_{in}) \times SD_N \times AF_N] \qquad (4)$$

where A = area of flow window
I_o = solar irradiation of window surface
RB = reduction factor for irradiation related to radiation barrier (shading device)
H_1 = secondary reaction energy flow at daytime, caused by solar radiation and resulting from absorption and re-radiation of glass (if $I_o = 0$ then $H_1 = 0$)
SD_D = correction factor for H_1 related to blinds at daytime and at constant air flow
AF_D = correction factor for H_1 related to air flow at daytime and at constant blind setting
U_1 = U value for nighttime at no air flow and open blind condition
SD_N = correction factor for U_1 related to blinds at nighttime and at constant air flow
AF_N = correction factor for U_1 related to air flow at nighttime and at constant blind setting

This equation relates to the heat flow through the window assembly into the room. It holds equally well for exhaust-air or return-air windows.

A second energy quantity required to describe the flow window performance is the sensible and latent heat transport. A form like Equation 2, but incorporating the latent contribution also, must be used.

Clearly, the percentage of the air recirculated is very important here.

For return air windows, the energy added to or removed from the air stream must be considered. This is treated similarly to Equation 4, and is given by Equation 5.

$$q_{RET} = A[U_2 \times (T_\infty - T_{in}) + H_2 \times I_o] \qquad (5)$$

Each of these parameters can be isolated from the measurements discussed earlier. Using these values and actual weather conditions, the energy impact of any flow window can be estimated for any location.

c) Reference Window Evaluation Technique

Initially, heat flow through the reference window was evaluated by some similar techniques as those described for the flow windows. In particular, the measured solar transmittance as well as the combined long wavelength radiation and natural convection from the inside pane to the space could be determined as noted above.

Because of the use of interior venetian blinds, a totally different approach was required in evaluating energy flows through the reference window. For this situation, an insulated air flow box was built over the window (see Figure 12). Air was forced downward through the box at low velocities to simulate a room-type environment. Heat transfer through the window translates itself as a sensible heat flow to the air. There is a tradeoff here between error in not representing room conditions accurately because of too high an air flow, and errors in possibly too high an average box temperature (periods of high heat gain) or too low an average box temperature (periods of high heat loss) at very low air flows. At any rate, an equation of the form of Equation 1 is used to infer the heat flow through the glass. Corrections were also made for heat transfer through the polystyrene-insulated-plywood box. This latter correction was relatively small.

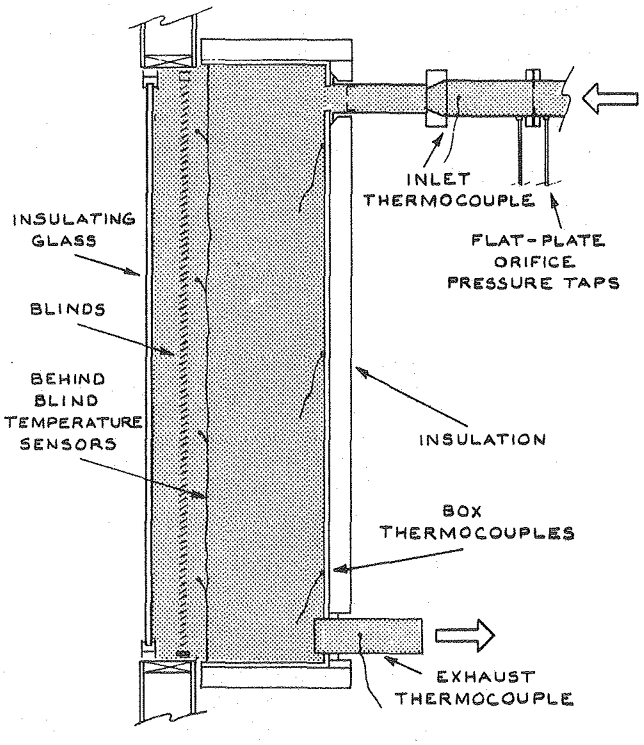

Figure 12. Reference Window

Clearly this approach cannot distinguish between the overall heat transfer coefficient effects and the solar transmissivity effects. However, comparisons between the techniques used on the flow windows (without blinds here), the flow box technique, and traditional values of U and shading coefficients all gave agreement within ten percent. This was considered excellent for in-situ type measurements.

The blinds, which were horizontal on both windows, had to be adjusted in a realistic manner. In an actual application, blinds will probably be set not to allow direct beam sunlight into the conditioned space. For this reason, the blinds were set either open (during overcast conditions) or partially closed to block direct radiation to the space (during clear sky conditions).

RESULTS AND DISCUSSION

Some typical types of results found in this study are given in Tables 1 and 2. Shown there are the heat

Table 1
Estimated Energy Flows for July
Based on Experimental Results*
West-facing Facade
Megajoules/Month

HEAT GAINS	EXHAUST	RETURN**	REFERENCE**
Through Glass	251	251	581
Return-Air Conditioning	0	25	0
Makeup-Air Conditioning Energy			
a. Sensible	40	30	30
b. Latent	0	0	0
Total	291	306	611
HEAT LOSSES			
Through Glass	28	28	75
Return-Air Conditioning Energy	0	5	0
Makeup-Air Conditioning Energy			
a. Sensible	84	63	63
b. Latent	106	80	80
Total	218	176	218

* Based upon 40.8° latitude, Salt Lake City weather and an interior temperature of 25.6°C (78°F) and an interior relative humidity of 30%. Air flow windows assume 4 cfm/ft width (0.37 m^3/min/m width).

