Energy Research and Development Division

FINAL PROJECT REPORT

Energy Research and Development Division

Optimizing Radiant Systems for Energy Efficiency and Comfort

California Energy Commission

Edmund G. Brown Jr., Governor

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PREFACE

The California Energy Commission's Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation and bring ideas from the lab to the marketplace. The California Energy Commission and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas & Electric Company and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The Energy Commission is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Optimizing Radiant Systems for Energy Efficiency and Comfort is the final report for the EPIC Radiant project (Contract Number: EPC-14-009) conducted by Center for the Built Environment, University of California, Berkeley; Taylor Engineering; New Buildings Institute; and TRC. The information from this project contributes to the Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

ABSTRACT

Radiant cooling and heating systems provide an opportunity to achieve significant energy savings, peak demand reduction, load shifting, and thermal comfort improvements compared to conventional all-air systems. As a result, application of these systems has increased in recent years, particularly in zero-net-energy (ZNE) and other advanced low-energy buildings. Despite this growth, completed installations to date have demonstrated that controls and operation of radiant systems can be challenging due to a lack of familiarity within the heating, ventilation, and air-conditioning (HVAC) design and operations professions, often involving new concepts (particularly related to the slow response in high thermal mass radiant systems). To achieve the significant reductions in building energy use proposed by California Public Utilities Commission's (CPUC's) Energy Efficiency Strategic Plan that all new non-residential buildings be ZNE by 2030, it is critical that new technologies that will play a major role in reaching this goal be applied in an effective manner.

This final report describes the results of a comprehensive multi-faceted research project that was undertaken to address these needed enhancements to radiant technology by developing the following: (1) sizing and operation tools (currently unavailable on the market) to provide reliable methods to take full advantage of the radiant systems to provide improved energy performance while maintaining comfortable conditions, (2) energy, cost, and occupant comfort data to provide real world examples of energy efficient, affordable, and comfortable buildings using radiant systems, and (3) Title-24 and ASHRAE Standards advancements to enhance the building industry's ability to achieve significant energy efficiency goals in California with radiant systems. The research team used a combination of full-scale fundamental laboratory experiments, whole-building energy simulations and simplified tool development, and detailed field studies and control demonstrations to assemble the new information, guidance and tools necessary to help the building industry achieve significant energy efficiency goals for radiant systems in California.

Keywords: *Radiant cooling and heating systems, thermally activated building systems, building system controls, sequences of operation, building energy use, cooling loads, thermal comfort, acoustic quality, design tool, building costs, codes and standards, laboratory studies, field studies, building performance simulation*

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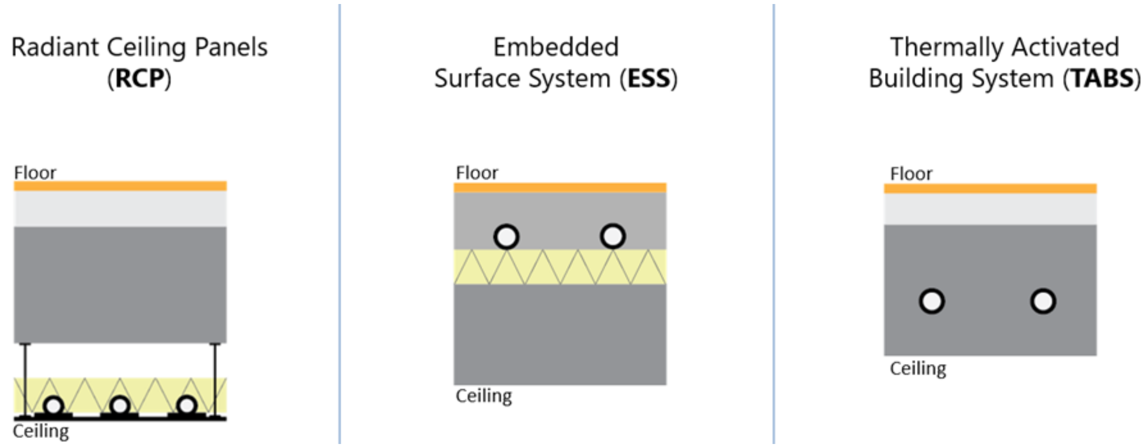
EXECUTIVE SUMMARY

Introduction

Radiant cooling and heating systems provide an opportunity to achieve significant energy savings, peak demand reduction, load shifting, and thermal comfort improvements compared to conventional all-air systems. As a result, application of these systems has increased in recent years, particularly in zero-net-energy (ZNE) and other advanced low-energy buildings. Despite this growth, completed installations to date have demonstrated that controls and operation of radiant systems can be challenging due to a lack of familiarity within the heating, ventilation, and air-conditioning (HVAC) design and operations professions, often involving new concepts (particularly related to the slow response in high thermal mass slab designs). Furthermore, recent research from Center for the Built Environment (CBE) has shown that the fundamental differences between radiant and all-air systems require new and/or revised definitions and methods for the design, sizing, and control of successful and effective radiant cooling and heating systems. These differences have created a situation where radiant systems are being designed, installed, and operated with only limited guidance and often inappropriate tools to assist the designer and building operator. To achieve the significant reductions in building energy use proposed by California Public Utilities Commission's (CPUC's) Energy Efficiency Strategic Plan that all new non-residential buildings be ZNE by 2030, it is critical that new technologies that will play a major role in reaching this goal be applied in an effective manner.

The most cost effective and energy efficient radiant systems are high thermal mass systems, in which plastic tubing (PEX) is embedded in a layer of concrete in the building. There are two types of high thermal mass radiant systems: (1) structural slabs (floor or ceiling) with embedded tubing for new construction (thermally activated building systems, TABS), and (2) for retrofit or new construction, thinner concrete floor layers (e.g., topping slabs) containing embedded PEX tubing that are isolated (insulated) from the building structure (embedded surface system, ESS). The third type is suspended metal ceiling panels with copper tubing attached to the top surface (radiant ceiling panel, RCP), also for retrofit or new construction. Figure 1 shows schematic diagrams of the three main types of radiant systems. Due to their high response time, TABS and ESS have proven to be the most difficult to design and control, particularly when designers and operators are unfamiliar with the system. In this project, we intended to provide improved fundamental and practical understanding and guidelines that will apply to all types of radiant systems, but the specific simplified design and operations tool that has been developed focuses on the more promising and challenging high thermal mass radiant systems, TABS and ESS.

