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Measuring Thermal Performance of Wall Assemblies under Dynamic Temperature Conditions

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ABSTRACT: The calibrated hot box (ASTM Test for Thermal Performance of Building Assemblies by Means of a Calibrated Hot Box [C 976]) is used to measure thermal performance of wall assemblies under dynamic temperature conditions. ASTM C 976 does not specify procedures for dynamic testing, or analysis and presentation of results. Dynamic testing procedures used by Construction Technology Laboratories (CTL), including instrumentation of test specimens, derivation of dynamic temperature cycles, acquisition of test data, and presentation of results, are described in this paper. Since 1979, CTL has applied dynamic temperature cycles to 25 wall assemblies using the calibrated hot box.

Thermal lag, reduction in amplitude, and the total heat flow ratio are three coefficients used by CTL to describe test specimen behavior under dynamic temperature conditions. These coefficients are derived from comparisons of measured results to values predicted by a steady-state analysis. Thermal lag, reduction in amplitude, and the total heat flow ratio characterize effects of thermal storage capacity. Derivation, usefulness, and limitations of these dynamic heat transmission coefficients are discussed.

KEY WORDS: calibrated hot box, energy, heat transmission, thermal resistance, thermal inertia, thermal storage capacity, transient response, walls

Nomenclature

- A Area of specimen surface normal to heat flow
- A' Reduction in amplitude
- α Thermal diffusivity of wall material
- C Average thermal conductance of test specimen
- c Specific heat of wall material
- k Thermal conductivity of wall material
- L Wall thickness
- M A theoretical factor related to wall thermal storage capacity
- P Period of dynamic cycle
- Q_c Heat removed by indoor chamber cooling
- Q_f Heat loss/gain from flanking path around specimen
- Q_{fan} Heat supplied by indoor chamber circulation fan
- Q_h Heat supplied by indoor chamber electrical resistance heaters
- Q_ℓ Heat loss/gain from laboratory
- Q_w Heat transfer through test wall
- q_1 Heat flux at indoor surface of test specimen
- q_2 Heat flux at outdoor surface of test specimen
- q' Maximum or minimum measured heat flux through test specimen
- $\bar{q}$ Mean measured heat flux through test specimen
- q'_{a+} Positive heat flux integrated over time as shown in Fig. 10
- q'_{a-} Negative heat flux integrated over time as shown in Fig. 10
- q_{ss} Heat flux through specimen predicted by steady-state analysis
- q'_{ss} Maximum or minimum heat flux through test specimen predicted by steady-state analysis
- $\bar{q}_{ss}$ Mean heat flux through test specimen predicted by steady-state analysis
- q^T_{ss} Total heat flux predicted by steady-state analysis for a 24-h period
- q_w Heat flux through specimen measured by calibrated hot box
- q^T_w Total heat flux measured by calibrated hot box for a 24-h period
- R Thermal resistance or average thermal resistance of test specimen
- ρ Wall density
- T Time
- t_1 Temperature at indoor surface of test specimen
- t_2 Temperature at outdoor surface of test specimen
- U Thermal transmittance of test specimen

Introduction and Objectives

Laboratory test results of building envelope components tested under steady-state and dynamic temperature conditions are needed to develop methods of accurately predicting energy losses and gains to the building envelope. Experimental data are needed to verify analytical models used to estimate energy requirements under dynamic conditions. Laboratory tests can provide a direct means of investigating dynamic response of various assemblies under controlled conditions. Accurately predicting energy consumption will allow architects and engineers to optimally size heating, ventilating, and air-conditioning equipment, and select viable alternative wall and roof systems.

The calibrated hot box (ASTM Test for Thermal Performance of Building Assemblies by Means of a Calibrated Hot Box [C 976]) is used to measure thermal performance of building elements such as walls under steady-state, transient. and periodically varying (dynamic) temperature conditions. Steady-state results are used to de-

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fine heat transmission coefficients such as thermal transmittance (U-value) and thermal resistance (R-value). Data obtained during transient and periodic temperature variations are used to define dynamic thermal response. Dynamic testing is particularly important for massive envelope components that store as well as transmit heat.

ASTM C 976 states that detailed written operating procedures "shall be developed that will ensure that tests are in accordance with the requirements of this method." Tests may be performed in many different ways, while still conforming to the specification. Operating procedures at Construction Technology Laboratories (CTL), described in this paper, have been developed to conform to the standard and to ensure consistency during tests.

Consistency of test procedures is particularly important for dynamic tests. Steady-state test results can be summarized in terms of thermal resistance (R). Operating procedures for steady-state tests and calculation methods for determining R are described in ASTM C 976. On the other hand, dynamic test results can be summarized by several coefficients, including thermal lag, reduction in amplitude when compared to steady-state predictions, and the total heat flow ratio. Dynamic test procedures and methods of calculating dynamic coefficients are *not* described in ASTM C 976. Furthermore, these dynamic coefficients are dependent on the particular dynamic cycle applied to the test wall. Detailed operating procedures are required to ensure that dynamic cycles are correctly applied to the test wall. Standard dynamic coefficients are useful for comparing results from different tests performed on the same wall, the same test performed on different walls, and interlaboratory results.

Since 1979, Construction Technology Laboratories has used the calibrated hot box to apply dynamic temperature cycles to 25 wall assemblies. Test procedures used by CTL, including instrumentation of test specimens, derivation of dynamic temperature cycles, acquisition of test data, and presentation of test results, are described.

Thermal lag, reduction in amplitude, and total heat flow ratio characterize thermal storage capacity. Derivation, usefulness, and limitations of these dynamic coefficients are discussed.

Background

Alternative wall systems are frequently evaluated by comparing steady-state heat transmission coefficients such as U and R values. Steady-state heat transmission coefficients do not include effects of thermal storage capacity present during dynamic temperature conditions. Benefits of storage capacity may be illustrated using the following example of transient heat flow.

When either bounding surface temperature on a wall in steady-state equilibrium is changed to another constant value, the subsequent steady-state condition is not achieved immediately. Heat flow from the time the temperature is changed until steady-state conditions are reached is referred to as *transient heat flow*. The difference between steady-state and transient conditions may be illustrated by considering idealized temperature profiles across an infinitely wide homogeneous wall section.

For example, Fig. 1*a* illustrates the condition where outdoor and indoor temperatures are equal and the homogeneous wall is in a steady-state condition. In this case, the temperature gradient is zero, and there is no heat flow through the wall.

