

HEAT TRANSFER ASSESSMENT OF STRAW BALE WALLED ROOM

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ABSTRACT

This research work explores the thermal performance of straw bale walled building (of $0.14 \text{ W/m}^2\text{K}$) in holistic sense, with concepts that determine: the interrelation of internal and external heat gain and loss, building envelope performance, the thermal demand of occupant and the balance point. The calculation result has shown that an outdoor temperature of 17°C will balance the internal heat gain to produce a comfortable temperature of 24.5°C inside the room. Considering the solar heat gain of 78.2 W/m^2 at the wall surface area, the amount of balance point required has shown the insulation efficiency of the strawbale masonry with a constant temperature inside the room with time variation.

INTRODUCTION

Straw is one of the finest, renewable building materials available and it's found in abundance around the world. It is a strong stalk of tall grain plants-such as wheat, maize, rice, hemp-that remains in the field after the seed grains have been harvested. Its chemical composition is primarily cellulose, just like trees. Straw in its natural form is shown in Figure 1. When bailed together into a bale it becomes a solid block that is highly resistant to decomposition.



Figure1. Straw in its natural form.

When assembled together and covered with a plaster skin, straw bale makes a beautiful, strong, energy efficient and ecologically sound house [1, 2]. There are two types of straw bale walls, the load bearing walls, where the bales support load of the roof and the other is the non-load bearing walls, where a frame supports the roof and the bales are filled. The wall are made by covering the bales with two or three coat of mixture that consist of cementing material, inert fine aggregates and water. Energy flow out of or into a building is driven by the difference between the building temperature and the outdoor ambient temperature. The rate of heat flow across the building enclosure is also proportional to the thermal quality of the building enclosure. Occupancy results in building heat gains due to both occupant metabolism and electric consumption in lights and equipment. Solar energy also adds heat to the building, primarily via glazing transmittance, but also by conduction through the building enclosure when solar energy is absorbed on the enclosure surface. The balance point temperature is a measure of the conditions required to balance heat entering the building with heat leaving the building in the absence of mechanical heating or cooling. It is defined as the ambient (or outdoor) air temperature which causes building heat transfer across the enclosure to balance building heat gains at the desired interior temperature (assumed to be the thermostat setting). The definition of the building balance point, T_{balance} , is given [3] mathematically as:

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Heat Transfer Assessment of Straw Bale Walled Room

$$T_{\text{balance}} = T_{\text{thermostat}} - \frac{Q_{\text{IHG}} + Q_{\text{SOL}}}{\dot{U}_{\text{bldg}}} \quad (1)$$

where $T_{\text{thermostat}}$ = the building thermostat setting. Q_{IHG} = the building internal heat generation rate due to occupancy and given per unit floor area, Q_{SOL} = the rate of solar heat gain to the building given per floor area, $\dot{U}_{\text{bldg}}$ = the rate of heat transfer across the building enclosure per degree temperature difference, also given per unit floor area. The balance point temperature is defined as the building thermostat temperature minus the ratio of total building heat gains divided by the rate of heat transfer across the building enclosure. The elements of the balance point are not constant Q_{IHG} changes with the occupancy schedule and Q_{SOL} changes with time of day and time of year. Even $\dot{U}_{\text{bldg}}$ can vary due to variation of the building fresh air ventilation rate. This project was undertaken to assess the rate of heat transfer in straw bale walled room, when openings are closed using the Balance Point Analysis. The specific objectives of this project work include: 1) To provide a quick order of magnitude estimate of building balance point, 2) To establish energy flow pattern through straw bale building and 3) To provide clues for appropriate energy conscious building design strategies. The scope of this project work is to access the rate of heat transferred across a straw bale walls when openings are closed. The building balance point temperature is an indicator of the relationship between the various thermal forces at play within a building, the heat generated by building occupancy, the heat of the sun entering the building, and the transfer of energy across the building enclosure due to the difference in temperature between building and environment. It is a measure of the dynamic interplay of several variables [3]. The building balance point temperature is a powerful conceptual tool used to evaluate the energy flows between a given building and its surroundings. The building balance point can be estimated as a design variable, a function of building design and program, as shown in Fig. 2. [3].

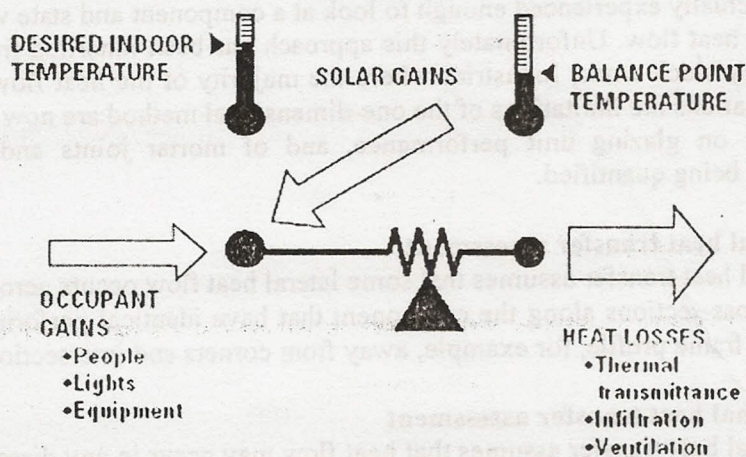


Figure 2. The Building Balance Point flow diagram

However, it can not be measured directly in the field. All building energy flows must be measured or estimated in the field to estimate the building balance point temperature.

The Structure of the Bales

There exists a misconception that straw and hay are similar substances and that both are suitable for bale buildings. It is important to acknowledge that this is not the case. Hay is for horses, and is full of grain and nutrition. Straw is the plant structure between the root crown and the grain head, and can be from just about any grass root that grows, although agricultural grains are by far the most typical for building. Straw for bale walls can come from rice, barley, wheat, maize, and rye. Straw lasts longer than hay as it is tough and fibrous and hay is leafy and easily eaten by creatures. According to the ASHRAE [4], straw is a viable building alternative, plentiful and inexpensive". It is grown annually and is a renewable resource. Straw Bales come in different shapes and sizes. The two most common bales being small two string bales and larger three string bales. The rectangular three string bales are preferred for building because they are more compact, and better structurally, and have a higher a U-value (i.e. they are more effective insulators). Typical, medium sized three-string bales might measure 500mm by 400mm by 1100mm and can weigh between 21 and 23 kg. The smaller two string bales are usually 460mm by 360mm by 950mm and have a mass of 18 kg [4]. See Figure 3.