Figure 1: Three main types of radiant systems



In terms of cooling in California climates, radiant slab systems can take advantage of the high thermal mass of the slab to significantly reduce peak cooling loads and allow structural pre-cooling strategies to be implemented during nighttime hours when both utility rates are lower and 'free cooling' can be achieved due to lower outside dry and wet-bulb temperatures. Overall, this can substantially reduce the required size of system components.

Lastly, the goal of any HVAC system is to provide occupants with a healthy and comfortable environment. Occupant thermal comfort in buildings depends highly on air and mean radiant temperatures. All-air systems can directly control only air temperature, but as radiant systems are always coupled with a separate ventilation system, they can control both parameters. Moreover, these systems can compensate for the negative radiant effect – that is usually unaccounted for - of perimeter walls and windows (cold in winter and warm in summer). Thus, radiant systems have the potential to improve thermal comfort. However, there are few human subject-based studies that show radiant systems provide higher comfort.

The building industry is interested, but poorly positioned to assimilate results and lessons learned from completed radiant projects as these projects are done by individual companies, and rarely are details of the design methods and control strategies made available to others. In addition, funding agencies other than EPIC simply do not support applied research on this scale within our field. For a project of this scope to be successful in assisting California and its ratepayers to meet their challenging sustainability goals, all of the tasks described below are needed to be completed simultaneously – from theoretical and laboratory research; to measured energy, comfort, and cost performance in a population of real buildings; and finally to new standards and codes.

Project Purpose

The overall goal of this project was to address these needed enhancements to radiant technology by developing the following: (1) simplified sizing and operation tools (currently available methods require time and expertise) to serve as reliable methods for taking full advantage of high thermal mass radiant systems to provide improved energy performance while maintaining comfortable conditions, (2) energy and occupant satisfaction data, as well as cost comparison analysis, to provide real world examples of energy efficient, affordable, and comfortable buildings using radiant systems, and (3) Title-24 and ASHRAE Standards advancements to enhance the building industry's ability to achieve significant energy efficiency goals in California with radiant systems.

The objectives of this project were to:

- Conduct fundamental full-scale laboratory experiments investigating:
  - Impact of suspended acoustical panels and air movement on chilled ceiling cooling performance;
  - Side-by-side comparison of zone cooling loads for radiant vs. air systems for different heat sources and control strategies including night cooling;
  - Impact of solar gain on radiant slab cooling capacity; and
  - Impact of zone valve type and control method on performance.
- Provide background on the state-of-the-art with current radiant design practice by conducting interviews with expert designers.
- Develop a simplified control method and a combined simplified web-based design and operation tool for high thermal mass radiant systems.
- Conduct detailed field studies of three buildings with radiant slab systems, including demonstration and further evaluation of the new simplified control and operations tool.
- Collect empirical evidence and document the energy performance and occupant perception of the indoor environment in buildings with installed radiant systems.
- Conduct a cost comparison study between radiant and all-air buildings.
- Propose changes to Title 24 to support improved modeling capabilities and ensure efficient performance of radiant systems in California.
- Propose changes, as needed, to relevant ASHRAE Standards, Handbooks, and Guidelines to provide new information and guidance on radiant systems.

Project Approach

This comprehensive research project to address needed enhancements to radiant systems technology was performed by a team of organizations and experts who have collectively been at the forefront of recent research on radiant systems and zero-net-energy buildings, as well as highly engaged in implementing changes related to research findings on advanced HVAC technologies to codes and standards. CBE and the major subcontractors, Taylor Engineering and TRC, have a long history of collaborating together, including several CEC/PIER- and EPIC-sponsored field studies and a significant ASHRAE research project on advanced HVAC controls and comfort. Taylor Engineering, in particular, has played a major role for many years in successfully updating Title-24 and ASHRAE Standard 90.1.

The technical approach for the project consisted of the following coordinated tasks.

1. Laboratory experiments: The research team completed six full-scale laboratory experiments to provide a thorough understanding of the fundamental principles of radiant systems. The experiments were performed in two world-class test facilities: (1)

Hydronic Systems Test Chamber at Price Industries in Winnipeg, and (2) FLEXLAB at Lawrence Berkeley National Laboratory. The results from these experiments provided new knowledge on practical applications like the use of acoustical panels and the effect of solar radiation on floor cooling capacity, the use of lower cost two-position valves instead of modulating valves on control performance, as well as verifying key differences between radiant and all-air systems.

2. Simplified design and operation tool: Representing one of the most significant products of the project, in this task the research team developed a simplified design and operation tool for high thermal mass radiant systems. The approach used to develop the tool involved performing over 2.5 million EnergyPlus simulations covering a wide range of radiant system designs and control strategies. A regression fit to the simulation results provides the basis for the simplified tool to estimate peak cooling loads and cooling capacity using a newly developed control strategy. The strategy is simple enough to be programmed in a typical Building Automation System.
3. Field studies and control demonstrations: The research team conducted detailed field studies in three high thermal mass radiant buildings in California. Two of the three buildings were used as demonstrations of the new control strategy developed in Task 2 above. With the assistance of building operators, the new control strategy was implemented into the building management system and the resulting thermal comfort conditions were carefully monitored over several months to assess compliance with thermal comfort standards. The impact of direct solar radiation on chilled radiant floor performance (also tested in FLEXLAB in Task 1) was investigated in the third building.
4. Energy analysis, occupant surveys, and cost assessment: To provide real world examples of radiant buildings, the research team conducted a large outreach effort to identify and gain access to as many radiant buildings across the United States and Canada as possible. Energy use data and surveys of occupant perception of the indoor environment were collected from these buildings and compared to data collected from a similar set of buildings using conventional all-air systems, as well as accepted national benchmark databases. This part gave a solid answer on the energy and comfort open questions. To assess cost considerations for radiant systems, the team performed a design stage cost analysis comparing a selected radiant building against an identical building with a traditional VAV system.
5. Codes and standards: To leverage the impact of this research, the research team recommended changes to relevant codes, handbooks, guidelines and standards. The primary frameworks for these changes were through the ASHRAE technical, standards and guidelines committees and the California Building Standards. The recommendations were intended to support effective coverage of high thermal mass radiant systems for Title 24 code compliance and to document and support best practices as uncovered by the research activities associated with this EPIC project.

The most significant barrier of field study and building assessment (tasks 3 and 4 above) was to gain access to the buildings. CBE and the entire research team (NBI, Taylor Engineering, and TRC) have a proven track record of successfully conducting field studies, performing measurements and collect energy and occupant satisfaction data in real buildings. Even so, it took a concentrated 2-year effort to collect the desired data from the nearly 30 radiant buildings included in this study. In some cases, when suitable cooperation or data were not made available, the research team had to drop that particular building from the dataset and move forward with other available buildings.