At time 0, illustrated in Fig. 1*b*, a heat flux is applied to the outdoor surface of the wall and the outdoor surface temperature

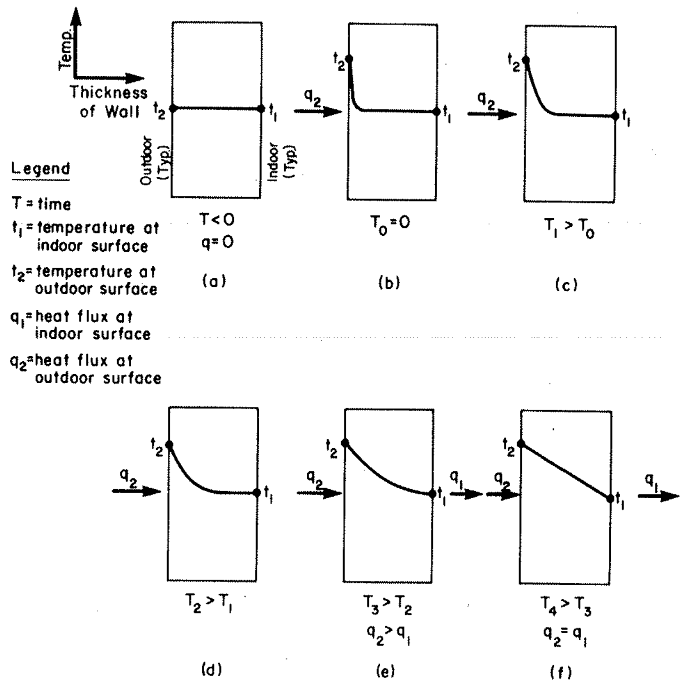

FIG. 1—*Temperature gradients for transient heat flow through a homogeneous wall.*

increases. Heat enters the wall from the outdoor surface, but only that part of the wall close to the outdoor surface responds to the temperature change. No heat leaves or passes through the wall on the indoor side, because the temperature gradient at the indoor surface is still zero. The accumulated heat is being stored by the wall.

Figures 1*c*, 1*d*, and 1*e* show temperature gradients as more time elapses. Since the temperature gradient at the indoor surface, t_1, is zero in Figs. 1*c* and 1*d*, heat enters the wall but does not pass out the indoor surface. Figure 1*e* illustrates the case where some heat is released through the indoor side of the wall. However, the heat flux leaving the wall, q_1, is less than the amount entering the wall, q_2. In the three cases illustrated in Figs. 1*c*, 1*d*, and 1*e*, heat is continually being stored by the wall. Predictions on the basis of steady-state heat transmission coefficients will overestimate heat flux during periods illustrated by Figs. 1*c*, 1*d*, and 1*e*.

Steady-state conditions have been reached in Fig. 1*f*. The temperature gradient is linear, and the amount of heat entering the wall is equal to the amount leaving.

Reference *1* gives quantitative expressions for the length of time and amount of energy required to bring a homogeneous wall to steady-state equilibrium.

Calibrated Hot Box Test Facility

Tests under dynamic temperature conditions were performed in the calibrated hot box facility shown in Figs. 2 and 3. The facility consists of two highly insulated chambers. Walls, ceiling, and floors of each chamber are insulated with foamed urethane sheets to a nominal thickness of 300 mm (12 in.). During tests, the chambers are clamped tightly against an insulated frame that surrounds the test wall. Air in each chamber is conditioned by heating and

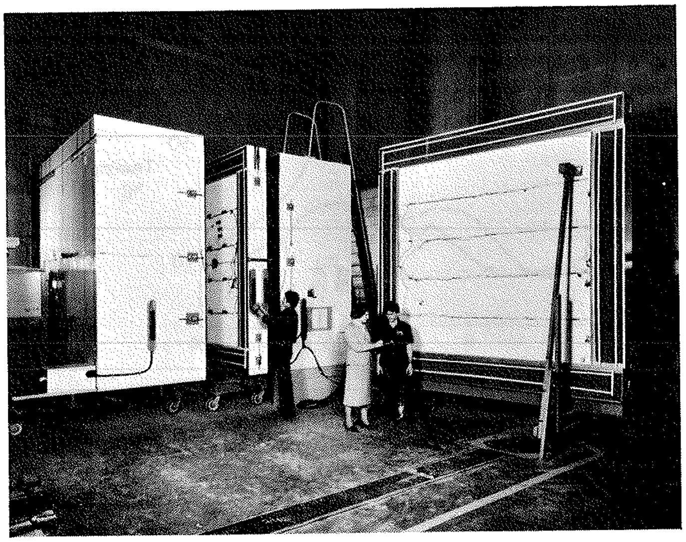

FIG. 2—*Calibrated hot box test facility.*

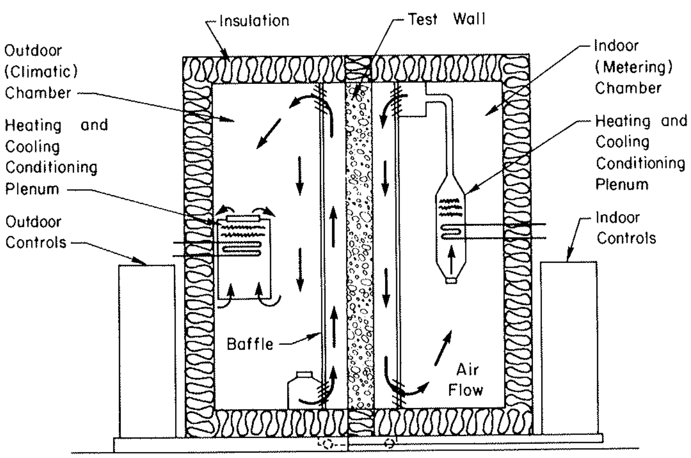

FIG. 3—*Schematic of calibrated hot box.*

cooling equipment to obtain desired temperatures on each side of the test wall.

The facility was designed to accommodate walls with thermal resistance values ranging from 0.26 to 3.25 $K \cdot m^2/W$ (1.5 to 20 $h \cdot ft^2 \cdot °F/Btu$). The outdoor (climatic) chamber can be held at a constant temperature or cycled between −26 and 54°C (−15 and 130°F). The indoor (metering) chamber, which simulates an indoor environment, can be maintained at a constant room temperature between 18 and 27°C (65 and 80°F). Outdoor chamber temperatures are held constant for steady-state tests and cycled for dynamic tests. Dynamic temperature cycles are programmed to obtain the desired time-temperature relationship.

