

USE OF INSULATED CONCRETE FORM (ICF) CONSTRUCTION FOR ENERGY CONSERVATION IN RESIDENTIAL CONSTRUCTION

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ABSTRACT

As a nation the United States must reduce its dependence on imported energy resources. Net imports of foreign oil as a percentage of total U.S. oil demand have increased from 37% in 1980 to 55% in 2001 and are predicted to increase to 65% by the year 2016. Since heating and air conditioning account for 44% of the energy usage in a typical U.S. home, residential energy conservation techniques hold great promise for significant savings.

Insulated concrete form (ICF) construction is a promising construction technique for both residential and commercial construction. Some advantages of ICF construction include: reduced construction time, compatibility with any inside or outside surface finish, insect resistance, strength, noise reduction, reduced infiltration, significant and continuing energy savings, lower HVAC capital costs for the building, and 12" (30 cm) wide window sills. Disadvantages of ICF construction include: resistance from builders and sub-contractors unfamiliar with the construction technique, higher material costs, the necessary custom window and door openings, and the difficulty and expense of making changes once the walls are in place. Even though the material costs are higher than typical (stick-frame) construction, labor savings might result in overall savings.

In this paper actual energy usage for an ICF house constructed in 1998 is compared to the energy usage for a 1988 conventional stick-frame building. Comparison of these two buildings indicates a 75% reduction in energy usage per square foot per degree-day for the ICF building when compared to the stick-frame building. During this same time period, energy (gas) usage for heating and hot water decreased 85%.

Computer simulations were made for both an ICF wall and for a conventional frame wall. These computer simulations indicate significant saving potential for the ICF wall when compared to a conventional frame wall section. In addition these simulations illustrate dramatically the effect of separating the thermal resistance and thermal capacitance inherent in this "sandwich" construction.

NOMENCLATURE

c_p	specific heat capacity (kJ/kg-°C)
k	thermal conductivity (W/m-°C)
ρ	density (kg/m ³)
T	temperature (°C)
t	time (seconds)
x	position (meters)

INTRODUCTION

Construction techniques used in the United States must change if we are to build cost effective, energy efficient structures. Over the past 25 years better insulating materials applied to the conventional stick-built frame wall construction have helped to make buildings more energy efficient. However, as will be demonstrated in this paper, shell insulation (R-value) alone is not enough to produce a truly energy efficient building.

The reduction of energy loss or gain through a building shell is a function not only of the shell insulation (R-value) but also of the shell thermal storage capacity (mass times specific heat capacity). Many older buildings, including those built by the cliff dwellers in the desert southwest, relied upon massive walls and ceilings to provide comfort in the structure.

The building shell is subjected to a daily variation in solar radiation and air temperature. During the cooling season, the outside surface of the building will increase in temperature during the day due to absorbed solar radiation and convection of energy from the hot outside air. Before this absorbed energy becomes a cooling problem, this energy must be conducted through the wall and into the living space. Conventional building techniques attempt to reduce this conduction through the walls by increasing insulation. In moderate climates, ICF construction (large wall heat capacity) takes advantage of cool nighttime temperatures to reduce the cooling load of the building. By increasing the mass of the walls, one can effectively store the absorbed (daytime) energy in the wall until it can be dissipated to the cool nighttime environment.

THEORY

The statement of conservation of thermal energy as applied to the one-dimensional wall section can be found in any heat transfer text and is given below:

$$\rho c_p \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2}$$

where all material properties including density (ρ), specific heat capacity (c_p) and thermal conductivity (k) are assumed constant and uniform in each material section.

The boundary conditions at the inside and outside wall surfaces must be specified in order to obtain a solution. At the inside wall surface, the boundary conditions are specified as a constant convection coefficient and constant inside air temperature. At the outside wall surface, the specified boundary conditions include a constant convection coefficient and a time-varying outside air temperature. Conventionally the ASHRAE "Sol-Air" temperature is used to account for both convection and radiation on the outside surface.

