Whole Wall Performance Analysis of Autoclaved Aerated Concrete: An Example of Collaboration between Industry and a Research Lab on Development of Energy Efficient Building Envelope Systems

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ABSTRACT

The main objective of this paper is presentation of results of the collaboration between an Autoclaved Aerated Concrete (AAC) concrete producer and a research laboratory on the thermal performance evaluation of AAC. Hot-box testing and finite difference computer modeling were used to analyze steady state and dynamic thermal performance of the clear wall area and wall interface details for the AAC wall systems with solid autoclaved aerated concrete blocks. Guarded hot box tests formed the basis for a finite difference computer model calibration. This computer model was then used to calculate local R-values for all typical wall interface details, the whole wall R-value, and dynamic thermal performance. This paper provides a description of the methodology used to evaluate building envelope systems. During this project detailed energy performance data for AAC concrete were created. Correlations developed can be used in designing energy efficient buildings.

Introduction

AAC is applied as a material for wall construction in residential and commercial buildings. It is a building material widely used in Europe for many years and now it is finding its place in the U.S market as well. However, there is still a very limited database for material properties of AAC in the USA. A lack of credible technical information about this material's thermal properties and the energy performance of AAC walls created several problems in designing and collaboration with code officials. That is why this project was initiated by one of the main US AAC concrete producers.

It took about three years to complete this project. During this time a very detailed experimental analysis of the AAC thermal properties was performed. Thermal conductivity of three different types of AAC blocks for various moisture contents was measured in ORNL Material Properties Laboratory using ASTM C-518 procedure. Approximate formulas expressing relations between thermal conductivity and the moisture content were developed. Next, a clear wall specimen was built in the lab and tested in the hot box. Steady state and dynamic test data were used to calibrate computer models which were utilized in thermal analysis of AAC walls. The finite difference computer code Heating 7.2 [Childs 1993] was used to analyze the clear wall area and wall interface details and to estimate zones affected by the existing thermal bridges. Whole wall R-value is calculated as a weighted-average R-value for the clear wall and its interface elements [Kośny & Desjarlais 1994]. Additionally, several cases of AAC walls with additional sheathing foam insulation are examined. Also, several changes in AAC wall details were suggested by ORNL. They were verified by structural designers from the AAC company. A notable improvement in whole wall R-value was found for a set of newly improved wall details.

Dynamic thermal performance of the AAC wall was analyzed based on dynamic guarded hot box test results. Previously calibrated for steady-state conditions, a finite difference model was used to validate thermal mass effects by comparing model-predicted and experimental values of heat flow through the test wall exposed to dynamic boundary conditions. Good agreement was found between the test and computer modeling results.

The computer model developed for the AAC wall was used in DOE 2.1E, a whole building thermal performance computer model. Six climate locations for the U.S., Atlanta, Denver, Miami, Minneapolis, Phoenix and Washington D.C., were used in simulations. The space heating and cooling loads were compared to the loads generated for similar buildings, but with light-weight wood frame exterior walls characterized by various R-values from 2.3 to 37.0 (hft^2F/Btu) range. They were used to estimate the R-values which would be needed in conventional wood frame construction to produce the same total heating and sensible cooling loads as the AAC wall building in each of the six climates. The resulting R-value equivalent is a steady-state R-value for the AAC wall multiplied by a DBMS factor (Dynamic Benefit for Massive Systems) [Kośny 1998]. To compare whole building annual energy demands of buildings constructed using AAC units, two-core CMUs, steel studs and wood frame walls, the whole building simulations of a one story ranch house, situated in six locations in the U.S., were performed as well.

Description of the AAC Wall

The AAC wall system is based on autoclaved aerated concrete solid units. AAC blocks (7-13/16 x 23-5/8 x 7 13/16-in.) are made of light-weight aerated concrete density of about 32 lb/ft^3. AAC blocks are joined using 1/16-in.-thick mortar. Normally, the AAC wall is covered by light weight stucco on the outside and plaster on the inside as shown in Figure 1. An unfinished wall was used for the hot box tests at ORNL Buildings Technology Center. The AAC wall was built and tested in the guarded hot-box under steady-state conditions.