Dynamic Test Procedures

Exterior building walls are seldom in a steady-state condition. Outdoor air temperatures and solar effects cause cyclic changes in outdoor surface temperatures. Generally, indoor surface temperatures are relatively constant compared with outdoor surface temperatures.

During dynamic calibrated hot box tests, diurnal temperature conditions are simulated by varying the outdoor chamber air temperature. Indoor chamber air temperature is held constant.

Derivation of Temperature Cycles

Sol-air temperatures can be used for outdoor chamber temperatures to simulate actual exterior wall surface temperatures. Sol-air temperature is defined as "that temperature of outdoor air which, in the absence of all radiation exchanges, would give the same rate of heat entry into the surface as would exist with the actual combination of incident solar radiation, radiant energy exchange with the sky and other outdoor surroundings, and convective heat exchange with the outdoor air" [*2*].

Thermal response of wall assemblies will vary depending on the temperature cycle applied. Wall assemblies are generally tested using a temperature cycle for a particular geographic location and season. Alternatively, a standard cycle may be used for comparison purposes.

One nominal 24-h (diurnal) temperature cycle, denoted the NBS Test Cycle, has been applied to every wall tested in CTL's calibrated hot box. This cycle is based on a simulated sol-air cycle used by the National Bureau of Standards (NBS) in their evaluation of dynamic thermal performance of an experimental masonry building [*3*]. Figure 4 illustrates the time-temperature relationship of the NBS Test Cycle. The cycle represents a large variation in outdoor temperature over a 24-h period. The mean outdoor temperature of the cycle is approximately equal to the mean indoor temperature. Dynamic test results of concrete, masonry, frame, brick veneer, and calibration walls previously tested by CTL may be compared using this nominal test cycle [*4*].

Other cycles developed at CTL have represented weather conditions for particular locations. Dynamic temperature cycles have been developed using either calculated sol-air temperatures or surface temperatures from field measurements.

Cycles developed from averages of Phoenix and Tucson temperatures were used for tests on walls representative of Arizona con-

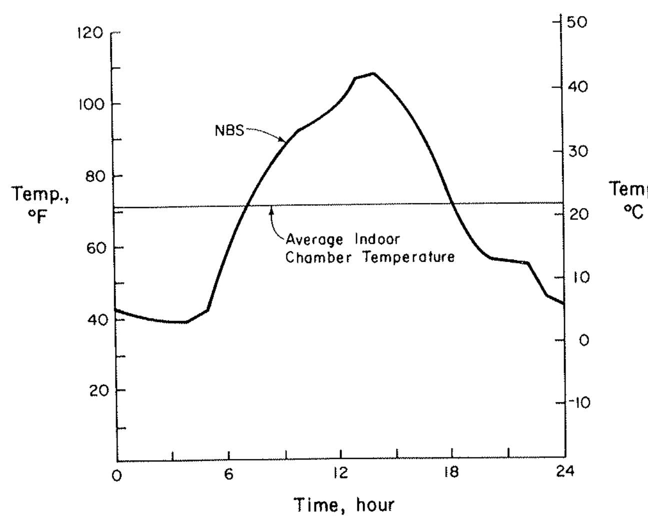

FIG. 4—*Outdoor chamber air temperature for NBS Dynamic Test Cycle.*

struction [5]. Thirty-year averages of temperatures on January 21, April 21, and August 21 were used to develop cycles representing the range of annual Phoenix-Tucson temperature conditions. Cycles have also been developed for Orlando in January, April, and August [6] and for Denver in January.

Sol-air temperatures for Phoenix-Tucson, Orlando, and Denver cycles were calculated using the method described in *ASHRAE Handbook-1981 Fundamentals* [2]. Values are averages for four primary orientations: north, south, east, and west; or eight secondary orientations: north, northwest, west, etc. Vertical orientation values were used, since calibrated hot box tests were performed on walls. Average hourly outdoor air temperatures used in calculations are generally available from state agencies.

Figure 5 illustrates the difference between sol-air and outdoor air temperatures for the Denver January cycle. Sol-air temperatures are greater than outdoor temperatures from 8:00 a.m. (Hour 8) until 4:00 p.m. (Hour 16). The maximum difference between outdoor and sol-air temperatures is 9°C (16°F).

Two dynamic temperature cycles used at CTL were derived from field measurements of wall surface temperatures. Cycles were developed for calibrated hot box tests of a block-brick cavity wall similar to cavity walls in a test building monitored by NBS in Gaithersburg, Maryland [7]. Outdoor surface temperatures of the west wall of NBS Test Building No. 6 were used to create cycles that produced similar outdoor surface temperatures on the test specimen. Dynamic test cycles were derived from data collected at the NBS Test Building from 10:00 a.m. April 23, 1982, through 10:00 a.m. April 24, 1982, and from 9:00 a.m. May 31, 1982, through 9:00 a.m. June 1, 1982.

Figure 6 illustrates the difference between west wall surface temperatures and outdoor air temperatures at the NBS test site on April 23 and 24, 1982. Surface temperatures rose sharply above air temperatures from noon (Hour 12) until 4:00 p.m. (Hour 16) and then decreased.

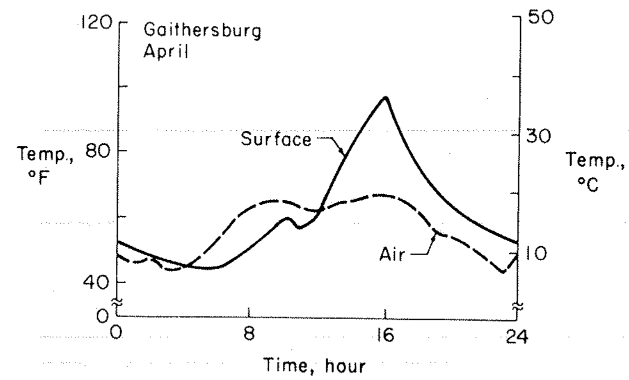

FIG. 6—*West wall surface and outdoor air temperatures of NBS Test Building No. 6.*

Instrumentation

Outdoor chamber air temperature is controlled by an electromechanical device that uses a photocell detector to track a curve for a 24-h cycle drawn on a program disk.