Standard finite-difference numerical solution techniques are used to solve the above equation to determine the temperature distribution throughout the wall and the surface heat fluxes. The spreadsheet used to analyze this ICF wall construction originated with a class project in an undergraduate heat and mass transfer course. Students were asked to assess the effect of the large energy storage capacity of a thick masonry wall, such as those at nearby Monticello. Those early nineteenth century walls were built of 16" (40.64 cm) of solid brick with an inch of plaster on the inside surface. Treating the wall as a single homogeneous layer with convection boundary conditions at both the inside and outside surface, students used a simple, explicit finite-difference technique to simulate the transient behavior of the wall over a several-day period. At the outside surface the effects of convective and radiative gains and losses were approximated using a constant convection heat transfer coefficient and hourly " T_{solair} " values for a dark, unshaded, west-facing wall in July taken from the ASHRAE handbook. The allowable timestep of 15 minutes found theoretically proved numerically stable and convenient. Even with the large thermal capacitance, this calculation came to a steady, periodic condition in a matter of 4-5 days.

With a much larger static thermal resistance than the Monticello walls ($R=2 \text{ ft}^2\text{-hr-}^\circ\text{F/Btu}$ ($0.352 \text{ m}^2\text{-C/W}$) vs. $R=30 \text{ ft}^2\text{-hr-}^\circ\text{F/Btu}$ ($5.283 \text{ m}^2\text{-C/W}$) for the ICF wall) but somewhat less thermal storage capacity (707 kJ/K for the brick, 353 kJ/K for ICF) the very long overall time constant for the ICF wall precluded using that simple, explicit technique. As an interim "fix," we transferred the temperature data from the row at the bottom of the spreadsheet representing midnight to the row corresponding to midnight of the previous day at the top and allowed the solution to iterate until a steady periodic condition was determined. This solution worked well and converged readily, but there was no way of determining how many actual days it took to get to the steady-periodic condition. Because the overall time constant of the wall was one of the outputs we were most interested in, we abandoned the spreadsheet calculation altogether, wrote a standard line-oriented code in Excel's macro programming language, Visual Basic for

Applications (a number of examples using VBA can be found at: www.people.virginia.edu/~rjr/modules/xls) and used the Excel worksheet strictly for input, output and display of the computed results.

The VBA program logic is very simple. An outer loop cycles over the maximum number of days to be simulated. The next inner loop cycles over the 24 hours of the day. Within this time loop special forms for the ends exposed to convection are set up, and still one more loop cycles over all internal nodes. Unlike the student project where linear interpolation was used to estimate intermediate values for the Sol-Air temperature, the current work uses a semi-implicit solution technique with a one-hour timestep to correspond with the ASHRAE Sol-Air temperature values. A semi-implicit scheme was implemented, so the Lapack routine for tridiagonal systems of linear equations (SGTSSV) was translated from Fortran into VBA and used to solve the resulting system. To keep track of the convergence the total heat transfer at the inner and outer surfaces for each day were computed and sent back to the Excel worksheet. With the given parameters these two values agreed with each other to within 0.5% at about 30 days into the transient and to within less than 0.01% at 50 days. While necessary, though not sufficient for program verification, this excellent agreement does indicate that the program conserves internally despite the complication of the two internal material interfaces.

A nodal schematic and photographs of the wall form are shown in Figure 1 for the ICF wall. A complete discussion of the above problem with a detailed solution scheme is presented by the second author in *Heat Transfer Tools*.

NUMERICAL RESULTS

Three wall types were studied for this paper. The first wall is a heavy masonry wall based on the Monticello wall with an R-value of $2 \text{ ft}^2\text{-hr-}^\circ\text{F/Btu}$ ($0.352 \text{ m}^2\text{-C/W}$), thermal storage capacity of 707 kJ/K. The second wall is a lightweight 2x6 ($5.08 \times 15.24 \text{ cm}$) frame wall with an R-value of $22 \text{ ft}^2\text{-hr-}^\circ\text{F/Btu}$ ($3.874 \text{ m}^2\text{-C/W}$), thermal storage capacity of 92 kJ/K. The third wall studied is the heavy weight ICF wall with an R-value of $30 \text{ ft}^2\text{-hr-}^\circ\text{F/Btu}$ ($5.283 \text{ m}^2\text{-C/W}$), thermal storage capacity of 353 kJ/K.