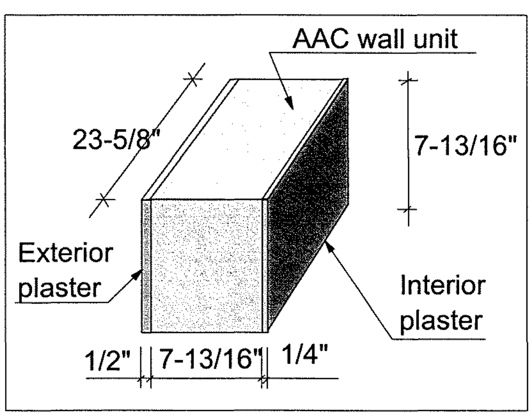

Figure 1. AAC Wall Unit with Finish Layers

Three-dimensional computer modeling was used for the AAC wall thermal performance study. A heat conduction, finite difference computer code, Heating 7.2 [Childs 1993], was used for ~~this~~ analysis. The resultant isotherm maps were used to calculate average heat fluxes and wall system R-values. The accuracy of Heating 7.2's ability to predict wall system R-values was verified by comparing simulation results with published test results for twenty-eight masonry, wood-framed, and steel-framed walls tested at other laboratories. The average differences between laboratory tests and Heating 7.2 simulation results for these walls were ± 4.7 percent [Kośny& Desjarlais 1994]. Considering that the precision of the guarded hot box method is reported to be approximately 8 percent, the ability of Heating 7.2 to reproduce the experimental data is within the accuracy of the test method [ASTM C 236].

The results of the computer modeling were then compared with R-values measured by the hot box test. Thermal conductivity of AAC block material was measured in the ORNL Material Properties Laboratory using the ASTM C 518 procedure [ASTM C 518-91]. The calibrated computer model was then used to simulate clear wall and wall interface details.

Clear Wall Thermal Performance

Wall dimensions obtained from the test AAC wall were used to develop a three-dimensional, finite difference, computer model. Thermal conductivity of AAC blocks was measured in ORNL Material Properties Laboratory using ASTM C 518 procedure. Results of ASTM C 518 tests on AAC concrete are summarized in Figure 2.

Heating 7.2 finite difference computer code was used to simulate the AAC wall. The results of the computer modeling were then compared with hot box experimental R-value measurements. This procedure enabled calibration of the computer model. Test and simulated R-values are within ±2% of each other. For thermal conductivities of all wall materials as presented in Table 1 and wall configuration as in Figure 1, the computer-generated, **surface-to-surface clear wall R-value for the AAC unit wall is 8.34 hft^{2}F/Btu.**

Table 1. Thermal properties for all wall materials used in computer simulations

Material:	Density lb/ft^3 [kg/m^3]	Conductivity k_a Btu-in./hft^{2}F [W/mK]	Specific heat Btu/lbF [kJ/kgK]	Resistivity R/in. hft^{2}F/Btu-in. [mK/W]
AAC AAC unit	31.90 [510.4]*	0.96 [0.14]**	0.25 [1.05]	1.04 [7.27]*
Mortar	80.0 [1280]***	5.0 [0.72]	0.25 [1.05]	0.2 [1.39]
Interior stucco	50.0 [800]***	1.39 [0.20]	0.25 [1.05]	0.72 [5.0]
Exterior plaster	50 .0 [800]***	1.39 [0.20]	0.25 [1.05]	0.72 [5.0]

* *As measured in ORNL BTC after the hot box test.*
** *Regression generated value based on ASTM C 518 measurements*
*** *Data submitted by AAC Building Systems [J. Achtziger - 1992, AAC - no date].*

Overall Wall Thermal Performance

Low R-values of wall interface details frequently lower overall wall R-value. Two options of wall/roof, wall/floor, door, and window header details were considered. The first option represents conventional AAC practice. The second option shows thermal improvements

