WHEN THERMAL MASS BECOMES RESISTANCE

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ABSTRACT

It is well known in the earthbuilding community that buildings constructed with earthen materials perform well thermally. However it is a continuous struggle to work with building officials, architects and engineers who are not thoroughly familiar with adobe, rammed earth, compressed earth blocks, sod and monolithic adobe. Most laboratory tests of building materials are done with steady state methodology although massive masonry walls in a climate with fluctuating diurnal temperatures are in a dynamic state. Earthen materials have high capacity to store heat and according to steady state laboratory tests, low resistance to the transfer of heat—that is, a high coefficient of heat transfer, known as conductance and symbolized as U.

In 1978, the State of New Mexico in the USA rated the thermal performance of adobe walls in terms of effective U. Effective U is calculated in the same way as U, but averaged over periods of many days using real weather data. The effective U-values showed that massive walls, with or without external insulation, performed better in New Mexico than predicted by standard steady-state calculations. Subsequent reports from the New Mexico Energy Institute (NMEI) at the University of New Mexico, the Los Alamos National Laboratory (LANL), and the Oak Ridge National Laboratory (ORNL) corroborate the original data and computer algorithms that provide the Tables of Effective U-Values and validate their use in building heat loss/heat gain calculations.

The State of New Mexico officially accepted these effective U-values into the New Mexico Energy Conservation Code. If the state accepts the 2009 International Energy Conservation Code this year, it will bring an end to their sanctioned use. This paper describes the history of the effective U-values, describes how they have been used and preserves them in this publication for use in climatic regions similar to the widely varied regions of New Mexico.

INTRODUCTION

In New Mexico is said that adobe homes are warm in the winter and cool in summer. As building construction codes began to encompass adobe in municipalities and then the State of New Mexico in the late 1950's and early 1960's, that quaint knowledge came into question. Energy conservation codes developed and in 1976 New Mexico adopted Chapter 53 of the Uniform Building Code. Chapter 53 is the energy chapter based on ASHRAE (the American Society of Heating, Refrigeration and Air-Conditioning Engineers) Standard 90-75. Suddenly the ASHRAE value of U=1.36 W/m^2-K (0.240 BTU/hr-·ft^{2}·-°F) for a wall 25 cm (10 inches) wide began to be used in calculations to determine winter heat loss in adobe buildings and the folklore was declared to be a false notion.[1] It became difficult to show compliance with energy conservation codes for construction permits for adobe. The neighboring state of Arizona actually forbade adobe construction for a two year period. The ASHRAE value was determined in a standard steady state laboratory test.

Many of us who actually lived in and enjoyed adobe homes felt that something was wrong. In New Mexico, due to fluctuations in winter temperature and solar radiation, a steady state condition rarely exists. At the national level, the Department of Energy (DOE) began the Thermal Mass Program that funded research at the National Bureau of Standards (NBS) in Maryland and at the Oak Ridge National Laboratory (ORNL) in Oak Ridge, Tennessee.[2] Fortunately, the New Mexico the Energy and Minerals Department could also see that there might be other ways of comparing different construction materials and funded several major efforts. From this came: "Effective U-Values – A New Method for Predicting Average Energy Consumption for Heating Buildings" authored by Wybe van der Meer, et al.[3] Another, was the Southwest Thermal Mass Study, Tesuque Pueblo, New Mexico (SWTMS), under the guidance of John Gustinis and David K. Robertson of the NMEI at the University of New Mexico. Bristol Stickney was the on-site data technician. Effective U-values were used with a combination of experimental buildings and computer modeling and verified on real buildings. They were tabulated in different climatic zones for walls of varying construction, cardinal direction, and exterior color. The SWTMS published its findings in three phases culminating in the publication, "SOUTHWEST THERMAL MASS STUDY."[4]

In 1981 David K. Robertson authored the Final Report from the New Mexico Energy Institute titled "EXPANDED REVISION OF EFFECTIVE U-VALUES, U-Values for Opaque Wall Sections, Glazing and Passive Solar Wall Types."[5] Although other publications had divided New Mexico into eleven climatic regions, this final report divides New Mexico into four regions.