The technical advisory committee (TAC) for this project consisted of the 46 industry partner firms for the Center for the Built Environment (cbe.berkeley.edu/aboutus/industrypartners.htm), representing leading building industry professionals. CBE met with their partners twice per year, presented research results, and thereby received valuable input on a regular basis throughout the project. In addition, the research team invited CBE partners to join a more focused Radiant Systems Technical Advisory Group (TAG), which was made up of a subset of CBE partners who had special interest and experience with radiant systems. The TAG members participated in two webinars (January and November 2018) during which the new online simplified radiant design and operations tool was demonstrated and the TAG provided feedback on its usability and features. This input was incorporated into the tool to improve its practicality for radiant system designers.

Project Results

The multi-institution research team was able to successfully complete all defined tasks in the work plan and to achieve the major goals of the project. The new information, simplified tools, real-world data and applications, and recommended revisions to codes and standards produced by this project are now available to aid and encourage the application of successful high thermal mass radiant systems by the building industry. Key project results include:

- New knowledge and improved understanding of the fundamental differences between high thermal mass radiant systems and conventional all-air systems, particularly related to cooling performance.
- Collection and analysis of the largest known database of energy performance and occupant satisfaction from commercial buildings in North America using radiant cooling and heating systems.
- Energy use data from 23 radiant buildings showing that almost all outperformed peer buildings and national benchmarks, suggesting that radiant systems are part of the integrated approach that can lead to low energy consumption in commercial buildings.
- An analysis of occupant survey data from 26 radiant buildings in comparison to 34 all-air buildings showing that radiant and all-air spaces have equal indoor environmental quality, including acoustic satisfaction, with a tendency towards improved temperature satisfaction in radiant buildings.
- Development of new simplified control strategy and combined simplified web-based design and operation tool (currently available methods require time and expertise) to serve as reliable methods for taking full advantage of high thermal mass radiant systems to provide improved energy performance while maintaining comfortable conditions.
- Field study demonstration of improved comfort and energy performance in two high thermal mass radiant buildings using the newly developed control strategy.
- Based on laboratory and field measurements, new practical guidance on radiant system applications, including: (1) use of acoustical clouds to enhance acoustical quality in chilled radiant ceiling systems, (2) use of fan-driven air movement to increase cooling capacity of both radiant ceiling and floor systems, (3) design of chilled radiant floor systems for increased cooling capacity under direct solar radiation, and (4) new pulsed flow control method for high thermal mass radiant systems that uses 2-position valves to provide a cost effective solution with equal or improved thermal performance compared to a system with modulating valves.
- Documentation of the state-of-the-art with current radiant design practice by conducting interviews with expert designers.

- Assessment of cost considerations for radiant systems based on a design stage cost analysis comparing a selected radiant building against an identical building with a traditional VAV system.
- Recommended changes to Title 24 to ensure efficient performance of radiant systems in California, and recommended changes, as needed, to relevant ASHRAE Standards, Handbooks, and Guidelines to provide new information and guidance on radiant systems.

With the conclusion of this project, there are several identified future research needs to support the continued growth of radiant systems technology.

- Development of a comprehensive design guide with updated information, data, and tools that reflect the latest knowledge on high thermal mass radiant systems.
- Investigation and development of best practice design for high thermal mass radiant systems in comparison to current practice that often fails to take advantage of the substantial energy and demand savings available with these systems.
- Development and field study demonstration testing of advanced control strategies for high thermal mass radiant systems.
- Research and development of practical design guidance for chilled radiant floor systems with direct solar radiation.

Technology/Knowledge Transfer/Market Adoption (Advancing the Research to Market)

The target audience for the results of this project will primarily be building design engineers, architects, and contractors, but will also include manufacturers, utility companies, building owners, and other interest parties. During the course of this 3 ½ year project, the research team met twice per year with the technical advisory committee, consisting of the 46 industry partner firms for the Center for the Built Environment (cbe.berkeley.edu/aboutus/industrypartners.htm) at CBE's semi-annual Industry Advisory Board Conference held at the UC Berkeley campus. The CBE partners represent many of the leading and most influential design firms who are actively involved with high performance, low-energy and sustainable building design projects that often incorporate radiant systems. Through the CBE Conferences, the TAC receives early access to the research findings, tools, and guidelines.

Many members of the research team have already and will continue to present project results to the industry at relevant conferences, including ASHRAE, ACEEE, Building Simulation 2017, COBEE 2018, and PLEA 2018. Recommendations for needed updates and revisions to relevant codes, standards, and handbooks will be communicated to the responsible organizations by members of the research team, who regularly attend and participate in technical committees and conferences related to Title-24 and ASHRAE. These recommendations are outlined in the Codes and Standards Report (Chapter 5).

At ASHRAE, the research team is heavily involved with the cognizant technical committee for radiant systems, TC 6.5. Over the course of the project, CBE presented research updates on this EPIC Radiant Project to the members of TC 6.5 at the ASHRAE Conferences held twice a year. As part of this collaboration, CBE organized the TC 6.5 Strategic Meeting on Future Research and Dissemination Needs for Radiant Heating and Cooling at the ASHRAE Winter Conference in Orlando on January 27, 2016. The event was co-hosted by the Technical University of Denmark

(DTU), a leading research organization on radiant systems, led by Bjarne Olesen. The meeting featured speakers from CBE, DTU and other leading institutions and design firms involved with the design and research on radiant systems. CBE has also closely coordinated with and exchanged information with Atila Novoselac at University of Texas, Austin, related to his group's ongoing ASHRAE research project (RP-1729) to investigate cooling load differences between radiant and all-air (convective) systems.

Benefits to California

The California Public Utilities Commission strategic plan requires that all new buildings and 50% of all existing buildings are net zero energy by 2030. More than 50% of current net zero energy buildings use hydronic radiant systems, despite the lack of US-based design and operational guidance for these systems, particularly when the radiant system also serves as the primary cooling system for the building. Completed installations to date have demonstrated that controls and operation of radiant systems can be challenging due to a lack of familiarity within the heating, ventilation, and air-conditioning (HVAC) design and operations professions, often involving new concepts (particularly related to the long response time in high thermal mass radiant systems). Recent studies have shown that hydronic radiant systems, when properly designed, can be far more efficient than even best-practice all-air systems. Depending on the study, values range from 34% to 67%. However, simulation studies conducted in this project (see Section 2.2.3) found that it's possible that radiant buildings will consume more energy than best practice VAV buildings if they are not optimally designed to take full advantage of radiant system benefits. To achieve the significant reductions in building energy use proposed by California Public Utilities Commission's (CPUC's) Energy Efficiency Strategic Plan that all new non-residential buildings be ZNE by 2030, it is critical that new technologies that will play a major role in reaching this goal be applied in an effective manner.

