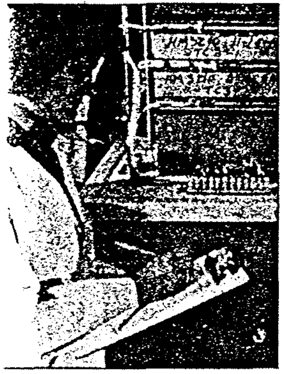
THERMAL MASS

What R-Values Neglect



Heat transmission coefficients, such as thermal resistance (R-value) and thermal transmittance (U-value), describe wall performance for constant temperature conditions. These values, however, do not hold true with masonry walls, which store and later release heat when subjected to dynamic temperatures—a phenomenon known as "thermal mass." For dynamic temperature conditions, R-values and U-values don't adequately describe the thermal performance of masonry walls.

Laboratory tests use a calibrated hot box (ASTM Designation: C 976)[1] to determine the thermal mass effects of walls and other building components. During dynamic calibrated hot box tests, heat flow is measured through a test specimen exposed to temperature changes typical of an exterior wall. The response of a test wall to temperature changes is a function of both thermal resistance and heat storage capacity.

This article describes calibrated hot box test results for four masonry walls and one frame wall. Measured heat flows are compared to predicted heat flows based on R-values.

Background

The energy crisis following the Arab oil embargo of 1973 significantly impacted the building industry. Increased costs for oil, natural gas, and electricity resulted in higher building operating costs. Building material costs escalated due to higher costs for manufacturing and transportation.

Government and industry concern for energy conservation led to the development of a number of energy standards[2–4] used by state governments as the basis for strict energy requirements in state enforced building codes. These codes and standards usually contain prescriptive requirements specifying insulating values, or R-values, for walls and other components of the building envelope.

Investigations performed by the Portland Cement Association[5–11] and

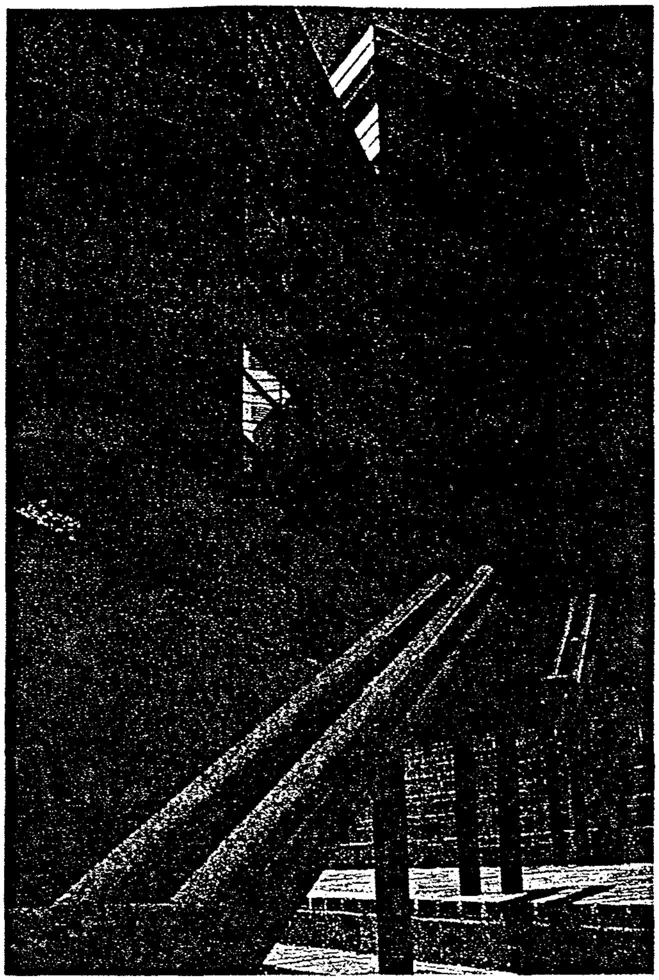


Photo by Bob Burgess

When planning for energy efficiency, consider the thermal storage capacity of a building's components.

other organizations[12–15] show that buildings constructed of concrete and masonry require less insulation to meet necessary heating and cooling loads than buildings constructed of lighter materials. This is because concrete and masonry can store and release large quantities of heat. In so doing, heat transfer through massive components is delayed, and some of the stored energy is later used to heat interior spaces. This mass effect has been observed in both heating and cooling seasons.

Some prescriptive energy standards require that certain R-values be met, regardless of the type of construction. On the other hand, performance energy standards state only the amount of energy a building can consume, without specifying how that limit is to be reached. This allows building designers to use innovative and cost effective energy conservation measures. Using performance standards, the benefits of thermal mass can be fully realized.