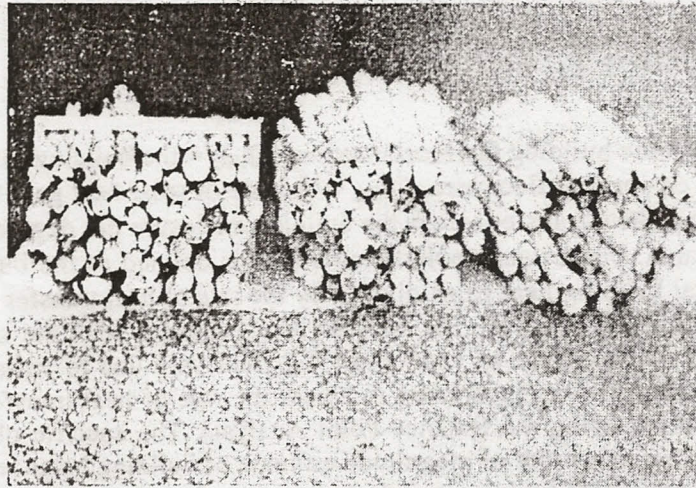


Fig. 3 Straw bales

According to [5], bales are easily modified to any shape or size. If the ties are cut the bale will fall apart, so it must be resized and tied again before use [5].

One-dimensional heat transfer assessment

One dimensional heat transfer assumes that heat flows in a straight line, from the warm side of a component to the cold side, and perpendicular to the plane of the component. This is typical of heat flow through a pane of single glazing. One-dimensional heat transfer is usually calculated by hand (using analytical formulae) or assessed by measurement. However, although based on the assumption that heat transfer is one-dimensional few people are actually experienced enough to look at a component and state whether it will truly experience one-dimensional heat flow. Unfortunately this approach has been inherited from the glazing and traditional wall (i.e. masonry/block work) industries where the majority of the heat flow is one-dimensional. In those traditional applications the limitations of the one-dimensional method are now being realized, as the effect of the edge spacer on glazing unit performance, and of mortar joints and wall ties on masonry wall performance, are being quantified.

Two-dimensional heat transfer assessment

Two-dimensional heat transfer assumes that some lateral heat flow occurs across the plane, but that there is a set of parallel cross-sections along the component that have identical performance. This might apply to an extruded glazing frame profile, for example, away from corners and intersections.

Three-dimensional heat transfer assessment

Three-dimensional heat transfer assumes that heat flow may occur in any direction. An example would be at an intersection between two or more framing components. Three-dimensional heat transfer assessment can be performed by a very detailed form of a hand calculation procedure, by simulation or by measurement.

BUILDING HEAT TRANSFER RATE

Internal heat and solar heat gains represent the primary paths for heat entry into buildings; heat transfer across the enclosure represents the primary potential for building heat loss. Heat flows between the building and surrounding environment by two major paths: conduction across the building enclosure and bulk air exchange via ventilation or infiltration. The rate of heat flow via either path is proportional to the temperature difference between building and environment. When the environment is hotter than the building, heat flows into the building and the only sources of heat loss are heat flow to the ground and through mechanical air-conditioning. Heat transfer across the building enclosure is a function of both the surface area of all enclosure components and their respective thermal conductance. There are five separate paths for heat transfer across the building enclosure: the roof, opaque walls, glazing, ground and ventilation. The roof, walls and glazing each have exposed area and thermal qualities based on the materials of composition. Heat transfer through the ground occurs primarily along the building perimeter. Heat transfer via ventilation depends on the rate of flow between the building and the environment. Heat transfer rates vary widely from a building to another due to size, exposed surface area, use and many other factors. Therefore, all the total separate path of heat transfer coefficient is estimated as:

Heat Transfer Assessment of Straw Bale Walled Room

$$\dot{U}_{\text{bldg}} = \dot{U}_{\text{wall}} + \dot{U}_{\text{roof}} + \dot{U}_{\text{glzg}} + \dot{U}_{\text{grnd}} + \dot{U}_{\text{vent}} \quad (2)$$

where: $\hat{U}_{\text{wall}}$ = wall heat transmission coefficient, $\hat{U}_{\text{roof}}$ = roof heat transmission coefficient, $\hat{U}_{\text{glzg}}$ = the glazing heat transmission coefficient, $\hat{U}_{\text{grnd}}$ = ground heat transmission coefficient and $\hat{U}_{\text{vent}}$ = heat transmission coefficient by ventilation.

Heat Transfer Rate through the Building Walls

Heat transfer rate through opaque walls is equal to the product of the wall area, A_w , and the wall heat transmission coefficient, U_{WALL} . To allow comparison of different sized of buildings, the heat transfer rate through the walls is divided by the floor area. The sum of heat transfer rate through opaque building walls per unit floor areas is expressed mathematically as,

$$U_{\text{WALL}} = U_{\text{WALL}1} \frac{A_{w1}}{A_w} + U_{\text{WALL}2} \frac{A_{w2}}{A_w} + \dots + U_{\text{WALL}n} \frac{A_{wn}}{A_w} \quad (3)$$

where each construction type has an associated wall area, $A_{w1...n}$ and heat transmission coefficient, $U_{\text{WALL}1...n}$. The influence of each construction type on the average heat transmission coefficient is dependant on the percentage of its area to the total opaque wall area, A_w . When the percentage of a given wall construction's area is low (under 5%, its effect can often be neglected to save the calculation time at little loss of accuracy.

Heat Transfer Rate through the Building Roof

Heat transfer rate through the building roof is equal to the product of the roof area A_r and the roof heat transmission coefficient U_{ROOF} divided by the floor area A_f , and is expressed mathematically as,

$$\dot{U}_{\text{roof}} = \frac{U_{\text{ROOF}} A_r}{A_f} \quad (4)$$

The procedure to estimate $\hat{U}_{\text{roof}}$ is similar to the procedure used to estimate $\hat{U}_{\text{wall}}$. A_r , the total roof area can be estimated in the field or from the drawings (as in the case of this work). U_{ROOF} is estimated from the site visit or the drawings (as in the case of this work). U_{ROOF} like U_{WALL} [6] will range between 0 and 5.678 W/(m²K) (0 and 1 Btu/Hr/°F/SF). (Note that 1 W = 3.42 Btu/Hr)

Heat Transfer Rate through the Building Glazing

Heat transfer rate through the building glazing is expressed mathematically as,

$$\dot{U}_{\text{glzg}} = \frac{U_{\text{GLZG}} A_g}{A_f} \quad (5)$$

where A_g = which is the total glazing area can be estimated in the field or from the drawings.. The procedure to estimate $\hat{U}_{\text{glzg}}$ is similar to the procedures used to estimate $\hat{U}_{\text{wall}}$ or $\hat{U}_{\text{roof}}$. The glazing heat transmission coefficient U_{GLZG} , depends on the glazing and frame of the openings construction.