The estimated impacts and benefits of the project are:

- 1352 million kWh per year of electricity savings
- $192 million per year of energy cost savings (at $0.1418 per kWh)
- 795 million pounds of CO_2e emissions per year avoided (at 0.588 lbs per kWh)
- 161 MW of avoided peak electric demand corresponding to an additional $70 million per year in TDV-weighted electricity costs (assuming that on average 1.5W/sf of peak demand is due to cooling energy, and the above assumptions regarding average costs during peak demand)
- There will be significant gas savings due to higher boiler efficiencies driven by the far lower supply water temperatures required by hydronic radiant systems, however we exclude these as this proposal is funded by the Electric Program Investment Charge.
- Additionally, radiant systems can operate with much higher temperature water for cooling and much lower temperature water for heating than conventional systems. This makes it far more feasible, cost-effective and efficient to use heat pump systems for all cooling and heating loads in a building. Such buildings do not require a natural gas supply, and can be 'all-'electric', providing significant support to decarbonization efforts and legislation such as SB-1477 (Low-emissions buildings and sources of heat energy).
- We have seen thermal comfort issues due to wide temperature variations in buildings with radiant systems. We have also encountered acoustics issues in preliminary case studies due to the exposed radiant slab. It is likely that this plays a role in the fact that

only 50% of ZNE buildings use radiant systems, as these issues (perceived, or real) deter the uptake of this technology in some cases. We aim to quantify these issues and develop approaches to mitigate them through improved design and operation guidance as part of this research.

- As part of the cost comparison study, new guidance is provided to improve the feasibility of designing and building cost-effective radiant buildings.

The large amount of new information, design guidelines, simplified design and operation tool, lessons learned and real-world data from existing radiant buildings, and recommendations for revisions to applicable codes, standards and handbooks is now publicly available through this final report. With all of this assembled information and the availability of many of the same research team members, the timing would be good for funding to support follow-up efforts aimed at developing a much needed newly updated radiant systems design guide.

CHAPTER 1:
Fundamental Full-scale Laboratory Testing

The research team conducted full-scale laboratory testing to provide a thorough understanding of the fundamental principles of radiant cooling systems. Previous CEC-sponsored research had shown that there are key differences between conventional all-air systems and radiant systems, particularly those involving high thermal mass (radiant slabs) (Feng et al. (2013, 2014), Bauman et al. 2013). As a result, the research plan called for carefully defined laboratory experiments to be performed during the early stages (first two years) of the project. This allowed the findings from these tests to inform simulation studies (Chapter 2) and field studies (Chapter 3). The results provided new knowledge on practical applications, as well as verifying in greater detail and under more realistic test conditions how radiant systems extract heat from buildings differently than all-air cooling systems.

The experiments were performed in two world-class test facilities: (1) Hydronic Test Chamber at Price Industries in Winnipeg, Manitoba, and (2) FLEXLAB at Lawrence Berkeley National Laboratory, Berkeley, CA. All experiments are summarized below, along with the separate technical publications that were prepared and published.

1.1. Laboratory Testing at Price Lab

Radiant slab ceiling systems are increasingly being used in office spaces. Yet, because these systems use exposed concrete, sound reflections often cause poor acoustical quality in the space. To address this problem, CBE investigated a ceiling solution that combines a radiant ceiling with free-hanging acoustical canopies and fans. The purpose of the study involving the two experiments described below was to conduct laboratory experiments for an office room with varying coverage of free-hanging acoustical canopies and different fan configurations below a radiant chilled ceiling.

The research team conducted two radiant ceiling cooling capacity experiments in the Hydronic Test Chamber at Price Industries in Winnipeg, MB. This chamber (4.27 m x 4.27 m x 3.0 m [14 ft. x 14 ft. x 9.8 ft.]) was equipped with radiant panels located in a suspended ceiling placed at a height of 2.5 m (8.2 ft.) above the floor. We modeled a typical interior zone office configuration using four simulated workstations and office heat loads. The chamber has no windows and the walls, ceiling, and floor have similar construction and are heavily insulated with an overall conductance of 0.135 W/m_2 K. This chamber is accredited by the EN 14240 [CEN 2004] for chilled ceiling testing. It is located inside a large laboratory facility maintained at 21.6 ˚C ± 0.5 ˚C (71˚F ± 1˚F). Figure 2 shows a photograph of the test chamber as configured for the two experiments.

Figure 2: Photograph of Hydronic Test Chamber, Price Lab

1.1.1. Laboratory Test #1: Cooling capacity and acoustic performance of radiant slab systems with free-hanging acoustical clouds

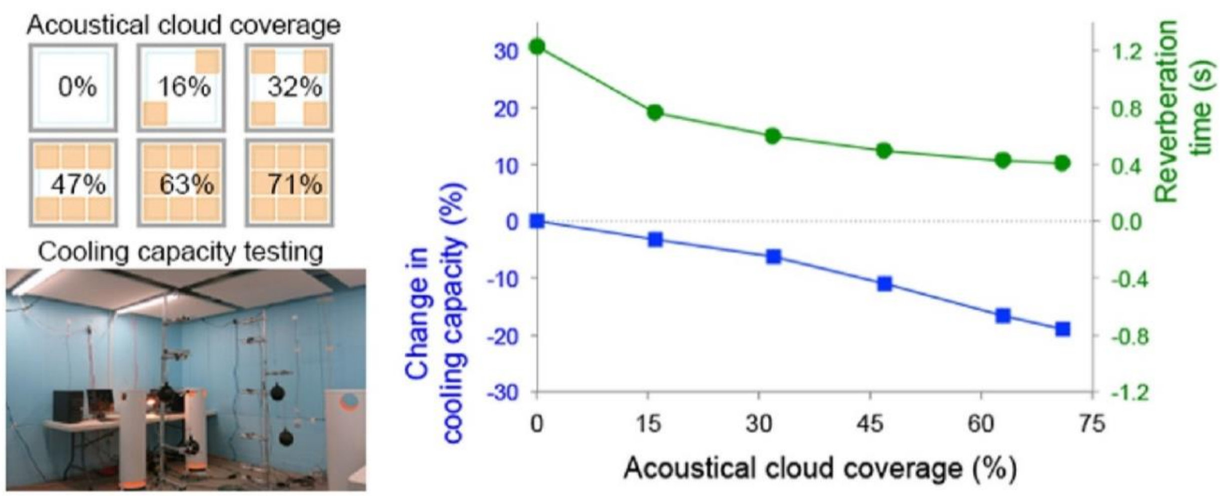
In this experiment, the research team proposed a combination of a radiant cooled ceiling with several configurations of free-hanging discontinuous acoustic clouds (sometimes called canopies). This type of sound absorber is known to have an increased acoustic performance compared to regular suspended ceilings due to the larger surface area exposed to sound, i.e., both the upper and lower surfaces, since sound has access to both sides of the cloud. As they are free-hanging, these clouds have an open air space above them. Air can freely circulate between the cloud and the ceiling allowing heat exchange by convection from the radiant cooled ceiling.

