MPM 04

Creative Comfort: Beyond Thermostat Set Point

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Abstract

Though few people can explain the dynamics, everyone knows when they're comfortable…or not. What is less clear is how to reframe comfort to save energy, money, and greenhouse gas emissions and contribute to health, satisfaction and well-being. Based on thermal comfort principles and responses from physiological, theoretical, and applied perspectives, we'll explore strategies from advanced diagnostics to clear communication that explains how people and buildings interact and explore ways – some counterintuitive – to creatively achieve more affordable comfort.

By attending this session, participants will:

1. Review the principles, range, and circumstances of human comfort responses
2. Learn to recognize how building components, systems, controls, and occupant behaviors can either negatively impact or enhance people's sense of comfort
3. Sample a range of technical and behavioral strategies to achieve increased energy savings and other benefits

Keyword(s): behavior, comfort, diagnostics, education, heat transfer, humidity, measurement, modeled results, occupant, predicted results, temperature, thermography

Type: Half-day short course

> "During the six years of my architectural education the subject of comfort was mentioned only once. It was by a mechanical engineer whose job it was to initiate my classmates and me into the mysteries of air conditioning and heating. He described something called the "comfort zone," which, as far as I can remember, was a kidney-shaped, crosshatched area on a graph that showed the relationship between temperature and humidity. Comfort was inside the kidney, discomfort was everywhere else. This, apparently, was all that we needed to know about the subject. It was a curious omission from an otherwise rigorous curriculum; one would have thought that comfort was a crucial issue in preparing for the architectural profession, like justice in law, or health in medicine."
>
> Witold Rybczynski
>
> *Home— A Short History of an Idea*

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INTRODUCTION

As building professionals, we have learned to recognize that many of the physical elements in our homes are interactive. We talk about "the house as a system" but generally we consider only the physical elements of the house and its mechanicals in that system—not the occupant—as being interactive. With very few exceptions, we have failed to ask the question of how the physical factors in our homes affect the *comfort* of the building occupant, even though this may be our ultimate goal. Even more critically, we have largely failed to recognize that those human occupants are the *ultimate* interactive component in the whole equation.

In almost all of our heat loss formulae
the occupant is conspicuous
only by his or her absence

For most homes, the central controlling processor by which the heating or cooling system is activated is the thermostat. Even the most sophisticated electronic thermostat, however, is essentially controlled by another processor—that of the human brain. It is the occupants' perception of thermal comfort that ultimately tells the furnace or boiler when it wants more heat and, hence, that more energy should be consumed to achieve the desired comfort level. And yet, in almost all of our heat loss formulae, check lists, prioritization charts and retrofit program designs, the occupant is only conspicuous by his or her absence. It is the purpose of this paper to lay out the basics of where the occupant fits into the overall shelter equation and help energy professional to think differently—more broadly—about their retrofit opportunities.

WHY COMFORT?

When we ask, "Why do we seek thermal comfort?" at least three considerations come to mind:

- to optimize performance at work and play
- to optimize health and well-being
- to improve our perceived quality of life.

The most important reason for creating comfort conditions, however, is that people *want and demand* comfort and will alter conditions how ever they can to achieve that comfort. As building professionals seeking to reduce energy use, we understand that the end point of our efforts is not some arbitrary set of conditions within a given space, but rather the degree to which we have helped our customers or clients reach satisfaction in achieving comfortable in their homes.

The 1949 US Housing Act declared the basic right of every person to the warmth and shelter of an affordable home, yet today we see an increasingly large number of people either homeless or ill-housed.

Great emphasis has been put on saving household energy by mainly concentrating on the building shell and heating or cooling equipment. Even client education programs tend to encourage homeowners to caulk around their windows or clean refrigerator coils and pay little heed to occupant behavior that can improve comfort. Although some energy savings may result, there has not been enough effort to include the occupants in the process of providing shelter and comfort in our housing stock.

If there was any improvement in client comfort resulting from retrofit activities, it was largely viewed as a bonus. Similarly, programs have excused poor measured realized energy savings by claiming residents "took back" the savings by raising the thermostat, expanded the heated/cooled space and being more comfortable. In fact, people actively seek comfortable conditions and for most, the easiest way to achieve that comfort is to adjust the thermostat setting

Houses Don't Use Energy--People Do

A general, often quoted rule of thumb is that for every one degree increase in air temperature, there is a three percent increase in overall seasonal energy use (Nelson and MacArthur). The opposite is also generally accepted to be true: if people turn down their thermostats by even one degree, it is usually estimated that a three percent energy savings can be achieved. The reason for this is clear. The difference in temperature between inside the house and the exterior is a key driving force in energy transfer by any means. Lower Delta T (ΔT) means less conductive heat loss, a smaller penalty for infiltration, lowered duct losses and reduced furnace run time.

It's as simple as that:
how to make people comfortable
without causing them to reach for the thermostat

The goal is to establish comfortable conditions. There is a wide range of potential strategies to do this beyond simple dependence on elevated house air temperature which otherwise significantly increases overall home energy usage.

It's as simple as that; how to make people comfortable without causing them to reach for the thermostat. This requires an understanding of the occupants' physiological needs and actions, heating and cooling systems, and some basic physics. Although the science may be similar to the understandings that housing specialists have used in the past, the central focus is quite different. We are no longer asking how we can heat houses more efficiently. Rather, we are asking how we can heat (or cool) *people* most efficiently . Although these concepts don't surface in heat loss calculations or computer programs, many are found in cultural traditions and vernacular architecture. It is these non-quantifiable but yet very real physical and psychological conditions that is the focus of this paper.

WHAT IS COMFORT?

Thermal comfort is but one element in a wide range of ergonomic and psychological considerations that lead people to a general satisfaction with their environment—that is, being comfortable. A case could certainly be made that many environmental influences that affect our overall sense of well being, may also affect our sense of thermal comfort. Appropriate color schemes versus harsh contrasts, background music or noise, natural daylighting, pleasant views or indirect ambient lighting on one side versus harsh glare on the other, presence of others(comforting friend or chilling apparition), furniture placement, traffic patterns and our associations regarding the use of the space (a library or a dentist office) all make us feel more or less comfortable and influence our perceptions of temperature balance as well. In fact, many of the expressions that we use to describe our overall sense of comfort in a situation have distinctively *thermal* implications:

"It sent a chill up my spine"	"I warmed-up to him quickly."
"Boy was she hot!"	"He was *very* cool!"
"Chill out, dude!"	"It was an icy stare."
"He gave me the cold shoulder."	"He broke out in a cold sweat."
"We were really cookin'"	"In a burning rage."
"You burn me up!"	"I have a very temperate mood."
"It gave me goose bumps."	"It was hellish in there."
"She was really frigid."	"I shiver at the thought of it."
"The boss went thermal!"	"It gave me a warm feeling."
"Can you take the heat?"	"He was fuming mad."

Although, as we shall see, some of these feelings and expressions have root in real physiological responses to emotional or social situations that may have thermal comfort implications, the greater message here is that humans, as a whole, equate thermal comfort with an overall sense of well-being.

ELEMENTS IN THERMAL COMFORT

Thermal comfort is a very subjective issue and varies greatly with individuals, cultures and can change over time. We say that thermal neutrality or comfort is that state when an individual prefers neither warmer nor cooler conditions and that *conditions* are comfortable when the largest percentage of people in any particular grouping are comfortable.

There has been a great deal of research into what factors determine human comfort. The elements that effect thermal comfort and the elements to be briefly discussed in this paper are the following:

1. Metabolism
2. Natural Body Responses
3. CO and Other Chemical Reactions
4. Activity Level
5. Clothing
6. Air Temperature
7. Relative Humidity
8. Conduction from Body
9. Air Movement
10. Mean Radiant Temperature

Although the study of ergonomics has designed the “perfect” airline seat for the “average” person, that design may or may not suit you or me. Since the comfort elements are highly interactive, it is dangerous to isolate any single one of them as being most important. It is even more difficult to quantify many of these, especially in real-world conditions. Nonetheless, by understanding the basic principles, strategies can be identified to meet specific situations.

Of the ten concerns listed above, most HVAC engineers and designers concentrate, at best, on three basic parameters and make a broad assumption about the fourth. According to ASHRAE Standard 55, thermal comfort (for most lightly-clothed people) is achieved when the following conditions are met:

- Air temperature between 73 and 77°F;
- Relative humidity from 20% to 60%;
- Air velocity in a range of 10-to-45 feet per minute;
- Mean radiant temperature (MRT) equaling the air temperature

Of course, when we leave our homes and spend time out of doors, we accept a much wider range within these parameters. We dress suitably, we maintain the appropriate activity levels, and we have certain expectations about the conditions we find ourselves in. For instance, no one would say that taking a walk wearing a light jacket on a sunny, 60°F day in March is an uncomfortable situation. Conversely, lying on the beach in 90°F weather is rarely defined as stressful.

As occupants, builders, retrofitters, and even researchers of interior spaces, however, most of us are particularly cognizant of only one of these elements: air temperature. Even here, however, there are no absolutes. As the following chart indicates, recommended temperatures vary greatly between cultures—even those from fairly similar climatic and racial backgrounds.

Space	**U.K. (IHVE guide 1965)**	**Germany**	**USA (ASHRAE 1963)**
Living Room	65°F	68°F	73-75°F

Bedroom	60°F	68°F	73-75°F
Kitchen	60°F	68°F	73-75°F
Bathroom	60°F	71.6°F	73-75°F

(Rapoport and Watson 1968)

When one looks across a greater range of cultural preferences (as well as considering how these preferences have changed with time, availability of central air conditioning, etc.) it becomes obvious that an “ideal” in terms of comfort conditions is illusive. A 50° day in September and people start pulling out their winter coats. The same temperature in March and you see college students out playing Frisbee in their shorts.

To intervene positively in achieving thermal comfort, it is necessary to look beyond air temperature. Understanding some elements of human physiology is helpful.

Metabolism

A primary difference between warm- and cold-blooded animals is the ability of warm-blooded creatures to adapt and live in a wide range of environments. We do this through a complex system by which we generate our own heat and regulate our internal temperatures.

The heat generation process is essentially an internal combustion process whereby hydrocarbon fuel intake in the form of food is primarily either directly converted into neurological activity or kinetic mechanical energy in the muscle tissue, stored as fat, or directly burned up or oxidized with the primary byproducts being carbon dioxide, water and heat. This food-to-heat conversion process we call “metabolism.”

Only a small percentage of the food consumed by a full-grown adult converts into long-term muscle growth. Most of it is either directly consumed in supporting our nervous system or producing the work generated by our muscle tissues with its accompanying waste heat. The rest is stored in fat tissue for the same purposes during periods when immediate food consumption is not available.

