RE-DEFINING AND DELIVERING
THERMAL COMFORT IN BUILDINGS

INSIGHT BRIEF

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HIGHLIGHTS

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- **Comfort is incredibly important to building occupants**, but the traditional air temperature-centric design approach used in buildings for decades is ineffective, inefficient, and expensive.
- **By focusing on six variables that drive a person's comfort**, a design strategy can become more targeted and focus the building's energy where it makes the biggest difference—moving from a one-size-fits-all approach to directly meeting the needs of each individual occupant.
- For RMI, this innovative approach to thermal comfort was used because it was **a central element to a whole-systems, passive design** that allowed us to economically meet our ambitious net-zero energy goals at the Innovation Center. While other building owners may not have net-zero energy goals, what we learned through our design process is just as applicable and important in designing around thermal comfort.

INTRODUCTION

The average American spends about 90% of his or her life indoors, and much of that time is spent at work in commercial office buildings. Mounting research shows that comfortable occupants are more alert, have better energy levels, and use less sick days, which all translate to more productive and satisfied employees. While comfort is clearly important, the traditional air temperature-centric design approach used in buildings for decades is inefficient and expensive.

Any person sitting next to a single pane window in the winter knows that a wall thermostat reading 72 degrees does not begin to tell the whole story. There are many other variables, such as radiant temperature and air speed, driving a person's comfort. By focusing on every variable, a design strategy can become more targeted and focus the building's energy where it makes the biggest difference in occupant comfort—moving from a one-size-fits-all approach to directly meeting the needs of each individual occupant.

While this targeted approach can make people more comfortable using less energy, owners and design teams may perceive this change as a significant risk. Concerns over litigation and risk across the construction industry have been barriers to progress. Therefore, a crucial aspect to enabling this shift is creating contracts and strategies to manage risk so all parties are comfortable moving forward. This requires open, honest communication among all stakeholders, acknowledging potential issues and managing this risk through contingency plans and clear risk allocation. This foundation allows the team to move past the traditional risk-averse mindset and deliver this innovative thermal comfort approach.

