Prioritizing thermal comfort for homes

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A Case Study in Using Standard 55 for a Residential Building

Prioritizing Thermal Comfort for Homes

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A 2015 ASHRAE news release corrected the assumption that thermal comfort research included only middle-aged men in suits working in offices.[1] Standard 55 is gender neutral and can be applied to most environments where people go—including into homes. ASHRAE stands behind this assertion through a 2014 interpretation, and includes the standard in its residential resources.[2]

Unfortunately for occupants thermal comfort analysis is not part of common engineering practice. Practitioners are taught how to perform load calculations, layout HVAC systems and specify equipment for the purposes of conditioning spaces for compliance to building codes and efficiency standards. Most have an intention to provide condition for comfort yet based on over 15 years of informal polls by the lead author less than 3% of those involved in the comfort industry have a working knowledge of Standard 55.[3] Failing to include comfort analysis as part of the engineering process explains in part why thermal discomfort is one of the leading complaints within the building sector.[4] Specifically to residential buildings, current research projects indicate whole-home improvement to enclosures are, more often than not, completed to enhance comfort.[5] Further, an underlying message from the research is the drive to improve comfort, is equal to or greater than the drive to improve energy efficiency.[6]

Thermal Comfort and the Design Practitioner

Residential building codes, standards and programs generally focus exclusively on regulation of just one of 10 key comfort metrics: control over dry-bulb temperature (ex.: NBC of Canada, Section 9.33.3). Hence, additional control of other metrics identified in Standard 55 can reduce thermal discomfort risks. To facilitate implementation, the document permits wide ranges in the primary factors of mean radiant temperatures (MRT), dry-bulb temperature, humidity and air velocity (*Figure 1*). This is also true for local factors of floor temperatures, radiant asymmetry, temperature stratification and drafts. It also recognizes a wide range of physical activities and choices in clothing. Furthermore, it includes a compliance method based on adaptability for naturally ventilated spaces.[7]

This article focuses on the analytical method in Standard 55. It is beyond the article's scope to discuss each compliance path. For further information, see the *Standard 55 User's Manual.*

Compliance Paths

The analytical method permits a wide range of conditions as shown in the shaded areas of *Figure 1*. There is a misplaced perception that the standard is too restrictive, when in fact the opposite is true. The standard is flexible but some building codes are not. For instance one code specifies air temperature of 70°F (20°C),[8] which is excessively restrictive and erroneously suggests that this single measure is a surrogate for thermal comfort. *Requiring a specific temperature has never been a requirement of Standard 55.*[9]

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Using the Standard

Pre-Design Method

The preferred method is to incorporate the standard's principles before the architect and interior designer get involved. Since this strategy is based on human factors, it requires designers to have a basic understanding of thermal (physiological) sensations and comfort (psychological) perceptions in relation to the design of enclosures.[10] This sits in parallel with similar understandings of other indoor environmental quality (IEQ) systems dealing with the air, light, odors, sound and vibrations.[11]

FIGURE 1 Standard 55's analytical method permits a wide range of conditions, as shown in the shaded area of the CBE Thermal Comfort Tool (comfort.cbe.berkeley.edu).

The combined understanding and application of IEQ principles and building science significantly lowers the probabilities of discomfort as they collectively drive better choices when it comes to:

Property Development

Passive House and Active House communities are examples where comfort is a key component within the program philosophies.

Building Orientation

Influences solar and wind loading, which affects:

- Inside surface temperatures thus radiant transfer to and from the occupant (radiant transfer represents 60% of the sensible heat transfer experienced by clothed people at low met rates and low air velocities [ASHRAE Fundamentals, 2013]).
- Natural ventilation and passive cooling strategies.

Fenestration

(Fenestration includes performance in opaque and fenestration systems including U-values, SHGC and VLT; and window-to-wall ratios [WWR] and shading strategies.)

Influences inside surface temperatures and thus has an effect on:

- The mean radiant temperature;
- The operative temperature;
- Radiant asymmetry;
- Temperature stratification and drafts.