When the metabolic rate is the same as the bodily heat loss, there is a heat balance. Mathematically it is expressed as:

$$Q = M \pm R \pm C_{onv.} \pm C_{ond.} — E$$

Where:

Q = heat gain or loss
M = metabolism
R = radiant gain or loss
$C_{onv.}$= convective gain or loss
$C_{ond.}$= conductive gain or loss
E= evaporative loss

Since the body consistently seeks a thermal balance, if food consumption outpaces heat dissipation, the result is weight gain. When work generated or heat is otherwise dispersed in excess of that in the food being consumed, the net result is weight loss.

Since metabolism is essentially an oxidation process, we can measure the metabolic rate by measuring the amount of oxygen absorption. In one study an average sedentary male consumed about 15.2 liters of oxygen per hour. Since we know that one liter of oxygen “burning” basic food stuffs (carbohydrates, proteins or fats) creates approximately 4.8 kcal/liter, we can calculate that there is approximately 73 kcal (289 Btu) per hour generated in this process. Since we cannot bear an ever-increasing build-up of temperature, the body must dissipate this heat in a variety of mechanisms—just as an automobile engine requires an active cooling system to keep it from overheating.

The metabolic process itself is hardly a static phenomenon as the rate of metabolism varies due to the following factors:

- Age
- Body temperature

- Gender
- Height, weight and skin surface area

- Growth
- Infection and other diseases

- Muscular activity
- Ambient temperature and other conditions

- Sleep cycle
- Pregnancy, menstruation, lactation

- Prolonged fasting
- Recent ingestion of food

- Emotional state
- Hormones

(Vander, Sherman, and Luciano, 1980.)

Food is the basic fuel that drive our metabolism but the Calories (Cal. with an upper-case “C”) as used by dietitians actually refers to kilogram-calorie (kcal) or 1000 of the (small-c) calories that we use in the energy field. Since 252 calories equals one Btu, one dietary Calorie (kcal) equals 252,000 Btu. Metabolic rates are measured in Mets with one Met equaling 50 kcal/m^2/(hr)

The average adult requires about 2,200 kcal or 8,730 Btu per day. This equals approximately 14 Hershey bars, four cans of baked beans, one cup No 2 fuel oil (not advised), or 2,560 Watt/hr. These figures are, of course, only averages as we all know different people make more efficient use of the food they consume, some tend to more readily convert the fuel to stored energy in the form of fat, while others dissipate more energy as body heat or tend to function at higher kinetic energy levels.

Sharing body heat, especially with one who has a higher metabolic rate than your own is a long-honored comfort strategy going back at least to the early parts of our countries history before central heating when “Bundling” was a widely accepted mode of courtship during the winter months. “Forty men in a boarding house bed,” is a strategy used by many under adverse conditions throughout history and the image of a “Three-dog night” (about 40 Watts each) implies a serious drop in ambient temperature.

Natural Body Responses

The basic body controller for thermal comfort is the hypothalamus. It is a gland at the base of the brain; essentially a thermostat set at 98.6°F. It senses blood temperature and gradients across the skin surface. Nerve cells in the hypothalamus sense changes in blood temperature and receive nerve impulses from the skin. The average-size man has about 1.82 m^2 or 20 ft^2 of surface area exposed for heat dissipation—by conduction, convection, radiation and evaporative cooling.

We have two sets of heat sensors: those that measure outflow located close to skin on fingertips, nose, elbows; and those that track inflow located deeper in the skin and body cavities. These two sets of sensors detect changes in environmental conditions before the blood temperature changes, and telegraph that information to the hypothalamus.

Leonard and Murphy point out that most houses have but one thermostat and one/possibly two system(s) to modify the energy balance in the system (homeostasis) whereas our bodies have 150,000 tiny sensors on our skin surface and another 16,000 deeper in the skin. Clearly the biological feedback loop makes our “smart houses” look primitive by comparison.

This mechanism is both elegant and essential. Unlike our cold-blooded brethren, the reptiles, fishes and amphibians, warm-blooded creatures must keep their core body organs within a fairly narrow band of temperature dysfunction and death may occur. For humans, this range is quite narrow:

Body Temp. (^{o}F)	Physical Effect
110	brain damage, pass out, nausea
100	sweating begins
98.6	state of health
95	shiver, goose bumps
90	treatment for exposure required; lose power of speech

80	**humped up; rigid**
70	**irreversibly cold**
60	**lowest temperature with recovery**

(Eagan)

Responses to Cold

When the hypothalamus senses that the body is loosing heat faster than it is generating it, it secretes hormones and sends nerve impulses to various parts of the body to increase the metabolic rate, constrict blood vessels and other changes. Veins in the hands, feet, (especially fingers and toes), nose, elbows, and knees constrict and auxiliary veins dilate, directing vital heat flow away from the extremities and preserving it for vital internal organs. All of these reactions have distinct purposes for preserving heat and allowing survival under a wide range of ambient conditions. The "logic" behind this pattern is that the fingers and toes are less essential to survival than the internal organs and especially the brain. The body will preserve the effective functioning of these critical resources, even if it means sacrificing fingers and toes to frost bite.

The hypothalamus also send signals to reduce sweating and philo-erector muscles raise hairs on the skin surface in an erect position in a (somewhat archaic, evolutionarily speaking) attempt to increase the loft of our "fur" thus adding insulating air pockets. The too-cold message also contracts muscle tissue and raises goose bumps on the skin thus reducing the total surface area exposed and sends impulses to muscles to create a shivering response which helps generate it own heat near the colder surfaces. We, of course, also make semi-conscious voluntary moves such as rubbing our hands, beating our arms or curling up into a fetal position to achieve these same heat generating or conserving goals.

When the body finally realizes that it is losing the battle against heat loss, it slows down the entire system, allowing the mind to get sluggish and reducing the body's core temperature—the proverbial 98.6°F. In some cases, such as with children who have fallen through the ice on lakes, such deep-core temperature reduction has proven to be a life-saving strategy. In other cases, as hypothermia sets in and the body loses its ability to recover from such a deep chill, the condition can become deadly.

Because the brain and the head that encases it is so central to our bodies sense of comfort, controlling the heat loss or gain of this most vital organ may be the easiest means of providing comfort to the rest of the body. Although my friends and family undoubtedly tire of me reminding them, if you really want to do something about your cold toes and fingers, a warm hat may be a far better strategy than heavier socks and mittens or certainly better than turning up the thermostat.

Responses to Heat

The human body is far less forgiving of high temperature conditions. Under over-heated situations, the hypothalamus sends out just the opposite signals. The skin relaxes, more heat is delivered to the skin surface from expanded blood vessels (flushing) and pores open up allowing for greater perspiration and, hopefully the resultant cooling from evaporation of that moisture. We also tend to reduce our conscious work activity and like to sprawl to expose more surface area for cooling. Under taxing conditions when the body's cooling mechanism can't keep up with the internal heat generation, *heat exhaustion* can occur resulting in moderately elevated core body temperatures and general collapse. Under truly extreme stress, these internal feedback mechanisms can break down resulting in *heat stroke* with resultant shut-down of the perspiration system and extreme elevated body core temperatures.

Responses to Illness

When certain pathogens or disease trigger the brain, many of these same temperature regulators are brought into play to raise the core body temperature to help fight off these viral and bacterial invaders. Although we tend to react negatively to fevers, they are actually our own body's defenses at work. However, while temperature may be working in our favor here, there is also the danger that extremely high core temperatures for extended periods of time can be particularly damaging to the brain cells that our bodies are so focused on protecting. Extended fever can result in brain damage, seizures or even spontaneous combustion (just kidding—seeing if you were paying attention).

CO and other Chemical Reactions

As has been already discussed, our bodies are indeed very complex systems with chemical stimuli and responses affecting all biological and physical activities.

The energy conservation community has admirably focused a great deal of attention on interior air quality issues including carbon monoxide (CO) levels. Besides the known health effects of even low levels of CO, this toxin also influences our perceptions of thermal comfort. Under conditions of reduced oxygen levels and increased levels of carbon monoxide or carbon dioxide, the heart is induced to increase the blood flow in order to try to deliver sufficient oxygen to body tissues. With increased blood flow, there can be a false sense of warmth and comfort with an attending feeling of wellbeing and lethargy.

Ingestion of alcohol while giving an immediate false sense of warmth, is a circulatory depressant. The degree to which prescription medications affect blood flow and other temperature sensing and controlling mechanisms is often not understood but may impact thermal comfort and may not be a standard part of all drug labeling requirements or included in standard doctor-patient guidance.

The most basic process of digestion draws blood flow away from the extremities. The digestive process, combined with the lethargy associated with consuming certain foods (the tryptophans in turkey for example), can cause some gourmands to seek especially warm and comforting environments following a large meal.

Activity Levels

The body generates heat at widely varying levels depending on activity: Being aware of what activities take place in various locations allows technicians to apply measures accordingly. It is far more cost-effective to upgrade a much-used sitting room where the occupants are sedentary rather than a basement room dominated by a ping-pong table or a weight set.

ACTIVITY	Btu per hour
Sleeping	**220**
Reading	**325**
Sweeping	**550**
Walking at 2 mph	**722**
Sexual intercourse	**1,111**
Walking at 4 mph	**1,372**
Sawing by hand	**1,588**
Jogging	**2,262**
Rowing 20 strokes/min	**3,286**
Maximal activity	**5,714**

Eagan

It is equally important to recognize that for many elderly individuals, poor blood circulation and reduced activity levels makes maintaining adequate body temperatures difficult. Higher temperatures must be maintained in order to avoid the dangers of hypothermia. Even minimal activity levels, such as occasionally getting up, walking around, stretching, rubbing hands together, etc. can generate additional heat and should be encouraged.

Careful thought as to what activities will take place at what time of day in relationship to ambient temperature, sunlight, earth cooling and natural ventilation strategies should be an integral part of every design process.

Zoning by Activity Level

The same kind of activity-level awareness should be recognized when designing or balancing heat delivery systems. Instead of assuming a uniform 70°F is needed throughout the home, one should ask what are the real temperature requirements of a particular space? How do these thermal needs change with time? Is not a zoned hot air, hydronic, or radiant electric system controlled by separate thermostats more appropriate than raising and lowering temperatures throughout the home? Can thermostat schedules be more complex than simply nighttime or workday setbacks? Particular with the advent of "intelligent," or "smart" homes, the technology is clearly more advanced than the typical algorithms we apply. Control mechanisms incorporating anticipated space-use assumptions along with on-site occupancy sensors can customize temperature selection to the micro-environmental level.