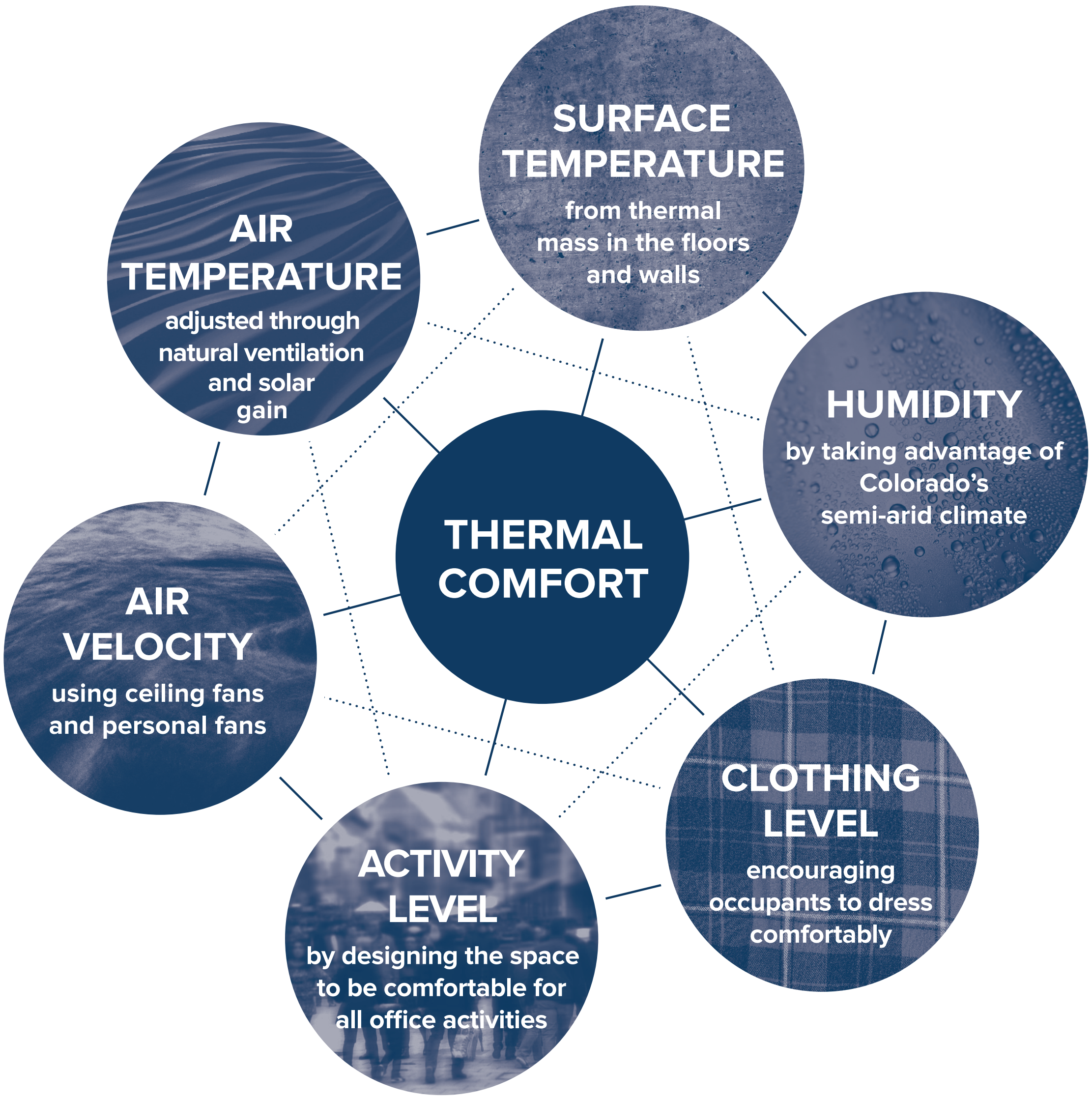
SHIFTING HOW WE DEFINE AND DELIVER COMFORT IN BUILDINGS

These personal comfort methodologies illustrate the importance of focusing on the person when designing for comfort, not the thermostat on the wall. To shift the focus from the traditional comfort metric of temperature, the conversation must evolve from space temperature to include all of the variables that affect a person's comfort. Instead of trying to cater to these variables with a large, monolithic central heating and cooling system, technologies are available that allow people to fine-tune their own personal comfort. These approaches can be as simple as a desk fan and as complex as a personal heating and cooling chair.

THE SIX VARIABLES THAT DRIVE OCCUPANT THERMAL COMFORT

Extensive research by the American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) and University of California Berkeley Center for the Built Environment (CBE) has found six variables that predict a person's thermal comfort.

Figure 1: Six Variables in Thermal Comfort



People intuitively know these factors affect their comfort, but they have not been translated into metrics building designers can use, until now. The ASHRAE 55 comfort standard uses a formula to translate these six variables into a single output, called predictive mean vote (PMV). Through extensive testing, the PMV predicts what percentage of people will be comfortable at a given condition. For instance, a PMV of 0.5 indicates that at those conditions 90% of people in the space will vote they are comfortable. With this metric, the language changes from abstracted variables like temperature, and shifts to a direct measurement of people's comfort.

From an owner's perspective, PMV provides a clear, standardized specification for a building. Only using temperature in the specification is so widespread because it is a single, easily measured variable that can be monitored to verify the building meets its specification. When the conversation changes to six variables, it is much more difficult to measure. Even when designing to all six variables, there are no set ranges for each that can be specified. Instead, the acceptable range for each variable varies with the state of the other five variables. This is the genius of using PMV. It can encompass all possible combinations of the six variables and translate these into a single, easily modeled, specifiable value.