Heat Transfer Rate through the Ground

Buildings transfer energy with the environment through the ground. The energy transfer occurs along the building perimeter. The rate of heat transfer can be estimated per unit area of wall below the ground. However, this rate will vary with depth below ground. Thus a characterization of the heat transmission rate per unit building perimeter will be the heat transfer rate from the building through the ground to the environment is equal to the product of the building perimeter in contact with the ground, perimeter. As in the estimate of $\hat{U}_{\text{wall}}$, the heat transfer rate through the ground is divided by the floor area giving. The heat transfer rate through the ground at the building perimeter $\hat{U}_{\text{grnd}}$, is expressed mathematically as,

$$U_{\text{grnd}} = \frac{U_{\text{GRND}} \text{Perimeter}}{A_f} \quad (6)$$

where U_{GRND} = the rate of heat flow through the ground per perimeter for a given building.

Heat Transfer Rate via Ventilation or Infiltration

Ventilation (controlled transfer of air between building and environment) and infiltration (uncontrolled transfer of air between building and environment) transfer energy between building and environment through the exchange of air. Infiltration can have a large impact on the total heat transfer rate of a small building such as a house, but has little impact on large structures. Ventilation can have a large impact on the total heat transfer rate on buildings of any size, and becomes a significant portion of the total building heat transfer rate in large commercial, educational and institutional structures. A building with an economizer cycle uses variable ventilation rates to balance building heat loss to the environment with internal and solar heat gains when the ambient air temperatures are mild. The building-ambient air exchange rates due to ventilation and/or infiltration are variable and difficult to determine from either a site visit or the drawings. For non-residential buildings, the best source of ventilation information is the building engineer. For large commercial or institutional buildings, fresh air ventilation is potentially the largest heat transfer path between building and environment. For this reason, many buildings, especially those located in very cold or very hot climates have heat recovery systems included in the total mechanical system. A heat recovery system will transfer heat between the fresh air supply and the building exhaust resulting in lower ventilation heat transfer rates between building and environment, the ventilation heat transfer rate should be corrected when a heat recovery system is present. The corrected ventilation rate is given as,

$$\dot{U}_{\text{vent,corrected}} = \dot{U}_{\text{vent}} (1 - \eta_{\text{HR}})$$

where $\dot{U}_{\text{vent}}$ = estimation heat transfer rate without heat recovery, η_{HR} = heat recovery system efficiency (between 60% and 80%, [7])

BUILDING INTERNAL HEAT GAINS

The two flow paths for building heat gains are internal heat generation due to occupancy, Q_{IHG} , and solar heat gains, Q_{SOL} . Internal heat gains are considered in this subsection while solar heat gains will be considered in the following subsection. Occupancy of buildings generates heat within the building. People give off the heat of metabolism to maintain a constant body temperature. Electric lights used during occupancy give off heat to the building equal to the electrical energy consumed in the luminaries. Equipment, computers, copiers, printers, coffee pots, etc. also give off heat to the building equal to the electrical energy they consume. The total internal heat gain rate per unit floor area, Q_{IHG} , can be estimated by,

$$Q_{\text{IHG}} = Q_{\text{people}} + Q_{\text{light}} + Q_{\text{equip}} \quad (8)$$

where Q_{people} = the heat gain from people occupying the building; Q_{light} = the heat gain from lights used in the building and Q_{equip} = the heat gain from electrical equipment used by the building occupants. All three paths for internal heat gains are given in Btu of heat added to the building per hour per square foot of floor area. These are briefly expressed in the following sections.

Building Heat Gain Rate from the Building Occupants

The building heat gain rate due to people is a function of both the heat generation rate per person and the density of people in the building. People generate heat at different rates based on their activity. An office worker is metabolizing energy at a slower rate than a ballet dancer during practice. For instance, at temperature of between 21°C to 28°C, the value of human metabolism ranges between 125 to 57 for a person sitting quietly and 290 to 78 respectively for a person walking 5km/h. (for the heat gain between 134 – 316 W, respectively) Jokl.[8] In addition to the rate of heat gain per person, the effect of the number of people in the building must be estimated. The density of people in buildings is a function of building use and can be represented by area in the building provided per person.

The building heat gain rate per unit floor area due to people, Q_{people} is expressed mathematically [7] as,

$$Q_{\text{people}} = \frac{M_{\text{people}}}{D_{\text{people}}} \quad (9)$$

where M_{people} = the metabolic heat gain per person and D_{people} = the occupant density in the building given in square metre of floor per person.

Building Heat Gain Rate from Lights

According to [7] all of the power consumed by lights is eventually dissipated as heat. The amount of heat gain from lights will depend on the type of lamp, its power rating and the number of lamps in the building:

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Building lighting levels are typically measured in watts per square metre of floor. A scale of heat gains due to lights can be obtained as in [4]. Unless the lights are turned off during a portion of the day, either manually or via day-lighting controls, the lighting heat gain during occupancy will be equal to the installed lighting power density. When day-lighting controls are employed, its effect on the building energy flows and the balance point can be estimated. For side-lighting, it is assumed that the daylight penetration is equal to twice the head height of the window. For a skylight, it is assumed that daylight illuminates the area under the skylight and a distance into the space equal to the room height. Using these two assumptions, the corrected heat gain from lights, is then estimated by[9],

$$Q_{\text{light, cor}} = Q_{\text{light}} \left(1 - \frac{f_{\text{daylight}}}{2} \right) \quad (10)$$

where Q_{light} = heat gained due to light (estimated directly from the scale ASHRAE [9]), f_{daylight} = % of total floor area lighted.