Materials and Methods of Construction

- Influences heat transfer, thermal bridging and thus inside surface temperatures.

Interior Design Components

(Particularly, lighting, colors and composition of finishes.)

- Influences visual, auditory, respiratory and thermal perceptions.
- Flooring conductivity affects foot level perceptions (see ASHRAE 2013 Fundamentals).

HVAC System Configuration, Layout, and Zoning

- Compensates for enclosure flaws.
- Enables user controlled environments for different spaces.
- Enables systems to achieve rated efficiencies.

Experienced practitioners can use these and other elements to influence the direction of the architectural design to diminish risks of thermal discomfort, which frequently has a collateral benefit of energy efficiency. There also tends to be less conflict related to redesigns, and it facilitates the commissioning process through simpler HVAC systems afforded by the better enclosure.

Post-Design Method

The less desirable method is to evaluate existing architectural and mechanical designs for the purpose of recommending corrective actions. Such after-the-fact exercises almost always expose high probabilities of discomfort in one or more IEQ metrics. Recommended advice commonly requires redesigns in

PHOTO 1 Original home (left); new front (middle), new back (right).

the enclosure, interior finishes and electromechanical systems. Ignoring solutions can result in unnecessary use of larger more energy-intensive mechanical and electrical solutions.

Case Study

The post-design method was used to evaluate a home for the purposes of making recommendations regarding the enclosure design and HVAC systems for mitigating risks of discomfort.

Climate Zone 7a in southern Alberta, Canada, has 18°C (64°F) degree days ranging between 5,000 and 6,000. Winter lows include temperatures down to –40°C (–40°F). The original house in Alberta was partially demolished, leaving behind the original basement slab, concrete foundation walls and wood subfloor (*Photo 1*). The existing boiler, solar system, fan/coil and basement floor heating system were reused in the new development. A new foundation was constructed south of the existing walls (left-hand side views from *Photo 1*, left and middle) to define the addition of an attached garage and provide support for two new levels (*Photo 1,* right-side view). New north side spaces (right-hand side views from *Photo 1* middle) were constructed on top of the existing subfloor.

Client's Objectives

As it related to the design scope, the client's prime objectives for the project were:

- Low maintenance exterior and interiors;
- An environment that enabled: thermal comfort with individual space control, sound quality, and air quality at levels that were acceptable to them;
- Extracting rated efficiency from reclaimed boiler; and
- Incorporating the reclaimed solar thermal system for heating domestic water.

Enclosure

The original below grade enclosure was 8 in. (200 mm) concrete foundation walls framed out with batt insulated 2 × 4 in. (38 × 89 mm) construction. All new above-grade vertical surfaces (pre-comfort analysis) were 2 × 6 in. (38 × 140 mm) wall framing with cellulose insulation. New above-grade horizontal surfaces were fabricated with wood joists with open web trusses for supporting the built-up roof. Pre-comfort analysis fenestration was double-pane, argon-filled with a single low-e coating. Summer shading from trees and overhangs provided partial relief from solar loads.

Based on the thermal comfort analysis, it was necessary to add exterior insulation on many vertical surfaces and bump up critical windows to triple-pane, argon-filled with two low-e coatings. However, the analysis revealed that even with these modifications those rooms with high window-to-wall ratios (WWR) had a high probability of thermal discomfort at peak loads. Greater discomfort risk occurred with closer proximity of occupants to glass. This is due to potential low mean radiant temperatures, radiant asymmetry,[12] stratification and down drafts; impacts are illustrated later in the article on Page 36 in *Figures 4* and *5*.

Mechanical System

To reduce risks primarily driven by radiant transfer and convection, a hybrid radiant-based HVAC system solution was employed. This approach used hydronic radiant floors (*Photo 3*, Page 40) and radiant walls (*Photo 4*, Page 40) to increase the MRT. At peak loads (about 5% of heating hours) heated air was also blown upwards against the glass surfaces to supplement the radiant system, and to reduce radiant asymmetry and down drafts. The heated air came from the reclaimed hydronic fan/coil. The same unit was also employed for makeup air (MUA) for the kitchen exhaust.