Instrumentation is designed to monitor temperatures inside and outside the indoor chamber, air and surface temperatures on both sides of the test wall, and heating energy input to the indoor chamber. Additional measurements monitor indoor chamber cooling system performance. Basically the instrumentation provides a means of monitoring the energy required to maintain constant temperature in the indoor chamber while temperatures in the outdoor chamber are varied. This energy, when corrected for thermal losses, provides a measure of heat flow through the test wall.

Thermocouples corresponding to ASTM Temperature Electromotive Force (EMF) Tables for Standardized Thermocouples (E 230), 20 gage, Type T, are used to measure temperatures in the air space of each chamber. There are 16 thermocouples in the air space of each chamber and 16 on each face of a test wall. These thermocouples are uniformly distributed over the wall area on a 525 mm (20⅗ in.) square grid as shown in Fig. 7.

Surface thermocouples are securely attached to the wall over a length of approximately 100 mm (4 in.). Tape that covers sensors mounted on surfaces of painted walls is painted the same color as the test wall surfaces. Thermocouples in air are located approximately 75 mm (3 in.) from the face of the test wall.

Supplementary thermocouples are used to measure tempera-

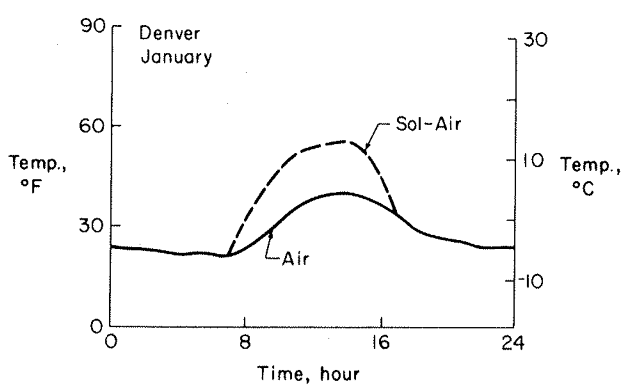

FIG. 5—*Sol-air versus outdoor air temperatures.*

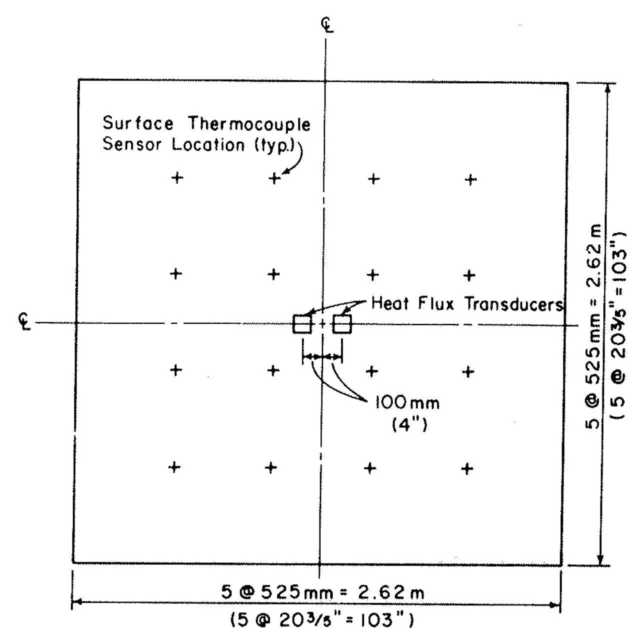

FIG. 7—*Surface thermocouple and heat flux transducer locations.*

tures at selected locations. Thermocouples may be embedded in concrete or placed between layers of insulated walls. For example, thermocouples were placed on block and brick surfaces facing the cavity in a block-brick cavity wall. Internal thermocouples are generally distributed over the same 525 mm (20⅗ in.) grid as surface and air thermocouples.

Laboratory and interior surface temperatures of the indoor chamber sides are measured. These temperatures provide data for evaluating heat transfer between the chamber and the laboratory. Temperature data are supplemented by measurements from heat flux transducers applied to one side and the ceiling of the indoor chamber.

Heat flux transducers measuring 100 by 100 mm (4 by 4 in.) are also applied to indoor and outdoor surfaces of test specimens. Locations are shown in Fig. 7. Transducers are calibrated using data from steady-state calibrated hot box tests. Five additional thermocouples are mounted on wall surfaces opposite each heat flux transducer.

A watt-hour transducer is used to measure cumulative electrical energy input to the indoor chamber by the heater and fan. A digital humidity and temperature measurement system is used to measure relative humidity and temperature in air streams on each side of most test specimens. Probes are located in the air streams approximately at the specimen mid-point. Air flow rates in each chamber are measured with air flow meters located approximately at the wall geometric center. Each flow rate meter is mounted perpendicular to the air flow. Data from air flow meters are monitored periodically and are not part of the automated data acquisition apparatus. Air flow rates in each chamber for all wall tests are approximately 0.1 m/s (20 ft/min). A more detailed description of calibrated hot box instrumentation is given in Ref *8*.

Data Acquisition

Measurements are monitored with a programmable digital data acquisition system capable of sampling and recording up to 124 independent channels of data at preselected time intervals. The data acquisition system is interfaced with a microcomputer that is programmed to reduce and store data. Channels are scanned every 2 min and readings are stored in the microcomputer memory. Average temperature and supplementary data are obtained from average readings for 1 h. The cumulative watt-hour transducer output is scanned every hour. Hourly data are stored on magnetic tape cassettes and printed on summary sheets. Hourly data may also be plotted.

Hourly summary sheets list measured values for each channel and summarize data in tabular form. A descriptive format facilitates monitoring calibrated hot box tests. Average chamber air temperatures, specimen surface temperatures, and internal specimen temperatures are listed. Heat flux transducer data, watt-hour transducer data, and measurements used to determine indoor chamber cooling energy are also summarized.

Dynamic temperature cycles are repeated until effects of the wall's past temperature history are negligible. This condition is established when primary trends from the transitional period no longer exist. Hourly temperature and heat flux data are compared with data for the same time on preceding days. For any given time of day, temperatures and heat flux transducer measurements should oscillate about a range of values rather than be steadily increasing or decreasing. Such repetition is usually attained within two days for lightweight frame wall systems and four days for heavy masonry wall systems. After a repetitive condition is reached, three days of data are accumulated. Reported results are based on average readings for three consecutive 24-h periods.