As seen in Figure 2, both the masonry and frame walls absorb a great deal of solar energy, and the outside surface heat fluxes (and temperatures) follow the outside ambient conditions closely. It should be noted that the ICF wall absorbs little energy and the corresponding surface heat flux is quite small. The heat flux at the outside surface of the ICF wall is two orders of magnitude smaller than those of the frame or masonry walls.

In Figure 3, we see that the heat flux on the inside surface of the masonry wall (low R-value, high storage capacity) is an order of magnitude smaller than that on the outside surface. This heat flux is also shifted approximately 12 hours in time with respect to the ambient driving conditions. From this figure, we also see that the frame wall (high R-value, low storage capacity) attenuates the ambient conditions quite well. The heat flux at the inside surface is quite low, but shifted very

little in time. Finally one sees that the ICF wall (high R-value, high storage capacity) has the lowest heat flux at the inside surface of all three walls. In fact the heat flux at the inside surface of the ICF wall is nearly constant and 70% less than that for the frame wall. This lower surface heat flux can be directly related to lower cooling system demands.

The numerical simulations were based on a periodic outside (ambient) boundary condition. The simulation was run until steady periodic values were obtained throughout the wall. It took about 5 days for the masonry wall to reach a steady periodic temperature distribution. The frame wall reached a steady periodic temperature distribution in 1 day. However, the ICF wall took about 30 days to reach a steady periodic temperature distribution.

Once a steady periodic temperature distribution was obtained, the temperatures in the wall were plotted for each hour of the day. This temperature distribution for the ICF wall is shown in Figure 4. As seen in this figure, the ICF wall very closely approximates a lumped capacitance system. The high ambient temperatures never penetrate further than the outside surface of the concrete. Most of the diurnal temperature variation is confined to the outside layer of insulation. As shown in Figure 5, the temperature throughout the entire thickness of the frame wall varies. The temperature of masonry wall, as seen in Figure 6, varies through more than half of the structure. Based upon these theoretical findings, one would predict that an ICF wall building would require substantially less energy to heat and cool when compared to either a standard frame wall or masonry wall building.

EXPERIMENTAL DESCRIPTION

Energy usage data for two different residential building was collected between August 1988 and January 2003. This data is normalized using floor square footage and published degree-day weather data.

A conventional stick-built frame wall construction residence was completed in August 1988. This building has nominal R-15 ($2.642 \text{ m}^2\text{-C/W}$) insulated walls and R-30 ($5.283 \text{ m}^2\text{-C/W}$) attic insulation. The building consists of 1200 square feet (34 square meters) of living space over an unheated crawl space. The floor has nominal R-19 ($3.346 \text{ m}^2\text{-C/W}$) insulation. This building has natural gas heating and hot water. The heating system was a nominal 30,000 BTUH (8.79 kW) gas furnace. The cooling system was a nominal 2.5-ton (8.79 kW) central air unit.

An insulated concrete form (ICF) residential building was built in 1997. The walls of the structure were nominal R-30 ($5.283 \text{ m}^2\text{-C/W}$), and the ceiling was nominal R-40 ($7.044 \text{ m}^2\text{-C/W}$). The building consisted of 4800 square feet (136 square meters) of living space. The primary heating system consisted of a high-efficiency gas furnace converted to burn propane. The design heating load for the building was calculated to be 32,000 BTUH (9.38 kW), but the installed gas furnace capacity is 45,000 BTUH (13.19 kW). The larger size unit was installed in order to get a larger fan needed to move more air around the building. The backup heat and primary cooling system is a 3-ton (10.55 kW) air-source heat pump. The installed thermal

mass in the building walls and basement floor is 250 tons ($2.27\text{E}5 \text{ kg}$) of concrete.

Five years of energy usage data for the ICF wall building is compared to seven years of energy usage data for a 1988 model frame wall construction residence. Energy usage data for a masonry wall home was unavailable.