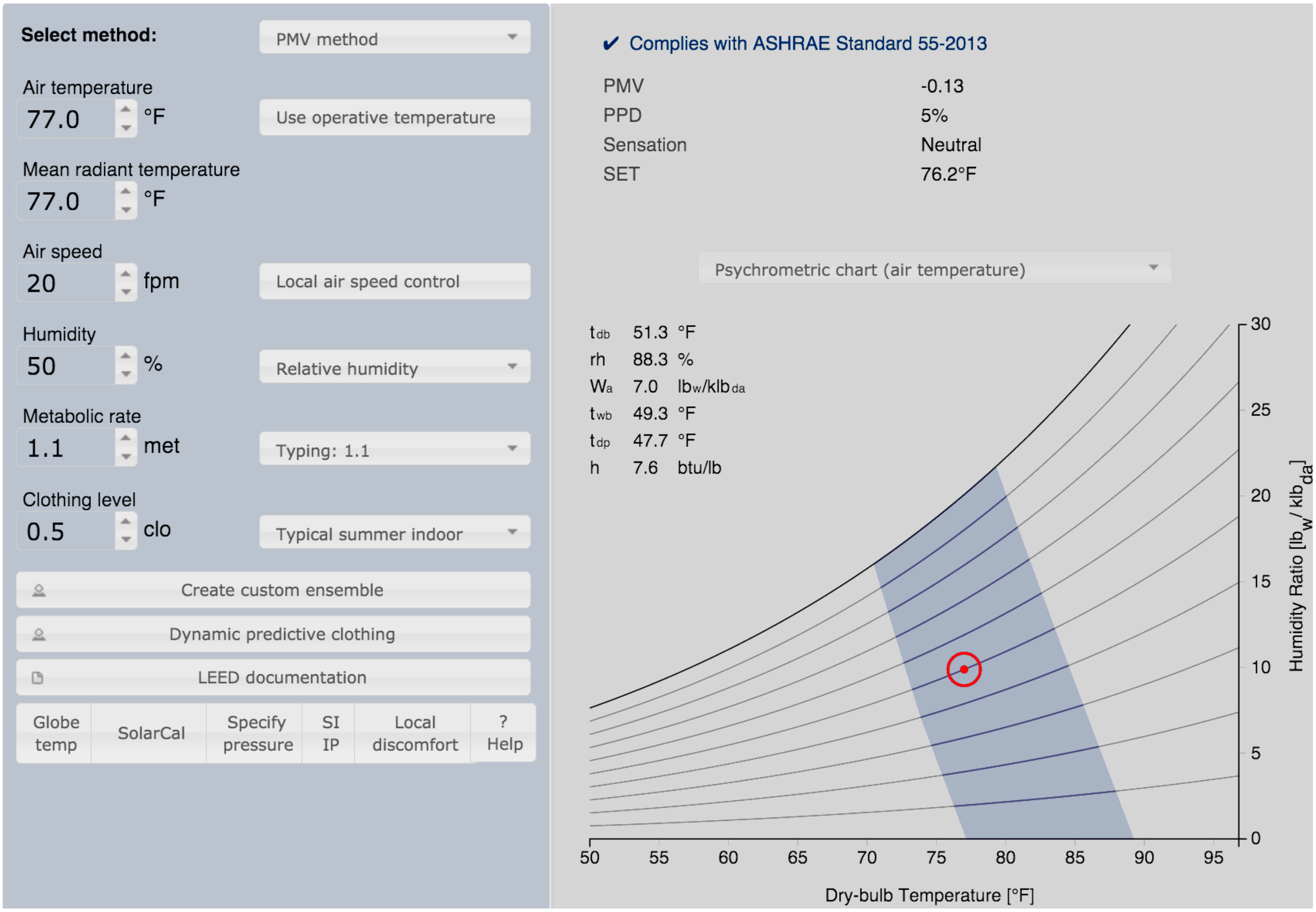
However, while the PMV formula can provide a clear single value to maintain, the role of each variable can be lost in the intimidating and complex formula.

Figure 2: PMV Formula

$$PMV = [0.303e^{-0.036M} + 0.028]\{(M - W) - 3.96E^{-8} f_{cl}[(t_{cl} + 273)^4 - (t_r + 273)^4] \\ - f_{cl} h_c (t_{cl} - t_a) - 3.05[5.73 - 0.007(M - W) - p_a] - 0.42[(M - W) \\ - 58.15] - 0.0173M(5.87 - p_a) - 0.0014M(34 - t_a)\}$$

As a result CBE took this complex formula and translated it into an interactive, graphical tool. By varying the inputs for each of the variables, a user can find not only the predictive PMV, but also where those conditions fall within the range of comfortable conditions. This tool is also key during the design process for the client and design team to experiment with different conditions and get a better feeling for the implications of design decisions. For instance, when weighing a trade-off between additional cooling and extensive ceiling fans, this tool can visually demonstrate the significant impact of air speed on an occupant's comfort.