R-values are frequently used to compare wall or roof systems. For example, promoters of an insulated wood frame wall or insulated prefabricated metal wall may publish literature showing higher (preferred) R-values for their walls when compared to a particular concrete or masonry wall. These R-value comparisons are misleading as they neglect the effect of thermal mass on energy performance.

Laboratory Tests

Thermal resistance of a homogeneous material, such as an insulation product, is usually measured in a guarded hot plate (ASTM Designation: C177)[1] or a heat flow meter (ASTM Designation: C518)[1].

The calibrated hot box (ASTM Designation: C976)[1] and guarded hot box (ASTM Designation: C236)[1] are specially suited for measuring thermal response of large nonhomogeneous specimens such as masonry, wood frame, or prefabricated metal walls.

Regardless of the test method, thermal resistance is determined from steady-state test results. Steady-state tests are performed by maintaining a constant, but different, temperature on each side of the test specimen. Thermal resistance is the temperature difference across the specimen divided by the heat flow per unit area.

Effects of thermal mass can be determined only from test facilities with dynamic capabilities. During dynamic testing, either one or both sides of the test specimen are subjected to fluctuating temperature conditions. Fluctuating the temperature on the outdoor side of the specimen simulates outdoor temperature conditions. Fluctuating the temperature on the indoor side simulates floating temperature conditions, such as nighttime set-back control strategies.

Since 1979, more than 25 walls

have been tested in Construction Technology Laboratories' calibrated hot box.[16, 17] Results from five of these walls are discussed in this article.

Test Procedures

An uninsulated concrete block wall, an insulated block wall, an uninsulated block-brick cavity wall, an insulated block-brick cavity wall, and a wood frame were tested in the calibrated hot box. Wall descriptions and properties are listed in *Table 1.*[16, 17] All specimens were full-size walls, and measured 8 feet 7 inches square. The insulated block wall and insulated block-brick cavity wall were constructed by adding expanded perlite insulation to the uninsulated block wall and cavity wall, respectively.

Tests for dynamic temperature conditions are conducted by conditioning air on the outside surface of the wall to simulate a particular daily tempera-

Table 1 — Wall Descriptions and Properties[16, 17]

Wall Designation	Wall Description	Measured Unit Weight, psf	Measured Thickness, in.	Measured Thermal Resistance R*, hr•ft²•°F/Btu
UM	Medium weight hollow core concrete block	40.1	7.6	2.8
IM	Medium weight hollow core concrete block with expanded perlite loose-fill insulation in cores	40.9	7.6	4.3
UC	Uninsulated cavity wall: 6-in. hollow core concrete block and 4-in. clay brick separated by a 2.8-in. air space	81.0	12.1	3.5
IC	Insulated cavity wall: 6-in. hollow core concrete block and 4-in. clay brick separated by 2.8-in. of expanded perlite loose-fill insulation	82.0	12.1	9.4
F	2×4-in. wood frame with R-11 fiberglass batt insulation between studs; gypsum wallboard on inside surface, and plywood cedar siding on outside surface	5.3	4.8	12.0

*For a 75°F wall mean temperature; interpolated from calibrated hot box test results.

Table 2 — Thermal Lag, Reduction in Amplitude, and Total Heat Flow from a Calibrated Hot Box Dynamic Temperature Test[16, 17]

Wall Designation	Wall Description	Thermal Lag, hrs	Reduction In Amplitude, %	Total Heat Flow,* Btu/ft² I Measured	II Calculated	I ÷ II %
UM	Uninsulated block	3.0	18	133	169	79
IM	Block with expanded perlite in cores	3.5	28	72	101	72
UC	Uninsulated block-brick cavity wall	5.5	43	70	121	57
IC	Block-brick cavity wall with expanded perlite in cavity	7.0	50	22	39	57
F	Wood frame with R-11 fiberglass batt insulation	1.5	7.5	38	43	89