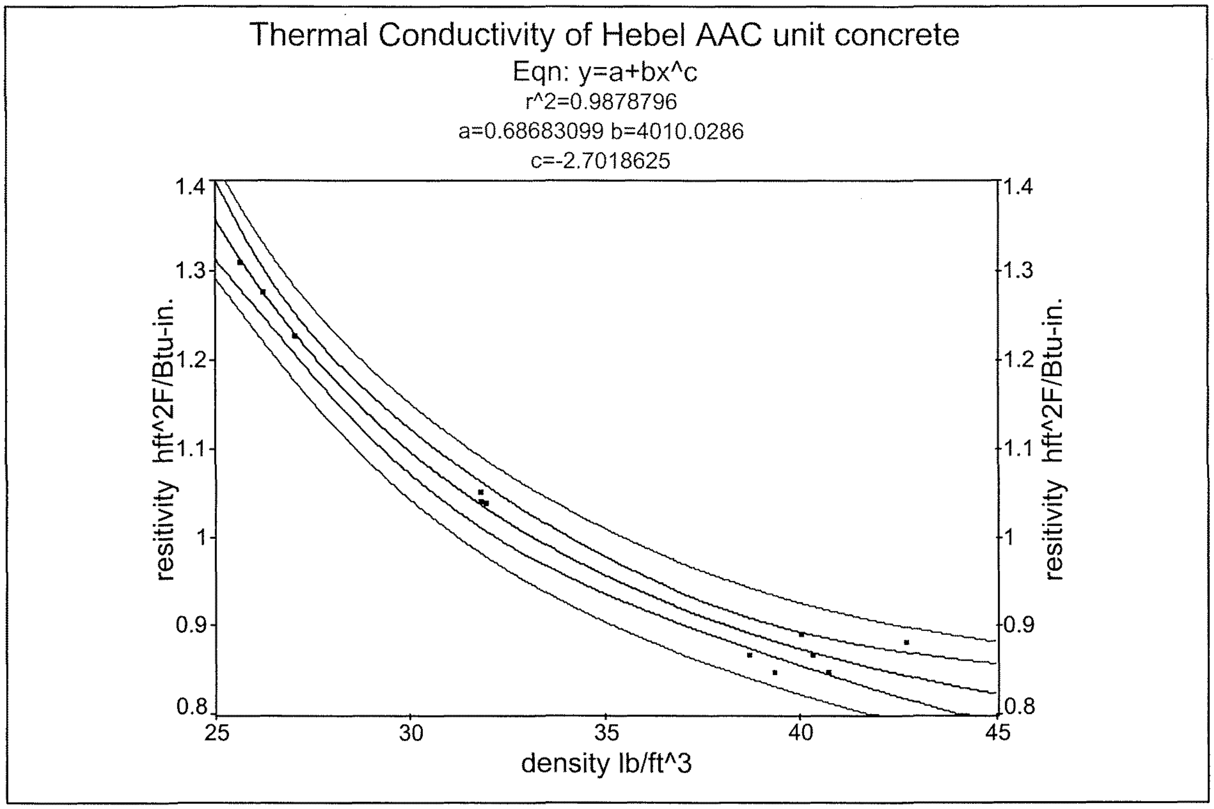

Figure 2. Relation Between Concrete Density and Thermal Resistivity for AAC Wall Units (Moisture Content/Weight 2.20 - 2.76%, Mean Temperature 50 °F)

proposed by the ORNL team. Example of thermal improvements of AAC wall details are presented in Figure 3. Most improvements introduced additional insulation inserts in locations of concrete bond beams and headers.

These details were used in computer modeling to determine the whole wall R-value. The whole-wall R-value was defined as the R-value for the whole opaque wall including the thermal performance of the "clear wall" area and all typical envelope interface details (e.g., wall/wall (corners), wall /roof, wall/floor, wall/door, and wall/window connections).

Three-dimensional computer models were developed for the AAC clear wall and wall details. Using properties presented in Table 1, **the surface-to-surface clear wall R-value of AAC wall is 8.34 [hft^{2}F/Btu]. The overall wall R-value of conventional AAC wall system is 7.13 [hft^{2}F/Btu].** The overall wall R-value is reduced by about 14% from the clear wall R-value. The impacts of wall interface details on the whole wall R-value for AAC wall system is illustrated in Figure 4.

For conventional details, the total area influenced by wall details represents about 60% of the opaque wall area. These wall details generate about 65.8% of the whole wall heat losses. The most significant impacts can be observed in case of the wall/roof interface (23.5% of wall area and 26.9% of wall heat losses).

As shown in Figure 4, for the improved set of wall details, **the overall wall R-value of AAC wall system is 7.75 [hft^{2}F/Btu].** Thermal improvement of wall details increased local wall/roof R-value about 22%, wall/ceiling R-value by about 10%, window header R-value by 39%, and door header R-value by 40%. These caused 8.7% increase of the whole wall R-value.

The total area influenced by new wall details represents about 60% of the opaque wall area. These wall details generate about 62.8% of the whole wall heat losses. The most significant impacts can be observed in case of the wall/roof interface (23.5% of wall area and 24.0% of wall heat losses). Thermal resistances of most of the wall details are very close to the clear wall R-value.

