Correlation/Prediction of Wall Heat Flow: Computer Models versus Field Data

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ABSTRACT

Recent field testing of 12 wall types in five climates from 1400 to 12,000 degree-days (°F) is analyzed using a proprietary transient-heat-flow program. Acceptably matched models are used to predict seasonal and annual heat flow through various wall types.

Two papers presented at the first ASHRAE-DOE Conference on the Thermal Performance of the Exterior Envelopes of Buildings described a method of making field measurements of wall (and other component) heat flows using thermopyle heat flowmeters (HFMs) and a finite-difference modeling technique for simulating wall and window heat flow. This paper reports on the latest large-scale wall study incorporating the two techniques.

Field measurements were made on a total of 12 wall types: three frame, four clay masonry, three concrete panel (with and without insulation), one concrete masonry, and one solid timber. Most of the walls were tested in the West Coast cities of Los Angeles, Portland, and Seattle. The timber walls were tested in Edmonton and Regina, Canada. Wall sections were tested in special test cells and in actual buildings.

One-dimensional transient models were used as the primary modeling tool, and the paper contains numeric and graphic "matches" of heat flow and surface temperatures for each wall type. For comparison, other techniques are shown, including ASHRAE response factors. Errors in all methods are discussed.

Various strategies for long-term seasonal and annual usage predictions are discussed and predictions and their sensitivity analyses are presented. Although whole-building analysis and simulation are valuable, much remains to be learned about individual component behavior. Indeed, unless each component routine is acceptably accurate, both in its long-term and transient behavior, the whole-building simulator has little chance of being a believable predictive tool. Examples of how the accuracy of predictions affects both heat flow and economic strategies and of predictive pitfalls are given.

FIELD TESTING

Los Angeles

During the winter and spring of 1982, a test structure containing six wall sections was built, instrumented, and monitored in the South Bay area of Los Angeles. Figure 1 shows a plan view of the test structure. Each of the six tests panels was about 8 x 8 ft. (2.4m) and the two rows of three panels were separated by about 1m. Each north-south pair of walls were enclosed from the outside and from above by 6 in. (.15m) of polystyrene plastic and from each other by 3 in. (.08m) of polystyrine plastic. All seams, including a 2 x 2 ft. (.6m) entry hatch, were scrupulously sealed for the test. The wall types tested are:

Wall #1:	Insulated 4 in. (.1m) brick veneer (3 1/2 in. [.09m) batt)
Wall #2:	Uninsulated 5 in. (.13m) hollow clay masonry
Wall #3:	Double wythe reinforced brick masonry (9 in. (.23m) total thickness grouted solid)
Wall #4:	Uninsulated 6 in. (.15m) concrete tilt-up panel
Wall #5:	Uninsulated 8 in. (.2m) hollow clay masonry
Wall #6:	Insulated frame with stucco (3 1/2 in. (.09m) batt)

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Each wall section was instrumented with inside and outside surface temperature thermocouples (T/Cs), an inside air temperature T/C, and a thermopyle-type heat flowmeter (HFM) at the inside surface. Additionally, the outside dry-bulb temperature, horizontal sun flux, and wind speed were measured hourly. All data were recorded by a computer-driven data logger. The inside temperature in each test cell was maintained with a separate resistance heater/thermostat and allowed to float above the thermostat set point. All power consumption (including monitoring equipment) was recorded during selected periods using a strip-chart ammeter and voltmeter.

The monitoring lasted from January 30 to February 26 and the weather encountered was typical for the Los Angeles heating season.

Pacific Northwest

In total, four wall types were tested in the Portland area and one in the Seattle area during winter and spring 1982. The Portland tests were conducted in a graphics building in Beaverton and the Seattle test was done in a small (5000 ft^2 (464.5m^2) savings and loan building in Bellevue. The Portland test setup consisted of four wall panels, of a size similar to that of the panels used in Los Angeles tests, adjacent to each other on the south wall. The wall types tested were:

- Wall #1: 8 in.(.2m) concrete masonry unit (through-wall, hollow cores)
- Wall #2: Frame/siding (3½ (.09m) fiberglass batt, gypsum board, wood siding)
- Wall #3: 6 in.(.15m) (nominal) concrete panel
- Wall #4: 6 in.(.15m) panel (same as 6 in.(.15m) above with 1 in. (.03) rigid foam outside).

Sets of measurements on each wall corresponded to those of the Los Angeles setups:

A. Outside and inside air temperature
B. Outside and inside wall surface temperature
C. Heat flow.

Additionally, the sun flux and wind speed were monitored. The Seattle test included similar measurements on the east, south, and west sides only, with all walls being made of 8 in.(.2m) hollow clay masonry units with both empty and grouted cores. All data were recorded for more than 21 days.

Western Canada

During the winter and spring of 1982, two existing cedar log homes were instrumented and analyzed, one in Regina, Saskatchewan, and one in Edmonton, Alberta. In particular, the walls (3.8 in.(.1m) red cedar timbers) were examined in detail to determine their in-place thermal performance. Several walls in each structure were instrumented to provide the usual measurements of inside surface temperatures, outside surface temperatures, and heat flow at the inside surface. Additionally, inside and outside air temperatures, sun flux and wind speed were monitored, with all hourly data recorded on computer-driven data loggers. The data were taken for roughly one month in each location.

Segments of the data from these five locations that roughly represent typical heating season conditions were chosen and used to obtain the matches described later. Experience has suggested that heat-flow data of this kind are accurate to about 6%.* The matching and prediction introduces an additional 5% to 10%, and building effects (radiation coupling, etc.) may add 5% to the uncertainty. With a maximum 15 to 20% error, the mean probable error is in the range of 10%, demonstratively better than standard steady-state techniques and allowing realistic calculations and subsequent designs of wall thermal behavior. The placement of the sensors on the walls is always of great concern, since one measurement will represent a whole wall. If a given point is far enough away from the nearest discontinuity. relative to its thickness, the point chosen will see little effect. Generally, a ratio of "influence radius" to the thickness of 10 will ensure this in homogeneous materials. All walls were inspected physically for composition to prevent surprises but one occurred anyway. When one of the Bellevue bank walls as a hollow block, was modeled, no part of its behavior could be matched. The data suggested a solid mass of concrete. Later removal of the block confirmed this -- it was grouted solid.