Because of the financial and philosophical backing of the NM Energy and Minerals Department, the effective U-values were incorporated into the 1978 New Mexico Energy Conservation Code and its Applications Manual. The Energy Crisis of 1972/3 was still in the minds of the public, and government officials wanted to make energy conservation the law while easy to implement. Democratic Governor Jerry Apodaca was supportive of all things to reduce energy consumption. The state of New Mexico spent at least USD1.3 million on grants to the various agencies that contributed to the state Energy Conservation Code and its Applications Manual. "The new code is not only a good idea (there is an energy crisis), but it is also the law."[6]

Adobe buildings could now meet the code in three ways: 1) simply wrap the building in insulation to meet the prescriptive standards that U had to be 0.298 W/m^2-K (0.0520 BTU/hr-ft^2-F) 2) provide tradeoffs with other building components such as roofs or floors super-insulated to balance less well-insulated walls; 3) perform a building heat loss/heat gain calculation to show that the building performed better than or equal to the Energy Code Model Home. The tables of Effective U-Values made it easy to calculate building heat loss wall by wall.

Also there is a large amount of information available for the person who spends time looking at effective U-values on the charts. The charts are an effective teaching tool, and when people see the variations in values based on cardinal direction and color, their understanding begins to affect the basic design of adobe buildings, especially those with a passive solar approach. In northern latitudes, designers are reinforced in their inclination to elongate buildings east and west to maximize the south side. They also might consider making the south side higher and the north side lower. Some buildings receive buffer spaces on the north to reduce winter heat loss there. This might be in the form of insulated frame structures such as garages or storage spaces on the north or placement there of adobe rooms such as closets, studios and workshops that do not require heating. North and south cardinal directions would be reversed in the southern hemisphere.

In New Mexico it has become routine to apply rigid nailed-on polystyrene insulation or sprayed-on polyurethane insulation on north walls especially and often on east and west walls and rarely on the south. The insulation is then covered with standard three-coat cement/lime/sand stucco, a well-known technique in the southwestern desert states. The technique is startling and perhaps offensive to the traditionalists who cannot easily accept the idea of a modern, petrochemical material used over the natural materials of the earth. It is a pragmatic method to comply with energy conservation requirements and it is clear to all that the practice yields structures that require less energy to heat and cool while providing a higher sense of human comfort. The United States is behind other countries that produce insulation materials from natural sources: straw panels, reed bundles, cotton and cork. Several US companies have formed develop compressed straw insulation panels during the past two decades but have not succeeded in bringing a product to market.

"The effective U-values are particularly useful in that they are simply substituted for the steady-state U-values prescribed in the code. Thus there is no change in methodology for determining compliance with the code. One simply substitutes effective U-values for steady-state U-values."[7]

As simple as it has been to use the effective U-Values, it did require some education of designers and of building officials who had to check the calculations for code compliance. Over time, their use declined until today, the New Mexico Construction Industries Division encourages construction permit applicants to use one number from the 2009 International Energy Conservation Code which gives some benefit to the adobe user compared to steady state values but that does not consider climatic zone, cardinal direction or color of building envelope walls.[8] Thus, support for the higher performance model of adobe walls in the real world better represented by the effective U-Values has nearly been forgotten. If New Mexico accepts the 2015 International Energy Conservation Code without addenda, the effective U-values tables will officially disappear. This is in spite of the abundant research, computer coding verification and political effort to get this information into the Code and the thirty-eight year history of its successful and beneficial use.

THE INFORMATION

U values are used to calculate heat flow through a material, such as a wall. In a steady-state test, $U = Q/A(\Delta T)t$, where Q is the amount of heat transferred through a wall area A in a time t when the temperature difference between the two sides of the wall is ΔT. The effective U-value is defined in the same way, except that Q represents the total heat flow over a period of days as the outdoor temperature, solar radiation, and other quantities fluctuate. Therefore effective U-values fit easily into the standard equation of $Q = UA(\Delta T)t$. The lower the U-value or effective U-value, the better the insulation.