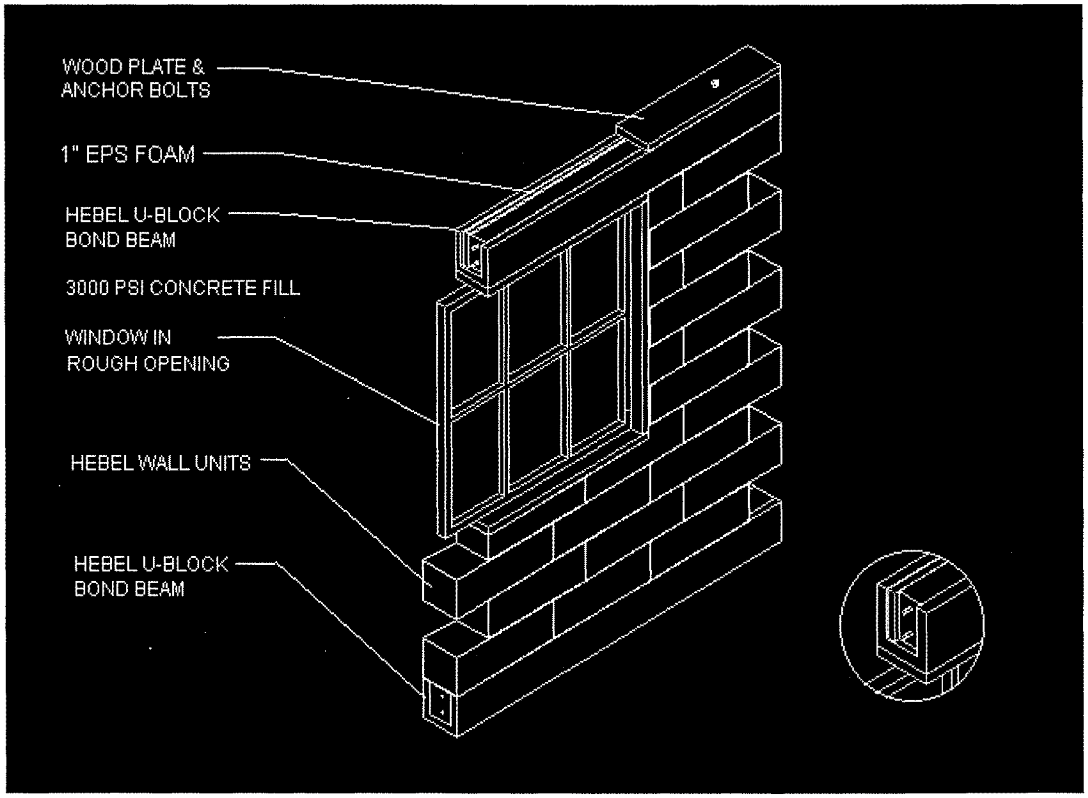

Figure 3. Example of Thermal Improvements in AAC Wall Details

Dynamic Thermal Test and Modeling of the AAC Wall

Dynamic measurements of wall systems are typically carried out by an apparatus such as described in ASTM C 236, Standard Test Method for "Steady-State Thermal Transmission Properties of Building Assemblies by Means of a Guarded Hot Box" [ASTM, 1989]. A full-scale representative (8 x 8 ft) cross-section of the clear wall area of the wall system is used to determine its dynamic thermal performance. A dynamic test typically consists of the three basic stages:

- Steady-state stage (steady temperatures on both sides of the wall),
- Thermal ramp (rapid change of the temperature on the one side of the wall), and
- Stabilizing stage (wall is kept under the second set of steady boundary temperatures until steady-state heat transfer occurs)

The precision of dynamic testing is assumed to be close to the precision of the steady-state test method which is reported to be approximately 8% [ASTM 1989]. The dynamic test results were used to calibrate the finite difference computer model that served in the analytical part of this project. A wall built with the AAC units was tested in the guarded hot box under the dynamic conditions.