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*All sensors were calibrated before the test. The HFMs were tested in an ASTMC177 apparatus at three heat flow levels, all within the actual levels experienced in the field, roughly -10 to 10 Btu/ft^2·hr. The calibrations were then adjusted and linearized for the tests. The age and usage levels of the HFMs did not correlate with their deviation from factory calibration (which was at 500 Btu/ft^2·hr), and the largest adjustment from factory specifications was 12%. T/C wire was 24 gauge or smaller (type J), purchased on single-strand rolls (no splices), and manufactured and tested at special tolerance limits.

ANALYTICAL TECHNIQUE

The analytical technique for wall and window heat flow is the result of an evolutionary process that began with several years' data from numerous real buildings in several widely varying climates. Statistical analysis was performed on both audit-level data (building geometry, occupancy and load schedules, utility consumption histories, etc.) and more detailed data. Data-acquisition systems were used to monitor mechanical system operation (instantaneous furnace efficiency, etc.) and sun, wind, outside air temperature, and suites of thermal parameters (surface temperatures, air film temperatures, heat flows) for each envelope component.

Standard analytical and predictive techniques to simulate instantaneous and integrated total heat flows proved inadequate for predicting heat flow in the total structure and in the individual components. Consequently, developing computer tools capable of accurately predicting heat flows measured under a wide range of real world conditions is desirable.

Ultimately, it is the goal of any such analysis to predict the behavior of an entire structure, allowing the contributions of the various components (walls, windows, floors, attics, furnaces, etc.) to interact fully. This goal has two subgoals: (1) to define accurately the response of any one component to the boundary conditions imposed on it and (2) to compose those individual responses into a system response. Early work in this area assumed that both the individual component response and the composition of these responses were essentially linear. It is now known that, in both areas, the response is nonlinear and, theoretically, no simple linear calculation of individual behavior, nor simple summing of the individual responses will yield correct results. Experience has given, however, some feel for the sensitive areas, and for those that affect the solution less.

The approach in this paper was to first develop accurate component models that address all the major factors affecting heat flow in an individual element but to neglect those insensitive ones that have little effect on the answers (e.g., surface roughness). These models have long-term value as parts of a full system analysis and allow careful examination of the factors affecting response on the microlevel. The extent to which the individual responses vary when coupled (nonlinear combination) ranges from small in normal residences (simple geometrics, average amounts of window, lighting, etc.) to noticeable (purely passive structures, large internal gains, complex shapes, etc.). But these coupling effects do not enter into the analysis if the question is asked in this way: If identical boundary conditions are imposed on two building elements of different construction for some period of time, what will be the net thermal response for each element? Armed with the benefit/liability values thus generated, and the costs of the various strategies, the designer can readily optimize a given component. As in any analysis, the reliability of the answer is largely dependent on the judgment of the analyst, both in formulating the input and in analyzing and applying the output. But the user of the data generated in programs such as this can be assured that, under the stated assumptions, heat flows are predicted at a confidence level of about 90%.

The proprietary computer program simulates one-dimensional heat flow through a wide variety of construction types under user-input conditions of weather and other relevant parameters. The program considers heat flow under the following regimes:

Conduction-through solid elements

Convection-(both natural and forced)--through air films and enclosed air spaces

Solar radiation--direct, diffuse, and reflected, as absorbed energy in walls and windows and as transmitted energy in windows

Long-wave radiation--complex interradiation between surfaces.

Conduction[1,2] is handled by an explicit finite-difference solution of the second-order partial-differential "diffusion" equation. The code is designed to run quickly on small machines.

Convection at the various surfaces is computed by correlations involving geometry, fluid properties, and mean film temperature. Correlations used are of the three-regime type relating the Nusselt number to a fractional power of the Grashof-Prandtl product. Solar influx[3, 4] is computed at the envelope surface by using computed solar position, monthly extraterrestrial intensity, and an exponential decay function for atmospheric effects. This maximum theoretical flux is then adjusted for cloud cover on a gross percentage basis applied to direct, diffuse, and ground-reflected portions. Large-order polynomial fits for absorption and transmission properties of glass and single values for total hemispherical emissivities and solar absorptivities of opaque components are used. Other radiation is handled by the Stefan-Boltzmann equation involving the difference in fourth powers of absolute temperatures. Conventional shape factors to ground and to the sky at a varying temperature relate the various gray-body emitters.

As mentioned before, the model disregards the effects of radiation coupling linking to any internal mass that differs from hourly average air temperature. In general, these effects are not large in ordinary structures, but any analysis must recognize this simplification. And if these coupling effects are to be explored, or are known to dominate the problem, this analysis is inappropriate. Experience suggests that deviations of 2% to 8% are to be expected between linked and non linked results in typical applications. Fig. 2 shows the results of a study of coupling effects in which the overall conductance between the walls and an internal mass was varied from U = 1 to U = 10. In this study, the overall energy use varied by about 6%. The model used to make the study was a linked-lump node response factor model of 24 terms. The assumed internal mass area was 1000 ft^2 ($92.9m^2$) for a 1200 ft^2($111.5m^2$) house

As in any analysis of this type, the tool used here depends on input data for material properties (density, heat capacity, conductivity, etc.). These published properties vary widely and randomly from source to source and are seldom truly representative of the real-world properties as measured in the wall. Thus, it must be understood that all results will include inherent uncertainties in properties as found in the real building.* This is one reason for the continued interest in matching real-world data, to broaden the knowledge base of actual thermal properties.

At all junctures, this analysis has been structured to estimate slightly higher heat flows than would be ordinarily predicted. The result is that the net heat flows reported represent an upper limit (a realistic one, however) on benefit or liability. This bias towards the upper end results in the designer being conservative by some amount in his design. This conservatism is prudent and probably changes the answer by no more than 5%.

COMPUTER MATCHING

In each geographic area, the measured climatic data for a number of six-day periods and a description of the various wall's physical makeup were input to the model, Fig. 3. The model's physical parameters were adjusted (tuned) until the heat flow and temperature behavior matched the real-wall response to a high degree. The daily total heat flow and the hour-by-hour behavior were matched carefully, so that the computer models would be expected to behave as the real walls would. The six-day matches represent over 120 separate experiments to test the model. Conditions encountered during the test were varied enough to ensure proper extrapolation to a typical year's weather. Fig. 4, 5 show examples of the heat flow and temperature matches used in the projection phase.