EXPERIMENTAL RESULTS

The ICF construction has many advantages. The most significant advantage is the energy savings. Other advantages include noise reduction, stronger walls (which are needed in places at risk for hurricanes like Dade Co. FL), reduced air infiltration, smaller heating and cooling plants, and deep windowsills. Many ICF buildings can be constructed in a shorter time, which results in reduced labor savings. Another advantage with ICF walls is the fact that insects do not eat concrete or polystyrene. As with conventional construction, any inside or outside surface finish may be used on the ICF walls.

There are several disadvantages with ICF walls. The most significant disadvantage is the resistance from builders and sub-contractors. Many of these professionals must be "educated" as to what ICF walls are. Once contractors obtain experience with the ICF wall, most find them superior to stick-built. Another disadvantage of ICF walls is the higher material cost. This higher material cost for the wall materials does not necessarily result in higher building cost. Potential savings in labor cost due to shorter construction time, and savings in the smaller heating and cooling systems tend to offset the higher wall material costs. Other disadvantages include the need for custom door and window openings. As noted above, many people consider this to be an advantage. As with any concrete wall, changes to the walls are harder to make once the wall is in place.

Estimated costs to frame a 2x6 (5.08x15.24 cm) wall home are $\$3.15/\text{ft}^2$ ($\$34/\text{m}^2$) for materials and labor for the walls. The estimated costs of materials and labor for an ICF wall (home) are $\$6.16/\text{ft}^2$ ($\$66/\text{m}^2$). Thus the ICF wall cost is almost twice that of the frame wall. Overall building cost will depend on total size and accumulated savings.

Energy usage in the frame wall home from August 1988 to December 1995 was $2.77\text{E-}4 \text{ Btu/hr-ft}^2\text{-DD}$. Energy usage in the ICF wall home from January 1998 through January 2003 was $6.81\text{E-}5 \text{ Btu/hr-ft}^2\text{-DD}$. This represents a 75% reduction in energy consumption per square foot per degree day. Over the same time span, the energy for heating hot water and heating the building (gas) decreased 85% with the ICF building.

REFERENCES

1. *2001 ASHRAE Handbook- Fundamentals Handbook*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, 2001.
2. *Annual Energy Outlook 2003*, DOE/EIA-0383(2003), Energy Information Administration, January, 2003.
3. U.S. Department of Energy Office of Building Technology, November, 2001.