Tables of effective U-values are presented here for four wall configurations: 25-cm (10-inch) walls without and with 5-cm (2-inch) rigid polystyrene insulation and 35-cm (14-inch) walls without and with 5-cm (2-inch) rigid polystyrene insulation. Each of the Tables 2 – 4 shows results for four regions of New Mexico:

Table 1, Climatic Regions in New Mexico and Equivalent Climates Worldwide[9]

Region	Heating degree days in °C (°F)	Average January high temp.	Average January average temp.	Average January low temp.
1 (North-central New Mexico)	4000 to 5000 (7200 to 9200)	3°C (37°F)	-6°C (21°F)	-14°C (6°F)
2 (Northern third except Region 1)	3000 to 4000 (5400 to 7200)	8°C (46°F)	-1°C (31°F)	-9°C (16°F)
3 (Central)	2000 to 3000 (3600 to 5400)	12°C (53°F)	4°C (39°F)	-4°C (25°F)
4 (Southern fourth)	1000 to 2000 (1800 to 3600)	14°C (57°F)	6°C (42°F)	-3°C (26°F)

These tables would be useful in those parts of the world with significant winter heating requirements between 1000 and 5000 degree days Celsius (1800 and 9000 heating degree days Fahrenheit), large diurnal temperature fluctuations, 45% or more sunny days and in the latitudes between 20 and 45 degrees latitude north and south.

In the tables below, numbers in roman type are in units of $\mathrm{BTU/hr \cdot ft^2 \cdot {}^\circ F}$ and those in *italics* are in SI units, $\mathrm{W/m^2 \cdot K}$.

The source of all data is from pages 16, 20, 17, 21 of "EXPANDED REVISION OF EFFECTIVE U-VALUES," David K. Robertson, NMEI 1981.

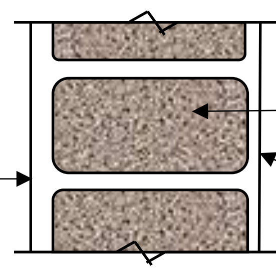
Table 2, Heating Effective U-Values Adobe Wall: 10-inch/25cm width, no insulation

Wall Type 1, ASHRAE Steady State U-Value $= 1.36\ \frac{\mathrm{W}}{\mathrm{m^2 \cdot K}} = 0.240\ \frac{\mathrm{BTU}}{\mathrm{hr \cdot ft^2 \cdot {}^\circ F}}$

10" Adobe		Climatic Region			
Wall Orientation	**Wall Color**	**1**	**2**	**3**	**4**
East	Light	0.226 *1.28*	0.217 *1.23*	0.222 *1.26*	0.211 *1.198*
	Medium	0.194 *1.10*	0.176 *0.999*	0.178 *1.01*	0.158 *0.897*

	Dark	0.161 *0.914*	0.135 *0.766*	0.133 *0.755*	0.106 *0.60*
South	Light	0.218 *1.237*	0.208 *1.18*	0.206 *1.169*	0.197 *1.118*
	Medium	0.174 *0.987*	0.152 *0.863*	0.136 *0.77*	0.123 *0.698*
	Dark	0.131 *0.74*	0.096 *0.545*	0.067 *0.38*	0.050 *0.284*
West	Light	0.232 *1.317*	0.224 *1.27*	0.229 *1.30*	0.218 *1.237*
	Medium	0.208 *1.18*	0.193 *1.095*	0.194 *1.10*	0.178 *1.01*
	Dark	0.185 *1.05*	0.162 *0.919*	0.160 *0.908*	0.137 *0.777*
North	Light	0.238 *1.35*	0.234 *1.328*	0.241 *1.368*	0.231 *1.31*
	Medium	0.223 *1.30*	0.217 *1.23*	0.224 *1.27*	0.210 *1.19*
	Dark	0.208 *1.18*	0.201 *1.14*	0.207 *1.175*	0.188 *1.067*

Source: "Expanded Revision of Effective U-Values", Robertson, David K. 1981.



Cross-Section
10" Adobe Wall Type #1

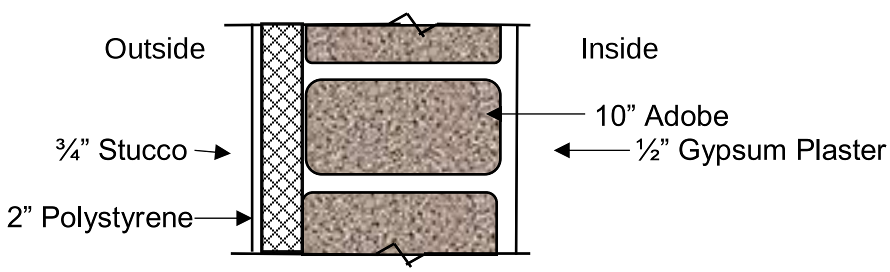
Table 3, Heating Effective U-Values for Adobe Wall: 10-inch/25cm width, 2-inch/5cm rigid polystyrene insulation