Clothing

According to laboratory studies, a naked person sitting quietly is comfortable at 82.4°F (Fanger, 1970) We all know we add clothing to stay warm, but this understanding is more intuitive than scientific. Researchers, in an attempt to quantify this critical element have assigned "Clo-values" to various levels of body coverage. A clo-value of 1 equals roughly R-0.88. There are reasons besides thermal comfort for wearing clothes, but people in all parts of the world existing in widely variable climates have evolved a plethora of clothing styles appropriate for local climate needs to protect themselves from both heat and cold and controlling moisture movement.

Indigenous clothing styles and even various period western fashions were most often based on principles of thermal comfort and can be a good indication of what makes sense in a particular environment. In hot humid climates, people can get away with little or no clothing - mostly decorative or for modesty. The forest canopy and dark skin pigmentation make shading and protection from the suns direct rays less necessary. When working in fields, wide brimmed, ventilated hats are the norm and evaporative cooling is encouraged, albeit not very successfully due to the high humidity.

In warm, dry climate (Mediterranean), people wear linens and natural fibers—from fine to moderately heavy weaves with light colors to reflect sunlight.

Hot, dry, sunny climates are characterized by hot days and cold nights. Here body covering is required to avoid dehydration and protect against sunburn and cancer. Despite what sun worshippers may claim, wearing some sort of protective clothing is almost always more cooling that exposed bare skin. Clothing typically includes loose flowing robes with no pants, wide sleeves which protect skin from direct sunlight and wind preserving moisture. The head covering exposes only the face. Sandals expose feet, but they are protected under the floor-length robes. Perspiration readily evaporates under robes and escapes out the neck. The Bedouin people of the Sahara carry this even further to a non-intuitive level by wearing black or dark blue wool robes which absorbs sunlight with lighter weight robes worn underneath. Turbans or even wool "watch caps" are also surprisingly common in this environment.

In very cold, snowy climates, clothes are made with fur cut to contour the body. In the summer, polar inhabitants wear their fur facing outward. In winter they wear two layers—the inside fur facing in, outside facing out. An adjustable draw at the waist and hood allow ventilation to expel moisture. Layering allows them to remove and replace clothing as needed. If the fur gets wet, it is taken off, allowed to freeze and the ice crystals are beaten off.

Above all, cold-climate clothing strategies emphasize effective insulation of the core body parts and especially the head. President John F. Kennedy's fashion example of a perpetually uncovered head probably did more damage to our common sense understanding of control over our personal thermal comfort than any other factor in the twentieth century.

In a temperate climates, layering and different clothing styles for summer and winter were the norm. The formality of hats, three-piece wool suits and ties in the business world was a response less to fashion than to long hours of sedentary work in poorly heated spaces. Straw boaters, white linen jackets and tennis shoes provided summer comfort.

Recent Advances

More recently, the hi-tech outdoor clothing industry has sought to capture the market once dominated by the high-loft fiber such as traditional down. One could equate the advent of Thinsolate™ glove liners with the popularity of foam board insulation products instead of cellulose or fiberglass blown insulation.

Clothing manufacturers, like builders, have also recognized the need to control moisture flow both in terms of water shedding and allowance for water vapor diffusion. Just as building professionals often differ over where to place air barriers and the dangers of trapping moisture, so too today's campers are likely sit around the camp fire and debate the benefits of one new high-tech fabric configuration over the other. Thus both the manufacturers of house wrap and the popular Gortex™ material used for outdoor wear recognize these principles by fabricating their product to allow for the two-way diffusion of water in its vapor state, but block its movement in a liquid state. The goals are similar and the end result is comfort.

While we may think seriously about appropriate clothing while hiking in the Grand Tetons, we often forget this element in our more mundane sedentary lives. Our contemporary over reliance on mechanical climate-control systems can make achieving personal thermal comfort difficult. Moving about in summer between sweltering, poorly designed, pedestrian-unfriendly city streets and buildings artificially cooled to a temperature lower than one would find acceptable in winter can make choosing an appropriate wardrobe a schizophrenic experience.

As we presently face a potential repeat of the '70's energy crises with inflated gasoline prices and low-income families without heating oil, it may be instructive to remember the symbol of Jimmy Carter's "moral equivalent of war" was not veiled threats against our OPEC-member allies but an exhortation to the people of America to simply put on a sweater rather than needlessly waste our precious fossil fuels.

Air Temperature

As has been said, air temperature is the only measurement typically adjusted by the home thermostat and monitored by thermometers. It is the basis of evaluating the effectiveness of most conservation strategies (Data-logger and utility bill-based studies rarely track anything but fuel consumption, ambient temperature and sometimes thermostat set points). Though other factors are key to comfort, we still concern ourselves with air temperature since it is a very important element in the overall comfort formula.

As a major component in convective heat transfer, air temperature moderates surface temperatures. These in turn further influence sensed temperature and comfort.

Strategies that focus on the actual efficient and strategic delivery of adequately tempered air for either heating or cooling can also have significant energy-saving side-benefits. Retrofit strategies based on human comfort make effective use of common sense and traditional practices combined with the latest in electronic control mechanisms. Anybody can turn back the thermostat at night, but that means they have to wake up to a cold house. A programmable thermostat anticipates the early morning needs and returns the house up to full comfort conditions by the time it is needed, no matter how far back it was set for the night or other unoccupied periods. Depending on the thermal mass of the house, however, it may take longer to warm up surrounding building components. Under such conditions, air temperature alone may not be an adequate measurement of comfort conditions. (See box: "The occupant may be right")

Zoned heating systems can maintain comfortable air temperatures when and where spaces are occupied while saving energy elsewhere in the building.

Infrared or sonic occupancy sensors make such zoned systems even more sophisticated, but quick response of the heating system is essential if users are to be satisfied.

Techniques for improving the temperature of delivery air by insulating exposed duct runs and eliminating drafts in the living space not only reduce Btu loss, but also improve comfort.

In extreme temperature conditions, poorly insulated buildings with excessive air leakage may lose more heat than the furnace can adequately provide. This is both an energy and a comfort liability. Identifying temperature stratification and directing the heat to where the occupants spend time can compensate. The "warm room" strategy is an example of this.

Selectively ventilating a house in summer can also improve comfort with minimal energy investment. Generally speaking, the North side of the house will be less affected by summer solar gain, and hence is a good location for intake of ventilating air. In the morning, the West side of the house is cool because the sun hasn't hit it yet. In late afternoon, the East side is cooler, but only after the ground cools off from the sunlight that has been beaming down on it all morning. Areas that are grass covered and well shaded by trees and bushes are also cooler. Not only do such plantings provide shade, but moisture from the leaves also cools the passing air. In terms of long-range planning, adding vegetation may be a significant strategy for meeting summer comfort cooling needs. Whole-house fans for rapidly flushing out hot house air in the evenings is particularly effective in many climates.

Relative Humidity

The impact of humidity levels is probably the most misunderstood element regarding comfort. At air temperatures above 75°F, the body begins perspiring. If the surrounding relative humidity is low enough, a significant amount of this perspiration undergoes a change of state and evaporates as water vapor. For each pound of water evaporated, the latent heat of vaporization extracts 970 Btu of heat from our bodies, thus providing significant cooling.

Similar to cooling by perspiration—heat dissipation by respiration or panting is both a convective heat transfer mechanism as well as a form of evaporative cooling. For most warm blooded animals other than humans, this is their primary cooling mechanism as they tend not to perspire. Under cold conditions, the best strategy is to breathe in and out through the nose which both humidifies the air and tempers its frigidity. In warm climates we are told to breathe in through the nose, out through the mouth. In hot conditions, the recommendation is to breath in and out through both the nose and the mouth to increase surface area that dissipates heat.

Only humans, horses and camels sweat as their primary cooling strategy. To be effective at evaporative cooling, the sweat must evaporate directly from the skin surface.

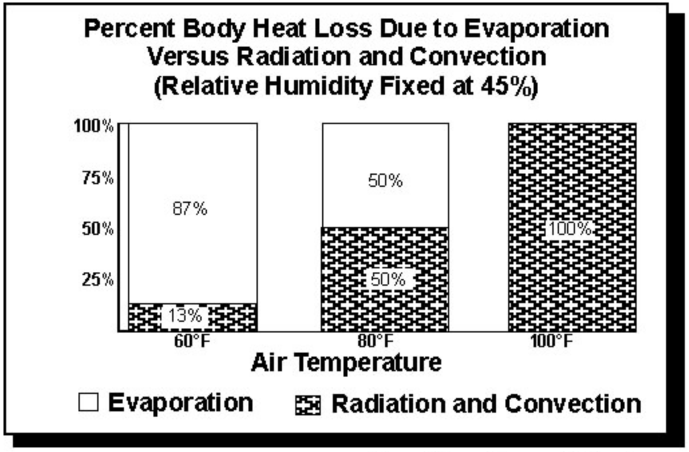
Perspiration originates in blood and is forced out capillaries to the sweat glands. If temperature and relative humidity are high, an active person will generate heat faster than the body can dissipate it. Thus perspiration only becomes a significant element in cooling with moderate to high temperatures.

Impact of Relative Humidity On Sensed Temperature

Relative	Air Temperature						
Humidity	70°F	75°F	80°F	85°F	90°F	95°F	100°F
0%	64°	69°	73°	78°	83	87°	91°
10%	65°	70°	75°	80°	85°	90°	95°
20%	66°	72°	77°	82°	87°	93°	99°
30%	67°	73°	78°	84°	90°	96°	104°
40%	68°	74°	79°	86°	93°	101°	110°
40%	69°	75°	81°	88°	96°	107°	120°
60%	70°	76°	82°	90°	100°	114°	132°
70%	70°	77°	85°	93°	106°	124°	144°
80%	71°	78°	86°	97°	113°	136°	
90%	71°	79°	88°	102°	122°		
100%	72°	80°	91°	108°			

At especially high air temperatures, the evaporative process is the *only* way our bodies can effectively dissipate heat as all convective and radiative heat transfer may be in the reverse direction. It is estimated that a person can survive at temperatures of 130°F *if* the air is absolutely dry (and the person is not dehydrated).

At higher relative humidity, however, the perspiration doesn't evaporate and little cooling takes place and we just feel hot and sticky. In humid conditions, an individual can survive at 115°F for barely a few minutes.



source: *More Other Homes & Garbage*

On the other hand, below about 58° or 60°, higher humidity makes us feel cold and clammy and is generally considered unacceptable.