Although the acceptance criterion (a numerical match on the daily heat flow total) was acheived (5%-10% in all cases) and the temperature match was quite good (except in extreme peaks), there are some systematic differences that bear noting. Actual night sky temperatures can vary from ambient to well over 100 °F (50 °C) lower, and wall losses to these sinks can depress the wall temperature by 10°F.(5.6C)or more below the ambient temperature. The model handles the extremes of clear and cloudy skies well but does not establish a ratio between these extremes because no useful correlation had been found at the model's inception. Additionally, if a clear period were followed by a cloudy one in the matching period for example, the model had to be run twice, once for each condition, and then spliced. These night sky effects are significant and were included in the projection phase that follows.

Certain errors are inevitably introduced when nondirectional wind data and horizontal sun flux only are recorded, and mathematical routines are relied on to convert these values to those for the various vertical faces; but in the main, these errors also are acceptably small. Careful examination of the matches will reveal the good quality of the match. Significantly, no error from radiation coupling could be seen and, since the Los Angeles tests in particular should have shown strong effects related to shape factors, the computer simulation conclusion that in ordinary structures these effects are in the simulator's noise level is vindicated.

During the Portland and Seattle tests, Dr. Henry Romer of Olympia, WA used the same data and a version of ASHRAE's response factor (Mitalas and Stephesen) method with sol-air-based exterior temperatures and modified coefficients for certain days of matching. Fig. 9 and 10 show examples of Romer's matches, which are felt to be of comparable quality to those obtained by the approach presented in this paper for these periods, with the following reservations: (1) the adjustments for night sky radiation, true wind speed, ground reflectivity, and solar flux, as well as the wall properties themselves, are roughly comparable in importance, and (2) the lumped form, more empirical nature of these adjustments in the response factor model makes the generalization of short-term testing to long-term results more

*The in-place conductivity of most materials can range widely. For concretes, 70psf has half the k value of 140. For woods, moisture content is a big variable and the density and conductivity of a given specimen may vary significantly.

uncertain. A comparison of long-term projections of these two models* illustrates several facts, including the overall agreement between the two methods once adjustments for the previously mentioned boundary conditions and wall properties had been made (however empirically). Furthermore, the entire exercise of matching field data, tuning the models, and analyzing long-term climatic and indoor environments is needed to assure a truly representative seasonal heat flow estimate. Additionally, it is clear that a rather sophisticated physical and mathematical model is required to capture the complex heatflow behavior of even the simplest wall configuration. The literature offers numerous examples of the differences between the less complex standard methods (r-value·ΔT) and measured behavior.+ The author's experience is that without sun, correct wind, and the capacitance effects present in all walls, the steady-state methods do not agree, either in hour-by-hour behavior or in integrated totals for any period with measured field data. The discrepancy between steady-state seasonal totals and the reported projections are discussed later.

YEARLY PROJECTIONS

the tuned models of the walls tested were given one-day-per-month weather data for the long-term average year[5] in the various climates. Each monthly "day" varies from the average high to the average low temperature to provide a realistic sun and wind profile for that month++. Runs were made for the four cardinal directions and for three colors from light to dark. The results are given in Tabs. 1 through 3. All heat flows are in therms (100,000 BTU) per square foot per season, and represent the algebraic sum of daily gains and losses past the inside plane of the wall. Inside temperatures are 63 to 68 ^{o}F (17.2-20^{o}C) winter and 73 to 78 ^{o}F 23 - 26^{o}C) summer. The monthly average weather data used in the projections is derived from the National Oceanographic and Atmospheric Adminstration long-term climatological data. Solar behavior is from SOLMET sources.**

Explanation of Colors

The analysis defines "color" of the outside surface in terms of the percentage of solar energy absorbed by the surface. Numerically, the color is expressed as the traditional solar absorptivity fraction, which varies from about 0.25 for light, smooth surfaces to about 0.95 for a rough, very dark surface. The relationship between the assumed values of light, medium, dark, the absorptivity, and a listing of typical colors and surfaces are given in table 4. Other colors may be estimated by interpolation on the absorptivity number (α) if known.

ANALYSIS

Tables 1 through 3 for the various climates reveal the numerical performance of the range of wall construction, orientation, and color, but an overview of the extent of discrepancy and the relative importance of the separate effects is difficult to obtain from the tables. Therefore, several illustrations are provided. Figures 6, 7, and 8 show the dependence of wall heat flow on computed steady-state R-value for Los Angeles, Portland, and Regina, respectively. Since only one wall type was tested in each of the Canadian cities, no complete analysis was possible there. The three curves show some similarities. All wall losses are less than predicted by the steady-state method and the return on investment for increased thermal resistance (the derivative or slope of the curves), is less than predicted. In the Los Angeles climate, all south walls and the average dark wall are all significant gainers of energy in the heating season and they suffer negative returns on insulation investment because their beneficial gain diminishes at higher R-values. The Portland curves show a surprising dependence on color (and hence, solar effects) for such a northern, cloudy climate and little benefit for additional thermal resistance past R-6 or so. An earlier study of walls in the northwest, in which all walls were tested, modeled, and projected independently, agreed with the present study to within 6% for the commonly tested wall types 1 and 2. These independent checks reinforce the results and attest to the repeatability of the method.

Figure 8 shows the relative performance of the cedar log walls in the most severe climates tested. The return-on-investment behavior is shown by an example. Taking an evenly weighted average of four directions (in real buildings this would represent equal areas of wall on the four cardinal directions,) allows comparison of actual heat flows for various colors to the steady-state projection in the following way. The steady-state equation for heat flow is:

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*Seasonal totals were within 10% for all cases.

+A classic example is the notkin report done in Seattle, in which projected savings by increasing (from 11/19 to 19/38) the insulation levels in existing homes proved to be greater than the whole energy bills of a sample of these homes. (Can the meter run backwards?)

++Start up inaccuracies were allowed to settle out for periods of up to 1 day to ensure stable answers.

**Clear night sky and cloudy night sky values are weighted by the long-term clear/cloudy mix for the area (for example, Portland had 19% clear nights).

$$Q = \frac{1}{R_{tot}} \times DD \times 24 \qquad (1)$$

Where:

Q = total heat flow

R_{tot} = thermal resistance of wall (including air films)

DD = degree days

Solving for R_{tot}, in the manner of Bickle and others, gives:

$$R_{tot} = \frac{1}{Q} \times DD \times 24$$

$$R_{tot} = \frac{1}{65{,}000} \times 5500 \times 24 = 2.03 \quad (12.0)$$

Where:

Q = 65,000 W/m^2 season (20,000 BTU Ft^{2}season)

DD = 5500 (10,000°F.)