Wall Type 5, ASHRAE Steady State U-Value $= 0.386\ \frac{\mathrm{W}}{\mathrm{m^2{\cdot}K}} = 0.068\ \frac{\mathrm{BTU}}{\mathrm{hr{\cdot}ft^2{\cdot}{}^{\circ}F}}$

10" Adobe and 2" Polystyrene		**Climatic Region**			
Wall Orientation	**Wall Color**	**1**	**2**	**3**	**4**
East	Light	0.069 *0.391*	0.066 *0.374*	0.067 *0.380*	0.064 *0.363*
	Medium	0.060 *0.340*	0.055 *0.312*	0.055 *0.312*	0.049 *0.278*

	Dark	0.051 *0.289*	0.043 *0.244*	0.042 *0.238*	0.035 *0.198*
South	Light	0.067 *0.380*	0.063 *0.357*	0.063 *0.357*	0.060 *0.340*
	Medium	0.055 *0.312*	0.048 *0.272*	0.043 *0.244*	0.040 *0.227*
	Dark	0.042 *0.238*	0.033 *0.187*	0.024 *0.136*	0.019 *0.107*
West	Light	0.071 0.40	0.068 *0.386*	0.069 *0.391*	0.066 *0.374*
	Medium	0.064 *0.363*	0.059 *0.335*	0.060 *0.340*	0.055 *0.312*
	Dark	0.058 *0.329*	0.051 *0.289*	0.050 *0.283*	0.043 *0.244*
North	Light	0.073 *0.414*	0.070 *0.397*	0.073 *0.414*	0.070 *0.397*
	Medium	0.069 *0.391*	0.066 *0.374*	0.068 *0.386*	0.064 *0.363*
	Dark	0.064 *0.363*	0.061 *0.346*	0.063 *0.357*	0.058 *0.329*

Source: “Expanded Revision of Effective U-Values”, Robertson, David K. 1981.



Cross-Section
10” Adobe with 2” Polystyrene
Wall Type #5

Note that on Table 2 with no insulation, the effective U-value in cell *South, Medium, Climatic Region 1* is $0.987\ \mathrm{W/m^2 \cdot K}$ while on Table 3 with insulation in the equivalent position the effective U-value is $0.312\ \mathrm{W/m^2 \cdot K}$. The U-value for the insulation is given to be $0.511\ \mathrm{W/m^2 \cdot K}$ by the manufacturer.

Using steady state methods to combine elements in a wall with $U_1 = 0.987\ \mathrm{W/m^2 \cdot K}$ and $U_2 = 0.511\ \mathrm{W/m^2 \cdot K}$, we would expect that the insulation combined with the adobe would give a U-Value of:

$$U_{\text{total}} = \frac{1}{\left(\frac{1}{U_1} + \frac{1}{U_2}\right)} = \frac{1}{(1.01 + 1.96)} = 0.337 W/m^2 \cdot K$$

The U-Effective of $0.312\ \mathrm{W/m^2 \cdot K}$ from the table is less than the above steady state predicted value of $0.337\ \mathrm{W/m^2 \cdot K}$.

Also note that on Table 2 in the cell *South, Dark, Climatic Zone 4* the Effective U-value of the uninsulated wall, 0.284 decreases to 0.107 at the corresponding position on Table 3 when insulated. That Effective U-Value of 0.107 is a very surprising improvement in U-Value over the stated ASHRAE steady state U-Value of 0.386 at the top of the table. However, it could be considered unnecessary to add exterior insulation to that south facing dark wall. The Effective U-Value of 0.284 seen on Table 1 for the wall without insulation meets the prescriptive energy conservation code requirement in New Mexico for the wall indicating that adding insulation may be considered beyond the point of diminishing returns.