At intermediate temperatures, 65-75°F (the comfort range) humidity levels make far less difference in perceived comfort. While at such temperatures there is more evaporation and slightly greater comfort at a lower relative humidity, there is still an energy penalty in most climates to humidify *or* dehumidify air. The Enthalpy or energy cost of vaporization is 970 Btu's per pound of water as water shifts from water to vapor or visa versa. This energy penalty often more than counteracts the savings from reduced temperature settings resulting from the improved comfort. If the dehumidification process actually freezes water vapor on the coils, there is an additional 144 Btu per pound of water is expended in the enthalpy of fusion in the change of state to ice.

Certainly one of the most cost-effective "base load" electrical-savings retrofits during summer months in an even moderately humid climate is to close the basement windows or otherwise air seal the house and shut off the dehumidifier that is working 24-hours a day trying to dehumidify the great outdoors.

On the other hand, in particularly dry climates, evaporative coolers, also known as swamp coolers provide an inexpensive alternative to compressor-based air conditioners as a modest water consumption and the electrical costs of running a fan are the only loads necessary to provide adequate cooling comfort where natural evaporation cools the incoming air.

Consumers in other parts of the country are not so lucky. In recent years as manufacturers have tried to meet increasingly stringent air conditioner efficiency standards, some less conscientious firms have met strict sensible temperature efficiency goals by redesigning coil and fan sizing resulting in reduced dehumidification of the house air. Enlarging the condenser coil or increasing the air flow improves the overall heat exchange, but it may not cool the coil down to a point where it condenses moisture from the house air. This can lead to either insufficient "sensible" cooling or an uncomfortable "clammy" feeling as well as promoting the growth of molds and mildew within the structure.

Dehumidifiers are expensive to operate. An easy way to save when using this technology is to be sure doors and windows are closed and the equipment is isolated from other moisture sources—unvented clothes dryers, etc..

Conduction from Body

Conduction of body heat through direct contact with cold surfaces is a far more efficient mode of heat transfer than convective losses to the air. Bare feet on cold floors are clearly more of a source of local discomfort than bare hands in air of the same temperature. Direct contact with cold surfaces allows these heat sinks to draw out body heat. Seating materials is an area where conduction plays a large part. For example, concrete park benches or stadium seats with the high conductivity and extensive thermal mass are uncomfortable in all but mid-summer conditions. Similarly, metal folding chairs are far less desirable than wood or padded seats unless the air and seat temperature is well into the comfort range. Seating comfort is less an issue of the surface temperature than the high conductivity and heat capacity of the seat material itself. This is one reason why real leather is a preferable seat-cover material to its look-alike vinyl.

Young children who play on cool, highly conductive concrete, linoleum, or tile floors are especially vulnerable to conductive heat loss and discomfort. This is one of the primary perceived benefits of in-floor radiant heating. In retrofit situations, insulating floors over cool basements (not yet cold enough to justify insulation simply on a heat loss-basis, may bring the floor temperature up to that of the average room temperature, and greater level of comfort achieved. Even a 72°F linoleum floor is uncomfortable to crawl on or lounge on in front of the TV. Adding carpet with a thick underlayment reduces that immediate conductive heat loss from the body to the cooler floor surface and may provide comfort at lower air temperature.

For people who work on their feet or sit at a desk over a cold floor, encouraging appropriate dress in the form of thick socks or boots can greatly improve comfort and allow lower thermostat temperature settings. Insulating rubber mats and cushions may also be appropriate, and less expensive than the ubiquitous electric space heaters.

Waterbeds are a case where many have to deal with direct conductive body heat loss to a massive thermal sink. The assumed solution is to raise the temperature of the water bed with an electric heater to a point where there is a neutral heat flow between bed and body. Insulating the sides and bottom of the bed and using heavy blankets and bedspreads can reduce the heat loss from the 90°+ bed to the surrounding environment, but it is still an expensive option. A far more economical alternative is to simply insulate the body from the bed and turn off the heater. A flexible foam pad (or a couple of layers of wool blankets) below the mattress pad and some flannel sheets make a water bed very comfortable with no energy liability at all.

Actually adding a quilted pad (and perhaps a wool blanket) over even a standard spring mattress can make them more thermally attractive and flannel sheets next to the skin is a fine defense against bodily heat loss. Why do we assume we only need a single sheet between our bodies and a cool mattress while piling on multiple layers of blankets and quilts on top of us when the conductive heat loss clearly outweighs the heat transfer to the air?

Although some do not recommend sleeping under an electric blanket with concern about on-going close proximity to any alternating electric current device, use of electric blankets to pre-warm the bed before retiring is a fairly inexpensive comfort solution where air temperature is being kept low. Our colonial ancestors used a brass bed warmer with hot coals from the fireplace to serve the same purpose. Before central heating, beds were often either of the four-poster design with canopy and insulating curtains or actually built into an insulated interior wall to provide an isolated comfort zone for the night.

Of course with all of these nighttime bed solutions, the assumption is that significant energy savings can be had by either keeping the bedroom cooler than the rest of the house or that the temperature in the whole house can be reduced with a setback thermostat. The latter offers the greatest savings.

Air Movement

The movement of air, either natural or induced, can be an important amplifying element of heat transfer either to or from the body. Most body surfaces are between 80° and 90°F. Convection of cooler air is established as the body heat is transferred to the air, thus elevating its temperature and encouraging it to move on. Appropriate clothing is the most suitable strategy.

Wind Chill

Wind chill is a concept originally introduced in 1939 by Antarctic explorer Paul Siple to give a qualitative measure of the relative discomfort of combinations of wind speed and low temperature on exposed skin and to warn against the risk of frostbite and other dangers of the outdoor environment.

Recent discussions within the comfort community have recently reevaluated the standard assumptions upon which the wind-chill index was based and the numbers have generally been revised upwards (the newspapers will not be reporting as low a wind-chill temperature as previously, not counting actual moderation driven by global warming).

From a building science perspective, it is not correct to say that wind chill itself is a direct determinant of heat loss from houses. It is fair to say, however, that increased velocity of air certainly impacts personal heat transfer and comfort. Sub-zero air temperatures are not the issue here. Rather we will examine the ways in which moving air provides a cooling or chilling effect.

Fans

Fan-forced moving air can be a real blessing during the cooling season as the moving air both removes sensible heat and promotes evaporation from the body. Although if the air temperature is significantly higher than the surface skin temperatures and humidity levels are excessive, little comfort will be achieved. On the other hand, fan-forced circulation of room temperature air during the heating season can be unwelcome as a wind chill-like effect takes over.

The use of ceiling fans for purposes of heat destratification is particularly suspect. For most standard ceiling heights, heat stratification or thermal layering is not great to begin with. Blowing air at even 75° F down on people's heads, may result in a cooling effect. Thus, fan manufacturers have introduced seasonably reversible blades.

Similarly, high efficiency furnaces and heat pumps gain a great deal of their efficiency by having reduced delivery air temperatures. To retrofit such a unit into a duct system designed for an older, high-temperature oil or gas burner can result in fairly low temperature air being delivered at high velocities. In any system, undersized ducts, oversized delivery fan output or poor register placement can lead to discomfort.

Don't run the fans if no one is present.
The electric motors themselves generate heat…
Their purpose is to create comfort, not to cool spaces

The cooling impact of moving air can be used to strategic advantage in Summer. If your goal is simply to create air movement within a closed space, portable room or ceiling fans may be appropriate. But don't run the fans if no one is present. The electric motors themselves generate heat and contribute to overheating load on these spaces. Their purpose is solely to create comfort, not to cool spaces.

Ventilation

Effective ventilation does not mean simply opening up all the windows throughout the house. Once that happens, control is lost. Whatever conditions exist outside (95° F, high humidity, still air) is what you've got inside. The house is no longer providing shelter from the weather.

It is a common misconception that during the summer one ought to ventilate, ventilate, ventilate. Many people leave their windows wide open from June through September, shutting them only in hard, driving rain. If you lived in a light, shaded, wood-framed home, 24-hour venting might be an acceptable solution to beat the summer heat. In most climates, especially with high mass structures, making use of the technique of nocturnal cooling can be quite effective. All that is required is to open a few selected windows and doors in the evening and allow the natural convective air currents to bathe the walls of the buildings, both inside and out, with cool, dry, nighttime air. First thing in the morning, close up all these doors and windows. Seal up the building as tight as you would in the winter (in fact, windows that you don't use for ventilation should be left with the storm windows installed -- they keep out heat as well as cold). After a couple of days of this procedure, you will find that you have begun to develop a cycle of the heat flow in the structure, making use of the thermal lag of the heavy masonry. You will find that the building is cool and dry, no matter how hot and muggy it is outdoors. The masonry provides both cool air temperatures and cool surfaces for radiant cooling (See next section).

Ideally ventilation can bring relatively cool dry air into the house (see Air Temperature previously). We also want to create air *movement*, because it is the movement of air by our skin that makes us feel cool. The greater the velocity of the air movements, the cooler we feel.

Where possible, identify and make use of prevailing winds. These tend to come more-or-less from the southwest, although there are many local variations. Think of this side as being where the air will enter the house. Leave an opening on the *other* side of the building where the hot house air can escape.

Just like in the winter, cooler air comes in at the lower levels and hotter air exhausts out the upper reaches. Make use of that principle in planning ventilation.: Intake low, exhaust high. Open the top sashes of exhaust windows. Seek a clear path between incoming and exhausting air sites. The fewer bends and turns the better.

Since moving air is the goal, there should be more area open for air to escape than for air entering. This speeds up the flow of air once it is in the building. Comfort benefits accrue from achieving the greatest air movement where people spend time in the summer. Moving a chair just a few feet into the path of the air flow could make all the difference in terms of comfort.

Power ventilation

When passive flow is insufficient, fans can augment flow. Don't try to overcome the natural forces with electric power. If you are using fans to improve ventilation, position them to exhaust the air (and their own generated heat) from the occupied spaces rather than pulling outside air in across the electric motors.

Whole-house attic fans can do a great job at flushing out a home’s overheated air at the end of a hot summer day. Preventing air leakage around it into the attic when not in use is required.

Although fans do use some energy, it is far less than an air conditioner, and the comfort levels can be high without creating the artificial, insulated environment of a fully conditioned interior space.

Mean Radiant Temperature

The human body is constantly radiating energy to objects around it, which in turn are also radiating energy back to us relative to their surface temperature and other characteristics. Depending on the relative temperature of the surfaces surrounding an occupied space, personal comfort can be greatly enhanced or compromised.

Mean Radiant Temperature (MRT) refers to the average ambient surface temperatures. The impact of MRT on the energy exchange balance between our bodies and the objects and building surfaces that surround us may be the least well understood comfort phenomenon by energy professionals.