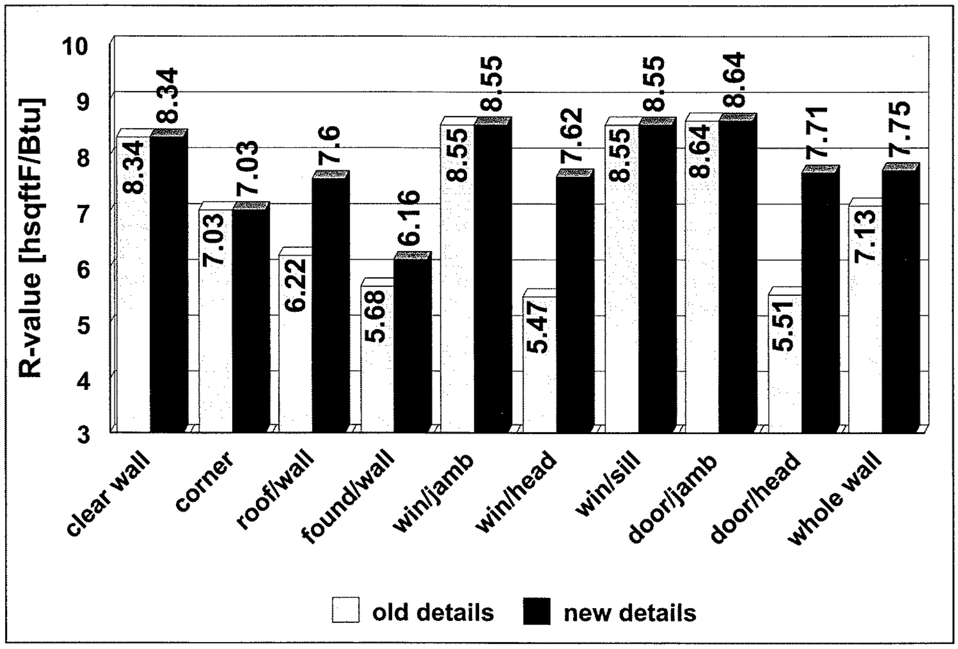

Figure 4. Whole Wall R-values for Old and New AAC Wall Details

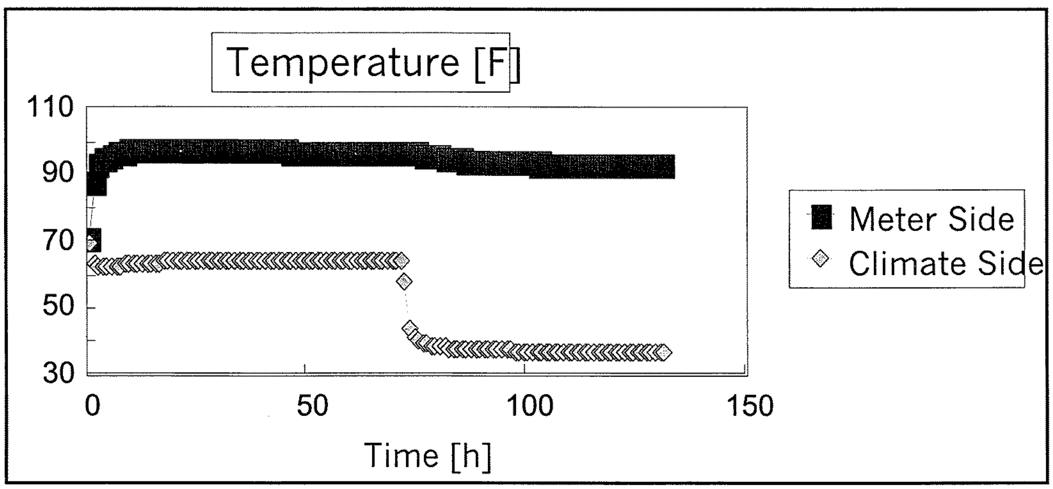

Figure 5. Temperature Profiles For Dynamic Hot Box Test of the AAC Wall

The dynamic response of the wall was analyzed for a 30°F thermal ramp. (It took 2 hours to change the surface temperature on the climate side of the wall from 60°F to 30°F.) Temperatures on both sides of the wall were stabilized and the experiment was continued until steady-state heat transfer occurred. During the first stage of the test process, air temperatures were stabilized at 100°F (metering chamber side) and 60°F (climate chamber side). During the second stage, the climate side air temperature was reduced from 60°F to 30°F. Next, the temperatures were stabilized at about 100°F (metering chamber side) and 30°F (climate chamber side). Air temperatures for the meter and climate sides of the wall are presented in Figure 5.

The measured air temperatures 6 inches away from the surface of the metering side and 14 inches away from the climate side, along with air velocities measured in the meter — and climate chambers, were used as boundary conditions for dynamic modeling of the AAC wall. The computer program reproduced all recorded test boundary conditions (temperatures and heat transfer coefficients) at one hour time intervals. Values of heat flux on the surface of the wall generated by the program were compared with the values measured during the dynamic test. The computer program reproduced the test data very well. The average discrepancy between tests generated and simulated heat fluxes was less than 2.5%. This comparison confirmed the ability of Heating 7.2 to reproduce the dynamic heat transfer process measured during the dynamic hot box test of the actual AAC wall.