Figure 3: CBE Thermal Comfort Tool



Source: Hoyt Tyler, Schiavon Stefano, Piccioli Alberto, Moon Dustin, and Steinfeld Kyle, 2013, CBE Thermal Comfort Tool. Center for the Built Environment, University of California Berkeley, http://cbe.berkeley.edu/comforttool/

DESIGNING FOR EXPANDED RANGE: A CASE STUDY AT ROCKY MOUNTAIN INSTITUTE'S INNOVATION CENTER

In December 2015, RMI moved into its new 15,610 sq. ft. office building and convening center in Basalt, Colo. This state-of-the-art beyond-net-zero energy building was constructed to advance the organization's mission and demonstrate how deep green buildings are designed, contracted, constructed, and occupied.

For RMI, this innovative approach to thermal comfort was used because it was a central element to a whole-systems, passive design that allowed us to meet our ambitious net-zero energy goals. While other building owners may not have net-zero energy goals, what we learned through our design process—that this approach requires collaboration, dedication, and shared goal commitments from a dedicated and skilled team—is just as applicable and important in designing around thermal comfort.

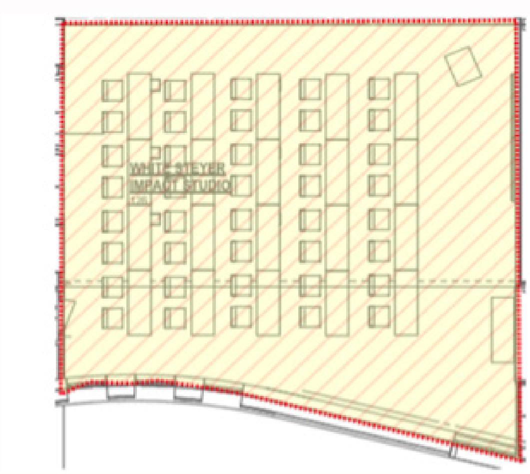
SETTING A CLEAR DIRECTION

When you expand the design to look at all six variables, the conversation shifts from which mechanical systems can meet the specified air temperature most efficiently to how the building can best meet all six variables. The significant role of mean radiant temperature and airflow requires the architects and contractors to become integrated in those early design conversations. The interplay between the variables controlled by architects, engineers, and contractors pushes the team to a truly integrated design process. Suddenly, the number of operable and south-facing windows is a key factor in the thermal design process. During the Innovation Center design process, our mechanical engineer joked, “Finally we have the power!”

As a result of so many parties having to simultaneously consider so many variables, we found we had to communicate differently. The engineers introduced room data sheets, which are usually reserved for complex lab buildings. These sheets outlined the key comfort parameters for each zone, including clothing, activity level, air speed, space utilization, and use schedules. This process pushed the owner and the design team to sit down and think through the anticipated use of each space. For the owner, it also provided clear direction on the intended use of each space. If the space is renovated or repurposed in ten years, there is clear documentation about how the change of use differs from the original design and the consequent potential implications.

Figure 4: Innovation Center Room Data Sheets

ROOM FLOOR PLAN



INTERNAL LOAD ASSUMPTIONS:	
People	77
Equipment (Installed)	0.47 W/SF
Equipment (Operational)	0.47 W/SF
Lighting (Installed)	0.55 W/SF
Lighting (Operational)	0.40 W/SF
Daylighting	Auto Dimmers
Installed Heating	6.8 kW
Heating Setpoint	72 °F
Weather File	Aspen, CO Custom TMY10, 2004-2013
Notes	5000 CFM Exhaust

HEATING	COOLING
Clo (max): 1.01 (Trousers, sweater, T-shirt)	**Clo (min): 0.57** (Trousers, short sleeves)
Met (min): 1.0 (Sitting, relaxed)	**Met (max) 1.7** (Active, speaking)
Air Speed (min): 19 FPM	**Air Speed (max) 100 FPM**

SCHEDULE DESCRIPTION
10% occupied 4 weekdays for 3 hours. 100% occupied 1 weekday from 8am to 5pm. Equipment tracks occupancy, turning down to 7% load when unoccupied. Lighting is on with automatic daylight dimming when occupied, off when unoccupied.

MEETING NEEDS WITH TARGETED SYSTEMS

Breaking down thermal comfort into six variables pushes the team to examine the best way to meet each requirement. Often, by breaking it down this way it lends itself to smaller systems targeted to meet each of those needs. External blinds can be tailored to meet radiant needs while ceiling fans control airflow. Instead of a large central system that is oversized to meet every need in all conditions, thereby reducing risk, smaller systems sized to only meet the needs of one variable are possible.