If we imagine a hypothetical space in the shape of a cube, we might measure the following surface temperatures within that space:

SURFACE	TEMPERATURE (^{o}F)
Ceiling	70°
Floor	65°
Wall #1	65°
Wall #2	68°
Wall #3	45°
Wall #4	55°
TOTAL	**368**
Average	**61.3**

If we assume that the space is a perfect cube and our occupant is located directly in the center of this space, we could divide this total by the 6 surfaces and get an area weighted average of the various individual surface temperatures. In this simple example, the average surface temperature or Mean Radiant Temperature is 61.3°F.

Because the factor of radiant heat transfer is typically dominant over that of convection, researches have determined that if we want to create an environment with an effective comfort temperature of 70°F, for every one degree Fahrenheit that the average surface temperature is below 70°, we would have to raise the air temperature 1.4°F to compensate for the radiant cooling of those cooler surfaces (see chart below). Similarly, for every degree above 70° in MRT would allow us to reduce the air temperature by 1.4° and still maintain the same level of comfort. Although in real life the calculations are complicated, it is fairly obvious that in occupied spaces, if you can improve the interior surface temperatures by adding storm windows or movable insulation systems or improve the radiant temperature flux through an improved heating system design, comfort can be achieved at significantly lower air temperatures or thermostat settings. The net result is energy savings throughout the house.

Equivalent MRT and Air Temperature for a Feeling of 70°F

MRT	**50**	**55**	**60**	**65**	**68**	**69**	**70**	**71**	**72**	**70**	**75**	**80**
Air Temp	**98**	**91**	**84**	**77**	**72.8**	**71.4**	**70**	**70**	**68.6**	**67.2**	**63**	**56**

Most passive solar heating systems use the building components themselves for the storage of the collected solar heat. Elevated wall and floor temperatures can make these spaces exceedingly comfortable, even if air temperatures are allowed to drop lower than one would expect in a conventionally heated home (thus, improving the thermal transfer necessary to make these systems work). A poorly designed system, on the other hand with excessive uninsulated glazing, could prove to be decidedly *Un*comfortable once the sun goes down.

Although MRT may be difficult to model, measurement of effective temperature within a particular space can be achieved with an easily-constructed globe thermometer that responds to both air and radiant temperatures.

The Occupant May Be Right
When They Turn The Thermostat Up To 80°.

It is almost gospel among energy education professionals to tell their clients not to turn up their thermostats above the desired set temperature. A thermostat, after all, is simply a switch, not an analogue dial that increases the heat output of the furnace or boiler. Research by Willet Kempton, however, shows that the misunderstanding of the nature of a thermostat and the resulting occupant behavior may more accurately meet the homeowners' comfort needs.

Setting back a thermostat for an extended period of time not only allows the air temperature to drop with the resulting energy savings, but it also cools the furniture and building surfaces significantly. Thus when one returns from a long absence with a deep temperature setback, both the air temperature *and* the mean radiant temperature are far below comfort levels. Since most thermostats only sense air temperature, turning up that control device to the desired comfort level will tell the furnace to run only until the air temperature reaches the desired set point. With a thermal lag in the surrounding surface temperature, the occupants are still cold until these surfaces heat up *or* unless the air temperature is further raised to compensate for the low MRT. Thus, although we may hate to admit it, the occupant may be right when they say they want to turn up the thermostat to 80° to make the room comfortable more quickly. The solution is, of course, to use a setback thermostat and program in sufficient lead time to preheat all building elements to the desired comfort temperature.

The impacts of MRT on client behavior can lead to a recognition of realities in building science that can be totally contradictory to standard assumptions. Two cases in point are documented in the boxes "The occupant may be right" and "Adding attic insulation increases energy use…"

Diagnosticians and energy auditors can identify trouble spots using moderately-priced remote thermal sensing devices or spot radiometers. Although not as flashy or pictorial as an infrared scanner, these devices give immediate feedback on surface temperatures which can answer important comfort questions as well as allow the auditor to calculate effective insulation values of wall or ceiling sections without invasive actions.

Perhaps the greatest contribution to architectural energy-efficient comfort design in the last couple of decades is the low-e window surface. The advantage of these windows is not, however, so much because they manage to “save” or “trap” the heat being lost to the exterior (r-value) but because of the improved comfort levels experienced by occupants near them. The low-e surface manages to “bounce back” the individual’s own body heat rather than absorbing it onto a cold surface. The occupant then feels more comfortable and is not tempted to turn up the thermostat a notch.

Adding Attic Insulation *Increases* Energy Use In a Multi-Family Building

Almost any consumer-advice pamphlet will tell you that the most cost-effective location to reinsulate your house is in the attic. On the contrary, we have documented where adding attic insulation actually increased energy consumption in a multi-family building.

The case in point is a three-story 1950’s multifamily structure with a central hydronic heating system. Before weatherization, energy bills were high but comfort levels were fairly uniform throughout the building. Although the top floor had only a couple of inches of insulation in the attic, the stack effect in the building more than compensated for the low MRT experienced by the third-floor occupants.

As part of the retrofit process, the weatherization crews added 10 inches of cellulose to the attic. Now the combination of internal stack effect and high third-floor MRT caused these upper apartments to overheat.

The natural response of the upper-level occupants was, of course, to open their windows which further exacerbated the stack effect infiltration levels at the lower levels.

Since the thermostat was controlled by the super who lived on the first floor, his immediate comfort response was to crank up the thermostat, resulting in significantly increased energy use.

This does not mean we should not insulate multifamily buildings, but rather to recognize that these interventions will change the comfort conditions in various locations and have an energy professional rebalance the distribution system to accommodate these changes.

(Wilson)

Simple r-value heat transfer savings numbers greatly underestimate the economic gains of retrofit measures appropriately applied to aid comfort needs.

We have demonstrated similar comfort-based energy savings from other window and building section retrofits particularly for occupied spaces. Simple r-value heat transfer savings numbers greatly underestimate the economic gains of retrofit measures appropriately applied to aid comfort needs. (Wilson and Belshe ASHRAE Journal 1987). The logic here is that if you improve the mean radiant temperature in those areas where the occupants spend most of their waking hours (such as the sitting room next to the television), you can expect that they will feel comfortable at a lower whole-house air temperature. Thus the savings attributable to retrofit measures in the sitting room show up throughout the home as a result of a lowered thermostat setting and a reduced ΔT.

The sun's radiation is clearly the greatest liability for summer cooling for both building energy use and comfort. As the sun penetrates through standard glass, it warms the interior surfaces and significantly raises the air temperature, but if you are actually sitting in that beam of sunlight, your experience of thermal discomfort is intensified. On the other hand, in the Winter, sitting in direct sunlight leads to comfort even at cooler air temperatures.

Sun screens, shades and awnings are a significant warm season comfort strategy as well as a recognized energy savers in southern climates. Choosing windows with a low coefficient of transmission in a heating dominated climate, however, may be a poor energy choice.

It is only recently that window manufacturers have begun to include this factor in their window labeling programs. Choosing glass, particularly for south-facing windows in a heating dominated climate should be done with great care counterbalancing heat loss (U-value) against desired solar gain (shading coefficient or light transmission) against winter comfort concerns (low-e ratings). Unfortunately, in most cases, window sales personnel and often even manufacturers are not qualified to help make those tradeoffs.

Heat delivery from radiators can be mildly enhanced through the application of dark-colored, high emissivity paints and reflective backer boards to redirect radiant energy into the occupied living space. The principle at work here is not so much improving the overall efficiency of delivering heat to the space, but rather, improving the efficacy of providing comfort by increasing the amount of heat delivered as radiant energy directed toward the building occupants rather than just heating up the air.

The same concern applies to other “radiant” heat sources as well. We talk about baseboard “radiators” (either hot water or electric) but most of their energy is delivered via air movement, most of which quickly rises up to the ceiling where it provides little comfort and exacerbates heat loss. New improved large surface area steel hot water radiators are making a big comeback, especially in Europe where there seems to be a higher awareness in the comfort factor.

In-floor or ceiling integrated radiant systems do provide good comfort, but there may be a liability in lag time for the interior surfaces to actually achieve the desired temperature levels. Experts generally agree that in-floor systems are preferable to ceiling systems. Because the ceiling is generally less obstructed than the floor, one could argue that a ceiling system would have a greater impact on the mean radiant temperature based on its geometry. With ceiling systems, however, some people complain of “hot heads” and “cold feet”—the latter when sitting with the feet under a table. On the plus side for floor heating, there is the conductive comfort factor on stocking feet and/or young children, cats or others who tend to play or sprawl on the floor. Since a certain amount of heat energy is transferred from the warm floor to the air above, this tends to encourage convective mixing.

Individual, portable electric *radiant* space heaters have the distinct advantage of providing direct comfort that you can carry with you (at least as long as your extension cord will allow) without trying to heat up the entire house to do so. The units will eventually heat up the air to their pre-set temperature, but in the mean time, comfort is achieved by the direct radiant heat. Since the high temperature from the space heater tends to counter balance other surrounding cooler surfaces, the *mean* radiant temperature needs are met allowing for comfort to be achieved at even below-average air temperatures.

The quick response time and directed nature of electric radiant panels share this benefit of being able to heat people instead of spaces and have the advantage of being able to be selectively controlled by a whole new generation of thermostat control devices that respond to a combination of air and mean radiant temperatures. (Watson and Chapman)

Thermal Mass

Just as thermal mass is an integral part of most passive solar heating systems, storing the energy gained from the sun during the day and releasing that heat at night when we need it most, so too can the walls of buildings store the "coolth" if the summer night-time air is used as natural air conditioning during the day.

Longer lag time in high mass houses requires a rethinking of operation schedules with regard to recovery after thermostat set-back regimes and even seasonal changes, especially where earth coupling is a prominent characteristic of the structure.

Many electric utilities and coops make use of thermal mass in offering time-of-use electrical rates or peak-load shaving cut-off systems as part of their demand-side management programs. Comfort is offered for all periods but the actual energy consumption only occurs when there is excess capacity available.

VERNACULAR ARCHITECTURE AND TRADITIONAL COMFORT STRATEGIES

If we look in history and examine the vernacular architecture of a particular time and place, we are likely to find exquisite examples of designs and construction practices that honor comfort. Not that all were thermal gems, but certainly many of those houses that survived both the deterioration of age and the wrecking ball were those that worked well and were worth preserving

Compact housing design for northern climates, sprawling earth-coupled ranch styles for hotter regions, broad overhangs for the sunbelt and large south-facing windows where winter sun is a blessing all provided regional designs that make sense thermally.

Even some of the less obvious construction systems make sense. Typically we see balloon-framed stud design as solely the result of the availability of long framing members, perhaps naïve building technology, lack of readily available insulation materials and a source of thermal bypasses. When these houses were built, however, often with integral "back-plastered" air spaces, reminiscent of the double-envelope designs of the '70's, they took advantage of natural convection, solar gain and earth coupling.