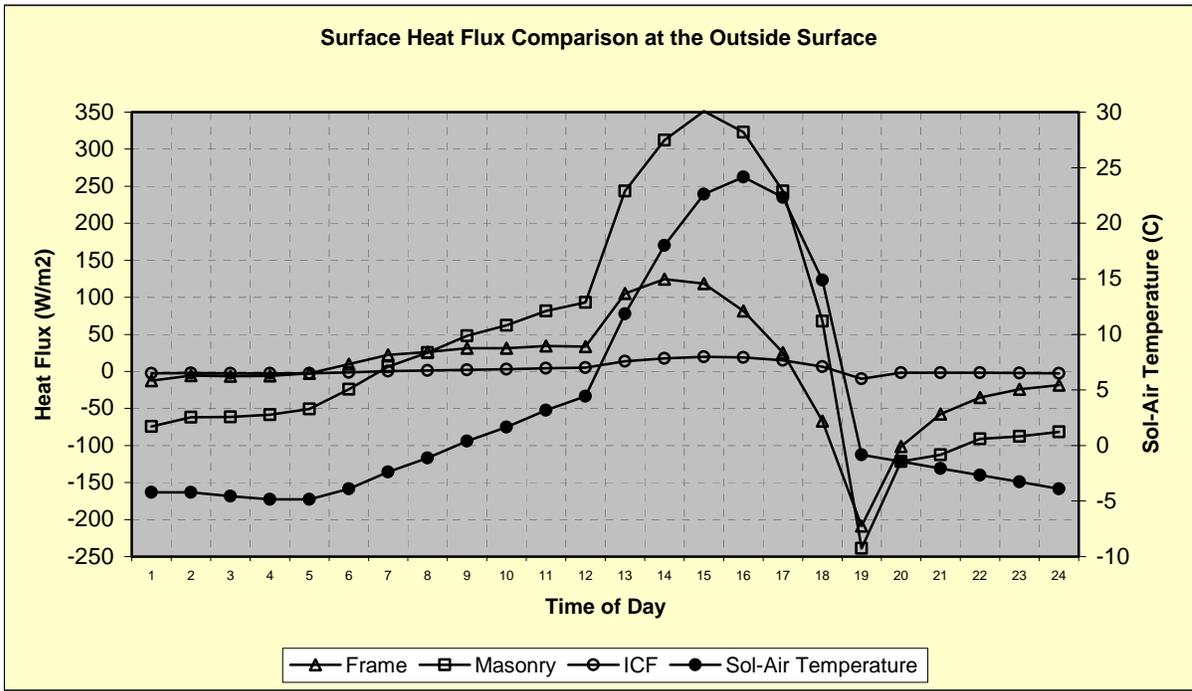


Figure 2. Predicted Outside Surface Heat Flux over 24-Hour Period for Three Constructions

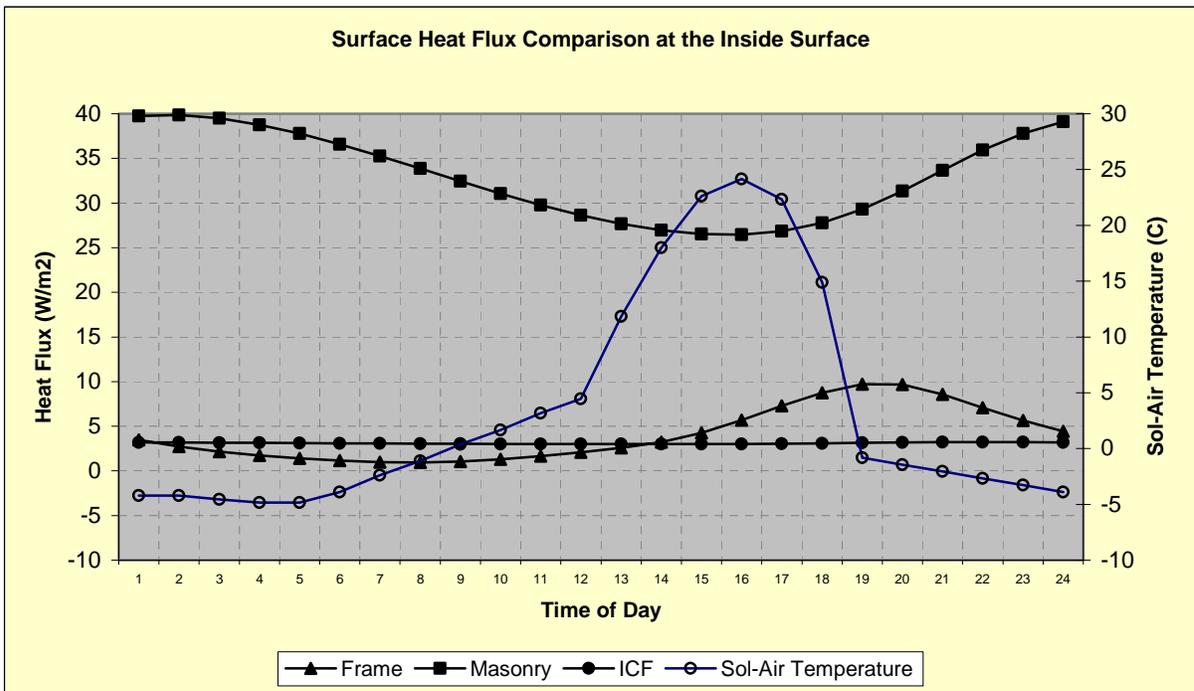


Figure 3. Predicted Inside Surface Heat Flux over 24-hour Period for Three Constructions