*For a 24-hr cycle

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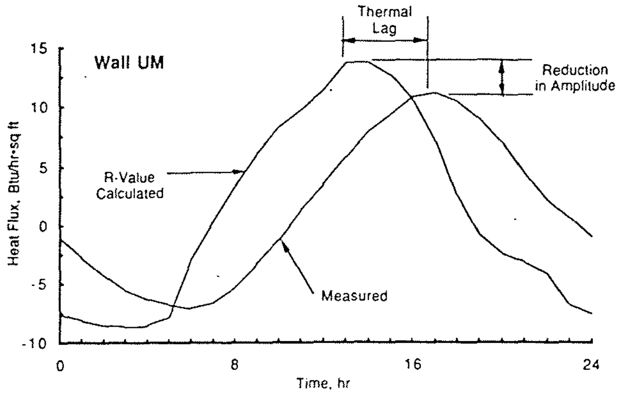
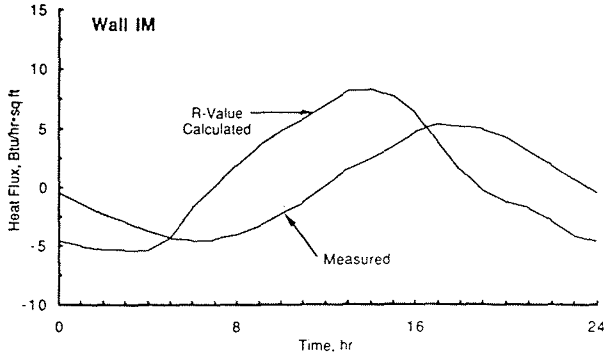
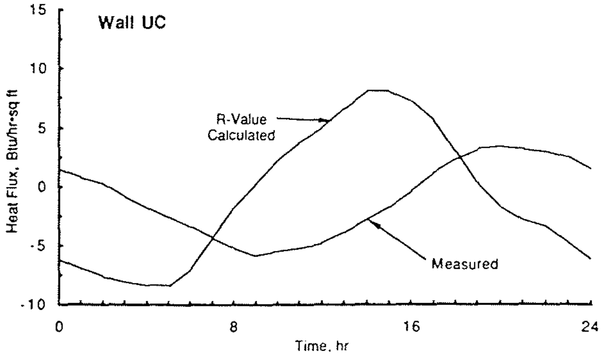
Figure 2: **Heat flux measure using a calibrated hot box and calculated from R-values.**



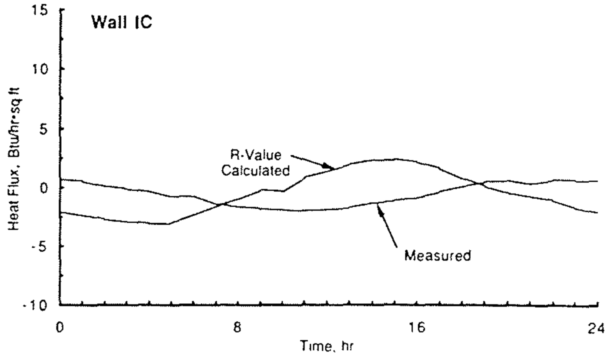
Uninsulated block



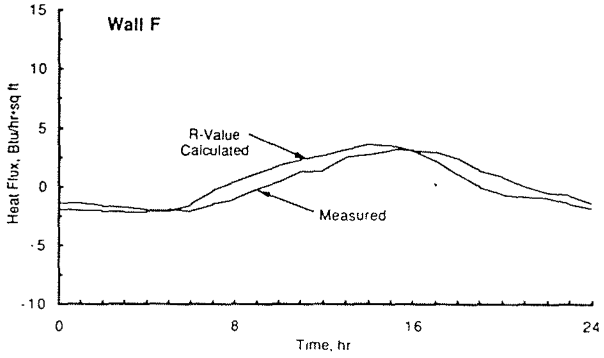
Block with expanded perlite in cores



Uninsulated block-brick cavity wall

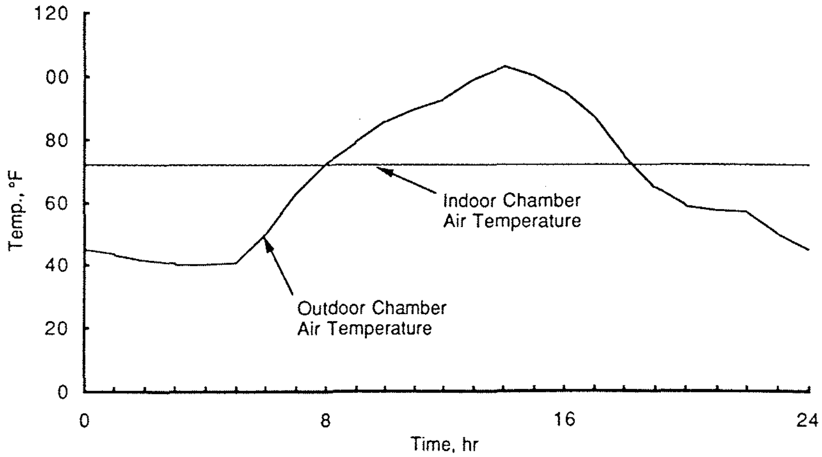


Block-brick cavity wall with expanded perlite in cores



Wood frame with R-11 fiberglass batt insulation

Figure 1: **Dynamic temperature cycle applied to all walls.**



ture cycle *(Figure 1)*. The early morning hours are cool, and peak temperatures are reached in the early afternoon. This 24-hour cycle, called the NBS Temperature Cycle, was used by the National Bureau of Standards to evaluate the dynamic thermal performance of an experimental masonry building.[15] The cycle accounts for the sun's radiation on a wall's surface. Air on the indoor side of the specimen was maintained at approximately 72°F for all tests.