Dynamic Thermal Performance of the AAC Wall

The computer model developed for the AAC wall was used in DOE 2.1E whole building computer simulations. The purpose was to determine the effective R-value of the AAC wall. The space heating and cooling load data which is output from the LOADS portion of DOE 2.1E report was utilized in this analysis. Six U.S. climates were used for whole building thermal modeling and determination of the effective R-value of the AAC wall system. A list of cities and climate data are presented in Table 4.

To normalize the calculations, a standard residential building elevation was used. The standard elevation selected for this purpose is a single-story, ranch-style house that has been the subject of previous energy efficiency modeling studies [Hasting 1977, Huang 1987, Christian 1991, Kośny 1998]. The house has approximately 1540 ft^2 of living area, 1328 ft^2 of exterior (or elevation) wall area, 8 windows, and 2 doors (one door is a glass slider; its impact is included with the windows). The elevation wall area includes 1146 ft^2 of opaque (or overall) wall area, 154 ft^2 of window area and 28 ft^2 of door area.

Table 4. Six U.S. climates used for DOE 2.1E computer modeling

Cities:	HDD (65 deg F)	CDD (65 deg F)
Atlanta	3070	1566
Denver	6083	567
Miami	185	4045
Minneapolis	8060	773
Phoenix	1382	3647
Washington D.C.	4828	1083

For the base case calculation of infiltration, we used the Sherman-Grimsrud Infiltration Method option in the DOE 2.1E whole building simulation model [Sherman & Grimsrud 1980]. We assumed an average total leakage area expressed as a fraction of the floor area of 0.0005. This is considered average for a single zone wood-framed residential structure. Cooling, heating, and total load (heating+cooling) were estimated for the AAC walls in the house described above. Simulated results are presented in Table 5 for the six U.S. climates.

For the same building and climates, similar energy simulations were performed for conventional wood-framed (2x4 construction) walls of R-value from 2 to 37 hft^2F/Btu. The total-space heating and cooling load consumption data for the wood-framed walls is used for the analysis of the dynamic thermal performance of the AAC wall. The DOE-2.1E input file with AAC walls, was modified. The AAC walls were replaced with light-weight wood-framed walls. The thermal mass benefit is put in terms of the effective R-value, which is the light-weight wall R-value for the same climate and the same heating and cooling loads as the building with AAC walls.

Table 5. Simulated heating and cooling energy required for the south-faced, ranch house built with the AAC walls (for the six U.S. locations).

Location	Cooling Energy [MBtu]	Heating Energy [MBtu]	Total Energy [MBtu]
Atlanta	7.4	25.1	32.5
Denver	1.21	48.32	49.5
Miami	37.36	0.65	38.01
Minneapolis	2.05	82.72	84.77
Phoenix	31.73	5.27	37.0
Washington, D.C.	4.33	42.56	46.89

For the south-facing house, cooling and heating loads needed for the light-weight wood-framed wall building are presented in Figure 6 (for double pane windows and R-30 roof insulation). Based on comparisons between total loads necessary for heating and cooling the light-weight wood-framed building and the AAC unit house, DBMS values (Dynamic Benefit for Massive Systems) [Kośny 1998] for the finished AAC walls are estimated for six U.S. climates and four building orientations. The product; **"[steady state R-value (for AAC wall)] x DBMS" expresses the R-value which would be needed in conventional wood-framed construction to produce the same loads as the AAC wall system in each of the six climates.** This product accounts for not only the steady state R-value but also the inherent thermal mass benefit. DBMS is a function of climate, building type, building orientation, and base envelope system (i.e. conventional 2x4 wood-framed technology). For AAC walls, DBMS values are presented in Figure 7. They were obtained by comparison of the thermal performance of the same house built with AAC wall units and light-weight wood-framed house. There is no physical meaning for the product "R-value x DBMS."