Analysis

Heat flow through a test wall is determined from measurements of the amount of energy input to the indoor chamber to maintain a constant temperature. The measured energy input must be adjusted for heat losses. Figure 8 shows sources of heat losses and gains by the indoor chamber where: Q_w = heat transfer through test specimen, Q_c = heat removed by indoor chamber cooling, Q_h = heat supplied by indoor chamber electrical resistance heaters, Q_{fan} = heat supplied by indoor chamber circulation fan, Q_ℓ = heat loss/gain from laboratory, and Q_f = heat loss/gain from flanking path around specimen. Because the temperature of the indoor chamber is held constant, the net energy into the control volume of the indoor chamber equals zero and the heat transfer through the test wall can be expressed by the following energy balance equation:

$$Q_w = Q_c - Q_h - Q_{fan} - Q_\ell - Q_f \tag{1}$$

The need for cooling in the indoor chamber results from requirements for dynamic tests. In cases where outdoor temperatures exceed indoor temperatures, cooling capacity is required to maintain a constant indoor temperature.

Indoor chamber cooling equipment operates continuously and is designed to remove heat at a constant rate. Control of indoor chamber temperature is obtained by varying the amount of input heat required to balance the amount of heat removed by the refrigeration system, the amount of heat that flows through the test specimen, flanking losses, and heat losses to laboratory space.

Losses from the indoor chamber to the laboratory, Q_ℓ, are calculated from thermal properties of component materials making up walls and ceilings of the indoor chamber, and temperature condi-

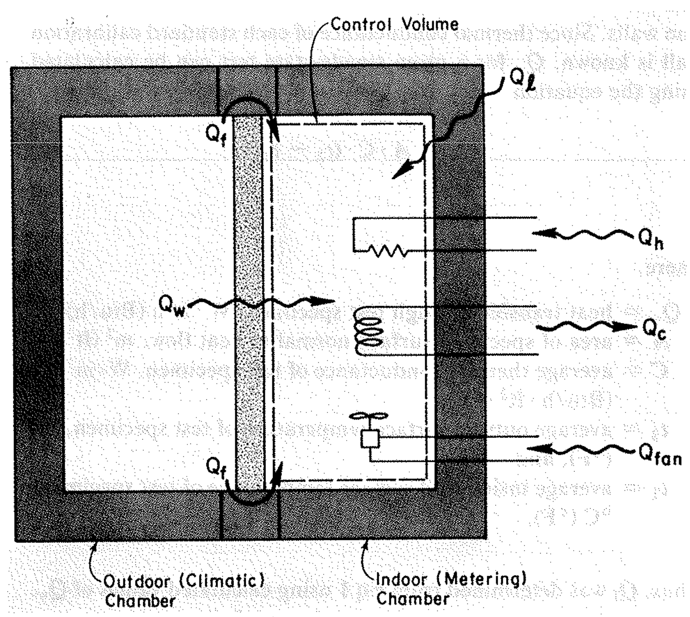

FIG. 8—*Indoor (metering) chamber energy balance.*

tions on the inner and outer surfaces of the indoor chamber. Heat flux transducers mounted on the inside surface of the indoor chamber are used to check calculations. Indoor chamber air and laboratory air temperatures are generally maintained at the same nominal value, 22°C (72°F), to minimize laboratory losses. Thus the value of Q_ℓ is small relative to other terms of the energy balance equation.

A watt-hour transducer is used to measure heat supplied to the indoor chamber by heaters and a fan, $Q_h + Q_{fan}$.

Calibration

Steady-state calibrated hot box tests on two "standard" calibration specimens were used to refine calculations of heat removed by indoor chamber cooling, Q_c, and flanking losses, Q_f. The first calibration specimen, S1, has a relatively low thermal resistance of 1.0 $m^2 \cdot K/W$ (5.7 $h \cdot ft^2 \cdot °F/Btu$). It consists of 35-mm (1.375-in.)-thick fiberglass and was specially fabricated by a fiberglass manufacturer to ensure uniformity. Fiber-reinforced foil was applied to each face of the specimen, and surfaces were painted off-white.

The second calibration specimen, S2, has a relatively high thermal resistance of 3.0 $m^2 \cdot K/W$ (17.3 $h \cdot ft^2 \cdot °F/Btu$) and a unit weight of 5.22 kg/m^3 (1.07 lb/ft^2). Material for Specimen S2 was selected as part of the ASTM Committee C-16 Hot Box Round Robin Program [9]. It consists of expanded polystyrene board that was specially produced and cut to ensure uniformity. Board faces are coated to provide surfaces suitable for attachment of instrumentation.

Steady-state and dynamic test results for Specimens S1 and S2 are presented in detail in Ref *10*.

Heat removed by indoor chamber cooling, Q_c, is calculated from refrigerant enthalpy and mass flow rate, assuming an ideal basic vapor compression refrigeration cycle. Results from steady-state calibrated hot box tests on the two "standard" calibration specimens were used to adjust for inefficiencies in the actual refrigeration cycle.

Heat loss or gain from flanking around the test specimen, Q_f, was determined from steady-state tests of the "standard" calibration walls. Since thermal conductance of each standard calibration wall is known, Q_w for a given steady-state test can be calculated using the equation

$$Q_w = A \cdot C \cdot (t_2 - t_1) \tag{2}$$

where

Q_w = heat transfer through test specimen, $W \cdot h/h$ (Btu/h),
A = area of specimen surface normal to heat flow, m^2 (ft^2),
C = average thermal conductance of test specimen, $W/m^2 \cdot K$ ($Btu/h \cdot ft^2 \cdot °F$),
t_2 = average outside surface temperature of test specimen, °C (°F), and
t_1 = average inside wall surface temperature of test specimen, °C (°F).

Thus, Q_f was determined from Eq 1 using calculated values of Q_w, Q_c, and Q_ℓ, and measured values of Q_h and Q_{fan}.

For both standard calibration walls, values of Q_f were observed to follow the empirical relationship

$$Q_f = 0.131\,(t_2 - t_1) \quad \text{SI units}$$
$$Q_f = 0.802\,(t_2 - t_1) \quad \text{(inch-pound units)} \tag{3}$$

where

Q_f = heat loss or gain from flanking around test specimen, $W \cdot h/h$ (Btu/h),
t_2 = average outside surface temperature of test specimen, °C (°F), and
t_1 = average inside surface temperature of test specimen, °C (°F).

Since Q_f is the residual from Eq 1, it may include other undetermined losses from the indoor chamber.