Often, many of these variables, such as air speed and mean radiant temperature, lend themselves to passive architectural solutions. These smaller, targeted systems are not only intrinsically more efficient, but they are often traditional, easily maintained systems.

Once these passive systems create a stable range of comfortable temperatures, smaller personal comfort approaches can be used to fine-tune people's comfort within that range. This approach can accommodate the significant range of perceived comfort due to metabolic, gender, health, or clothing differences. Personal fans and user-adjustable windows/blinds are simple solutions. Emerging research into personal comfort is also producing exciting new technologies like a heated and cooled chair controlled by a user's iPhone.

Unfortunately, during the commissioning of the Innovation Center we found that using multiple targeted systems trades off potentially higher maintenance technology for significant complexity in system integration and commissioning. Each of our disparate systems has its own proprietary control system designed to operate independently for the standard application. However, our strategy requires all systems to be integrated into the central control system, creating two main technical and scope issues during construction: 1) technically how can these control systems talk to each other? and 2) who is responsible for making that happen? Even when the systems are integrated, each system has internal control algorithms that can conflict with the central strategy and result in fighting between systems. Often, these systems can only uncover limited points for the central control system to view and change, making troubleshooting these issues difficult. This complexity resonated from the additional integration costs during construction through to operation, where we are still troubleshooting integration issues.

Continued standardization of communication protocols is partially addressing this issue, but the integration must be closely tracked throughout the entire design and construction process. While our controls contractor was involved early in the design process, we assumed applying standard communication protocols would address integration issues. In retrospect, it would have been crucial to map out all system interactions with clear scope boundaries and protocols. For future projects, we would designate a third-party master integrator to ensure technical and scope implications are considered in every design decision. In addition, the integrator could ground the design team with the potential operational challenges implicit in complex system interactions. During the excitement of the design process, it can be easy to forget that as the number of system interactions increases, the knowledge required for a building operator to manage and respond to any issues grows exponentially.

TRANSLATING PMV INTO REALITY

While RMI was excited about the innovative, occupant-centric design approach provided by PMV, we still wanted a replicable, straightforward control strategy that could be implemented by local controls contractors and managed by any building owner. Translating this theory of PMV into reality was difficult with available packaged control systems. Controls sequences excel at optimizing one variable, like temperature, and become very complex when multiple variables are dependent on each other. To add complexity, two of those variables, clothing and activity level, are highly personal and unmeasurable, while air speed, mean radiant temperature, and humidity are measurable but controlled independently by users.

We decided to shift our focus from actively controlling all aspects of thermal performance to ensuring a comfortable range of temperatures is provided for users and trusting they will adjust their clothing, air speed, and radiant temperature accordingly. To achieve this, we made assumptions based on anticipated occupant use and held these variables constant. First, we set the upper and lower bounds for activity and clothing levels in each zone. In the convening center, a seated audience member wearing a light sweater dictated heating conditions while an active, agitated speaker wearing a traditional long sleeve button up shirt and slacks drove summer cooling. Through modeling, we found the range of airflows and mean radiant temperatures required to keep these occupants comfortable. We held these variables constant at their maximum values and ensured that the provided systems could deliver these conditions.

At the end of this process, the combination of assumptions and anticipated occupant responses held clothing, activity level, airflow, radiant temperature, and humidity constant, leaving only temperature varying in the control strategy. This provided a standard temperature control strategy delivering a wider temperature band that enabled our occupants to control all other variables. On the surface, it appears that PMV only translates to a wider temperature band. However, this misses the significant influence clothing, activity levels, and mean radiant temperature play in setting the temperature boundaries, in addition to the design of all complementary occupant-controlled systems.

IIIIIIII EMBRACING AND MANAGING RISK

THE IMPORTANCE OF INTEGRATED PROJECT DELIVERY

Overall, we used integrated project delivery (IPD) to align incentives and bring the team together very early in the design process. IPD is an emerging contracting methodology that creates a framework for team relationships and decision making. It creates a risk and reward pool to incentivize the whole team to work together and identify cost savings, which will then be shared among all team members. This process drives early integration of the construction and design team into the design process, as all parties have a crucial contractual responsibility in the success of the design. This not only provided input from all parties, but also built buy-in from those implementing the approach, such as the mechanical contractor.