Test Results

Figure 2 shows heat flows measured by the calibrated hot box through each of the five walls. *Figure 2* also shows heat flows calculated assuming R-values are true predictors of heat flow through walls. These values, denoted "R-Value Calculated," are based on the basic steady-state heat transfer equation:[1] $q_{ss} = (t_2 - t_1)/R$
where:

q_{ss} = heat flow through test wall predicted from steady-state heat transfer, Btu/hr•ft^2

R = thermal resistance of wall, hr•ft^2•°F/Btu

t_2 = temperature of outdoor wall surface

t_1 = temperature of indoor wall surface

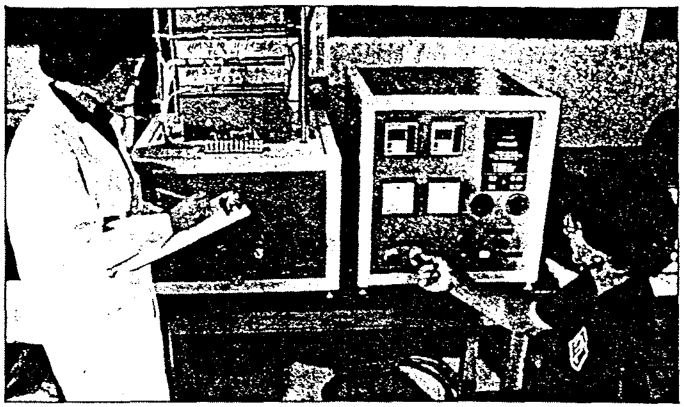
The peaks of the measured curves for all walls in *Figure 2* are shifted several hours later compared to peaks for the calculated curves. This shift in peaks is called thermal lag. Thermal lags for the five walls are listed in *Table 2*. These values are the average of the difference in hours between calculated and measured heat flows at the points of maximum and minimum heat flow.

Thermal lag is of interest because the time peak heat flows occur will affect overall building envelope response. If the envelope can be used to delay peak loads, it may be possible to improve energy efficiency. The lag effect is also useful for passive solar applications.

Figure 2 also shows that the amplitude of the measured heat flow curves is less than that for the calculated heat flow curves. The percent reduction in amplitude for the five walls is also listed in *Table 2*. These values are the average of the reduction in amplitudes at the points of maximum and minimum heat flow.

Actual maximum heat flow through a wall is important to determine the peak energy load for a building envelope. Using actual peak heat flow rather than heat flow based on steady-state theory may reduce peak energy demands.

Thermal lags and reduction in amplitudes are greater for the four



Guarded hot plate test equipment.

masonry walls compared to the wood frame wall. This is due to the thermal storage capacity, or mass, of the masonry.

Wood is also a thermal storage material. The thermal lag of 1.5 hours and reduction in amplitude of 7.5 percent for the insulated frame wall are partly due to wood studs.

Thermal lag and reduction in amplitude are dependent on both the wall's thermal resistance and heat storage capacity. Thermal lags increased ½ hour and 1½ hours, respectively, when expanded perlite insulation was added to the block wall and cavity wall. Reduction in amplitudes increased ten percent and seven percent respectively, when expanded perlite insulation was added to the block wall and cavity wall.

Total heat flow through each wall for a 24-hour cycle is also listed in *Table 2.* Measured total heat flow is determined from calibrated hot box test results, and is equal to the sum of the absolute values of the areas between the axis of zero heat flow and the measured heat flow curves in *Figure 2.* Calculated total heat flow is similarly determined using the calculated heat flow curves.

Total heat flow is the amount of energy that must be supplied to the indoor side of the wall to keep that side at a constant temperature. Total heat flow can be used to compare the energy efficiency of different wall systems for a particular dynamic temperature cycle.

Table 2 shows that the ratio of measured to calculated total heat flow is closest to unity for the wood frame wall. For the masonry walls, measured total heat flow is 21 percent to 43 percent less than total heat flow calculated from R-values. This means that 21 percent to 43 percent less heat will be lost or gained through the masonry walls than would be predicted using R-values. This difference between measured and calculated performance is due to the thermal storage capacity of the masonry walls.