Results from the ASTM Committee C-16 Hot Box Round Robin will provide information on the precision of the calibration hot box test method [9].

Heat Flow Through Specimen

Heat flow through the test specimen, Q_w, is determined for each hour of dynamic test data using Eq 1. Heat removed by indoor chamber cooling, Q_c, and losses from the indoor chamber to the laboratory, Q_ℓ, are calculated as previously described. Heat loss or gain from flanking around the test specimen, Q_f, is determined from Eq 3. Heat supplied to the indoor chamber by heaters and a fan, $Q_h + Q_{fan}$, is measured by a watt-hour transducer. Reported values of heat flow and temperatures are three-day averages for 24 h.

Dynamic Heat Transmission Coefficients

Thermal lag, reduction in amplitude when compared with steady-state predictions, and the total heat flow ratio are three coefficients used to describe test specimen behavior under dynamic temperature conditions. These coefficients characterize thermal storage capacity and are derived from comparisons of measured results to values predicted on the basis of steady-state analysis.

Thermal Lag and Reduction in Amplitude

Thermal lag and reduction in amplitude are measures of the response of indoor surface temperatures and heat flow to fluctuations in outdoor air temperatures.

Heat flux measured by the calibrated hot box, denoted q_w, and heat flux predicted by steady-state analysis, denoted q_{ss}, are shown in Fig. 9. Heat flux is positive when heat flows from the outdoor chamber to the indoor chamber. Values of q_{ss} are calculated on an hourly basis from wall surface temperatures using the equation

$$q_{ss} = (t_2 - t_1)/R \tag{4}$$

where

q_{ss} = heat flux through test specimen predicted by steady-state analysis, W/m^2 ($Btu/h \cdot ft^2$),
R = average thermal resistance of test specimen, $m^2 \cdot K/W$ ($h \cdot ft^2 \cdot °F/Btu$),
t_2 = average outdoor surface temperature of test specimen, °C (°F), and
t_1 = average indoor surface temperature of test specimen, °C (°F).

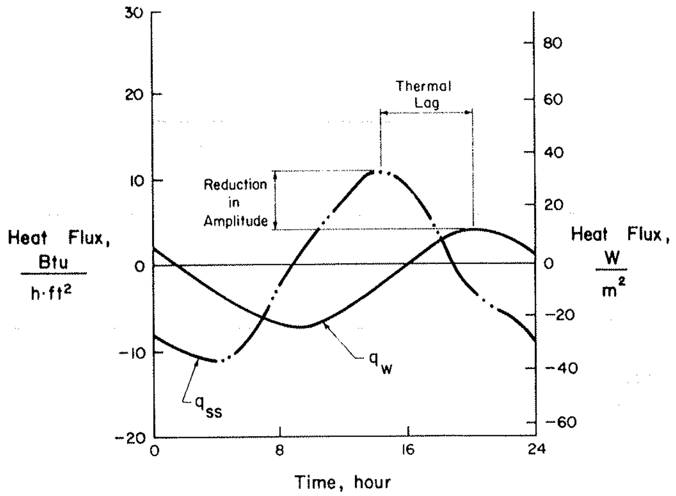

FIG. 9—*Definition of thermal lag and reduction in amplitude.*

Resistances are dependent on wall mean temperature and are derived from steady-state calibrated hot box tests.

Calibrated hot box thermal lag is quantified by two methods. In one measure, lag is calculated as the time required for the maximum or minimum indoor surface temperature to be reached after the maximum or minimum outdoor air temperature is attained. In the second measure, illustrated in Fig. 9, lag is calculated as the time required for the maximum or minimum heat flux, q_w, to be reached after the maximum or minimum heat flux based on steady-state predictions, q_{ss}, is attained. The two methods give similar results.

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

Reduction in amplitude, also illustrated in Fig. 9, is the percent reduction in actual peak heat flux when compared with peak heat flux calculated using the steady-state theory. Actual maximum heat flow through a wall is important in determining 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. Reduction in amplitude is calculated using the equation

$$A' = [1 - (q' - \bar{q})/(q'_{ss} - \bar{q}_{ss})] \cdot 100 \qquad (5)$$

where

A' = reduction in amplitude, %,
q' = maximum or minimum measured heat flux through test specimen,
$\bar{q}$ = mean measured heat flux through test specimen,
q'_{ss} = maximum or minimum heat flux through test specimen predicted by steady-state analysis, and
$\bar{q}_{ss}$ = mean heat flux through test specimen predicted by steady-state analysis.

Total Heat Flow Ratio

Results of dynamic tests are compared also using measures of total heat flux through a test specimen (Fig. 10). The curve marked "q_w" is a measure of heat flux through the test wall. Areas enclosed by the measured heat flux curve and the horizontal axis, denoted q'_{a+} and q'_{a-}, are used to determine total measured heat flux. The sum of the absolute values of positive and negative areas is the total heat flux over a 24-h period.

A similar procedure is used to calculate total heat flux over a 24-h period for predictions based on steady-state analysis. The total heat flow ratio is measured total heat flux as a percentage of predicted heat flux based on steady-state analysis.

It should be noted that comparison of measured heat flux values for the test walls is limited to specimens and dynamic cycles evaluated in this program. Results are for diurnal test cycles and should not be arbitrarily assumed to represent annual heating and cooling loads. In addition, results are for individual opaque wall assemblies. As such, they are representative of only one component of the building envelope.

Applications

Dynamic heat transmission coefficients are used to compare measured results from different dynamic temperature cycles applied to a wall system. Coefficients are also used to compare alternative walls systems tested using the same dynamic temperature cycle.