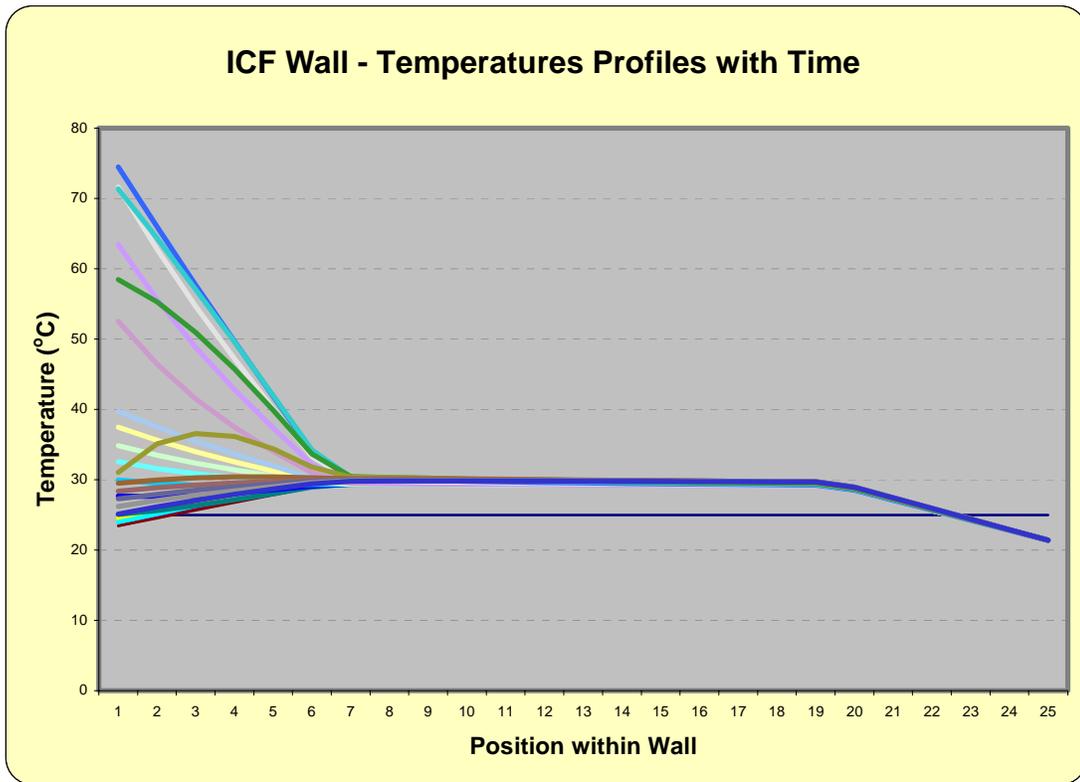


Figure 4. Predicted Hourly Temperature Profiles for the ICF Wall (left side = outside)