BUILDING EXTERNAL HEAT GAINS

Heat gain by Solar Energy

Solar energy enters the building through two paths. Solar gains are transmitted directly through glazing into buildings and absorbed by room surfaces and furnishings. Indirect solar gains result from solar radiation absorbed by exterior surfaces and conducted through the enclosure into the building. The sum of both entry paths for solar radiation is defined to be the building's solar heat gain. Solar gains are the primary heat gain source which the architect can control through design. Internal gains, such as caused by equipment loads, are primarily a function of building occupants. Lighting loads can be lowered with the appropriate use of new lighting technologies, but more importantly it is through the use of day-lighting that electrical lighting loads can be minimized and day-lighting is directly tied to the issue of solar control. Solar radiation levels vary not only with solar geometry, but also with clouds. Furthermore, the amount of incident solar radiation transmitted by a window will depend on both the glazing's optical characteristics and the external shading strategy. Using the building drawing the shading coefficient and area for the orientation of the glazing system is estimated. This is expressed for an hour of the period of observation per unit floor area, so that the glazing solar gain per unit area is given as[7],

$$Q_{\text{sol}} = \sum_{i=1}^n I_{\text{sol}-i} SC_i \frac{A_{\text{GLZG}-i}}{A_f} \quad (11)$$

where n = no of orientations with the glazing system, SC_i = shading coefficient (is a reduction factor to account for various ways that the amount of solar energy passing through an aperture is reduced. In other word it is taken as percentage of the available energy being transmitted and ranges between 0 – 1(acrylic polycarbonate clear). (A window with an SC of 0.7 due to external shading may have a low emissive coated glazing with Sc of 0.74 so that the aperture Sc will be 0.7×0.74) for the glazing system of orientation i . I_{sol} = average solar gain for the season and time and $A_{\text{GLZG}-i}$ = area of the glazing at orientation i .

Building Energy Gain and Loss

Degree hours provide a means of representing the temperature difference across the building enclosure of a day. In this analysis, the average ambient temperature was used as the base line data. The difference between the time that an ambient air temperature was recorded and the time the next thermostat temperature was recorded represents lack of synchronisation of the data. The offset is divided by the time step and the fraction used to linearly interpolate the thermostat temperature to its values when the ambient temperature is recorded. The degree hours of heating supply each day are expressed mathematically as,

$$DHr = \sum_{\text{day}} (T_{\text{supply}} - T_{\text{thermostat}}) + \Delta t \quad (12)$$

where T_{supply} = measured data of heating supply temperature by the solar radiation, $T_{\text{thermostat}}$ = measured thermostat temperature and Δt = time interval between temperature measurement in hours

METHODOLOGY

EXPERIMENTAL WORK

The experimental study was carried out at Ilorin, Nigeria (Lat $4^\circ 32'N$ Long $4^\circ 34'E$) which is close to the Equator and in the tropics. The weather pattern is made up of 4 months of dry season and 8 months of rainy season. The local climatic condition of Ilorin for its ambient temperature is $32^\circ C$ during dry season of month

of February at the average relative humidity of 70 % [10]. The size of the baled straw panel used to build the room specimen is 220mm x 120mm x 200mm. An example of the unit panel is shown in Figure 4.



Figure 4. A typical example of the straw bale panel

Production of Bale

The straw used were fully dried (sun dried, air-dried) and clean. It is free from debris and other leaves. The matured sorghum straw used were thick, long stemmed that is free from seed heads, A three-string bale size was chosen to stabilize the bales and they are often more compact.

Preparation of Plastering Materials

Particle size distribution of sand particles

Sieve analysis test was carried out to determine the particle size distribution of the fine aggregate used in mortar/plaster mix using sieve components in accordance to BS410. 1000g of dry fine aggregate sample was weighed to calculate the cumulative percentage passing and a grading curve plotted. Results obtained are shown in Table 1.

Table 1 Result of Sieve Analysis

Sieve size (mm)	Sieve weight (g)	Sieve weight Retained (g)	Retained weight (g)	Percentage Retained %	Cumulative percentage retained %	Cumulative percentage passing %
5	-	-	-	0	0	100
4	555	558.3	3.5	0.35	0.35	99.65
2.36	480	511.5	31.5	3.15	3.5	96.5
1	521	664.5	143.5	14.35	17.85	82.15
0.5	493	765.5	272.5	27.25	45.1	54.9
0.4	479	585	106.5	10.65	55.1	44.25
0.25	481	711	230.5	23.05	78.8	21.2
0.063	451	640.5	189.5	18.95	97.75	2.125
Recording pan	269	291.5	22.5	2.25	100	0

$$\text{Percentage retained} = \text{Weight retained} \times 100\% / \text{Total weight of sample}$$

Proportions of the ordinary Portland cement (OPC) and fine aggregate were used to specify the mortar/plaster mix. In this project, batching was made by volume. The plastering mortar was made from a mix of 1:8 (cement to sand ratio) of the average dry density of 1874.42 kg/m³ and average compressive strength of 2.81 Nmm⁻² and moisture content of 2.4%. Water was added intermittently to the batched mortar to provide sufficient workability for adequate application. The cement and sand were thoroughly mixed dry such that no trace of unmixed cement was found in the mixture before adding water and thoroughly mixed again. A sufficient amount of water was added to the mix to avoid shrinkage and distortion of the plaster on drying. The dry unit weight of strawbale were determined by recording the weight of the prism with the aid of weighing machine, The gross density is the complete dry plastered strawbale unit mass divided by its gross volume. The test measures the long-term absorption rate at which water was drawn into the plastered

Heat Transfer Assessment of Straw Bale Walled Room

strawbale through pore opening for 24 hrs. At room temperature, 3 prisms were immersed in for 24 hrs; each specimen was weighed and was completely submerged in water. The specimens were removed from water and allowed to drain for a minute and weighed after been cleaned and damped with cloth. The subsequent to saturation, the specimen were dried at $100 \pm 5^\circ\text{C}$ for 24hrs interval for increments of determined weight. Percentage of Absorption test was obtained. Moisture Contents was determined by putting the separately weighed specimen in a dry oven ($100 \pm 5^\circ\text{C}$) for 3 days. They were removed and put in desiccators, when the temperature fell below 60°C each specimen was weighed. Table 2 shows the test results.

Table 2. Tests Results for physical properties of plastered strawbale panel

S/No.	Length (mm)	Breadth (mm)	Height (mm)	Dry weight (kg)	Gross area ($\times 10^3 \text{ mm}^2$)	Gross volume ($\times 10^3 \text{ mm}^3$)	Gross density (kg/m^3)	% Absorption	% Moisture content
1	120	80	60	1.082	9.6	57.6	1878.5	13.72	2.807
2	120	80	60	1.088	9.6	57.6	1888.9	11.91	1.745
3	120	80	60	1.078	9.6	57.6	1871.5	12.25	1.587

The building basic data were obtained [11, 12], by measuring the length, breadth and height of the room via the use of measuring tape and was tabulated as shown in Table 3. Some relevant properties of materials for strawbale panel [13] roofing and floor slab on grade block wall veneer [14] are summarized in Table 4. Table shows the database of the specimen building.