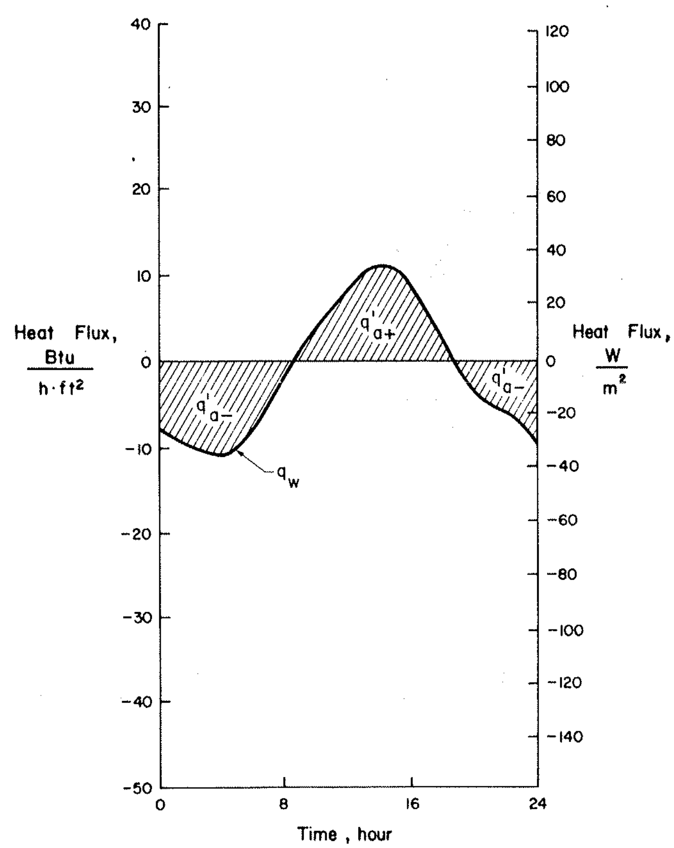

FIG. 10—*Definition of total measured heat flux.*

Comparing Dynamic Temperature Cycles—Four dynamic temperature cycles were applied to an insulated masonry wall illustrated in Fig. 11. The wall was constructed using 200 mm (8 in.) hollow core blocks having an ovendry unit weight of 1780 kg/m^3 (111 lb/ft^3). Unfaced fiberglass batt insulation was placed between vertical furring strips applied at a nominal center-to-center spacing of 400 mm (16 in.). Insulation was 65 mm (2.5 in.) thick and had a thermal resistance rating of 1.4 m$^2 \cdot$ K/W (8 h $\cdot$ ft$^2 \cdot$ °F/Btu). The 13-mm (1/2-in.)-thick gypsum wallboard was applied to the interior wall surface [*5*].

Temperatures applied to the wall during three of the dynamic cycles represented averages for Phoenix and Tucson for January 21, April 21, and August 21. The fourth dynamic cycle applied to the wall was the NBS Test Cycle, shown in Fig. 4, which has been applied to all walls tested at CTL.

Measured heat flux is shown in Fig. 12 for the four dynamic temperature cycles applied to the insulated masonry wall. Reversals in heat flow are indicated by both positive and negative heat flux. Reversals occur when the April and NBS Test Cycles are applied to the wall. Some reversal also occurs for the January Cycle at about 16 h. During the August Cycle, heat flux is always positive into the indoor chamber.

Dynamic heat transmission coefficients for the four cycles applied to the insulated masonry wall are given in Table 1. Thermal lags for the four cycles vary from 3.5 to 4.5 h. Since measurements are collected hourly during calibrated hot box tests, values of lag are accurate to within 1 h. Within the accuracies of measurement, lag is essentially the same for the four cycles. An accuracy of thermal lag to the nearest hour is adequate for most situations encountered. Taking data more frequently than hourly is expensive and reduces the accuracy of measured heat flow values.

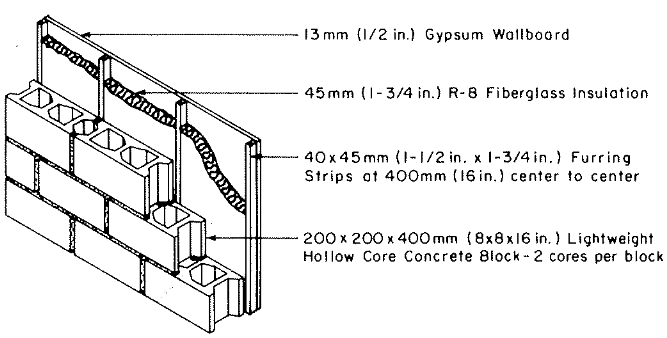

FIG. 11—*Schematic of insulated masonry wall.*

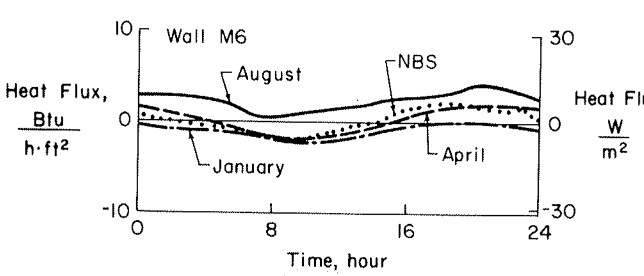

FIG. 12—*Measured heat flux for insulated masonry wall.*

TABLE 1—*Summary of dynamic test results for an insulated masonry wall.*

Temperature Cycle	Average Thermal Lag, h	Average Reduction in Amplitude, %	Total Heat Flux for 24-h Period, W · h/m² (Btu/ft²) Measured q_w^T	Calculated q_{ss}^T	Total Heat Flow Ratio (q_w^T/q_{ss}^T)
Phoenix January	4	33	97.0 (30.7)	129.3 (41.0)	75
Phoenix April	4.5	30	84.3 (26.7)	119.6 (37.9)	70
Phoenix August	3.5	25	181.4 (57.5)	175.7 (55.7)	103
NBS	4.5	31	105.4 (33.4)	152.4 (48.3)	69

Measured reduction in amplitude and the total heat flow ratio vary depending on the temperature cycle. Reduction in amplitude values are relatively constant for the January, April, and NBS Test Cycles, which exhibit reversals in heat flow. The August Test Cycle, which has no reversal in heat flow, has a lower reduction in amplitude.

Measured and calculated total heat flux are approximately equal for the August Test Cycle. Also, the total heat flow ratio is greatest for this cycle. The ratio is smaller for the test cycles with reversals in heat flow.

The large reduction in amplitude and the decrease in the total heat flow ratio are indicative of the wall's resistance and thermal storage capacity.

Comparing Wall Systems—Three 200-mm (8-in.)-thick concrete walls were tested in the calibrated hot box using the same dynamic temperature cycles. Walls, designated C1, C2, and C3, were constructed of normal weight concrete, structural lightweight concrete, and low density concrete, respectively. Aggregate used in wall construction, wall unit weight, concrete thermal conductivity, and dynamic heat transmission coefficients are listed in Table 2. Dynamic test results are for the NBS-10 Test Cycle applied to the three walls. The NBS-10 Cycle was derived by decreasing hourly outdoor temperatures of the NBS Cycle, shown in Fig. 4, by 6°C (10°F) [*11*].