The projected heat flow can be used to determine an effective resistance for the various colors of wall in the various climates.

Essentially, the walls perform identically in both climates, with light-colored walls having an effective resistance of 1.2, medium walls about 1.4, and dark walls 1.6. Most timber walls are in the medium-to-dark range, so the typical effective resistance is near 1.5. The traditional analysis would give this wall an R-value of about 1.1, so that the real wall performs nearly 50% better than expected.

The economics of wall construction are changed appreciably by this conclusion, as the following example indicates

Savings from Adding Insulation

If a wall actually performing at R-1.4 is insulated to the current standards of R-2.1, the generated savings are

$$Q_R = 1.4 - R = 2.1, \text{ or } \frac{1}{1.4} \cdot DD \cdot 24 - \frac{1}{2.1} \cdot DD \cdot 24, \text{ or } (5.712)$$

$$\times\ DD\ (\text{W/m}^2\text{-season})$$

For a 5500 (C) degree day climate, this amounts to 31,416 W/m^2 (10,000 BTU/Ft^2-season) @ 3.4¢/KWH for example, savings are \$1.07/m^2 season. 10¢/ft^2

If however, the uninsulated wall was assumed, using the series resistance method, to be performing at R=1.1, the savings would be

$$\frac{1}{1.1} - \frac{1}{2.1} \cdot DD \cdot 24 \quad \text{or} \quad (10.4) \cdot DD \quad \text{or } 57{,}143 \text{ W/m}^2 \text{ season. } (19{,}000 \text{ BTU/ft}^2)$$

Expected savings would be \$1.94/m^2 (19¢/Ft^2), or almost twice the real return on investment. Clearly, the exact behavior of the wall in the climate must be known and used in all relevent calculations or an intolerable error is introduced. Unfortunately, the standard method is always biased against lightly insulated products, and any building code or practice using the steady-state method will require heavier levels of insulation than are neccessary--and does so in the name of unattainable energy savings. The result of these errors are: (1) gratuitous costs for the designer, builder, and home owner (2) technically inappropriate building practices and (3) decreased respect for codes, code bodies, and the regulation process in general that results when people invest in insulation and the projected savings do not ensue.

The study also demonstrates one acceptable method of analysis, measurement, and projection that allows proper conclusions to be drawn about wall design and thermal behavior. Further refinement of the process, better models, and more experience in the field will be needed to reduce the probable error from the current ±10% to 15%, but these goals are attainable and work is in progress in all of these areas.

The implications of lowered envelope liability are many and significant. Only if estimates of savings are realistic can technically appropriate design proceed. This statement applies to all parts of a building, envelope components, mechanical systems, microenvironment, etc. Many existing and proposed buildings have, by this analysis, adequate insulation to meet the intent of codes, including totally uninsulated buildings in some climates.

CONCLUSIONS

The work described here clearly shows that sizable differences exist between various orientations and across the range of colors of walls in terms of their respective thermal behavior. Walls can be significant gainers of energy when traditional analysis predicts significant losses. Color can change the behavior of walls as dramatically as can insulation in many cases. Economically optimum thermal resistance values are different for each orientation in each climate and depend further on building use and mechanical systems. Even more significant is that the return-on-investment on insulation that is generally predicted using traditional methods is universally lessened by the estimates of this paper to about half of its original value. Clearly, revised estimates of wall behavior are needed for many more climates and building types before generalizations may be easily made, but the current study of a wide range of constructions in climates of 1400 to 12,000 °F. heating degree-days shows that (1) walls are much less of a liability than assumed at low and moderate insulation levels (R-1 to R-15) and (2) the energy saved by increasing the R-value is similarly much less than expected in this range.

Recent code efforts in the states and provinces in which testing was done appear responsive to the increased financial burdens of builders and manufacturers; notable progress has been made in the proposed California Residential code. The "point system" concept seems workable and helps to illustrate the physics of structural energy use. The sponsors and collaborators in the various field tests are hopeful that the real benefits and liabilities of walls will be recognized in all upcoming code changes and in the mainstream of design as well.

REFERENCES

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4. T. Kusuda, NBSLD Handbook (Washington: NBS, 1978).

5. NOAA, Local Climatological Data (Ashville: NOAA, 1977).

TABLE 1

WALL HEAT FLOW

LOCATION: Los Angeles, California

UNIT TYPE:

SIZE:

WEIGHT:

NET SEASONAL HEAT FLOW

THERMS/SQ FT.-SEA. (1 TH=100,000 BTU)

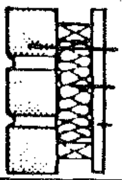
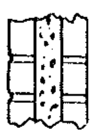
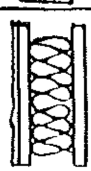
Wall Type	OUT		DIR.	HEATING LOT	HEATING MED	HEATING DRK	COOLING LOT	COOLING MED	COOLING DRK
1		3" Fc. Brick 1/2" Air Gap 3 1/2" Batt (F.G.) 1/2" Gyp. Board	SO.	.010	.017	.044	-.001	-.001	.008
			E./W.	-.013	.000	.013	-.007	.004	.016
			NO.	-.035	-.029	-.024	-.014	-.008	003
2		5" Hollow Clay Thru-Wall No Insulation	SO.	-.035	.096	.228	-.036	.004	.004
			E./W.	-.083	-.008	.072	-.027	.029	.085
			NO.	-.129	-.111	-.092	-.051	-.014	.018
3		3" Fc. Brick 3" Concrete 3" Fc. Brick	SO.	-.048	.094	.236	-.043	.000	.044
			E./W.	-.106	-.030	.046	-.030	.027	.081
			NO.	-.166	-.129	-.108	-.053	-.033	-.011
4		6" Tilt-up Concrete	SO.	-.030	.126	.281	-.049	.003	.054
			E./W.	-.116	-.019	.077	-.033	.035	.103
			NO.	-.182	-.150	-.118	-.068	-.105	.142
5		8" Hollow Clay Thru-Wall No Insulation	SO.	-.036	.084	.203	-.034	.003	.040
			E./W.	-.081	-.011	.058	-.015	.031	.074
			NO.	-.126	-.105	-.083	-.048	.029	-.010
6		Stucco 3 1/2" Batt (F.G.) 1/2" Gyp Board	SO.	-.013	.017	.048	-.011	-.001	.009
			E./W.	-.023	-.006	.012	-.004	.007	.017
			NO.	-.038	-.032	-.026	-.015	-.026	-.038