Table 3. Properties of materials

Materials	Heat transfer rate ($\text{W}/(\text{m}^2\text{K})$)	Coefficient of thermal expansion $\times 10^6 (^\circ\text{C})^{-1}$	Density (kg/m^3)
Cement plastered strawbale panel	0.14*	3.1*	2200*
Corrugated iron roof cover	2.47	23.6	2710
Glazing, single pane + wooden frame	5.905	3.3	2600
Un-insulated slab on grade block wall veneer	1.120	12.3	2400

* Values obtained through test of material (Adedeji[])

Table 4. Basic data for specimen building

BASIC BUILDING DATA

Date: 21 – 28 August, 2006
 Building: Strawbale building
 Builder: Blk 8 Faculty of Engineering & Technology

BUILDING THERMOSTAT SETTING

24.5°C

BUILDING OCCUPANCY SCHEDULE/DATA

Time starting: 10 AM
 Time ending: 3 PM
 Occupant heat gain: 200 [8]
 People density D_{PPL} : 41.86 per person

BUILDING FLOOR AREA

Perimeter (L_{perm}): 5.2m
 Floor area (A_f): 2.24m²

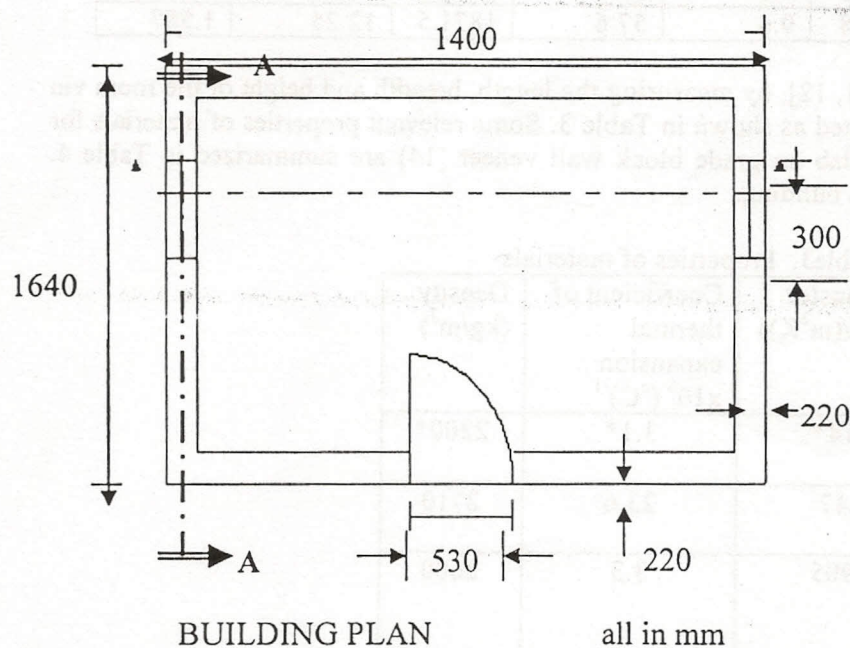
BUILDING ROOF AND

Gross roof area (A_{ROOF}): 1.848m²

HORIZONTAL GLAZING AREA

Glazing area (A_{GLZG}) in wooden frame	0.782m ²
Glazing shading coefficients (clear glass of Low-e coating) south facing window without overhang	0.70

The window of the straw bale room was closed, then Thermostats (4 nos) were placed at equal spacing inside the straw bale room, temperature readings of the room were recorded at 1 hour interval from 10 am – 3 pm for 5 consecutive days. The readings were recorded. The plan of the room is shown in Figure 5.



Hole was bored into the straw bale wall using drill bit, thermometer (3 No) were then inserted into the straw bale wall at 0.75 metres apart vertically as shown in Figure 6. Temperature variations through the straw bale wall were recorded at 1 hour interval from 10 am – 3 pm for 5 days.

Heat Transfer Assessment of Straw Bale Walled Room

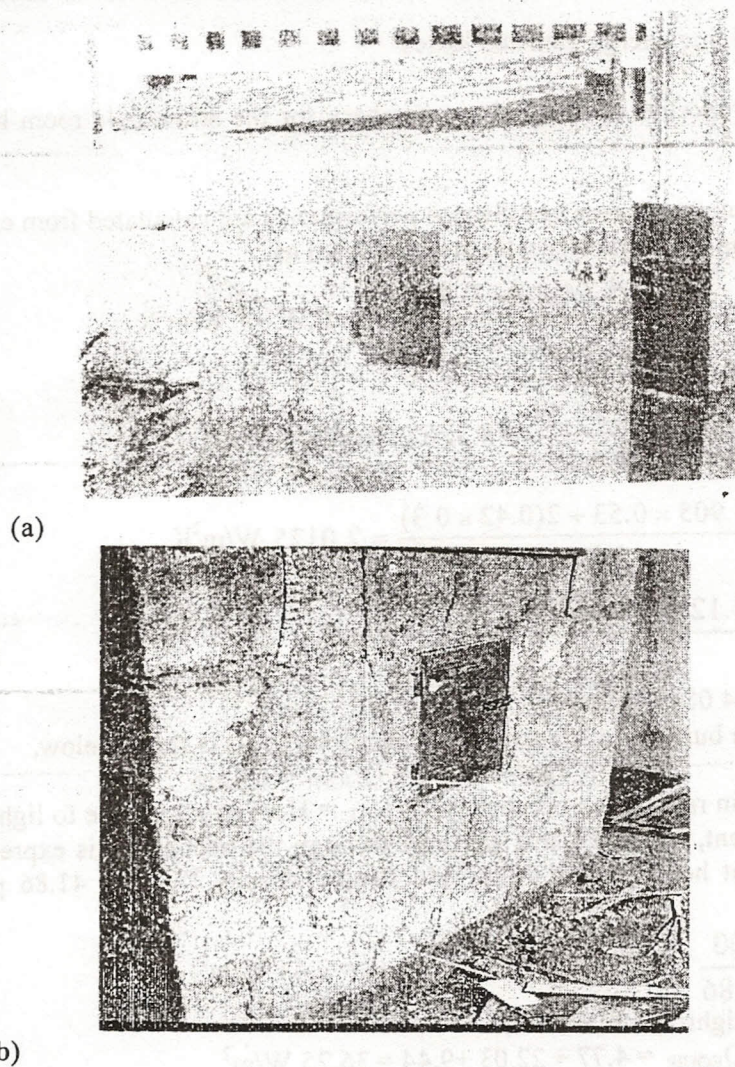


Figure 6 of straw bale walled room
(a) Model Building
(b) Temperature measurement