The low density concrete, Wall C3, has the greatest thermal lag and reduction in amplitude. This result is consistent with that indicated by thermal and physical properties of the concretes.

For homogeneous walls, thermal lag and reduction in amplitude increase with an increase in M [*1*]:

$$M = \left(\frac{L^2/\alpha}{P}\right)^{1/2} = \left(\frac{(R)\cdot(\rho c L)}{P}\right)^{1/2} \tag{6}$$

where

L = wall thickness, m (ft),
α = thermal diffusivity of wall material, $k/\rho c$, m^2/s (ft^2/h),
k = thermal conductivity of wall material, W/m $\cdot$ K (Btu/h $\cdot$ ft $\cdot$ °F),

TABLE 2—*Summary of dynamic test results for three 200-mm (8-in.) concrete walls.*[a]

Wall Designation	Concrete Aggregate	Measured Unit Weight, kg/m² (lb/ft³)	Thermal Conductivity,[b] W/m · K (Btu · in/h · ft² · °F)	Average Thermal Lag, h	Average Reduction in Amplitude, %	Total Heat Flux, W · h/m² (Btu/ft²) Measured q_w^T	Calculated q_{ss}^T	Total Heat Flow Ratio (q_w^T/q_{ss}^T)
C1	gravel, sand	488 (100)	2.32 (16.1)	4	45	677.7 (214.8)	1034.1 (327.8)	66
C2	expanded shale	344 (70.4)	0.65 (4.5)	5.5	54	373.0 (118.2)	625.7 (198.3)	60
C3	expanded perlite	160 (32.7)	0.207 (1.44)	8.5	63	132.6 (42.0)	243.3 (77.1)	55

[a]Dynamic test results are for NBS-10 Test Cycle applied to each wall.
[b]Measured by Dynatech R/D Company on oven-dry specimens with embedded thermocouples.

ρ = wall density, kg/m³ (lb/ft³),
c = specific heat of wall material, J/kg · K (Btu/lb · °F),
R = wall resistance, m² · K/W (h · ft² · °F/Btu), and
P = period of dynamic cycle, h.

Equation 6 shows that dynamic heat transmission coefficients are dependent on both thermal resistance, R, and heat storage capacity, ρcL.

Wall thickness, period of dynamic cycle, and specific heat are approximately equal for Walls C1, C2, and C3. Therefore differences in thermal lags for the three walls are due to differences in thermal conductivities and unit weights of the concretes.

Thermal lags for Walls C2 and C3 are, respectively, 1.4 and 2.1 times greater than the thermal lag for Wall C1. Percent reductions in amplitude for Walls C2 and C3 are 1.2 and 1.4 times greater than that for Wall C1. These numbers compare to values of M for Walls C2 and C3 that are, respectively, 1.3 and 1.7 times greater than the value of M for Wall C1. Thus the measured increase in thermal lag and percent reduction in amplitude are consistent with that indicated by theory.

Thermal conductivity and unit weight influence total measured heat flow. If total measured heat flow were dependent solely on thermal conductivity, the ratio of total heat flow for two walls would be equal to the ratio of conductivities of the walls. Conductivities for Walls C1 and C2 are, respectively, 8.4 and 3.4 times greater than the conductivity of Wall C3. Values of total heat flow for Walls C1 and C2 are, respectively, 5.1 and 2.8 times greater than that for Wall C3. Therefore total measured heat flow is less than what would be predicted on the basis of conductivities of the concretes used in the walls.

Limitations

The previous section showed that thermal lag, reduction in amplitude, and the total heat flow ratio characterize thermal performance of a wall assembly under dynamic temperature conditions. Thermal lag is not dependent on the temperature cycle applied to the test wall, but reduction in amplitude and the total heat flow ratio are.

Clients sponsoring hot box tests are generally interested in comparing wall systems on the basis of annual total performance. One dynamic cycle applied to a wall represents only one day of temperature conditions and cannot be assumed to represent annual heating and cooling loads. Therefore dynamic heat transmission coefficients of reduction in amplitude and total heat flow cannot be used to characterize annual performance.

Annual loads may be determined from a research 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 desired climate or climates. An example of this type of program is that described previously for the insulated masonry wall. Wall thermal properties developed from test results are used in computer simulations to predict annual heating and cooling loads for particular locations. Examples of computer programs used for evaluating building energy use are the BLAST [*12*] and DOE-2 programs [*13*].

An alternative solution for evaluating annual performance is to develop standard dynamic temperature cycles representing a wide range of climates within the United States. 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.

Construction Technology Laboratories has taken the first step in implementing the alternative of standard dynamic test cycles. One nominal dynamic cycle, the NBS Test Cycle, is applied to all walls tested in CTL's calibrated hot box. Also, comparative test programs always use the same dynamic cycles applied to all wall systems.

Standard dynamic heat transfer coefficients and standard dynamic temperature cycles are needed to compare interlaboratory results and to increase usefulness of laboratory test results without performing computer simulations.

Summary and Conclusions

This paper has presented a discussion of test procedures for calibrated hot box tests of specimens under dynamic temperature conditions, and dynamic heat transmission coefficients used to characterize test results.

The following points summarize the discussion:

1. During dynamic tests, diurnal temperature conditions are simulated by varying the outdoor chamber air temperature. Sol-air temperatures or field measurements of surface temperatures are used to develop dynamic temperature cycles.

2. Construction Technology Laboratories has applied one dynamic temperature cycle, the NBS Cycle, to 25 wall assemblies tested in the calibrated hot box since 1979.

3. During dynamic tests, three days of data are accumulated after equilibrium is achieved. Reported results are based on average readings for three consecutive 24-h periods.

4. Thermal lag, reduction in amplitude, and the total heat flow ratio are three dynamic heat transmission coefficients used to characterize specimens tested under dynamic temperature conditions. These three coefficients are measures of both thermal resistance and heat storage capacity.

5. Thermal lag for a given assembly is independent of the applied dynamic temperature cycle.

6. Reduction in amplitude and the total heat flow ratio vary depending on the temperature cycle applied to the test specimen, and may be used to compare effects of different dynamic temperature cycles.

7. Dynamic heat transmission coefficients are used to compare alternative wall systems tested using the same dynamic temperature cycle.

8. Standard dynamic heat transmission coefficients and standard dynamic temperature cycles are needed to compare interlaboratory results and to increase usefulness of laboratory test results without performing computer simulations.

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