The use of wool tapestries hung
on cold castle walls in medieval Europe
allowed the occupants to "see" a surface
that more closely matched
the interior room air temperature.

Like a firred-out plaster wall in a brick house, these air spaces are less important as an insulating dead-air space than as a thermal break improving interior mean radiant temperatures. The same concept stands behind the use of wool tapestries hung on cold castle walls in medieval Europe. The effect is not so much to improve R-value and reduce heat loss, but rather to allow the occupants to "see" a surface that more closely matched the interior room air temperature rather that of the cold exterior brick walls. Double wythe brick walls combine the effects of thermal mass and an air space to create essentially two levels of thermal storage between the occupant an exterior temperatures.

The extensive use of brick or adobe in mixed hot and humid and hot dry climates allows occupants to make use of the thermal mass to achieve comfort levels by moderating temperature swings between day and night. Traditionally local populations operated their homes to make effective use of these characteristics, but currently homeowners tend to rely solely on air conditioning regardless of climate or building type.

When assessing older homes for energy retrofit there is great opportunity to look not only at thermal weaknesses that lose heat from the structure, but also appraise the building elements that work well with the climate and the comfort needs of the occupants. When occupants recognize their function and significance, they can incorporate them into their thermal comfort strategies.

There is great opportunity to look
not only at thermal weaknesses
that lose heat from the structure,
but also appraise the building elements
that work well with the climate
and the comfort needs of the occupants.

Looking back to traditional modes of building operation can also be instructive. Victorian homemakers would perform a semi-annual redecoration with more than a nod towards comfort. Installing storm windows, heavy drapes and wool carpeting and seasonally replacing these items with screens, venetian or bamboo blinds, and straw mats on the floor; converting a sun porch to a verandah.; moving the bedrooms to a 2nd floor screened sleeping porch.

Even today, many homeowners exhibit unconscious energy/comfort strategies without understanding the principles behind them. Note where clients tend to spend most of their time and look for comfort clues that indicate either a thermal anomaly or a particularly cozy nook. Note how furniture is arranged, and perhaps the best comfort sign of all, note where the family cat is lounging—it is undoubtedly the most comfortable spot in the house.

THERMOGRAPHY, COMFORT AND ADVANCED BUILDING DIAGNOSIS

There is an adage, widely quoted in the computer world, that "garbage-in equals garbage-out." meaning if you don't ask the right questions, you can't expect your answers to be useful. There is a corollary to this message from the building trades: "If the only tool you have is a hammer, everything begins to look like a nail," or if you only have a limited selection of tools, you are tempted to either misapply those tools, or simply ignore those problems that can't be solved with those tools.

Our diagnostic and analytical tools, rather than broadening our perspectives and understanding, more often than not, have limited both our retrofit opportunities and, more importantly, how we understand how houses work.

When weatherization programs were first instituted back in the early '70s, only a few select measures were allowed and auditors were restricted to a check-list approach to decision making. In 1976, the Federal Energy Administration introduced "Project Retrotech", a notebook-based simplified version of the ASHRAE steady-state heat loss calculations. It provided a numerical justification for expenditures of retrofit dollars, but shed little light on how a particular building actually performed.

Now there is certainly nothing inherently wrong with the steady-state approach as *part* of understanding how houses work, as long as one recognizes their inherent limitations. Typically the simplified steady-state model tracks only two elements of housing heat loss (or gain): conductive heat transfer and air leakage and possible a third, combustion efficiency. For this, we have two very simple formulae, one for what we define as convective heat flow or infiltration losses:

$$Btu/hr = V \times ach \times .018 \times \Delta T$$

Where:
Btu/hr = the heat loss per hour due to infiltration measured in British thermal units
V = house volume in cubic feet
Ach= measured or estimated air changes per hour
.018 = the heat capacity of air, and
ΔT = difference in temperature between infiltrating and exfiltrating air -- typically 65°F — exterior temperature

And the other which models conductive heat losses:

$$Btu/hr = U \times A \times \Delta T$$

Where:
Btu/hr = the heat loss per hour due to conduction measured in British thermal units
U= U-value or the reciprocal of the total R-value of a building surface
A= area of that building surface measured in square feet, and
ΔT = difference in temperature between interior and exterior air -- typically 65°F — exterior temperature

Unfortunately, there are many areas where both of these formulae fall short of absolute, or sometimes even useful accuracy: the formulae are based on controlled laboratory conditions, not actual field-installed conditions. The convective formula for instance, is good as far as it goes except it assumes we can know what the accurate number of air changes per hour is over a heating season. The fact that this process is constantly changing depending on wind conditions, indoor and outdoor temperatures and pressures created by exhaust fans and heating distribution systems makes this a decidedly elusive concept. Building scientists and retrofitters have at their disposal a tool for measuring air leakage, the blower door, but it creates a very unnatural condition akin to a 25 mile per hour wind blowing into the house from all directions. Although this is a very useful tool both for finding air leakage sites and comparing one house against another, attempts at correcting the blower door numbers to some concept of normal average infiltration rates is wishful thinking at best.

The conductive heat transfer formula is also fraught with uncertainty when we try to compare its model with the real world conditions. Conduction is not, despite what the formula suggests, in strict linear proportion to Delta T but changes fairly radically depending on the materials in question. Both modes of heat transfer are neither discrete nor steady-state, etc, but these issues are beyond the scope of this paper. The most critical failing is these two formulae is they describe only part of the complex physical (and psychological) phenomena that drive the energy budgets in our homes.

The advent of the personal computer made this simplistic “engineering” approach even more popular because the calculations could now be done more quickly and even be carried to seven decimal places, although the basic algorithms were rarely expanded. That these essentially very simple calculations were “computer generated” led to perceptions of accuracy and scientific veracity far beyond their real capabilities. Equally damaging was the fact that since the building auditor had only to fill in the blanks of the “black box” computer screen, he was further divorced from the underlying physics and the assumptions of the steady-state calculations. This tended to breed *less* understanding of both the analytical process and the physical realities that drive the heat loss and define the comfort conditions we are seeking.

Even the most high-powered computer audits are limited because they only model those components of energy loss which are easily measured and quantified. It has long been known, if not commonly recognized, that excessive energy usage in our houses results from a wide range of influences including combustion inefficiency, conduction, radiation, natural convection, pressure driven air leakage, thermal loops, delivery system inefficiencies, moisture change of state, appliance inefficiencies and, most importantly, thermostat settings--and combinations of all these factors and more as they occur simultaneously to provide comfort for the building’s occupants—successfully or not. With increased research and field experience, one-by-one, we have managed to develop methods to identify these different factors and in some cases, even measure them. Nonetheless, we have generally failed to include them in our models of energy usage in our structures because they are so difficult to quantify or to integrate into the overall building model or analysis packages. Those of us with the skill, understanding and equipment to make accurate thermal measurements can, however, go beyond these simple formula, provide clearer and more accurate diagnoses to our clients, and distinguish ourselves as a higher order of building scientist beyond the confines of the basic steady state assumptions.

Using Air and Surface Temperatures to Calculate Effective R-value

CASE STUDY

The problem was a common one to building investigators: You run diagnostics on a building until you understand what is going wrong but you are unable to present your findings in terms that your clients can either understand or use effectively for redressing poor construction practices.

In this case, the home was a double-wide manufactured home less than two years old. The homeowners had complained about discomfort even at high thermostat settings, high heating bills and, even worse, condensation and *frost* on exterior walls. They had complained to the manufacturer but they insisted the home was built to HUD standards and at this point the homeowners needed hard evidence that the building wasn’t performing as promised.

Since blower door tests indicated only 700 cubic feet per minute air leakage at 50 Pascals pressure, which translated to less than 1/4 air change per hour, it was clear that the low air exchange rate and other source problems were significant contributors to the moisture problem. But even under the worst conditions of Wisconsin winters, one would not expect to see condensation and *frost* on wall surfaces. Clearly, there were some serious problems with the effectiveness of the wall insulation system.

Infrared imaging equipment will give you a quality image indicating an anomaly, and surface temperatures, either integral with the imaging device or collected with a fairly low-cost spot radiometer can be easily collected. These surface temperature measurements, combined with some basic understanding and mathematical modeling, can provide an opportunity to document insulation performance in terms that even a layman or a code official can understand: *Effective R-value.*

Terms such as “bypass,” “intrusion” and “convective looping” are often unfamiliar to the general public. Years of hammering on the same theme by utilities and governments publications, however, has made most people familiar with the terminology of "R-values" even if their understanding implies little more than "thickness" or "more is better."

The basic assumption on a calculated R-value for a given wall section is that it is made up of the combined r-values of the various materials in that section plus an assumed air-film r-value for both the interior and exterior interface between the surface temperature and the ambient air. A typical wall section may be comprised of the following assigned r-values:

Interior air film	.68
Sheetrock	.45
3 ½ inches of fiberglass	11.00
Siding and sheathing	.61
Exterior air film	.17
Total R-value	12.91

The air film r-values are different here because it is assumed that the exterior wall surface is being impacted by a certain amount of wind wash thus increasing the heat transfer at that point as compared to the interior.

What is often not recognized, however, is that the theory of conductive heat loss and the r-values we use allows us to predict the temperature at any particular point through a building section. Specifically, the temperature at any particular point within a building section should be somewhere between the outside and the inside air temperatures *proportional to the effective r-value of the section components on either side of the location of the temperature measurement.* That is to say, if you measured the temperature in the middle of a wall section with an equal R-5 on either side of your temperature probe and you had an interior temperature of 70°F and an exterior temperature of 30°F, you would expect to read 50°F at your probe--half way between 30°F and 70°F. As you move through the building section, you would expect the measured temperature to change proportional to the degree to which you have passed though the cumulative R-values of the building section. This basic concept can be used to advantage as field investigators since we can use fairly inexpensive equipment and simple mathematics to model the performance of building sections with only a limited data points available.