Table 5. shows a typical example of average of ambient, inside straw wall, inside room and centre of the room temperatures

Table 5. Typical example (Day 1) of average of ambient, inside straw wall, inside room and centre of the room temperatures

TIME (Hr)	$T_{(AMBIENT)}$ °C	$T_{(INSIDE\ BALE)}$ °C	$T_{(INSIDE\ ROOM)}$ °C	$T_{(ENCLOSED)}$ °C
10	28	24	22.7	23
11	27	24	23.33	24
12	27	24.8	22.7	24
13	26.6	24.8	22.7	24
14	26.8	24.8	22.7	24
15	29.6	25.7	30.3	24

BALANCE POINT ANALYSIS

The procedure adopted for this analysis is stated below:

- Step 1: Establishing the basic building data, floor area and enclosed area
- Step 2: Estimating the building's enclosure area and thermal performance.
- Step 3: Estimating the building's internal heat generation due to occupancy
- Step 4: Estimating the building's solar gains.
- Step 5: Estimating the building's balance point temperature.

Step 6. Evaluate the building energy gain and losses

Step 1: The building properties of materials an database for the straw bale room have been presented in Table.1 to 4.

Step 2: The building's enclosure area and thermal performance are calculated from equation (1). The area of wall excludes the opening. Heat transfer rates are calculated as:

$$\dot{U}_{WALL} = \frac{U_{wall} * A_w}{A_f} = \frac{0.14 \times (1.64 \times 1.4 - 0.3 \times 0.5)}{1.2 \times 1.4} = 0.0287 \text{ W/m}^2\text{K}$$

$$\dot{U}_{ROOF} = \frac{U_{roof} \times A_r}{A_f} = \frac{7.617 \times 1.2 \times 1.54}{1.2 \times 1.4} = 8.3767 \text{ W/m}^2\text{K}$$

$$\dot{U}_{GLZG} = \frac{U_{glzg} \times A_w}{A_f} = \frac{5.905 \times 0.53 + 2(0.42 \times 0.3)}{1.2 \times 1.4} = 2.0125 \text{ W/m}^2\text{K}$$

$$\dot{U}_{GRND} = \frac{U_{grnd} \times P_{floor}}{A_f} = \frac{1.12 \times 2(1.2 + 1.4)}{1.2 \times 1.4} = 3.667 \text{ W/m}^2\text{K}$$

Therefore, $\dot{U}_{bldg} = 14.0849 \text{ W/m}^2\text{K}$

Step 3: Estimation of the building's internal heat generation (Q_{IHG}) is stated below,

$$Q_{IHG} = Q_{PPLE} + Q_{LIGHT} + Q_{EQUIP}$$

Where: Q_{PPLE} = Heat gain rate due to occupancy, Q_{LIGHT} = Heat gain rate due to lighting and Q_{EQUIP} = Heat gain rate due to equipment, while the heat gain rate through the occupancy is expressed in equation (9) in which M_{PPLE} = Occupant heat gain (200) [8] and People density D_{PPLE} is 41.86 per person (ASHRAE, Standard 62-1989).

$$Q_{PPLE} = M_{PPLE} / D_{PPLE} = \frac{200}{41.86} = 4.777 \text{ W/m}^2\text{K} \text{ and } Q_{EQUIP} = 9.44 \text{ W/m}^2$$

$$Q_{LIGHT} = Q_{LIGHT}(1 - f_{daylight}/2) = 22.03 \text{ W/m}^2$$

$$Q_{IHG} = Q_{PPLE} + Q_{LIGHT} + Q_{EQUIP} = 4.77 + 22.03 + 9.44 = 36.25 \text{ W/m}^2$$

Step 4: Estimate the building's solar gains.

This is estimated, at the sun intensity of 320 W/m^2 , using equation and data in Table 4 and equation (11), $Q_{sol} = 78.2 \text{ W/m}^2$.

Step 5: Estimate the building's balance point temperature ($T_{balance}$). $T_{balance}$, is the building balance point temperature during occupancy which is estimated by subtracting temperature due to the total gain and the heat transfer gain of the building from the building thermostat temperature. From Equation (1) therefore the building balance point temperature = $24.5^\circ\text{C} - 7.71^\circ\text{C} = 16.74^\circ\text{C} \approx 17^\circ\text{C}$.

See Appendin1 for wall U-factors.

DATA ANALYSIS AND DISCUSSION OF RESULTS

Discussion of the Results

The bar graph in Figure 7 shows the individual Enclosure Heat Transfer ratios. Each of the rectangle represents a variable that as been estimated using the individual area take off from balance point analysis. Looking at the straw bale building critically, losses through the ground, ventilation and roof all stand out as the major heat transfer path.

Heat Transfer Assessment of Straw Bale Walled Room

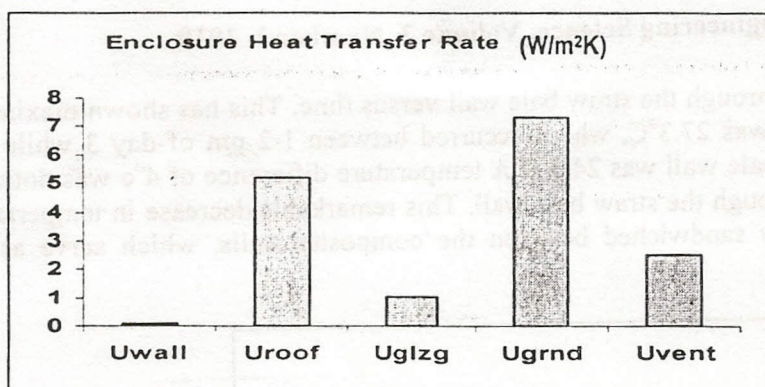


Figure 7. The bar chart of enclosure heat transfer rate through straw bale building

In Figure 8 shows the sources of internal heat through straw bale building is showing that light accounts for over half of the internal heat gain. The values for occupant heat gain rate ratio and the thermostat have been set. These values were selected from the protocol scales as representative of residential building.