TABLE 2

WALL HEAT FLOW

LOCATION: Portland, Oregon
UNIT TYPE:
SIZE:
WEIGHT:

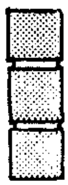
Wall Type	OUT	DIR.	Net Seasonal Heat Flow, Therms/SQ FT-SFA (1 TH=100,000 BTU): Heating LGT	Heating MED	Heating DRK	Cooling LGT	Cooling MED	Cooling DRK
1	 8" Conc.Mas. (thru-wall, hollow cores)	SO.	-.213	-.138	-.063	.028	.077	.126
		E./W.	-.252	-.209	-.167	.028	.076	.124
		NO.	-.280	-.267	-.251	.000	.019	.037
2	 Frame-siding (3.5" batt, gyp.bd.)	SO.	-.074	-.047	.019	.009	.022	.035
		E./W.	-.082	-.065	.047	.009	.021	.034
		NO.	-.086	-.085	.083	-.004	.004	.012
3	 6" Conc. Panel (no insul.)	SO.	-.323	-.216	-.109	.037	.107	.177
		E./W.	-.386	-.317	-.258	.037	.105	.173
		NO.	-.424	-.406	-.389	.000	.125	.050
4	 6" Conc. Panel (1" styro. outside)	SO.	.121	-.089	-.058	.007	.029	.052
		E./W.	-.161	-.138	-.115	.007	.027	.049
		NO.	-.177	-.166	-.156	-.002	.004	.012
		SO.						
		E./W.						
		NO.						

TABLE 3

WALL HEAT FLOW

LOCATION: Regina, Sask.
UNIT TYPE: Western Cedar
SIZE: 0.1m
WEIGHT: 30 lbs/ft.^{3}

OUT

		NET SEASONAL HEAT FLOW THERMS/SQ.FT.-SEA. (1 TH=100,000 BTU)					
	DIR.	HEATING			COOLING		
		LGT	MED	DRK	LGT	MED	DRK
Thru-Wall  0.1m (Solid) Western Red Cedar	SO.	-.308	-.263	-.218	-.010	.012	.034
	E./W.	-.339	-.315	-.291	.011	.008	.027
	NO.	-.377	-.348	-.319	-.026	-.017	.008
Metric (kw/m^2-Season)	SO.	-97.2	-83.0	-68.8	- 3.1	3.8	10.7
	E./W.	-106.9	-99.4	-91.8	- 3.5	2.5	8.5
	NO.	-118.9	-109.7	-100.6	- 8.2	-5.3	2.5

LOCATION: Edmonton, Alberta
UNIT TYPE: Western Cedar
SIZE: 0.1m
WEIGHT: 30 lbs/ft.^{3}

OUT

		NET SEASONAL HEAT FLOW THERMS/SQ.FT.-SEA. (1 TH=100,000 BTU)					
	DIR.	HEATING			COOLING		
		LGT	MED	DRK	LGT	MED	DRK
Thru-Wall  0.1m (Solid) Western Red Cedar	SO.	-.279	-.235	-.191	-.011	.015	.041
	E./W.	-.315	-.291	-.267	-.017	.007	.031
	NO.	-.378	-.334	-.290	-.028	-.019	-.010
Metric (kw/m^2-Season)	SO.	-88.0	- 74.1	-60.3	3.5	+ 4.7	12.9
	E./W.	-99.8	- 91.8	-84.2	- 5.4	+ 2.2	9.8
	NO.	-119.2	-105.4	-91.5	- 8.8	- 6.0	- 3.2

Table 4

Color Index

Color Index	(α) Solar Abs.	Typcial Examples Color	Texture
	0.25	White	Smooth
Light	0.30		
	0.35	White	Masonry, rough wood
	0.55	Cream, buff	Masonry, wood, rock chips, etc.
Medium	0.60	Medium Blue, red	
	0.75	Brown, red, natural wood	Masonry, wood, tile shingles
Dark	0.90	Dark brown, dark green	Somewhat rough

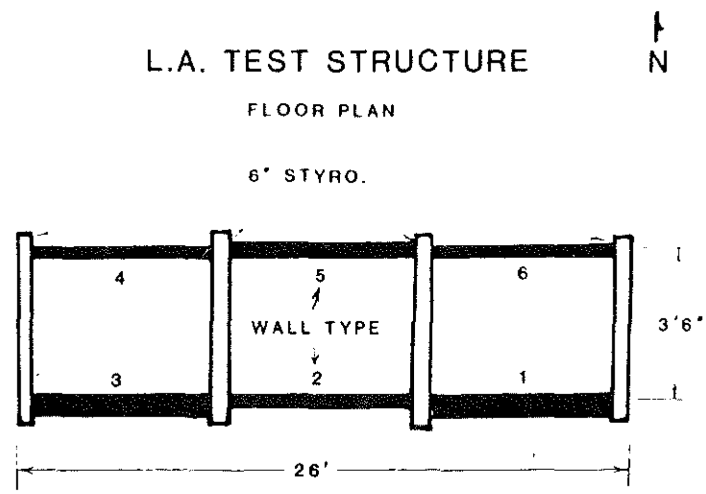


Figure 1. Test building allowed six wall types to be tested concurrently. Northwest testing covered five wall types, while only timer walls were tested in Canada.