In these early IPD design sessions with the design team and contractors, we began opening up about our fears and the risk we all felt as a result of this new approach to thermal comfort.

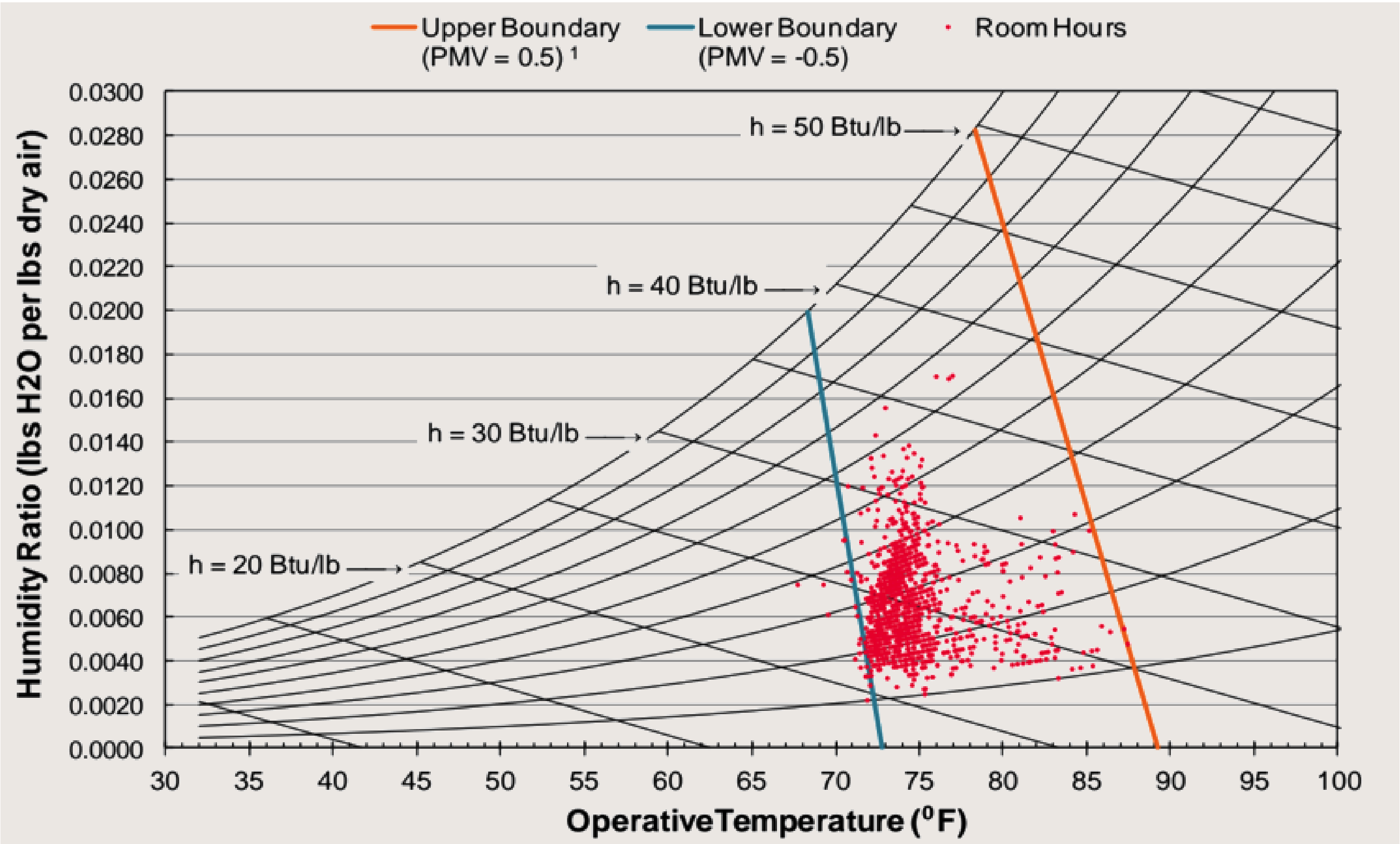
The design team and contracting team were taking significant risk in trying a relatively untested thermal comfort approach all while giving up their usual factor of safety that comes from an oversized central system. In such a passive building, the team could not just turn up the heating and get an instant response. In these early design discussions we acknowledged how losing our traditional active heating and cooling systems and factors of safety was like losing our collective security blanket. We talked through all scenarios, including the possibility of it not working properly, to really understand these perceptions of risk. After these discussions we collaboratively drafted a contractual document explicitly stating who assumes what risk and what the implications are if that risk contains an issue.