Cooling was based on adaptive strategies including elevated air speeds with fans and nighttime flushing with outdoor air.

Zoning Analysis

For this case study (and other projects), the lead author in consultation with clients, uses the following criteria (general list) for establishing zoning for load calculations, comfort analysis and control:

Orientation to North

What are the solar loading potentials on east, south and west surfaces as well as roof surfaces?

Extraordinary loads should be controlled separately (*Figure 2*, Page 34).

Room Use

Does the client have room temperature preferences? For example, do the following rooms need separate controls?

- Hobby rooms;
- Sleeping/ resting rooms;
- Hygiene/personal grooming/ linen, etc., rooms; and
- Socializing/entertaining/food preparation rooms.

Floor Coverings

Will radiant floor systems be used? If so, how will the client's choice in flooring drive thermal conductivity and ultimately impact:

- Tube spacing choices?
- Supply and return fluid temperatures?
- Boiler / heat pump efficiency?

Expected Loads

The authors experience for cold and very cold climates suggests peak winter loads of <20 Btu/h·ft^2 (63 W/m^2) are obtainable with:[13]

- Advanced framing;
- Exterior insulation;
- Fully insulated slabs; and
- <40% window-to-wall ratio with high performance fenestration.

Thermal comfort benefits (winter) from the above include:

- Higher mean radiant and operative temperatures;
- Ability to push interior winter relative humidity limits between 25% to 35%;
- Reduced downdraft and stratification risk; and
- Reduced discomfort risks due to radiant asymmetry and unacceptable floor temperatures.

Is there potential for one or more zones to exceed typical loads? If so, what enclosure, mechanical and interior design strategies can be implemented to harmonize the loads with lower load zones to reduce discomfort risks?

- Solutions might include to reduce the WWR, improve glazing performance and/or add more exterior insulation and use more conductive flooring such as masonry surfaces.

FIGURE 2 Heating loads. Shown are surface fluxes for each zone.

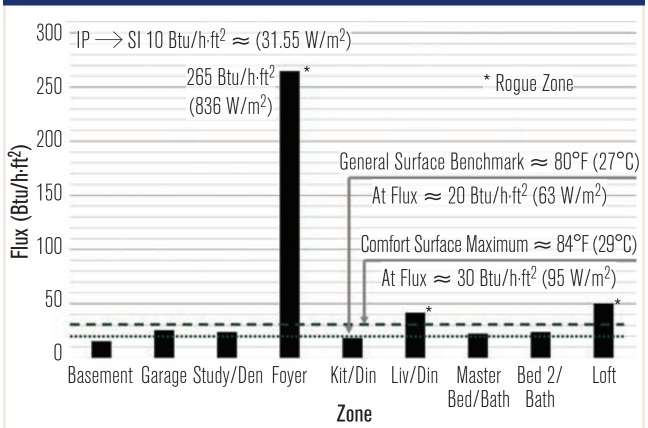


FIGURE 3 Heating flux from floor served by radiant floor with supplemental heat provided with MUA unit (fan/coil).

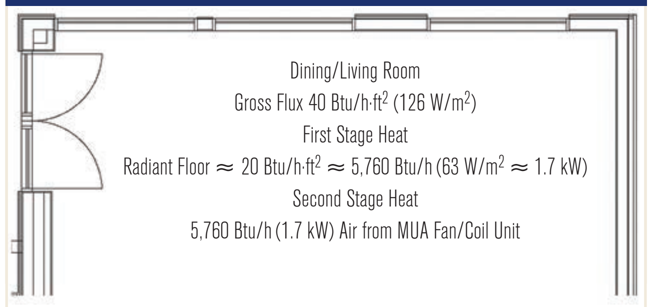


PHOTO 2 Looking out through living room windows from kitchen/dining area.