As shown in Figures 6 and 7, the AAC wall is most effective in Phoenix. Minneapolis is the location where the effectiveness of the AAC wall units is lowest. However, even in Minneapolis, wood-framed construction would require R-value 31% higher than the AAC wall to produce the same loads as the AAC house. Dynamic R-value equivalents reflecting the inherent "dynamic thermal performance effect" are presented in Figure 8. These effective R-values were calculated by multyplying the **AAC wall steady-state R-value and DBMS values. They express the R-values which would be needed in conventional wood-framed construction to produce the same total loads as the AAC wall system in each of the six climates.**

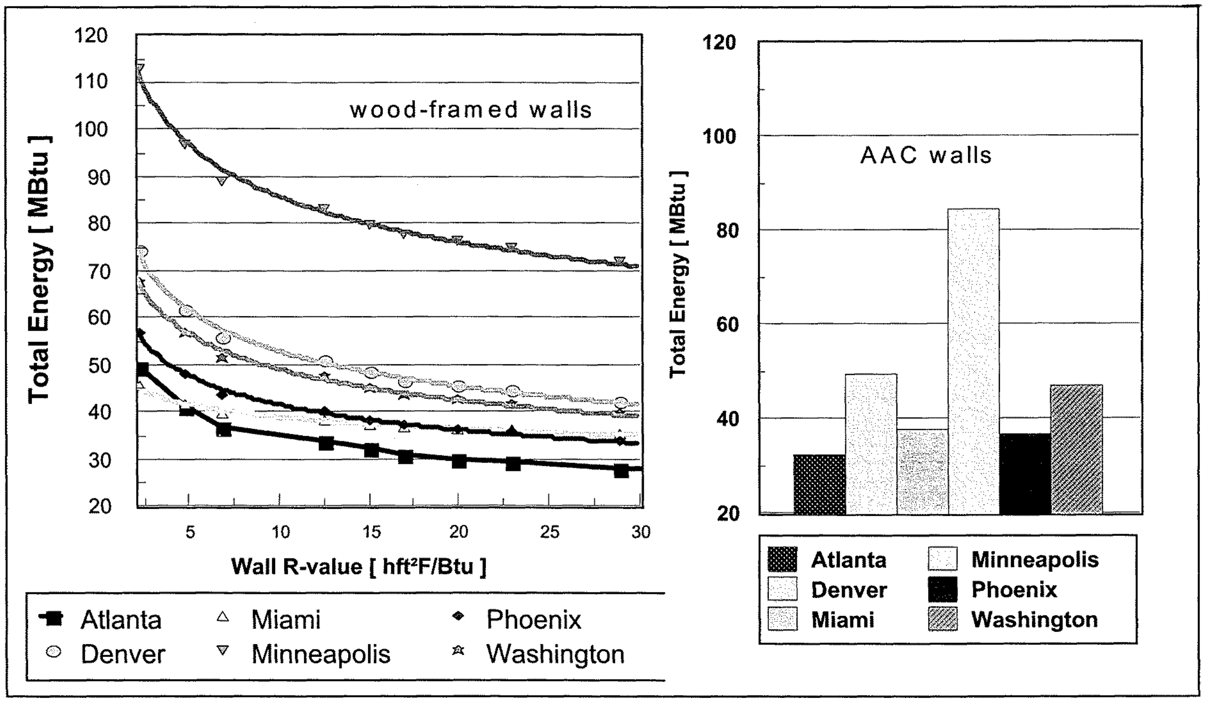

Figure 6. Comparison of Total Energy Consumption for One-story Residential Building Built with Wood-framed Structure and AAC Masonry Units