SHARING RISK

One of the biggest risks explicitly assumed by RMI was whether or not people would be comfortable within this expanded comfort range. Instead of requiring the design and construction team to provide comfort, we specified the design parameters for all six variables of comfort using a PMV of 0.5. The design and construction team was only responsible for meeting those conditions. RMI assumed the liability if we were within those conditions and occupants were cold. This includes RMI's accountability for ensuring all occupants are dressing appropriately and using the spaces per design. This process also pushed us early in the design to consider how we would measure those six variables, including visual surveys of clothing and activity levels.

During the process of discussing risk as a team, we realized we had to find a better way to quantify and discuss the performance risks. Again, this is where room data sheets provided a framework to facilitate these discussions (see below). For each zone, the room data sheets graph the hourly thermal performance superimposed over the graphic of the acceptable comfort range from the CBE tool. This ties the design process back to the visual approach of the CBE tool. By viewing these, the team was able to easily evaluate the risk for each zone by seeing the number of hours on the outer boundaries of comfort. We could then decide as a team if we wanted to take that performance risk or trade off energy consumption. Since these trade-offs on risk and energy consumption affected the whole team's profit through the IPD contract, it was important to involve the entire team in these conversations.

Figure 5: Room Data Sheet Showing Hourly Modeled Data for Each Zone



A significant perceived risk was the inability to just "turn up" large central systems. With a passive system, if people are uncomfortable, the only option after tuning the control strategy is installing additional capacity. This means there is additional financial risk for performance issues. To address this we created a troubleshooting flowchart identifying and responding to the root cause of performance issues. This approach identified the biggest factors affecting performance and how they could fail. We then identified what targets these factors must meet, how these targets could be verified, and who would be responsible for this testing. While there are many issues that may not be identified, this collaborative process makes people work through the risks and severity of potential issues while giving all parties a chance to discuss the implications of design decisions.

While many of these conversations were more thorough due to RMI being the owner occupant, and therefore having influence on many of the operational risks, the open discussion of risk is still crucial for all ownership structures. In fact, it is even more important to discuss how the team will manage risks out of the team's control, such as third-party leases. These conversations could be crucial in crafting green leases or other approaches to manage these additional risks.

PLANNING FOR THE UNEXPECTED (BUT NOT UNPLANNED)

Once we examined the greatest project risks, it became clear that the largest risk was thermal comfort concerns due to our passive systems. To proactively manage this, we created a contingency plan where the design team created a conceptual design for additional capacity backup systems. Where it made financial sense, we even designed the existing systems for easy installation or upgrades of the plan B systems in the future. These plan B systems were modeled to create a second set of room data sheets addressing any specific areas of risk. We ensured ducts, panels, and conduits were sized to allow flexibility for these future plan B upgrades, thereby reducing the costs and the risk to the team. As an owner, knowing we had feasible and clear options was crucial for helping us decide to take on more risk.

Planning for and enabling these contingency systems on day one did increase initial capital costs. However, we would have incurred these costs even if the team had not decided to take on the risk of lower capacity. Instead, we have the option of paying for the additional capacity based on the building's actual performance. By openly discussing and planning for these additional systems, we significantly reduced the costs of future changes. If we decide to use all of our contingency systems, the final cost will only be slightly higher than if we had shied away from taking that risk and installed full capacity from the beginning.

SETTING A TRAJECTORY FOR LONG-TERM SUCCESS

MOVING BEYOND EQUIPMENT-BASED COMMISSIONING

Even with a dedicated and fully engaged design and construction team, thorough commissioning is always key to ensure the building is truly working. In fact, studies indicate that many green buildings are using up to four times more energy than their models predict, predominantly due to commissioning and operations and maintenance issues. Traditional commissioning looks at each individual piece of equipment and ensures it goes through its own sequence. Does the air handler ramp up and down? Does the ceiling fan turn on and does the automated window open when commanded? All of these systems are viewed separately.