Auxiliary Loads

Are there any spaces or loads that could have an impact on controllability of adjacent spaces? These might include:

- Home theater spaces;
- Spaces with fireplaces; and
- Spaces needing a primary system for base loads and secondary system for peak loads (see extraordinary loads above).

These room types are best to be isolated and controlled separately from other rooms:

- Special rooms and applications.

Are there any spaces or loads that are seasonable or extraordinary? These might include:

- Indoor or outdoor pools and spas;
- Solariums and greenhouses; and
- Snow and ice melt systems.

These spaces and surfaces need independent analysis and controls.

Unconditioned Spaces

Are there spaces that need to be isolated or decoupled from other spaces or systems? These might include:

- Wine coolers;
- Cold storage; and
- Underneath appliances and cabinets.

Case Study Observations

From the author's initial review using the above approach, the following conclusions were made.

There was a high probability of discomfort risk in the:

- Foyer;
- Loft; and
- Living/dining room.

The reasons for the risk were due to:

- Summer solar gains;
- Winter solar gains and radiant asymmetry with down drafts and cold floor risks; and
- Low MRT due to inside surface temperatures of glass.

There was medium-to-low probability of discomfort risk in remaining areas to due to shading from trees, lower WWR with exterior insulation on above-grade walls and reduced exposures for below-grade spaces.

Zoning for Load Calculations and Comfort Control

Based on the review using the criteria above, and the clients request for individual space control the home was zoned with separate thermostatic valves in the following manner:

- Basement;
- Garage;
- Studio/den;
- Foyer;
- Kitchen/dining;
- Living/dining;
- Master bedroom/bath;

- Bedroom 2/bath; and
- Loft.

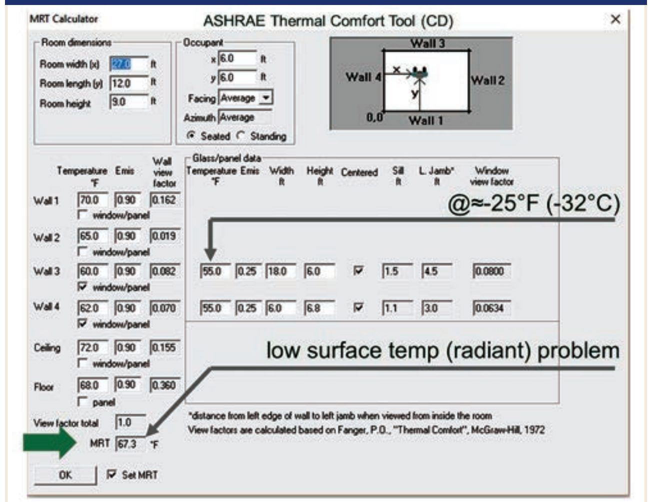
(The studio/den, foyer and loft are zones with loads exceeding 30 Btu/h·ft^2 [94 W/m^2].)

Note: multiple zone systems are not uncommon in homes built to code using hydronic heating systems; although improvements to enclosures to high-performance standards encourages simplification through reduction in zones and controls. It is typical in Passive House or R2000 homes to only have one or two zones.

Summary of Zone Loads (Heating Only)

The heating load calculation results derived with a proprietary ASHRAE based Excel load calculation tool are shown in *Figure 2*.