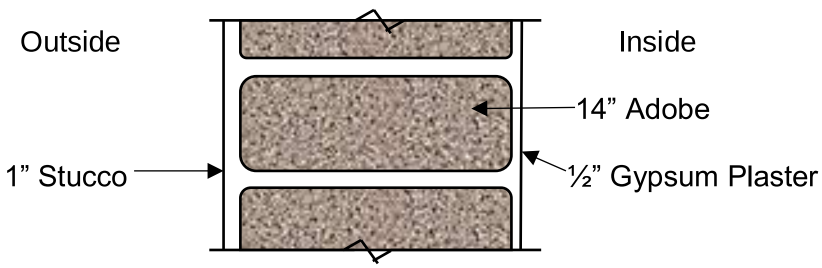
Also note that on Table 2 in the cell *North, Light, Climatic Region 4* the Effective U-Value is 1.386 which is actually slightly higher than the ASHRAE steady state U-Value of 1.38 at the top of the table. This climatic region has the most severe winter conditions with heating degree days of 4000 – 5000 HDD 18. This seems a clear indication that a light-colored wall on the north side of a structure needs to be minimized, buffered with non-heated space, or insulated. The corresponding cell in Table 3 for the wall with exterior insulation shows an effective U-value of 0.397, which is also slightly larger than the stated ASHRAE steady state U-value of 0.386. These effective U-values for north walls demonstrate that it is important to strongly regard cardinal orientation and color of a wall in the design phase of a structure in order to fully anticipate its energy performance.

Table 4, Heating Effective U-Values for Adobe Wall: 35-cm (14-inch) width

Wall Type 2, ASHRAE Steady State U-Value $= 1.07\ \frac{\mathrm{W}}{\mathrm{m^2 \cdot K}} = 0.189\ \frac{\mathrm{BTU}}{\mathrm{hr \cdot ft^2 \cdot {}^{\circ}F}}$

14" Adobe		**Climatic Region**			
Wall Orientation	**Wall Color**	**1**	**2**	**3**	**4**
East	Light	0.181 *1.027*	0.174 *0.987*	0.178 *1.01*	0.168 *0.95*
	Medium	0.155 *0.88*	0.141 *0.80*	0.142 *0.806*	0.126 *0.715*
	Dark	0.129 *0.73*	0.108 *0.613*	0.106 *0.601*	0.084 *0.476*
South	Light	0.175 0.993	0.166 *0.94*	0.165 *0.936*	0.157 *0.89*
	Medium	0.140 *0.794*	0.122 *0.692*	0.109 *0.618*	0.098 *0.556*
	Dark	0.105 *0.596*	0.077 *0.437*	0.053 *0.300*	0.040 *0.227*
West	Light	0.186 *1.056*	0.179 *1.016*	0.183 *1.039*	0.174 *0.987*

	Medium	0.167 *0.948*	0.155 *0.88*	0.155 *0.88*	0.142 *0.806*
	Dark	0.148 *0.840*	0.130 *0.738*	0.128 *0.726*	0.142 *0.806*
North	Light	0.191 *1.08*	0.187 *1.06*	0.193 *1.095*	0.185 *1.050*
	Medium	0.179 *1.016*	0.174 *0.987*	0.179 *1.016*	0.167 *0.948*
	Dark	0.167 *0.948*	0.161 *0.914*	0.165 *0.936*	0.150 *0.851*



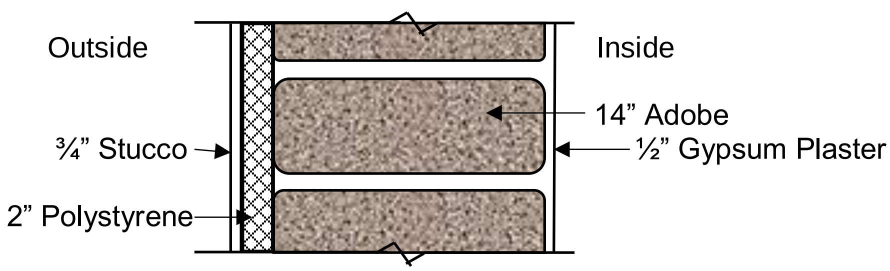
Cross-Section
14” Adobe
Wall Type #2

Table 5, Heating Effective U-Values for Adobe Wall: 14-inch/35cm width, 2-inch/5cm rigid polystyrene insulation

Wall Type 6, ASHRAE Steady State U-Value $= 0.358\ \frac{\mathrm{W}}{\mathrm{m^2 \cdot K}} = 0.063\ \frac{\mathrm{BTU}}{\mathrm{hr \cdot ft^2 \cdot {}^{\circ}F}}$