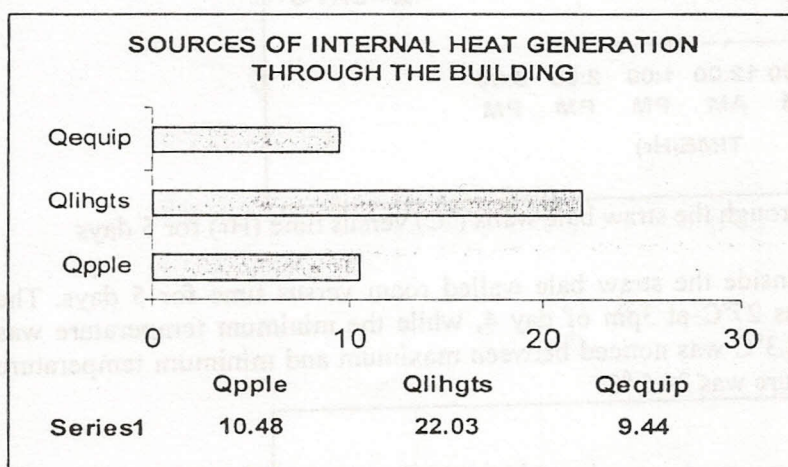


Figure 8. Sources of internal heat generation through the straw bale building

From the balance point analysis, an out door temperature of 17°C will balance these heat gains to produce a comfortable temperature of 24.5°C in the room.

Temperature Variations

Figure 9. shows the plot of ambient temperature versus time from 10 am -3 pm for 5 days. It was observed that the maximum ambient temperature was 31°C at 1pm of day 3, while the minimum ambient temperature was 27°C at 11 am of day 3. The difference between max and min ambient temperature was 4°C . The average external temperature for the period of this study was 28.8°C .

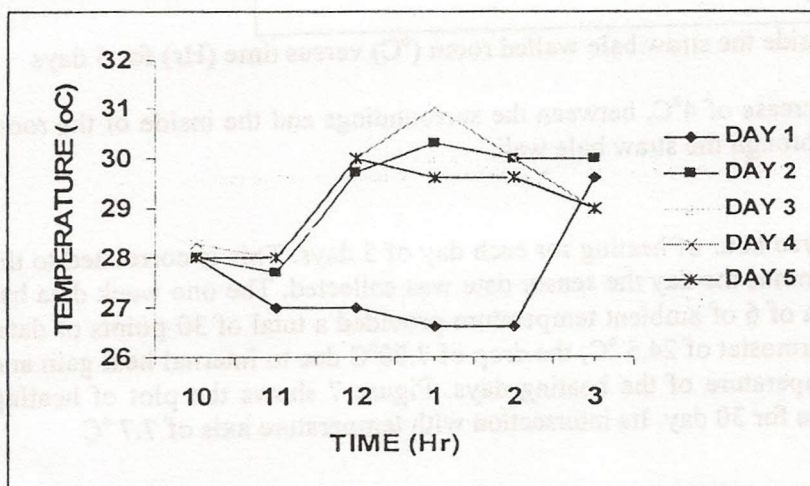


Figure 9 Variation of ambient temperature ($^{\circ}\text{C}$) versus time (Hr) for 5 consecutive days

Figure 10 shows the plot of temperature through the straw bale wall versus time. This has shown maximum temperature through the straw bale wall was 27.3°C, which occurred between 1-2 pm of day 3 while the minimum temperature through the straw bale wall was 24.3°C. A temperature difference of 4°C was noticed, between the max and min temperature through the straw bale wall. This remarkable decrease in temperature was possible because of the baled straw sandwiched between the composite walls, which serve as an insulator.

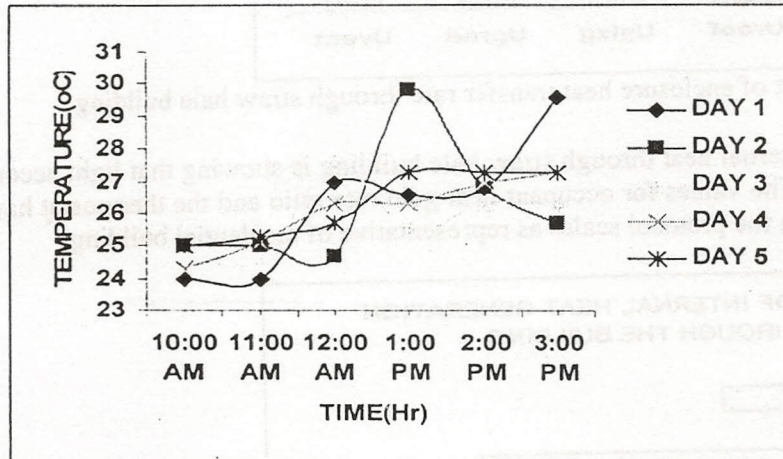


Figure 10 variation of temperature through the straw bale walls (°C) versus time (Hr) for 5 days

Figure 11 shows the plot of temperature inside the straw bale walled room versus time for 5 days. The maximum temperature inside the room was 27°C at 3pm of day 4, while the minimum temperature was 22.7°C at 10am of day 1. A difference of 4.3°C was noticed between maximum and minimum temperature inside the room, while the average temperature was 24.5 °C.

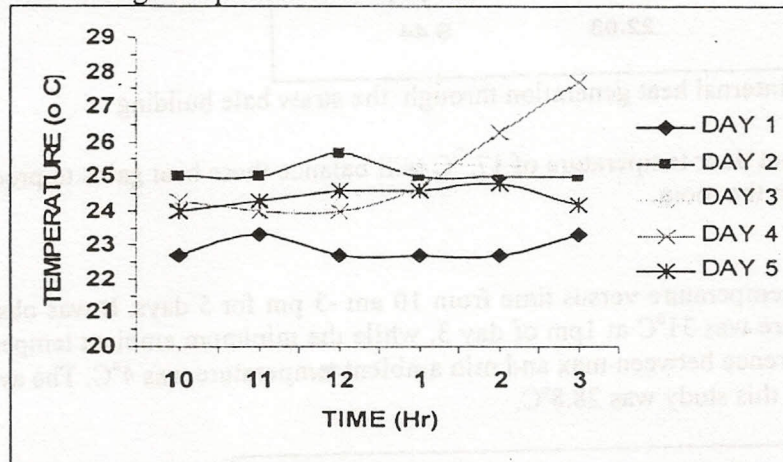


Figure 11 variation of temperature inside the straw bale walled room (°C) versus time (Hr) for 5 days

From these plots above there is a net decrease of 4°C, between the surroundings and the inside of the room suggesting the low transmission of heat through the straw bale wall.