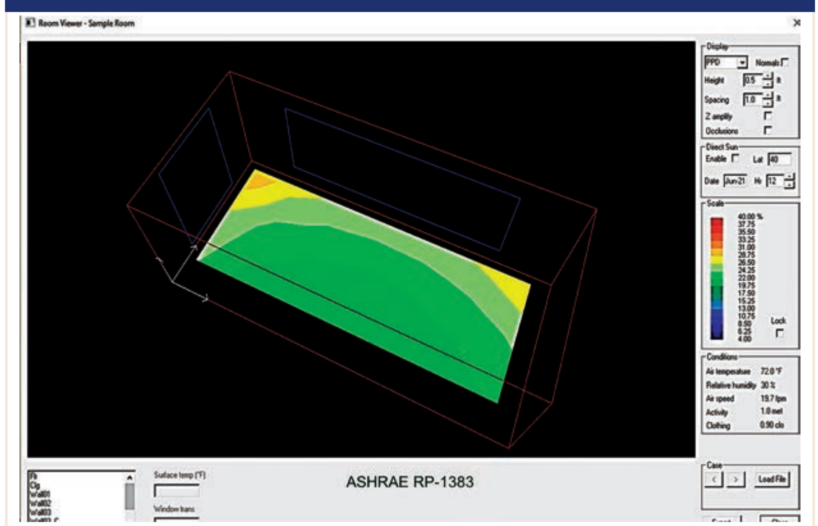
FIGURE 4 Using ASHRAE Thermal Comfort Tool (CD) to determine mean radiant temperature (MRT). Due to inside surface temperatures, the MRT is 67.3°F (19.5°C) or 5°F (3°C) lower than the minimum acceptable air temperatures defined by codes.



Discussion

To illustrate the use of ASHRAE Standard 55, the living/dining room is selected. As per *Figure 2* and *Figure 3*, this space had an extraordinary gross floor flux of 40 Btu/h·ft^2 (128 W/m^2). With an inside glass temperature dropping potentially below 58°F (14°C) at –25°F (–32°C) it was necessary to use a hybrid radiant/air system to correct for the potential radiant temperature asymmetry and down draft problems leading to cold floors (foot and ankle discomfort). The radiant asymmetry and downdraft risk assessment can be accomplished with an online glazing and winter comfort tool.[14] Inside glass temperatures can be calculated using the LBNL Window tool or extracted from the tables in *ASHRAE Handbook—Fundamentals*. The impact of these problems becomes apparent when the window-to-wall ratio is very high—in this case exceeding 80% (*Figure 3* and *Photo 2*). Entering calculated surface temperature values[15] into the ASHRAE Thermal Comfort Tool (CD) [note: for Standard 55-2010] delivers a MRT of 67.3°F (19.5°C) (*Figure 4*), resulting in a distributed predicted percentage dissatisfied (PPD) ranging from 20% to 26% (*Figure 5*) and non-compliance with the standard.

FIGURE 5 Using ASHRAE RP-1383 to see distributed predicted percentage dissatisfied (PPD) / predicted mean vote (PMV). Note: non-compliance throughout.



The non-compliance is directly related to the large amount of glass. Regardless of fenestration performance it is the primary source of thermal discomfort in the case study. Correcting or compensating for this case could include reducing the WWR, but the client had a view of the downtown and was not prepared to sacrifice that view. With the high WWR and correlating framing factor, adding external insulation would have insignificant effects on the MRT. The logical solutions were to raise the MRT, control the radiant asymmetry, and reduce the draft. In this zone, a radiant floor system was selected (*Figure 6*) and augmented with an air system for peak loads. Taking the floor from 68°F (20°C) up to 85°F (29°C) had the potential to raise the MRT from 67.3°F (19.6°C) to 74.4°F (23.6°C) (*Figure 7*). This results in a new

PPD distribution ranging from 7% to 10% in the occupied space for Standard 55 compliance (*Figure 8*). This type of analysis was done for all the zones that had extraordinary loads and resulted in the installed systems as shown in *Figure 6*, *Photos 3* and *4*.

Conclusions

The task for the practitioner is to evaluate not only the loads by traditional means of calculations, but also to evaluate the thermal discomfort risks. That is to say load calculations *are not* comfort calculations and HVAC design in of themselves *are not* comfort design. Because the thermal (sensible) transmission between clothed occupants and the enclosure at low velocities and met rates is driven significantly by radiant exchanges (60% of sensible),[16,17] it is not always enough to hold a room at 72°F (22°C) dry bulb.[18] Because of this, inside surface temperatures have an impact on the occupant's thermal sensation and ultimately their perception of comfort.[19] Therefore, it behooves the designer to learn about human factors and building physics.