Calibrated hot box test results also show that the insulated cavity wall with an R-value of 9.4 hr•ft^2•°F/Btu had 42 percent less total measured heat flow than the wood frame wall with a higher R-value, equal to 12.0 hr•ft^2•°F/Btu. Total measured heat flows for the insulated cavity wall and wood frame wall, respectively, were 22 and 38 Btu/ft^2. For the dynamic temperature cycle applied to these walls, R-value is not a good indicator of wall performance.

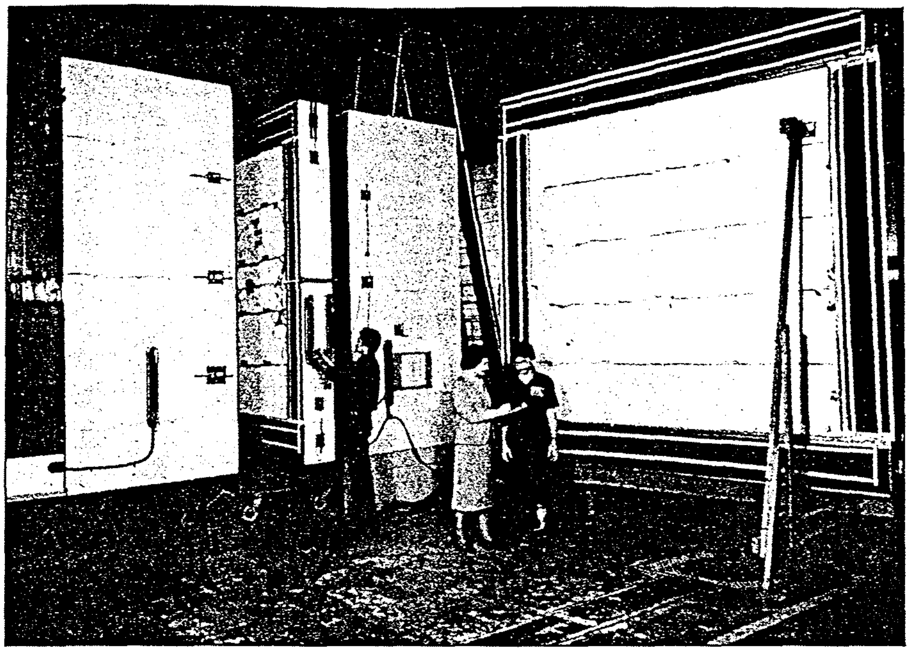
Limitations

Comparisons of total measured heat flow through test walls is limited to specimens and dynamic cycles evaluated in this program. Results are for 24-hour (diurnal) test cycles, and should not be arbitrarily assumed to represent annual heating and cooling loads. A complete analysis of building energy requirements must consider the entire building envelope, building orientation, operation, and yearly weather conditions.

Reduction in amplitude and the ratio of measured to calculated heat flow vary depending on the temperature cycle applied to a wall. The difference between measured performance and heat flow calculated from R-values will be greatest for temperature cycles that cause reversals of heat flow through walls. An example is a cycle with an outdoor air temperature that fluctuates above and below an indoor air temperature of 70°F.

Annual loads may be determined from a program that includes calibrated hot box tests and computer simulations. Calibrated hot box tests should be performed on a test specimen under a range of dynamic temperature conditions representative of a desired climate or climates. Wall thermal properties developed from test results are used in computer simulations to predict annual heating and cooling loads for particular locations. The BLAST program[18] and DOE-2 program[19] are two computer programs used to evaluate building energy use.

An alternative solution for evaluating annual performance is to develop



Calibrated hot box test facility.

standard dynamic temperature cycles representing a wide range of climates within the U.S. Alternative wall systems would be tested using selected standard cycles for the climate being evaluated. Dynamic heat transmission coefficients from walls tested using the same cycle could be compared.

A task force on Dynamic Response within ASTM Committee C16 on Thermal Insulation is developing a standard method for dynamic temperature testing using hot boxes. Preliminary indications are that standard cycles will be applied to walls, and test results will be used to analytically determine the test specimen's transfer functions. Transfer functions can then be used to predict wall performance for any dynamic temperature condition.[20]

Most code officials and building energy modelers are aware of mass effects. Yet R-values, because of their simplicity, continue to be used to compare alternative wall systems. A universally accepted coefficient for characterizing mass effects has not been developed because the effects of mass vary depending on the temperature cycle applied to a wall. □

Notes

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