The objectives of this study were to: (1) experimentally assess the effect on radiant ceiling system cooling capacity for various coverage areas of free-hanging acoustic clouds, and (2) determine the change in sound absorption for the same configurations. Different ceiling coverage fractions (calculated as percentage of total ceiling area: 0%, 16%, 32%, 47% and 63%) were tested. These tests were complemented by acoustical tests performed by Armstrong World Industries in their certified reverberant chamber in Lancaster, PA. The same ceiling configurations and percent coverages were tested in both laboratories.

The acoustical results showed that if the canopies covered 40-50% of the ceiling area, acceptable acoustic quality was achieved. The cooling experiments showed that the acoustical canopies caused a smaller reduction in cooling capacity than previously thought (only 11% reduction at 47% coverage). The combined results demonstrated a practical solution in which free-hanging acoustical clouds are positioned below a radiant chilled ceiling, thereby achieving acceptable acoustical quality without overly compromising the cooling performance of the radiant ceiling.

A separate technical paper describing the experiment was prepared and published (Karmann et al. 2017a). Figure 3 shows the graphical abstract from the paper. The paper represents a deliverable for the project, Final Laboratory Test #1 Report, and is contained in Appendix A: Cooling Capacity and Acoustic Performance of Radiant Slab Systems with Free-Hanging Acoustical Clouds.

Figure 3: Laboratory test of impact of acoustical clouds on cooling capacity and acoustic quality

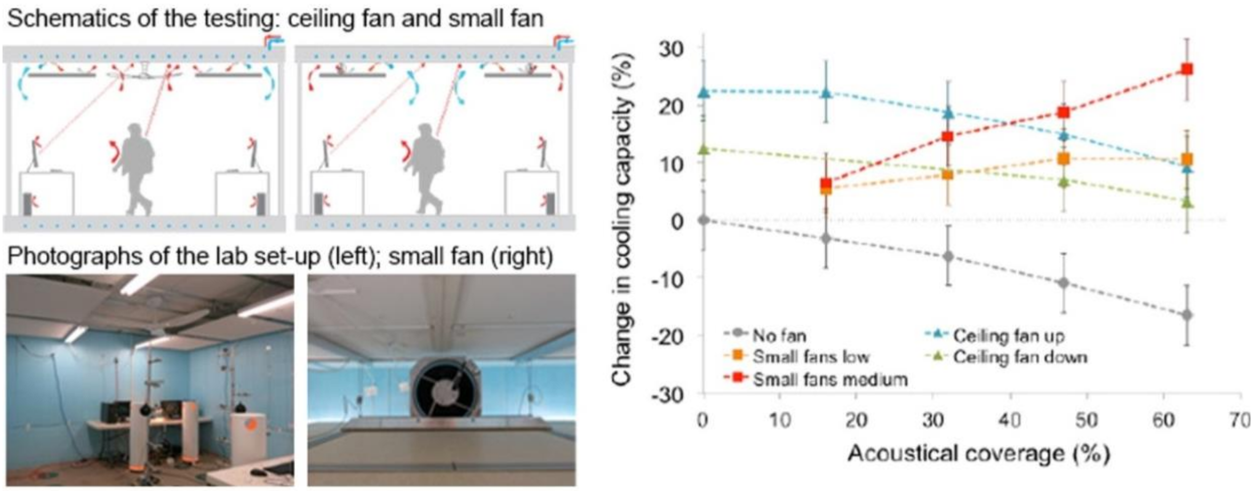


Schematic of acoustical cloud coverage; photograph of laboratory test chamber; measurement results of cooling capacity and reverberation time as a function of acoustical cloud coverage.

1.1.2. Laboratory Test #2: Effect of acoustical clouds coverage and air movement on radiant chilled ceiling cooling capacity

In the second experiment at Price Lab, the research team investigated the combined effects of acoustical clouds and fans on the cooling capacity for an office room. Fans were installed at ceiling level in the same test chamber to increase the convective heat transfer along the chilled ceiling. We tested two fan configurations: ceiling fan (blowing up and down between the canopies) and small fans (low and medium speed) hidden above the canopies (see Figure 4).

Figure 4: Laboratory test of effect of acoustical clouds coverage and air movement on cooling capacity



Schematics of test configurations; photographs of lab set-up; measurement results of cooling capacity as a function of acoustical coverage for different fan configurations.

The results showed that the ceiling fan increased cooling capacity by up to 22% when blowing upward and up to 12% when blowing downward compared to the reference case over the different cloud coverage ratios. For the variants with small fans, cooling capacity increased with coverage, up to a maximum increase of 26% . In this study, combining acoustical clouds and fans not only offset the modest reduction in cooling capacity from a radiant cooled ceiling caused by the presence of the clouds, but also provided an overall increase in cooling capacity compared to the reference case with no clouds and fan. This study offers a very promising and practical design solution regarding implementation of radiant slab ceiling systems.

A separate technical paper describing the experiment was prepared and published (Karmann et al. 2018a). The paper represents a deliverable for the project, Final Laboratory Test #2 Report, and is contained in Appendix B: Effect of Acoustical Clouds Coverage and Air Movement on Radiant Chilled Ceiling Cooling Capacity.

1.2. Laboratory Testing at FLEXLAB®

The research team conducted a second series of experiments in FLEXLAB® (https://flexlab.lbl.gov/) at Lawrence Berkeley National Laboratory (LBNL). The facility had recently been completed at the beginning of our research project and our team performed the first comprehensive experiment involving radiant systems at FLEXLAB®. Figure 5 shows a photograph of FLEXLAB®, which consists of four large double-chamber test beds exposed to direct solar radiation and outdoor conditions through their exchangeable south-facing window/wall assemblies. Representing one of the world's most advanced building efficiency testbeds, FLEXLAB® enables thorough assessment of building energy systems at a realistic physical scale, with naturally occurring solar gains, and natural interaction with the surrounding environment.