In this case study, there were three zones with high potential for discomfort due to low MRTs, radiant asymmetry, downdraft and cold floors. This is a result of the enclosure design and specifically the combination of window performance and high WWR. The discomfort risk would not have been picked up by load calculations alone, especially those performed by inexperienced members of the design team. An experienced designer could make a judgement call on these areas but the Standard 55 tools quantify the risk. By performing the analysis and making recommendations, the designer is proactively drawing attention to the problems and solving them before a poor system type is selected and installed.

At the very least, the exercise provides an opportunity to correct the enclosure before it reaches finishing stages. Such foresight offers the chance to reduce conflicts between homeowners, builders and their HVAC contractors over thermal discomfort from designing systems according to the common residential design approach of, "ready, fire, aim."[20]

Forethought with thermal comfort analysis puts the design sequence in its correct order.

1. Perform a zone analysis for loads, controls and comfort as discussed above. The inexperienced designer may find it necessary to perform preliminary comfort analysis's to help with zoning selections.
2. Calculate the loads and inside surface temperatures for system design and MRT evaluations.
3. Evaluate enclosure and systems for thermal discomfort risks (MRT, radiant asymmetry, draft, floor surface temperature, temperature stratification etc.)
4. Correct the enclosure;
   a. Reduce WWRs, thermal bridging, and infiltration.
   b. Decrease U-values in transparent and opaque surfaces.
5. Redo Step 2 then proceed to Step 6.
6. Compensate for remaining flaws in the enclosure with an appropriate HVAC system.
   a. Solve convective problems with convective

FIGURE 6 The low MRT problem in the living/dining room was solved with a radiant solution of heated floors. During peak loads heated air was blown vertically up across the windows to reduce radiant asymmetry and downdrafts.

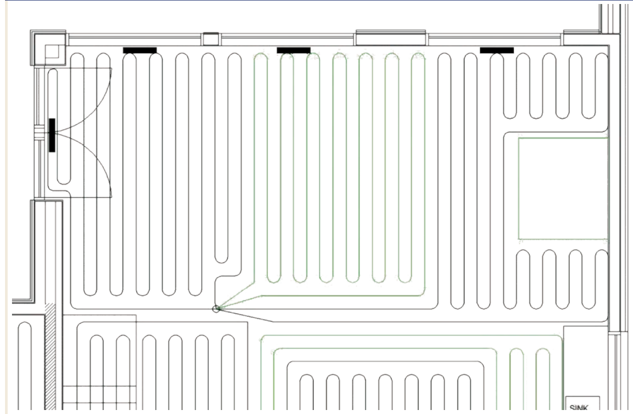
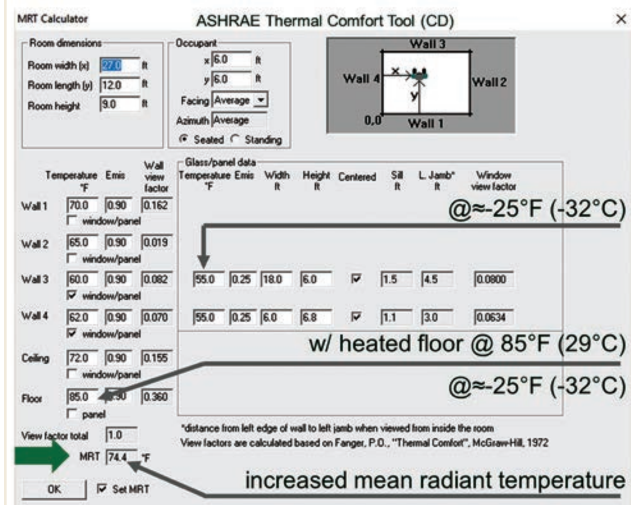


FIGURE 7 Adjusted MRT up to 74.4°F (23.6°C) after correcting with a radiant floor heating system



solutions, i.e., downdraft problems can be solved with forced or natural convection solutions (fin/tube).

b. Solve radiant problems with radiant solutions (radiant walls, ceilings and floors).