** Assume fresh air makeup of 75% of the equivalent flow through the exhaust air window.

Table 2

Estimated Energy Flows for January
Based on Experimental Results*
South-facing Facade
Megajoules/Month

HEAT GAINS	EXHAUST	RETURN**	REFERENCE**
Through Glass	106	106	300
Return-Air Conditioning	0	11	0
Makeup-Air Conditioning			
a. Sensible	0	0	0
b. Latent	0	0	0
Total	106	117	300
HEAT LOSSES			
Through Glass	119	119	326
Return-Air Conditioning	0	21	0
Makeup-Air Conditioning			
a. Sensible	426	320	320
b. Latent	119	90	90
Total	664	550	736

* Based upon 40.8° latitude, Salt Lake City weather and an interior temperature of 20° C (68° F) and an interior relative humidity of 30%. Air-flow windows assume 4 cfm/ft width (0.37 m^3/min/m width).

** Assume fresh air makeup of 75% of the equivalent flow through the exhaust air window.

gains and heat losses (they, in general, must be considered separately) for an exhaust-air window, a return-air window and a reference (2 glazing with venetian blind) window. Accumulative totals for a south-facing facade in January and for a west-facing facade in July are shown. All data pertains to a representative weather pattern for Salt Lake City, Utah. Where flow windows are considered, the flow rate is taken as 4 cfm/ft width (0.37 m^3/min/m width). The numbers given for both the return-air and reference windows reflect a fresh air makeup of 75% of the air flow through the exhaust-air window. The amount of fresh air makeup was arbitrarily chosen as 75%, and it clearly can have a wide range of values for a variety of applications. Summertime indoor conditions were normalized to 25.6°C (78°F) and 30% relative humidity. Wintertime conditions assume 20°C (68°F) and 30% relative humidity indoors. Clearly the number of variables affecting the performance evaluations is large, and only a few can be examined here. A much more extensive examination of the implications of the data is in preparation (4).

Minimization of HVAC energy in summertime operations for facades facing the sun clearly favor the air flow windows over the reference window. This result can be readily generalized to other climates where summer air conditioning loads play an important role. The relatively high heat losses shown in Table 1 result from the 78°F (25.6°C) assumed. In practical applications the temperature would be allowed to float downward in periods of heat loss.

What is somewhat less obvious is the minimization of wintertime heating loads by the air-flow windows (see Table 2). While the reference and return-air windows' performance is heavily impacted by the amount of makeup air used, the trends still indicate the flow windows' superior performance.

During the change-over seasons (spring and autumn), the situation becomes very complex with the preliminary results from the flow windows not indicating a clear-cut better performer. Studies for specific climates will probably reach different conclusions (4). (See more discussion on this below.)

There are basic performance differences between the three types of windows evaluated (exhaust-air and return-air flow windows and the reference window). It is clear that the flow windows require less HVAC energy than does the reference window. In making this comment, it should also be noted that the flow windows evaluated are triple-glazed, compared to double glazed conventional windows, and this fact alone should make some performance improvement due to more glazings. In addition, there appears to be a premium capital cost associated with the flow windows not due solely to the additional glazing. Hence, at this point, total cost benefit ratios are not known.

What is obvious as a result of this testing program is that simply side-by-side test data are not enough to really evaluate which window is the most desirable investment. For a given application, computer simulations should be used to model various kinds of windows and their possible operational modes (blind settings, air flows and percent of air recirculated). The natural lighting furnished by the windows and the reduction of the aritifical lighting required should also be included.

We are in the midst of generalizing our data so that it can be used in a variety of climates and orientations. When this is completed the designer will be able to incorporate this information into computer simulations for building energy performance estimation.

A RESIDENTIAL APPLICATION

In 1979 a local developer/builder, Prowswood Corportion, received a HUD grant for incorporating the flow window concept into a tract-type residence. While a detailed summary of the design of this building is given elsewhere (5), a brief description here may be of interest.

A design typical of those used by the developer/builder but to be built on the north side of the street was taken as a starting point. The building was redesigned only in minor ways into what is termed a sun-tempering concept. Window sizes on the north, east and west facades were minimized. Window sizes on the south were enlarged. The design used return-air windows on this facade. Ceiling air ducts with blowers and duct heaters (for temperature boost when needed) were incorporated in the structure. The air ducts span the house south to north were the air can be blown into a storage wall made of conventional concrete block. Actually the air flow control (on-off-into north room-into storage wall) is functioned by a controller/damper arrangement. A picture of the south facade of the house is shown in Figure 13.

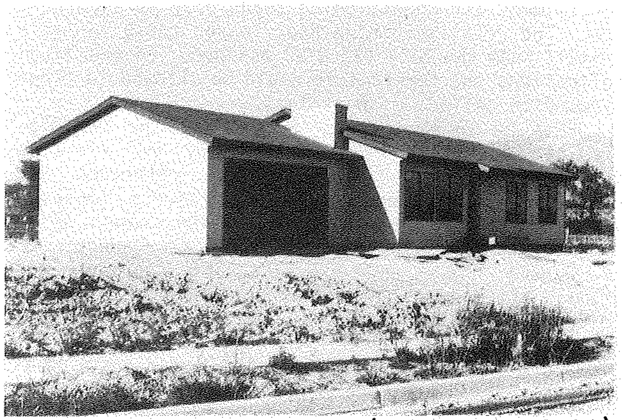

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Figure 13. South facade of Prowswood/HUD house incorporating return-air windows and sun tempering system.

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ACKNOWLEDGEMENTS

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