Figure 5: Photograph of FLEXLAB® at LBNL

Credit: LBNL

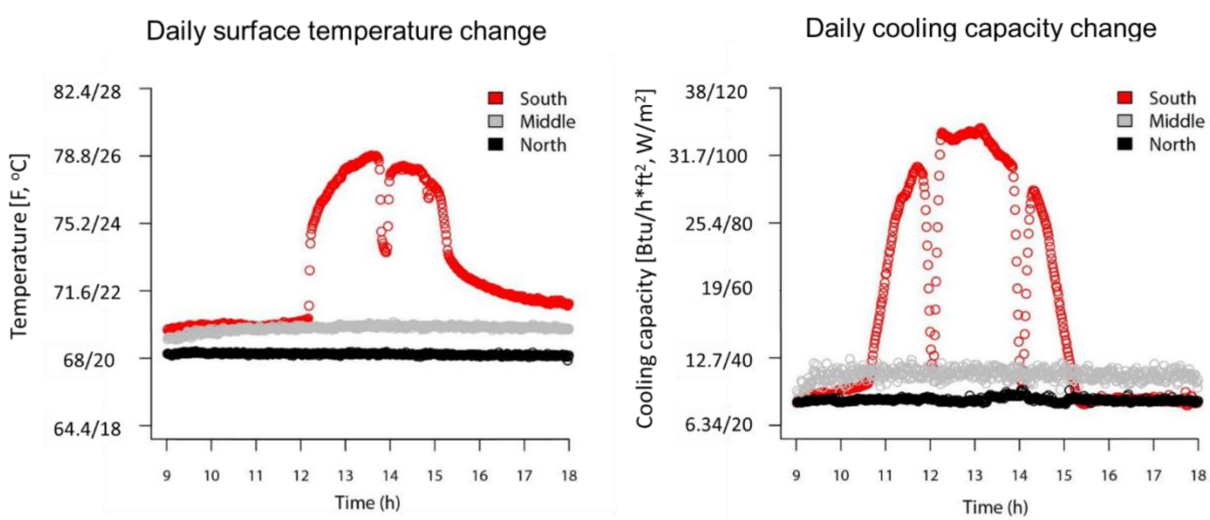
1.2.1. Laboratory Test #3: Full-scale laboratory experiment on the cooling capacity of a radiant floor system

Direct solar radiation on a chilled radiant floor is known to increase its cooling capacity, but there is limited measured evidence of this phenomenon reported in the literature. The objective of this study was to measure, in a highly controlled laboratory facility with outdoor solar exposure, the effect on radiant floor cooling capacity of (1) direct solar radiation exposure, (2) elevated air movement caused by ceiling fans, and (3) presence of carpet tiles. Figure 5 shows photographs of the test configuration inside the FLEXLAB® test room. Each room had 57.6 m^2 (620 ft^2) floor area (6.1 m (20 ft) by 9.1 m (30 ft) interior dimensions, excluding the equipment room) and a 3.66 m (12 ft) high ceiling, with a drop ceiling at 2.74 m (9 ft). The floor was a 15.25 cm (0.5 ft) thick concrete slab with embedded PEX tubing. The southern wall conformed to ASHRAE 90.1–2010 (ASHRAE 2010).

Figure 6: Photographs of test room at FLEXLAB®

The cooling capacity of the chilled radiant floor was measured to increase from 32 up to 110 W/m^2 (10 to 35 $Btu/h\text{-}ft^2$) under direct solar radiation. The surface temperature region exposed to solar radiation reached a peak temperature of 26˚C (79˚F) while the unexposed areas were between 20 and 21˚C (68-70˚F) (see Figure 7). Higher air speeds along the floor created by ceiling fans increased the radiant slab cooling capacity by ~12% (from 32 to 36 W/m^2 [10 to 11 $Btu/h\text{-}ft^2$]) when the operative temperature was 24˚C (75˚F) and, up to ~19% (40 W/m^2 [13 $Btu/h\text{-}ft^2$]) when it is increased to 26˚C (79˚F). The presence of thin carpet tiles reduced the radiant floor cooling capacity by ~5% compared to a bare floor slab.

Figure 7: Measurement results of impact of direct solar radiation



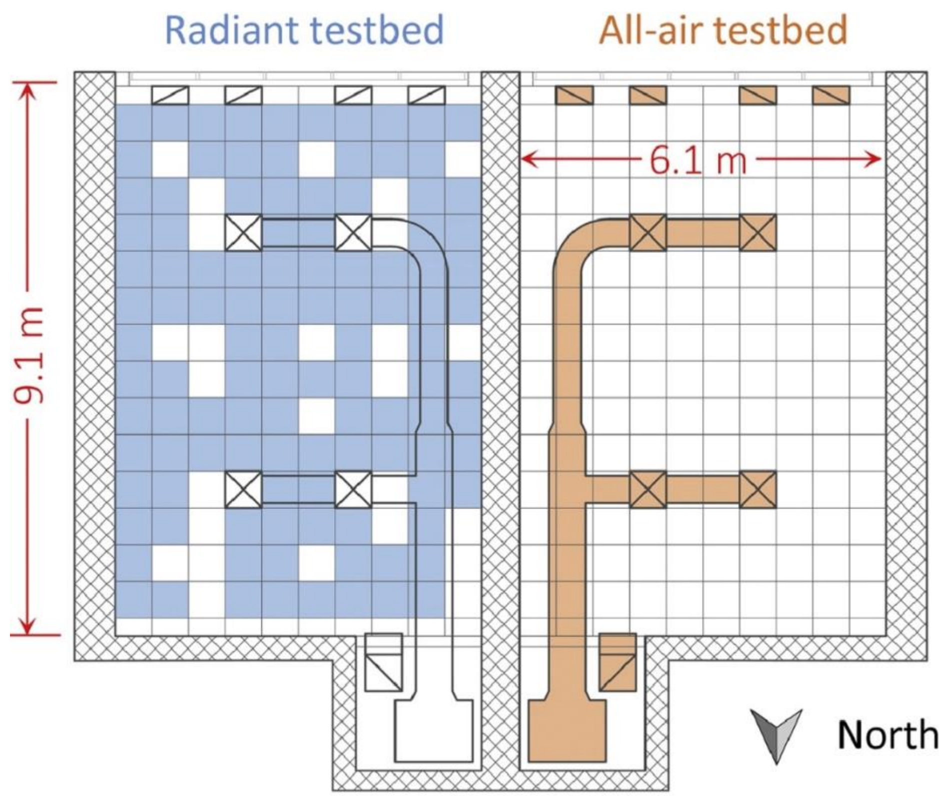
Measured floor surface temperatures at 3 locations: south (near window), middle and north; measured floor cooling capacity at 3 locations.