FIGURE 8 Distributed PPD/PMV. Note compliance throughout.

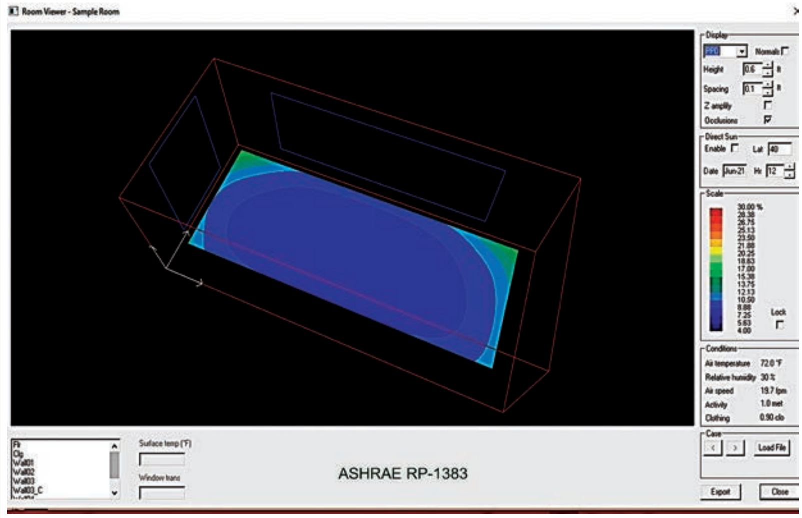


PHOTO 3 Installed floor heating system: cork on PEX-a in plywood tracks on aluminum heat transfer plates on shiplap over batt insulation.

PHOTO 4 Radiant walls fabricated with drywall on PEX-a in plywood tracking on aluminum heat transfer plates on insulation, were added to the bathroom, foyer and loft areas for supplemental heat and to help reduce down drafts and reduce radiant asymmetry. Shown north wall of foyer, note air outlet for additional supplemental heat.

References and Notes

1. ASHRAE. 2015. "Keeping Occupants Comfortable Without Raising Energy Costs." ASHRAE News Release. August.

2. ASHRAE. 2014. Interpretation IC 55-2013-1 of ANSI/ASHRAE Standard 55-2013, *Thermal Environmental Conditions for Human Occupancy*. September.

3. As an example: The 2015 Building Science Summer Camp (USA) and 2016 Building Science Spring Camp (CDN) had a combined 600 participants in the poll with the same results.

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8. Depending on what country you are from the value can be +/- 2°F (1°C).

9. ASHRAE Standard 55, *Thermal Environmental Conditions for Human Occupancy.*

10. Rohles, F. 2007. "Temperature and temperament; a psychologist view of comfort." *ASHRAE Journal* (2):14-22.

11. IEQ is not a proxy for indoor air quality but rather encompasses all the sensory systems. Likewise IAQ is not a surrogate for IEQ.

12. Radiant asymmetry defined as: the difference between the plane radiant temperature of the two opposite sides of a small plane element.

13. Bean, R. 2011. "Building Classifications." www.healthyheating.com/Comfortech-2011/Comfortech-2011-Robert-Bean.htm. accessed January 2018.

14. Payette Glazing and Winter Comfort.

15. Equation 13. *2012 ASHRAE Handbook—HVAC Systems and Equipment,* Section 6.5.

16. *2013 ASHRAE Handbook— Fundamentals.* Table 1, Representative Rates at Which Heat and Moisture are Given Off by Human Beings in Different States of Activity.

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18. McClurg, C. 2016. "Re-Defining and Delivering Thermal Comfort in Buildings." Insight Brief. Rocky Mountain Institute.

19. Bean, R. 2017. Integrated Design Course www.healthyheating.com/Integrated-Building-HVAC-Design-Course-Curriculum.htm, accessed Feb 2018.

20. Nod to 2018 ASHRAE RBC Chair Chris Mathis for reminding us that we tend to do this a lot! ■