Degree Hour Estimation

Calculated from Equation (12) is the degree hour of heating for each day of 5 days. This is correlated to the average daily (ambient) air temperature minus the day the sensor date was collected. The one week data has provided 5 average hours. The 5 day data of 6 of ambient temperature provided a total of 30 points of data. As the building was maintained at the thermostat of 24.5 °C, the drop of 7.70°C due to internal heat gain and the solar heat gain lead to base line temperature of the heating days. Figure 7 shows the plot of heating degree hours vs. average daily temperature for 30 day. Its intersection with temperature axis of 7.7 °C

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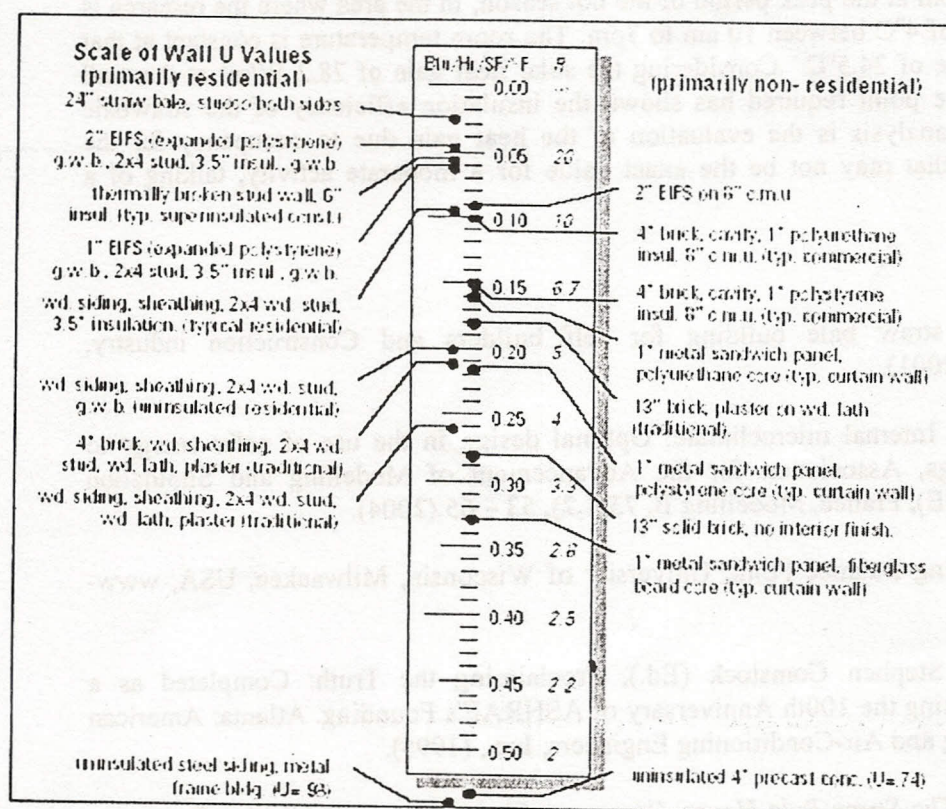
CONCLUSIONS

It has been shown that an outdoor temperature of 17 °C will balance the internal heat gain to produce a comfortable temperature of 24.5 °C inside the room of the strawbale walled building. Minimum temperature in the straw bale wall occurred at 3pm at the peak period of the hot season, in the area where the research is been carried out, with a difference of 4°C between 10 am to 3pm. The room temperature is constant at that interval of time at the average value of 24.5°C. Considering the solar heat gain of 78.2 W/m² at the wall surface area, the amount of balance point required has shown the insulation efficiency of the strawbale masonry. Major limitation in this analysis is the evaluation of the heat gain due to occupancy for the assumption of human metabolism that may not be the exact value for a moderate activity, talking of a residential building.

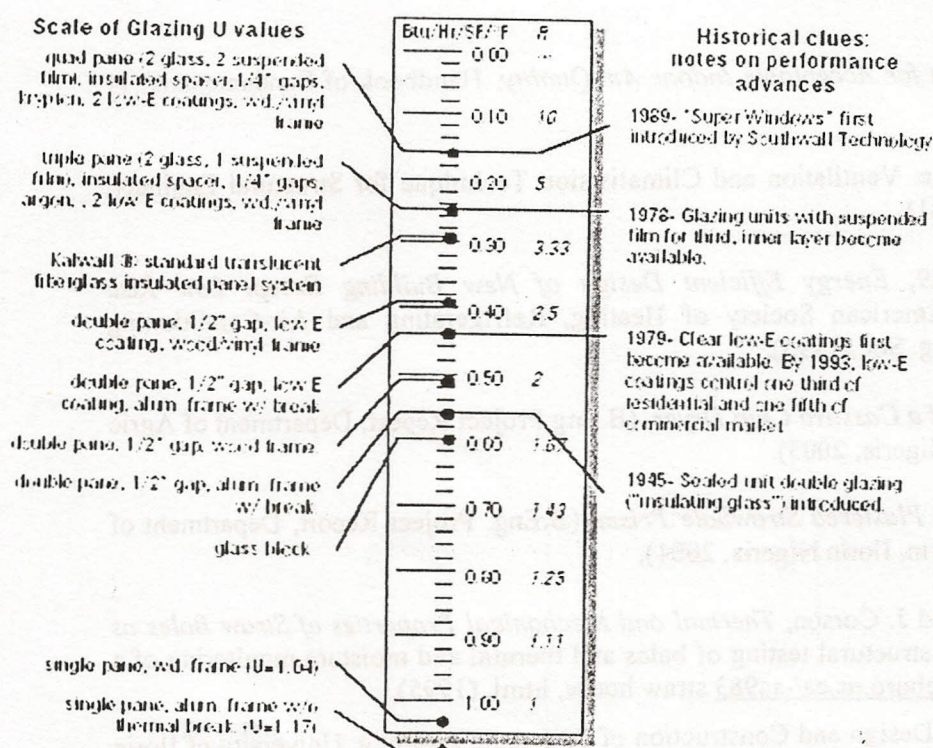
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APPENDIX I



Typical example of scale of ASHRAE wall U-factors



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