A separate technical paper describing the experiment was prepared and published (Pantelic et al. 2018a). The paper represents a deliverable for the project, Final Laboratory Test #3 Report, and is contained in Appendix C: Full-Scale Laboratory Experiment on the Cooling Capacity of a Radiant Floor System.

1.2.2. Laboratory Test #4: Side-by-side laboratory comparison of space heat extraction rates and thermal energy use for radiant and all-air systems

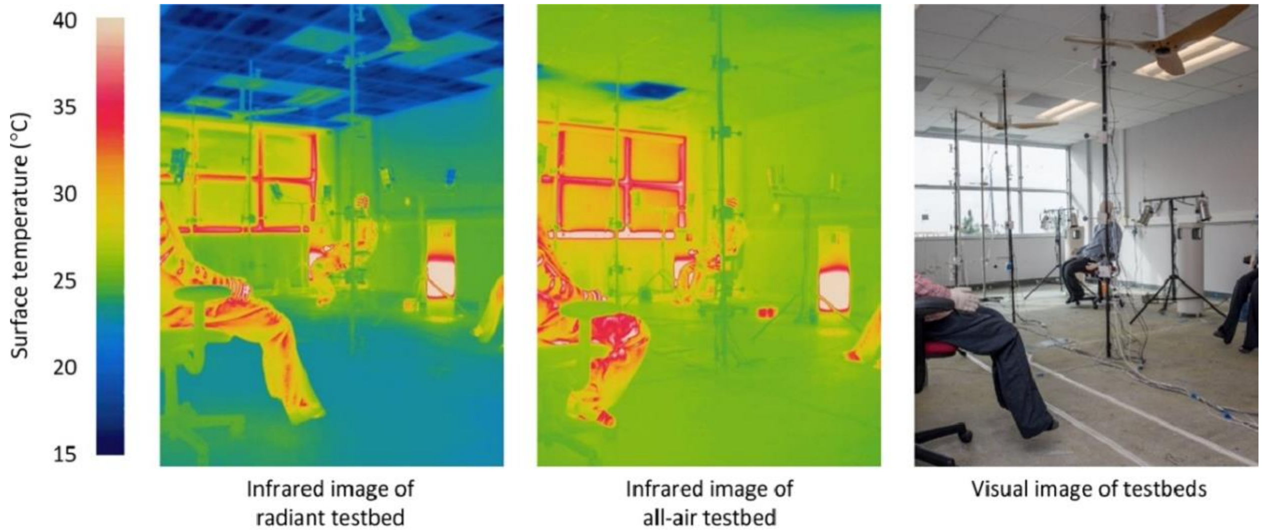
In this second experiment in FLEXLAB, the research team conducted a series of controlled tests in a pair of equivalent testbed buildings – one with radiant cooling and one with all-air cooling. For each experiment we operated the two testbeds simultaneously, imposed equivalent internal gains, and controlled each system to maintain equivalent operative temperatures. Figure 8 shows a plan view of the two testbed buildings. The radiant testbed was cooled by a low thermal mass metal radiant ceiling panel system in the drop ceiling. The panels covered 73% of the floor area, as highlighted in blue in the figure. The air handler circulated air at a constant 135 m^3/hr (80 cfm), a flow rate representative of typical ventilation rates in radiant buildings. In the all-air testbed the air handler circulated air at a constant flow rate of 1000 m^3/hr (590 cfm) and a proportional integral control sequence adjusted supply air temperature to control the operative temperature. Figure 9 compares infrared images of the two testbeds with equal operative temperatures being maintained in both testbeds.

Figure 8: Plan view of side-by-side testbed buildings at FLEXLAB®



Air handler, overhead ductwork, supply diffusers, and return registers in the all-air testbed are highlighted in orange. Low thermal mass metal ceiling panels in the radiant testbed are highlighted in blue.

Figure 9: Comparison of infrared images of radiant and all-air testbeds at FLEXLAB®



Equal comfort conditions			Environmental conditions
26 °C	Operative temperature	26 °C	Outdoor air temp. ≈ 30 °C
≈ 26.5 °C	Air temperature	≈ 25.5 °C	Exterior surface temp. ≈ 60 °C
≈ 25.5 °C	Mean radiant temp.	≈ 26.5 °C	

The results showed that radiant cooling must remove more heat than all-air cooling – 2% more in an experiment with constant internal heat gains, and 7% more with periodic scheduled internal heat gains. Moreover, the peak sensible space heat extraction rate for radiant cooling (heat transfer at the cooled surface, not the cooling plant) must be larger than the peak sensible space heat extraction rate for all-air systems, and it must occur earlier. The daily peak sensible space heat extraction rate for the radiant system was 1–10% larger than for the all air system, and it occurred 1–2 hours earlier. These findings have consequences for the design of radiant systems. In particular, this study confirmed that cooling load estimates for all-air systems will not represent the space heat extraction rates required for radiant systems.