The assumption to this model is that all we can easily measure is the interior air temperature, the exterior air temperature, the interior surface temperature (measured with spot radiometer or infrared camera that compensates for emissivity). The other key assumption to this model is that the interior air film has an r-value of .68 according to on standard ASHRAE steady-state calculations. With this premise we can calculate the total *effective* R-value of a particular cross section using the following formula based the AHRAE model and solving for the total R of the section.

$$\frac{.68}{R} = \frac{T_i - T_{si}}{T_i - T_o}$$

$$R = \frac{.68(T_i - T_o)}{T_i - T_{si}}$$

Where: R = total R-value of section
.68= r-value of interior surface film
T_i =interior air temperature
T_o= exterior air temperature
T_{si}=interior surface temperature

In the case of this particular manufactured home, we measured an exterior air temperature of 20°F and an interior air temperature of 67°F. Given the theoretical design configuration described above, had we been able to actually insert temperature probes into the wall and measure temperatures at various locations within a wall section, we would expect to record temperatures at various locations as shown in the following graphic and Table 1:

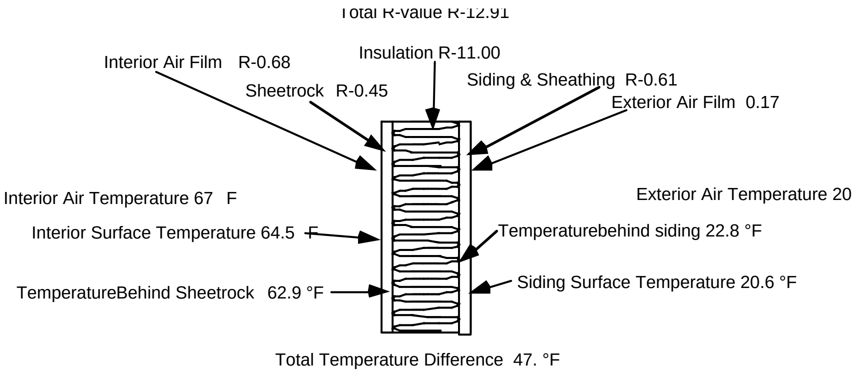


Table 1 Theoretical Performance of Wall Systems

Building material	Nominal R-value	Interior air temperature	67.0°F
Interior air film	0.68	Interior surface temperature	64.5°F
Sheetrock	0.45	Behind sheetrock	62.9°F
Insulation	11.00	Behind insulation	22.8°F
Siding & sheathing	0.61	Siding surface temp	20.6°F
Exterior air film	0.17	Exterior air temperature	20.0°F
Total	12.91	Temperature difference	47.0°F

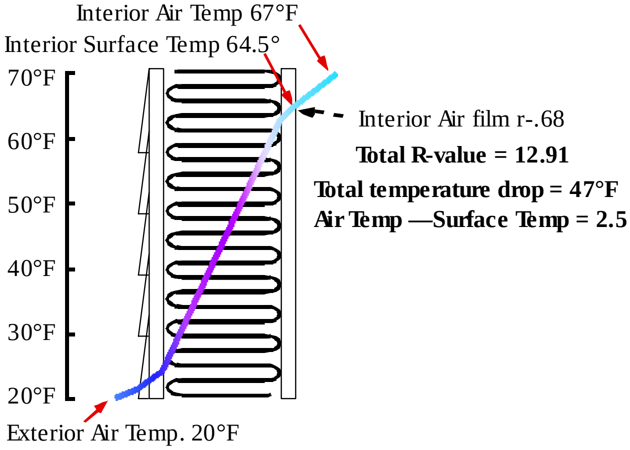


Table 2 Actual Measured Temperatures

Interior air temperature	67.0°F
Exterior air temperatures	20.0°F
Typical wall temperature at top of wall	64.0°F

Typical wall temperature in middle of wall	62.0°F
Typical wall temperature at bottom of wall	58.0°F
Wall temperature at bottom of problem corners	48.0°F

When we looked at the measured performance of the wall systems, we saw that *at the top of the walls*, the interior surface temperatures of 64°F was also very close to the theoretical temperature predicted in Table 1. The more we moved down the wall toward the floor surface, however, the more we found the actual performance deteriorating. One might be tempted to explain this phenomenon as a result of stratification of air temperatures within the room. Actual measured air temperatures did not indicate significant stratification. And most importantly, this phenomenon did not explain the extreme variation we saw in *some* walls of this home but not in others; nor would stratification explain the low surface temperatures measured at the ceiling surfaces.

Since it was impractical to measure actual temperatures at various locations throughout a building section, it was necessary to use the information we had to interpolate the unknown. In the case of a wall section, we knew the following:

- The interior air temperature,
- The exterior air temperature, and
- The surface temperature on the interior of the sheetrock as measured by the spot radiometer.

We also assumed the following:

- The effective insulating value of the interior air film to be R-0.68 from ASHRAE Standards. and
- An R-0.45 for the sheetrock, also from ASHRAE tables.

What was unknown, however, was the effective R-value of the remainder of the wall section, which included any insulation materials, the sheathing, the siding and the exterior air film. It was assumed from visual inspection that one or more of these components had been compromised resulting in fairly significant cold air intrusion into the wall cavity. By considering these remaining components as one and reducing their combined R-value until the proportional simulated interior surface temperature matches our measured temperature, the performance of this wall section can be estimated and represented as an effective or equivalent R-Value for the entire wall section.

In the case of the measured performance of the walls at the four-foot height, we were able to mathematically simulate the walls performance by reducing the effective R-values of the exterior sheathings and insulation until our formula matched the measured interior surface temperature of 62°F. Thus, we found the overall performance of this section of the wall system at that height to be similar to that of a wall section with an R-value of only R-6.33 (see Table 4):

Table 3 Wall Performance at Four Foot Height

Building material	**Nominal r-value**	Interior air temperature	67.0°F
Interior air film	0.68	**Interior surface temp**	**62.0°F**
Sheetrock	0.45	Behind sheetrock	58.6°F
Insulation	**5.20**	Behind insulation	20.0°F
Siding & sheathing	0	Siding surface temp	20.0°F
Exterior air film	0	Exterior air temperature	20.0°F
Total	**6.33**	Temperature difference	47.0°F

It should be noted that this performance was even less than the R-7.9 average R-value required by the now outdated 1976 HUD code for manufactured homes in this climate. Current HUD standards call for U-.096 (R-10.4) as an overall heat transmission factor for manufactured homes. [1]

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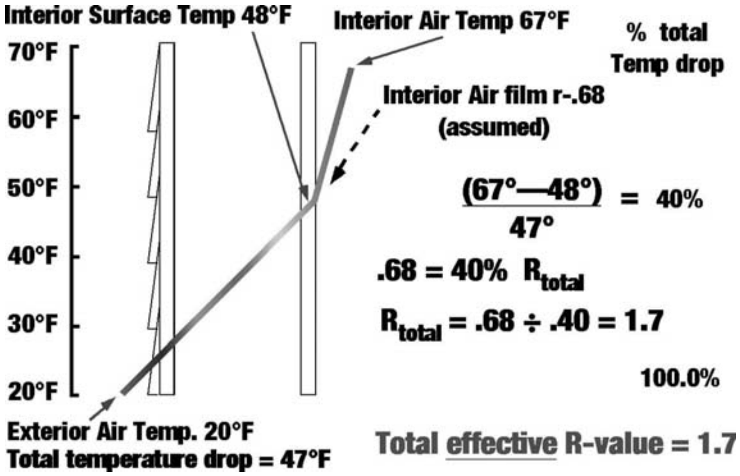
[1] HUD standards for manufactured homes, document 24 CFR 3280 is available for free from the Department of Housing and Urban Development at 1-800-767-7468. A companion document 24 CFR 3282 on enforcement of these standards is also available free from the same source.

Down near the floor, the interior wall temperatures in this home typically measured about 58° F meaning the wall was performing as if it had a total R-value of only 3.63

In the worst-case locations where the homeowner reported frost on the interior wall surfaces, we measured surface temperatures as low as 48° implying performance values as low as R-1.68.

Table 4 Worst-Case Wall Performance

Building material	*Nominal r-value*	Interior air temperature	67.0°F
Interior air film	0.68	**Interior surface temp**	**48.0°F**
Sheetrock	0.45	Behind sheetrock	35.4°F
Insulation	0.55	Behind insulation	20.0°F
Siding & sheathing	0	Siding surface temp	20.0°F
Exterior air film	0	Exterior air temperature	20.0°F
Total	**1.68**	Temperature difference	47.0°F



By doing a little invasive investigation of these wall structures (pulling back the siding material), we saw clearly that there were both major gaps in the exterior sheathing and insulation voids around framing members at the problem corners. The temperature gradients here implied there was massive general air leakage *into* wall cavities along most of the exterior, and particularly at the corners and interior wall intersections. It also seemed likely there were significant insulation voids or dislocations as well that should be filled or otherwise corrected.

This methodology is not a commonly-used analysis technique. It is, however, based on actual surface temperature measurements and accepted building heat loss theory as codified by the American Society of Heating and Air-conditioning Engineers (ASHRAE). It is also true that whatever the interior surface temperature is, that *IS* what determines the heat loss from the interior air and radiative heat transfer. If you know what the air and the interior surface temperature is, you could at least theoretically calculate the whole wall section conductive heat loss based solely on this ΔT and an R-value of .68. Where the heat goes once it is absorbed by the sheetrock is immaterial from a theoretical standpoint.

The predictive results from the analysis of these numbers should not be construed to imply that specified insulation materials were not installed, but rather that the whole wall assembly was not performing as the engineering assumptions said it should. That is to say, if measurements of a wall section indicated that the *effective* R-value is R-5, that doesn't mean that there is no insulation in that wall. Rather, it simply means the insulation is not performing as it is supposed to because of excessive air intrusion, thermal bridging through framing members, high moisture content, improper installation resulting in either bypasses or convective looping or some other anomaly affecting its performance. Without actually tearing into the wall and surface cavities, it is not always clear what specifically is occurring when a building section fails to perform effectively. Even with infrared imaging, these distinctions are often hard to differentiate.

The benefit of this combined diagnostic and reporting tool, however, is the ability to provide an easily understood evaluation of questionable building system. Rather than saying "Well the house is pretty tight but you've got high energy bills and we think the insulation isn't working like it should," even augmented with picture in your report with a big blue splotch in the middle of a wall section, you can report that "Local building codes call for R-22 wall insulation but in this home, the wall sections are only performing as if they were R-8." These numbers are based on the same science by which the building codes were written, and as such, should have legitimate standing for a homeowner taking their case to a code official, a builder, or in this case, a building manufacturer. It is not enough for us to ask that a certain amount or quality of materials be installed in a home. What counts is performance and this is a quick and easy way to quantify that performance for individual building sections where anomalies are suspect.

It should be noted that this approach only begins to approach meaningful numbers when the total R-value is fairly low, the ΔT between indoor and outdoor temperatures is fairly large, one can accurately measure air temperatures in the area of the surface being examined, the spot radiometer is calibrated to the device used for measuring air temperatures (or better yet, use the same instrument to measure the temperature of a low mass element in the interior space that could be assumed to equal the ambient air temperature. It is also assumed that emissivity of the surface being tested is close to 1 or can be compensated for and that that section is not overly impacted by radiant energy being absorbed or reflected from nearby warmer surface or that it is not being impacted by unusual air surface-contact phenomena such as being right over a hot air register.