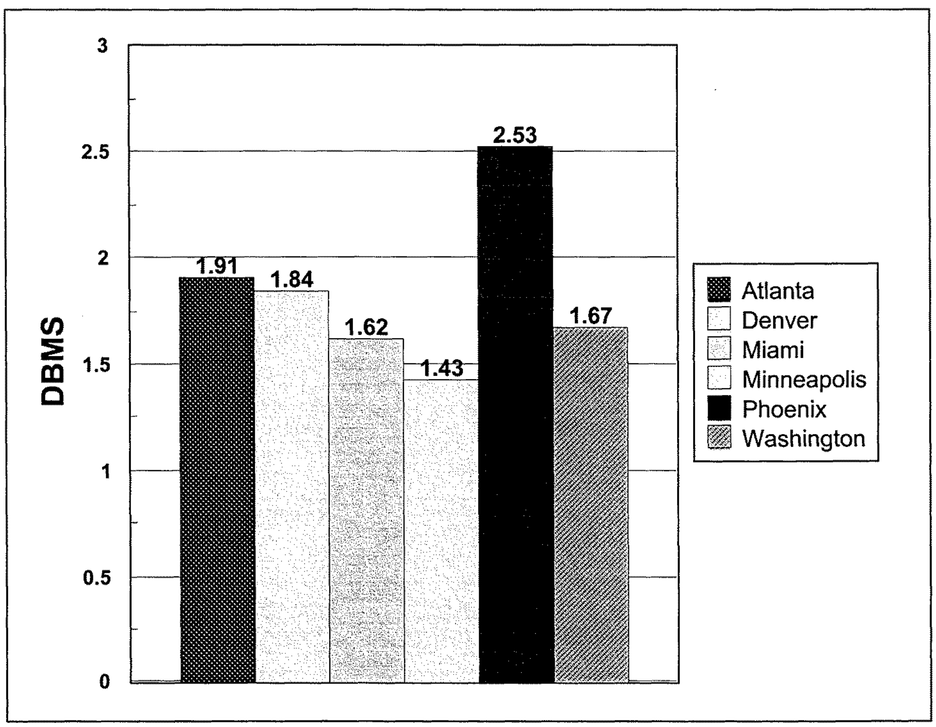

Figure 7. DBMS Values for Wall Made Using AAC Units

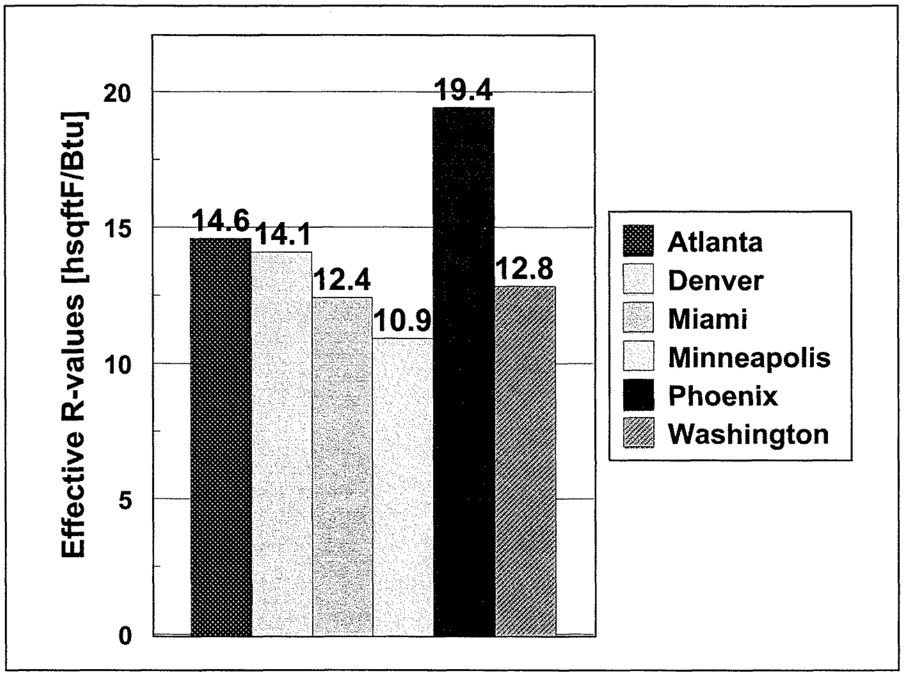

Figure 8. Dynamic R-value Equivalents for the AAC Wall

Conclusions

Calibrated finite-difference computer modeling was used to examine the steady-state thermal performance of the AAC wall system. Steady-state **surface-to-surface clear wall R-value for the AAC unit wall is 8.34-hft^{2}F/Btu**. For a set of typical wall details, **the overall wall R-value of the AAC wall system is 7.13- hft^{2}F/Btu.**

New wall details were proposed by ORNL team to improve overall wall thermal performance of the AAC wall system. For **improved wall details, the overall wall R-value of the AAC wall system is 7.75- hft^{2}F/Btu.** It is only about 7% lower than clear wall R-value. For a conventional 2x4 wood-framed wall, this reduction is about 9%. Due to thermal improvement of wall details the whole wall thermal performance of the AAC unit wall system was improved. Redesigning wall details caused an increase of local wall/roof R-value of about 22%, wall/ceiling R-value of about 10%, window header R-value of 39%, and door header R-value of 40%. These changes in detail configuration caused 8.7% increase of the whole wall R-value.

Thanks to the solid concrete walls, the total space heating and cooling load of the house built with the AAC wall can be significantly reduced when compared to a light frame wall with the same steady-state R-value. It was found that the most effective application of the AAC walls is in Phoenix. Minneapolis is the location where energy efficiency of AAC wall units is lowest. However, even in Minneapolis, wood frame construction would require R-value 31% higher than the AAC wall to generate the same total heating and cooling loads as the AAC wall system. In Phoenix, wood frame construction would require R-value 133% higher for equivalent energy performance.

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