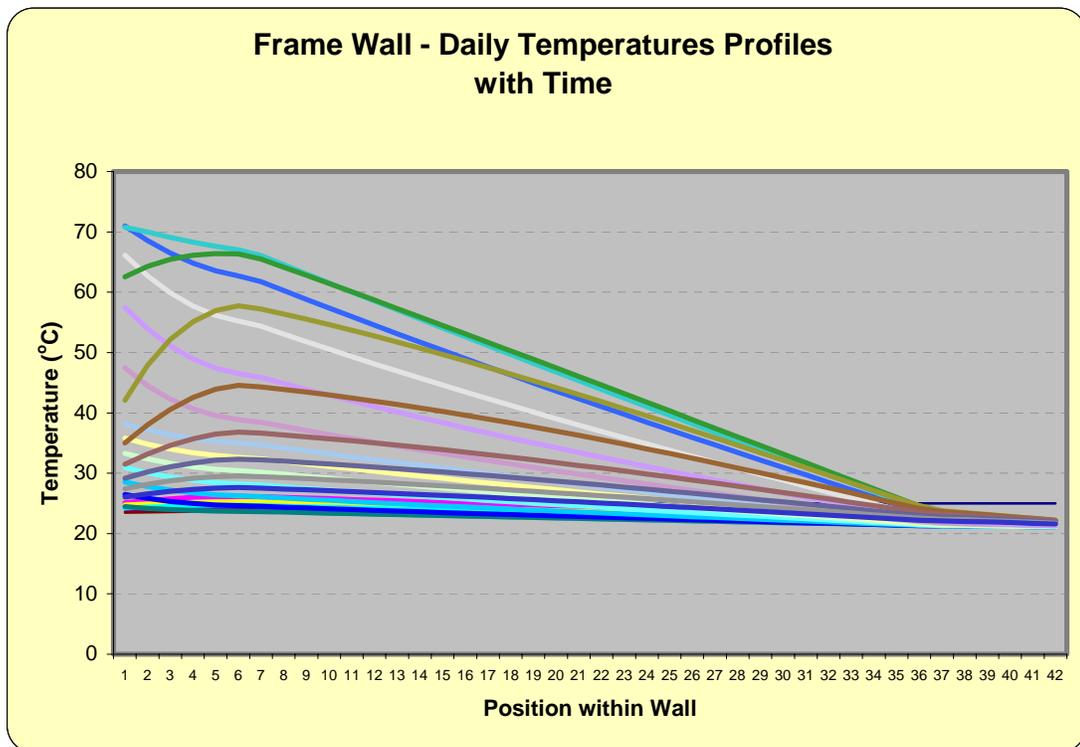


Figure 5. Predicted Hourly Temperature Profiles for the Frame Wall (left side = outside)

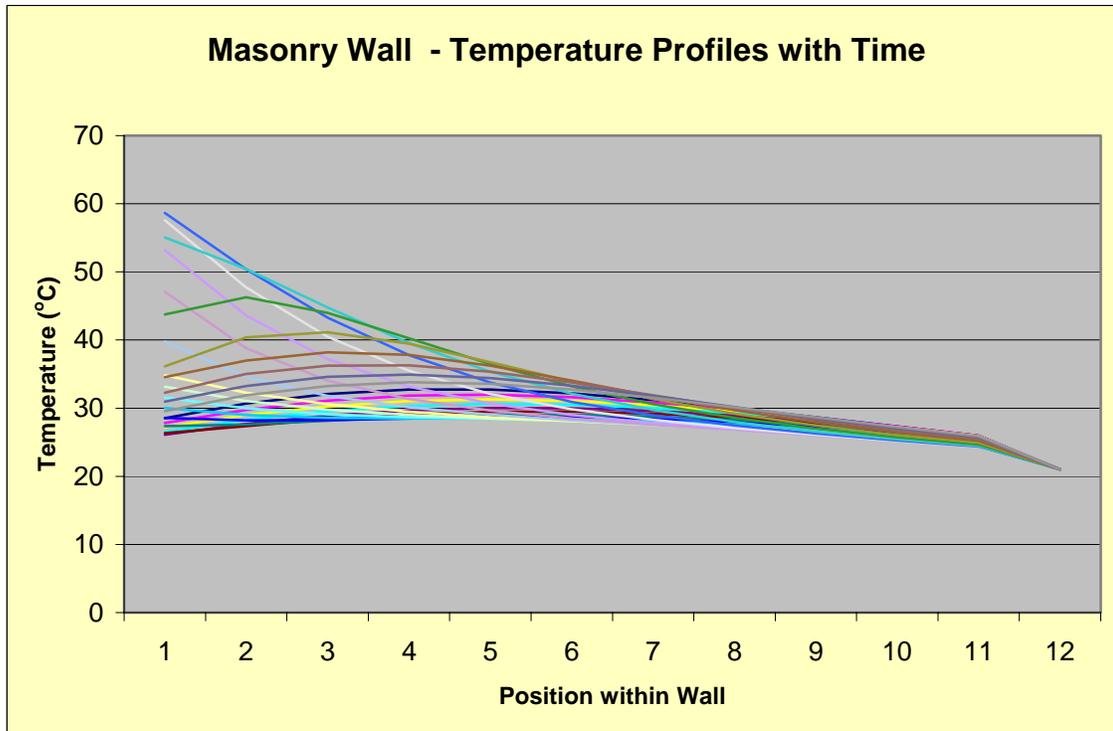


Figure 6. Predicted Hourly Temperature Profiles for the Masonry Wall (left side = outside)