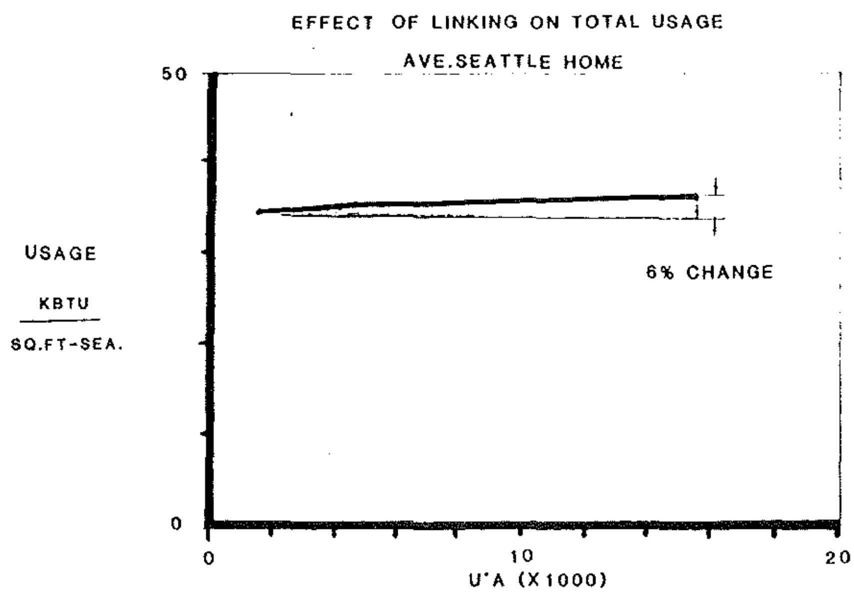


Figure 2. Radiation coupling of internal mass to ordinary walls appears to affect overall usage little.

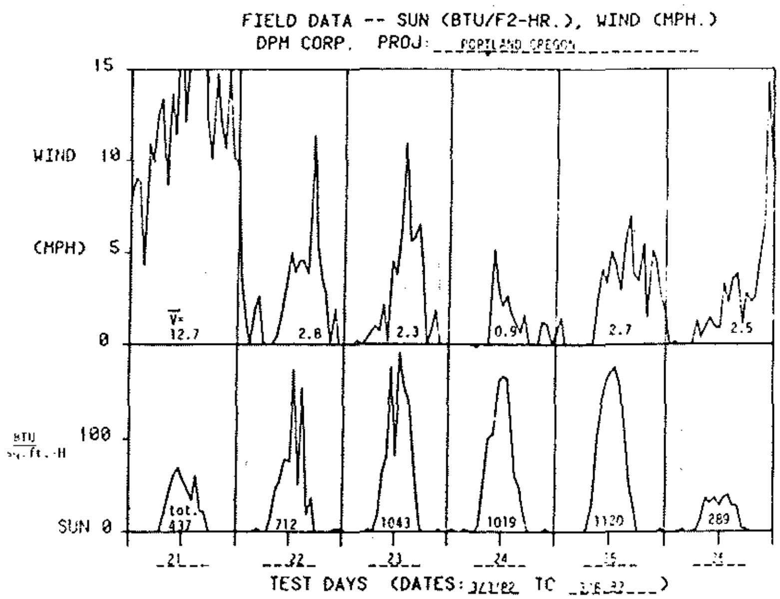


Figure 3. Example of wind speed and solar flux data shows wide variation in conditions essential to matching effort.

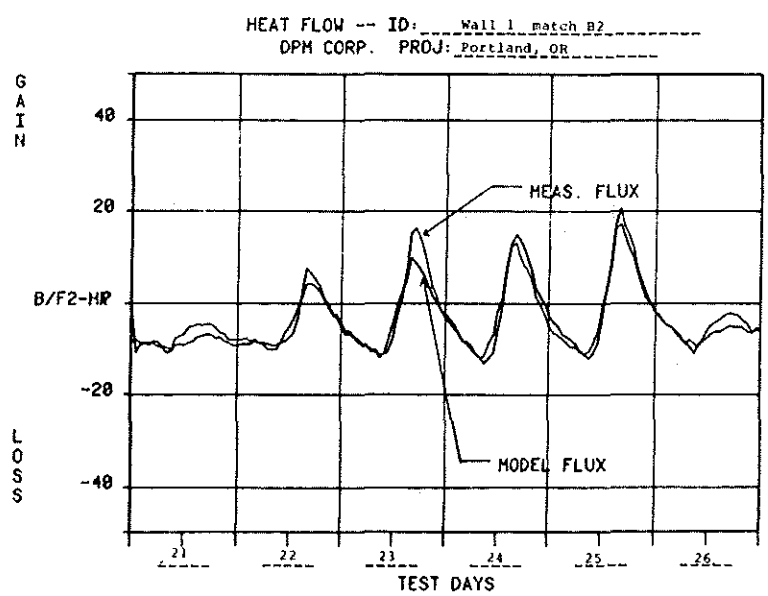


Figure 4. Typical heat flow match shows good model resolution (5% agreement in daily total was acheived in most matches). Overall error ranges from 10 to 20%.

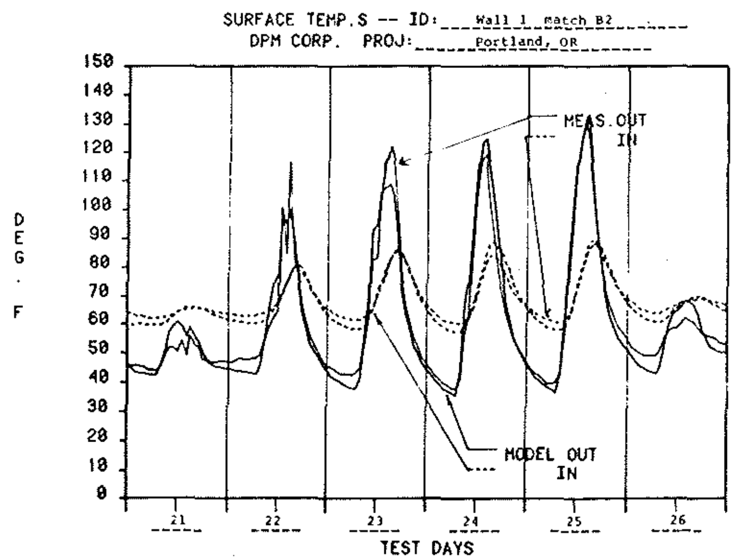


Figure 5. Temperature matches for the same period reflect proper adjustment of relevent wall parameters. Both heat flow and temperature behavior must agree to insure the validity of the models.