For a traditional complex central system where the majority of the technical complexity and thermal control comes from a single, independent system, this can be sufficient. However, in our building the many targeted, simple systems look straightforward and simple to commission but are actually deceptively difficult. It is easy to test if each system performs independently but it is their interactions in the space that will dictate the overall success of the strategy. These interactions are often controlled by many factors, and due to the passive nature of many of the systems, difficult to simulate.

Instead, the commissioning approach must evolve to look at how the building performs as a system. It includes the usual functional testing of individual pieces of equipment then shifts to a long-term building-tuning perspective. To understand how the systems interact and react to situations, every point must be monitored through a range of conditions over an extended period of time. Most building owners do not have the knowledge or capacity to perform this long-term building monitoring and analysis. This approach requires a long-term relationship with the commissioning agent and design team, along with the associated operating budget for this work. This relatively short-term investment will quickly pay back in lower energy consumption and reduced occupant complaints.

CREATING ENGAGED AND INFORMED OCCUPANTS

It is also crucial that all occupants and all of the owner's senior leadership are informed of the approach and associated risks. Occupants in the space can no longer be passive and expect a central system to provide for their comfort but must be informed and able to control all of these systems themselves. This is especially true in our building where we have many passive, simple systems that work together to make an occupant comfortable. From an occupant's perspective, if he or she is hot there are four systems to personally adjust: personal heated and cooled chair, desk fan, ceiling fan, and windows.

This challenge requires a different approach to occupant engagement and training. Instead of the usual user manual and high-level trainings provided to new occupants, it is crucial to get people engaging the space and testing how the systems affect their comfort. We achieved this by using games to get people excited and engaged. These games challenged people to use all the systems available to achieve the highest and lowest PMV. By doing this they could not only experience every system and its interactions with adjacent systems, but also gain a deeper understanding of the underlying comfort methodology.

With such a different approach, it is crucial that the engagement strategy goes beyond occupants to all possible stakeholders, including senior management and external building users. In our building, we decided to require occupants to dress appropriately for the seasons, meaning no suits during the summer and a sweater during the winter. While it is reasonable to require building occupants to do this, senior management and external stakeholders must decide if it is reasonable to expect visitors to follow this protocol as well. Is the owner willing to inform outside visitors of this requirement before they come to the building? Again, this planning for plan B systems allows the owner to respond to inevitable changes in risk tolerance and expectations of occupants and management.

These engagement programs all work with current staff, but in a building designed to last 100 years, there will be a significant amount of personnel turnover. How does one ensure the maintenance staff and occupants are informed in five or twenty years? With such complex system interactions and requirements for engaged staff, the approach cannot stop at a user's guide and maintenance log. RMI is working to address this through recorded trainings and extensive system manuals that focus on the design conversations and strategies underlying the final approach. However, this is a significant outstanding question that we are continuing to research and develop.

CONCLUSION

Adopting a more targeted, comfort-centric approach could be a crucial step in creating scalable and comfortable net-zero buildings. However, this is a significant paradigm shift in what can be a very conservative industry. RMI hopes that by taking the first steps in implementing this approach, it can pave the way for wider adoption.

This comfort approach can be scaled to fit any situation. The core concept of considering all six variables when designing a building is applicable to every environment and contract structure. This foundation can then drive a more integrated design that uses targeted systems to enable personal comfort approaches. However, a more conservative, centrally based approach can still significantly increase occupants' comfort by considering all aspects of their perceived comfort. The CBE comfort tool and emerging personal comfort technologies can enable that conversation and provide lower-risk options to complement a traditional system.

Aspects can also be applied to existing buildings. Building managers or occupants in an over-conditioned building can turn down the central heating or cooling and instead use personal comfort approaches to fine-tune their comfort. By stepping back and examining the best way to meet those comfort variables through often cheap and easy passive means, building managers can reduce their dependence on expensive and energy-intensive central systems.

However, the greatest power lies not just in the design strategy but also in the open and integrated design process. To move beyond safe, oversized central systems the design team must openly discuss and mitigate risks. This can be addressed contractually through an explicit risk-sharing framework, or by designing and installing a contingency plan. Like any good relationship, this open and honest communication is fundamental to a successful project.

Most of all, the industry's conversation needs to evolve from conservative, oversized central systems to a more sophisticated approach enabling teams to take measured risks and focus on occupants' comfort. New tools, technologies, and processes are enabling this discussion while the need for highly efficient buildings is compelling owners and occupants to speak up and drive the conversation forward.