14” Adobe and 2” polystyrene		**Climatic Region**			
Wall Orientation	**Wall Color**	**1**	**2**	**3**	**4**
East	Light	0.064 *0.363*	0.061 *0.346*	0.063 *0.357*	0.059 *0.335*
	Medium	0.056 *0.317*	0.051 *0.289*	0.051 *0.289*	0.046 *0.261*
	Dark	0.048 *0.272*	0.040 *0.227*	0.039 *0.204*	0.032 *0.181*
South	Light	0.062 *0.352*	0.059 *0.335*	0.058 *0.329*	0.055 *0.312*
	Medium	0.051 *0.289*	0.044 *0.249*	0.040 *0.227*	0.037 *0.210*

	Dark	0.039 *0.221*	0.030 *0.170*	0.022 *0.124*	0.018 *0.102*
West	Light	0.066 *0.374*	0.063 *0.357*	0.064 *0.363*	0.061 *0.346*
	Medium	0.060 *0.340*	0.055 *0.312*	0.055 *0.312*	0.051 *0.289*
	Dark	0.054 *0.306*	0.047 *0.266*	0.046 *0.261*	0.051 *0.289*
North	Light	0.068 *0.386*	0.065 *0.369*	0.067 *0.380*	0.064 *0.363*
	Medium	0.064 *0.363*	0.061 *0.346*	0.063 *0.357*	0.059 *0.335*
	Dark	0.060 *0.340*	0.057 *0.323*	0.059 *0.335*	0.053 *0.300*



Cross-Section
14” Adobe with 2” Polystyrene
Wall Type #6

CONCLUSIONS

The unexpectedly high thermal efficiency of adobe walls in New Mexico, indicated by their low effective U-values, arises from their thermal mass. Thermal mass is the ability to gain or lose a good deal of heat without changing much in temperature. The advantage of thermal mass in a climate like New Mexico’s was explained by Robertson[10] and in a comprehensive review of the effects of thermal mass by scientists at Oak Ridge National Laboratory.[11]

To take the heating season as an example, the advantage occurs when the interior temperature rises above the thermostat setpoint or the minimum temperature for comfort, as may result during the day from a combination of warmth outside, solar gain, and heat generation inside by human bodies, appliances, etc. Heat loss from the interior is roughly proportional to the temperature difference between inside and outside, so unnecessarily high temperatures inside increase the heat loss, and all heat lost must be replaced. High thermal mass reduces temperature changes and thus reduces or eliminates the time during which the inside temperature swings too high and heat is lost unnecessarily. Therefore adobe buildings and others with higher thermal mass can use heat from solar gain and other sources more efficiently than low-thermal-mass buildings. Computer models and field testing corroborate this analysis.

A similar benefit occurs during the cooling season: high thermal mass can prevent the temperature inside from falling unnecessarily low at night and thus prevent unnecessary heat from flowing in.

Thermal mass provides those benefits only when outdoor temperatures swing widely between day and night and sometimes come close to desired indoor temperatures. There is no benefit when the heat or the cooling must be on all the time. In winter, thermal mass is especially beneficial when solar heating is significant. Thus adobe walls are not beneficial in moist climates with narrow temperature swings and cloudy winters. Adobe walls are highly beneficial in conditions such as winter in much of New Mexico, with mild sunny days and cold nights. It would be of great benefit in similar climates around the world.

Combining adobe with a layer of foam or other insulation, as in Tables 2 and 4 above, works best when the insulation is on the outside. Again, the result may seem surprising, because in a steady-state heat-flow experiment, which layer is on the warmer side does not affect the outcome. However, in a building the thermal mass is most beneficial when it directly moderates the indoor temperature.

These conclusions agree with centuries of experience.

FOOTNOTES

1. ASHRAE, 1983
2. Childs *et al*, 1983
3. van der Meer, 1978
4. Robertson, 1984
5. Robertson, 1981
6. Dritt and England, 1978, see also Baumgartel, 1995
7. Dexter *et al*, 1979
8. International Code Council 2009
9. *Ibid*, see also Fosdick and Bahm, 1983, Benson *et al*, 1980 and www.degreedays.net
10. Robertson, 1981
11. Childs *et al*, 1983

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Bristol Stickney has a long term interest in thermal performance of buildings especially their passive solar heating and cooling. As far back as 1978 he was monitoring adobe buildings and he has lived in an adobe home for twelve years.

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