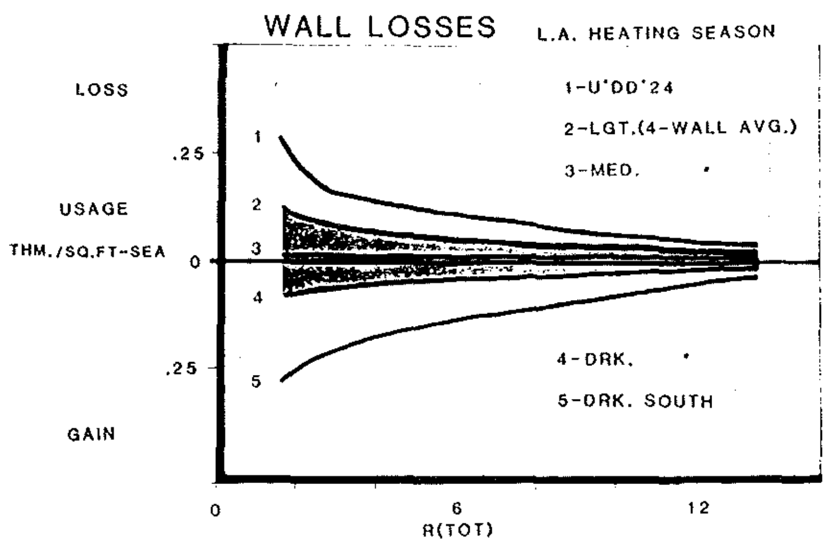


Figure 6. Results of seasonal projections show marked variations from steady-state behavior. Estimates of real wall behavior range from half the assumed loss to significant net gains for four directional averages (curves 2 through 4). Color affects heat flow more than R-value in L.A. climate.

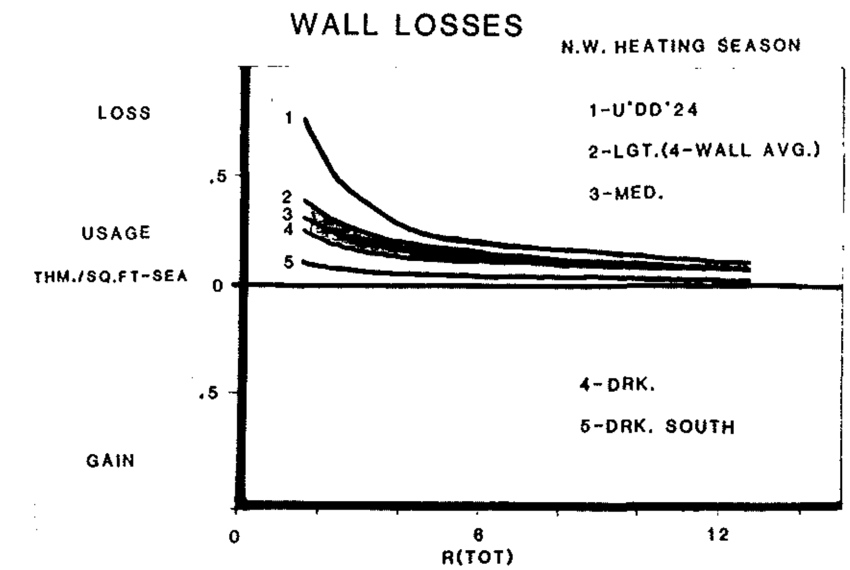


Figure 7. Northwest climate results show little reduction in heat flow for resistance levels over 7. South walls appear to lose little energy at any resistance level.

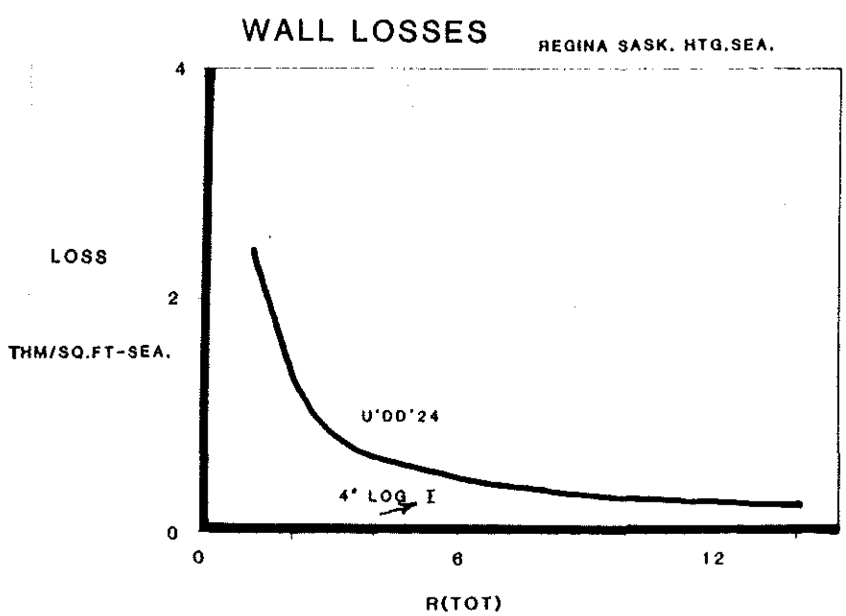


Figure 8. Uninsulated timber walls perform nearly 50% better than steady-state methods would predict in a climate with 12,000 D.D. (F.)