It is suggested that the same devices and procedures be used both on the suspect cross section and other parts of the building where actual (more normal) R-values are known. If these sections demonstrate reasonable results using the same equipment and procedures, there can be more confidence in the veracity of the anomalies found in the suspect cross-sections.

Measuring Air and Surface Temperatures to Determine Comfort Conditions

In our previous discussion of the importance of mean radiant temperature (MRT) we showed how researchers have determined that for every one degree Fahrenheit that the average surface temperature is below the desired comfort temperature, we would have to raise the air temperature 1.4°F to compensate for the radiant cooling of those cooler surfaces. In turn, these higher air temperatures or thermostat settings would result in significantly greater energy use throughout the house.

In the previous example, if we assumed the family really wanted to keep their house at an even fairly Spartan average 67° comfort temperature, and that the average surrounding surface temperatures (mean radiant temperature) was only 62°F, in order to achieve that comfort level, the occupants would have to raise their thermostat 7°F --up to 74°F-- to compensate (1.4 x (67-62)). This increased interior temperature would imply an increased energy usage of some 21%.* Adding insulation to improve these interior surface temperatures would both reduce the conductive heat loss through the walls but it would also allow the lower thermostat setting resulting in far greater savings than the basic steady-state model would predict.

Although it may be difficult to model with detailed accuracy, you can get a rough idea of people's comfort levels by backing out from the same R-value calculations we used in the previous case study. If we assume that the relationship between the air temperature and the surface temperature is based on the r-.68 of the interior air film, one can calculate the surface temperature of each building section based on ΔT and the remaining R-value numbers. The good news, however, is that those of us who are now armed with infrared measuring devices can fairly easily measure actual interior building surface temperatures. Plotting these temperatures on a three dimensional model of the occupied space can provide you with an average measured mean radiant temperature for that space to which you can then compensate by varying the recommended air temperature necessary to achieve comfort conditions and proceed with energy savings calculations based on likely actual conditions

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* It is true that increased air temperature would impact the various interior surface temperatures so to do an actual model you have to run several iterations until the variables stabilized, but in contrast, no standard heat loss programs even consider these relationships.

within the home.

A measurement of effective comfort temperature within a particular space can be achieved with an globe thermometer that responds to both air and radiant temperatures in an approximate relationship to our own thermal senses. A globe thermometer, spherical in shape with high absorption/emissivity and good conductive characteristics is available commercially for about $350 (NovaLynx Corporation 530 823-7185 nova@novalynx.com). Our research has found, however, that reasonable results can be achieved using and older-style copper toilet tank float, darkened with liver of sulfur (a sulfur-based tarnishing agent found in hobby/craft stores) and outfitted with either a thermister or thermocouple temperature sensor. A decided advantage to this approach is you can move the device around to different locations within the space or otherwise modify the conditions within the space and fairly quickly sense the differing conditions. No mathematics required.

Clearly the methods outlined in this paper are not something that every building energy auditor is going to carry out as a regular part of every house they go into. The detailed measurements and calculations are burdensome, and in many cases the hard numbers are insignificant. Just because it is difficult to model, however, does not mean it is in any way insignificant in the comfort of our clients or the calculated heat loss from our buildings based on flawed steady-state assumptions. As thermographers we are armed with some of the most sophisticated diagnostic tools available to building science. To use them solely to identify insulation voids, moisture accumulation or convective bypasses is overlooking some of their greatest benefits; the ability to more accurately track actual comfort conditions within the home. The goal of constructing (or retrofitting) better buildings is not to trap Btus. The goal is to provide better shelter and comfort at a lower energy cost. To ignore the impact of human comfort on the behavior of our clients is missing a great opportunity to provide a vital service to our community.

Resources

Allen, Edward, *How Buildings Work*, Oxford University Press, New York, 1995

Ackerman, Diane, *A Natural History of the Senses*, Vintage Books, New York, 1991.

Adlam, T. Napier, *Radiant Heating*, Industrial Press, New York, 1947.

American Society of Heating, Refrigeration and Air Conditioning Engineers, *A.S.H.R.A.E. Handbook of Fundamentals*, Atlanta.

Aurand, A. Monroe, Jr., *Little Known Facts about Bundling in the New World*, Aurand Press, Lancaster, PA 1938.

Chandra, Subrato, et al., *Cooling with Ventilation*, Solar Energy Research Institute, Golden CO, 1986.

Comfortzone listserve: send mail to <Majordomo@penman.es.mq.edu.au> with “unsubscribe comfortzone” in the body of your email message

Eagan, David, *Concepts in Thermal Comfort,* Prentice Hall, Englewood Cliffs, NJ, 1975.

Fanger, P.O., *Thermal Comfort*, McGraw-Hill, New York, 1970.

Farallones Institute, *The Integral Urban House*, Sierra Club Books, San Francisco, 1979.

Fitch, James Martin and Bobenhausen, William, *American Building, the Environmental Forces that Shape It*, , Oxford University Press, Oxford, New York, 1999

Hall, Esward T. *Let's Heat People Instead of Houses*, self-published monograph.

Richard B. Hayter, Ph.D., P.E., *Designing for Comfort,* Kansas State University, Manhattan, KS, USA

Heinrich, Bernd, *Winter World, the ingenuity of animal survival,* Harper Collins, New York, 2003.

Ierley, Merritt, *The Comforts of Home,* Clarkson Potter, New York, 1999.

James, Alan, *Homes in Cold Places*, Lerner Publications, Minneapolis, 1989.

James, Alan, *Homes in Hot Places*, Lerner Publications, Minneapolis, 1989.

Kempton, Willet, “Two Theories of Home Heat Control,” *Cultural Models in Language & Thought*, Cambridge University Press, 1987.

Konzo, Sechi, *The Quiet Indoor Revolution*, Small Homes Council, Champaign, 1992.

Langley, Billy C., *Comfort Heating,* Reston Publishing, Reston, Virginia, 1978.

Leonard, George and Murphy, Michael *The Life We Are Given*, G.P. Putnam's Sons, New York, 1995.

Leckie et al, Sierra Club, *More Other Homes and Garbage*, San Francisco, 1981.

Lstiburek, Joseph, "Relative Humidity" Presented at Healthy Indoor Environments, Auston, Texas , Building Science Corporation, Westford, MA, 2002.

Maarouf, Abdel and Bitzos, Melynda, "Wind-chill Indices: A Review of Science, Current Applications and Future Directions for Canada." Ontario, February 2000.

Mahnke**,** Frank H., *Color, Environment, & Human Response,* John Wiley & Sons, 1996

McCormick, Ernest, *Human Factors in Engineering and Design*, McGraw-Hill, New York. 1976.

McMullan, *Environmental Science in Building 3rd edition,* Macmillan, Houndsmills, 1992.

Meier, Alan, "Body Coolth," *Energy Auditor & Retrofitter*, Vol.2, No.3, May/June 1985.

Meier, Alan, "Some Like It Hot," *Energy Auditor & Retrofitter*, Vol.3, No.2, Mar/April 1986.

Meteorological Service of Canada, "Internet Workshop On Wind chill", http://windchill.ec.gc.ca , April 2000.

Nelson, Leone W, and Mac Arthur, Ward., "Energy Savings through Temperature Setback," *ASHRAE Journal*, September 1978 © Honeywell Inc. 1977.

Olson, Harold L., *Energy and the Home Heating System,* University of Wisconsin, 1980.

Parks, Alexis, *People Heaters*, Brick House Publishing, Andover, Ma, 1981.

Rahn, Joan Elma, *Keeping Warm, Keeping Cool*, Atheneum, New York 1983.

Rapoport, Amos and Watson, Newton, "Cultural Variability in Physical Standards" 1968 reprinted in Gutman, Robert *People and Buildings*, Basic Books, London 1972.

Reid, Esmond, *Understanding Buildings, a Multidisciplinary Approach*, MIT Press, Cambridge, MA 1984.

Rybczynski, Witold, *Home - A short History of an Idea*, Penguin, England 1986.

Saperstein, Alvin M. *Physics: Energy in the Environment*, Little Brown, Boston, 1975.

Severns, William H., *Heating, Ventilating, and Air Conditioning Fundamentals,* John Wiley & Sons, New York, 1937.

Slater, Keith, *Human Comfort*, Charles Thomas, Springfield, IL, 1985.

Stiles, Henry Reed, *Bundling, its Origins, Progress and Decline in America*, Book Collectors Association, New York, 1934.

Vander, Arthur J., Sherman, James H. and Luciano, Dorothy S., *Human Physiology The Mechanisms of Body Function*, McGraw-Hill, New York 1980.

Von Frisch, Karl, *Animal Architecture*, Harcourt, Brace, Janovich, New York, 1974.

Walker, Jearl, *The Flying Circus of Physics With Answers,* John Wiley & sons, New York, 1977.

Weiss, Hal, *Secrets of Warmth for Comfort or Survival,* The Mountaineers, Seattle, 1992.

Watson, Donald and Labs, Kenneth, *Climatic Design*, McGraw Hill, New York, 1983.

Watson Richard D. and Chapman, Kirby S., *Radiant Heating & Cooling Handbook*, McGraw-Hill Books, New York, 2002.

Wilson, Tom, *Multifamily Building Case Study, St Paul, Minnesota,* Synertech Systems Corporation for Oak Ridge National Laboratory, 1995.

Wilson, Tom and Belshe, Rana, "Movable Insulation Systems", *ASHRAE Journal* , February ,1987.

Wilson, Tom and Belshe, Rana, "PRISM-A Second Look," Proceedings of the 1987 Conference Energy Conservation Program Evaluation: Practical Methods, Useful results, Vol 1, p.175.

Wray, William O. *A Simple Procedure for Assessing Thermal Comfort in Passive Solar Heated Buildings*, Los Alamos Scientific Laboratory, 1979.

RECOMMENDED WEB RESOURCES

http://www.meanradianttemperature.com/index.htm

http://www.eere.energy.gov/buildings/tools_directory/software.cfm/ID=371/pagename=alpha_list

http://www.cbe.berkeley.edu/research/briefs-thermmodel.htm

http://www.esru.strath.ac.uk/Courseware/Class-16293/6-Comfort.pdf

http://ergo.human.cornell.edu/studentdownloads/DEA350notes/Thermal/thcomnotes1.html

http://ergo.human.cornell.edu/studentdownloads/DEA350notes/Thermal/thcomnotes2.html

http://personal.cityu.edu.hk/~bsapplec/thermal.htm