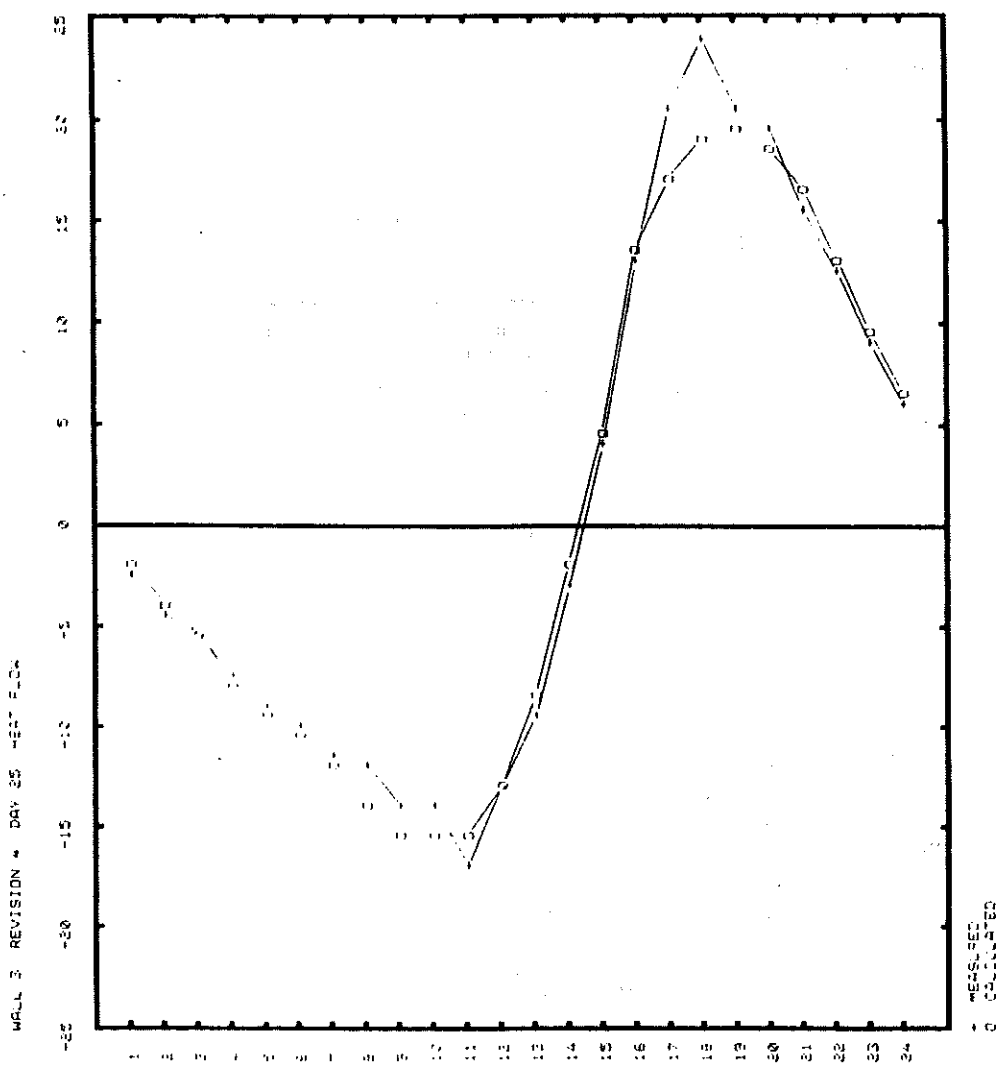


Figure 9. Matches made with response factor model show good agreement with field data. This level of matching was achieved only after major adjustments to film coefficients and solar gain.

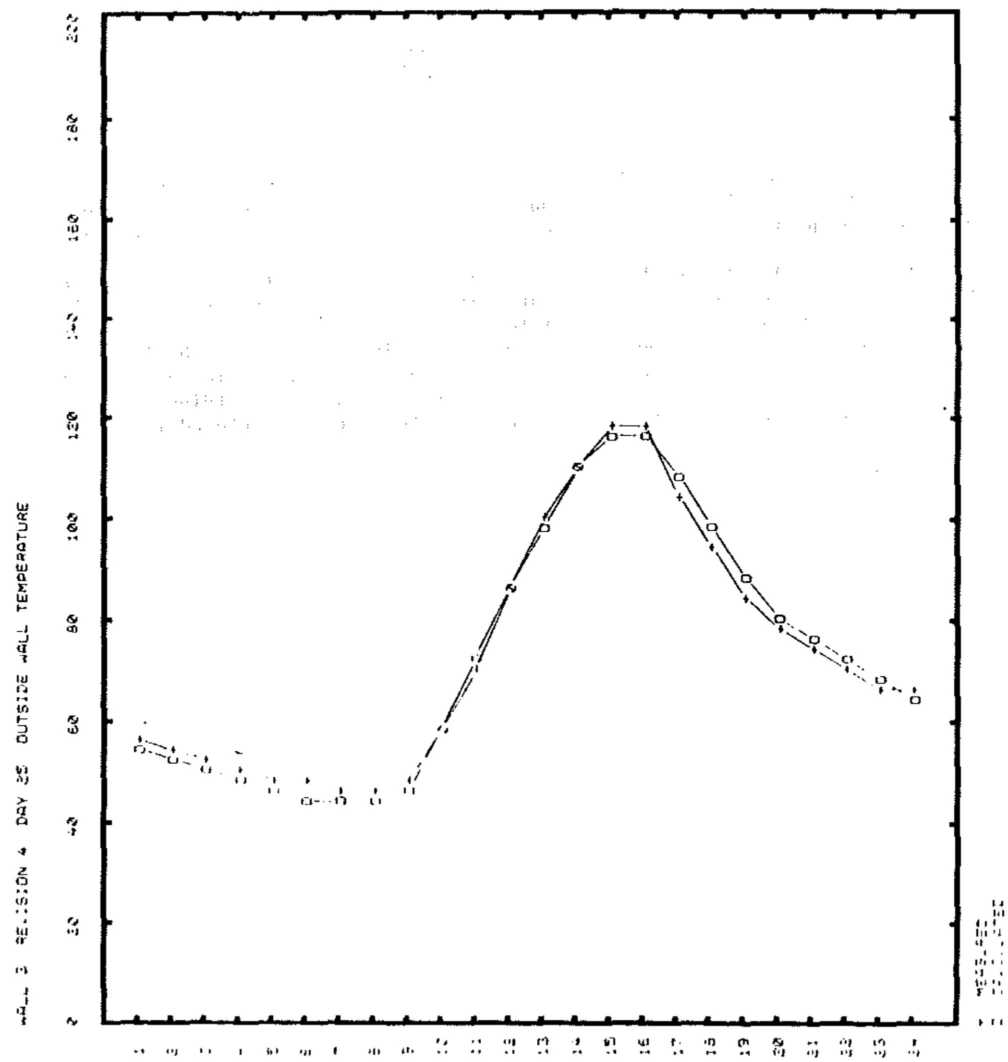


Figure 10. Temperature matches are limited to outside temperature only. Seasonal projections agreed with DPM model within 10%.

Discussion

S. Flanders, U.S. Army CRREL, Hanover, NH: Since you mask your outdoor sensors, so that they "feel" the walls, do you feel that the radiation and windspeed measurements are essential to the building thermal properties (as distinct from being necessary for valid modeling)?

D.P. McGrew: Actual microclimate, both inside and outside, highly affects any component flow. We have endeavored to show that the use of actual radiation and wind data for the building (even our limited approximation of "actual") yields substantial deviation from the widely used U T analysis (with the impoicit assumptions of no solar radiation and 15 mph wind). Clearly, further refinement of the boundary conditions assumed in all cases is indicated. The integrated effects of shading, wind-breaks, siting, etc. are significant in real buildings, and allow for further tuning of response beyond "color" and thermal diffusivity as explored in this paper.