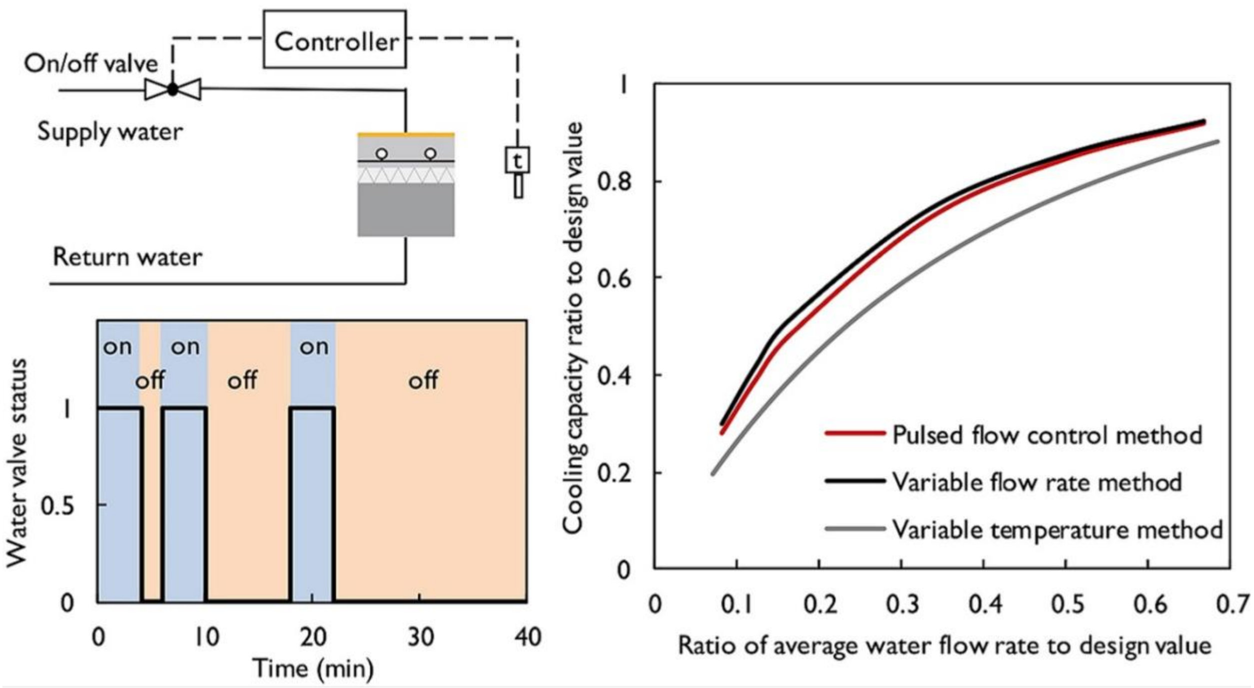
A separate technical paper describing the experiment was prepared and published (Woolley et al. 2018a). The paper represents a deliverable for the project, Final Laboratory Test #4 Report, and is contained in Appendix D: Side-by-Side Laboratory Comparison of Space Heat Extraction Rates and Thermal Energy Use for Radiant and All-Air Systems.

1.2.3. Laboratory Test #5: Performance analysis of pulsed flow control method for radiant slab system

While using the FLEXLAB test facility, the research team had the opportunity to conduct two additional experiments, which are briefly summarized in Sections 1.2.3 and 1.2.4.

The first experiment was an experimental validation of a newly developed pulsed flow control method (PFM) using a two-position valve to regulate the capacity of radiant slab systems. Compared with previous intermittent control strategies (with on-time durations over 30 min), at 50% part load the PFM requires 27% lower water flow rates and increases supply to return water temperature differential. The energy performance of PFM is comparable to that of an idealized variable flow rate control, and significantly better than actual variable flow control (unless pressure-independent valves are used). Additionally, it has more accurate capacity control, achieves a more uniform surface temperature distribution, and reduces initial investment by substituting two-position for modulating valves, thus showing promise for engineering applications. Figure 10 shows a schematic of the pulsed flow control method, example control operation of the two-position valve, and comparison of cooling capacities for different control methods.

Figure 10: Pulsed flow control method for high thermal mass radiant systems



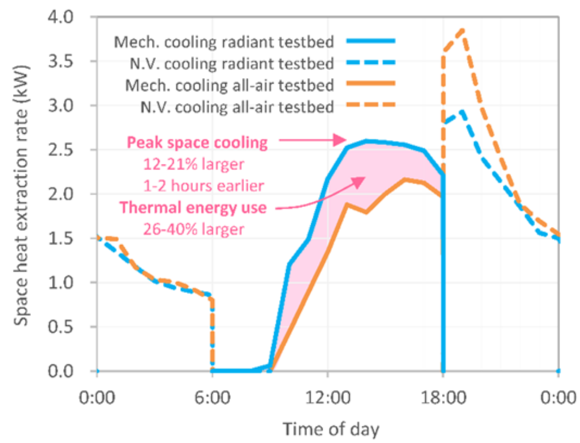
Schematic of pulsed flow control method; example control operation of two-position valve; comparison of cooling capacities for different control methods.

A separate technical paper describing the experiment was prepared and published (Tang et al. 2018). The paper is contained in Appendix E: Performance Analysis of Pulsed Flow Control Method for Radiant Slab System. As part of this work, we also developed and validated the world's first three-dimensional and transient numerical model of a radiant slab system.

1.2.4. Laboratory Test #6: Side-by-side laboratory comparison of radiant and all-air cooling: How natural ventilation cooling and heat gain characteristics impact space heat extraction rates and daily thermal energy use

The research team also performed a series of multi-day side-by-side comparisons of radiant cooling and all-air cooling in the same two FLEXLAB testbed buildings, with equal heat gains, and maintained at equivalent comfort conditions. In a five-day experiment with mixed internal heat gains, solar gains, and natural ventilation night precooling, radiant cooling had to remove 35% more heat than the all-air system in equivalent circumstances; and the peak heat extraction rate was 20% larger (median difference on multiple days). In a similar experiment with highly convective internal gains the differences were smaller (26% more thermal energy, 12% larger peak), while in an experiment with highly radiant gains the differences were larger (40% more thermal energy, and 21% larger peak). The differences were much smaller in an experiment without natural ventilation night precooling (7% more thermal energy, 5% larger peak). These findings have consequences for the choice, design, and control of mechanical cooling systems, especially in buildings that also use passive cooling strategies such as natural ventilation night precooling.

Figure 11: Five-day side-by-side comparison of radiant and all-air systems



(left) Side-by-side testbeds at FLEXLAB; (right) Results from 5-day experiment with natural ventilation night precooling.

A separate technical paper describing the experiment was prepared and submitted for publication (Woolley et al. In press). The paper is contained in Appendix F: Side-by-Side Laboratory Comparison of Radiant and All-Air Cooling: How Natural Ventilation Cooling and Heat Gain Characteristics Impact Space Heat Extraction Rates and Daily Thermal Energy Use.

CHAPTER 2: Simplified Tools for Design Sizing and Control of Radiant Systems

The overall goal of this task was to review and assess cooling load and design sizing issues for radiant systems, develop new control methods for the operation of radiant systems, and make this information available to the public in a user-friendly format through a web-interface.

2.1. Cooling Load and Design Sizing Research

2.1.1. Expert interviews

To better understand current design practices, the research team interviewed eleven prominent professionals with substantial experience in the design, construction and operation of radiant buildings in North America. These professionals collectively have designed more than 330 radiant system buildings. The interviews focused specifically on design and control of high thermal mass radiant systems — referred to as thermally activated building systems (TABS). A TABS system has radiant tubing embedded in a structural slab. Also included are radiant systems with tubing embedded in topping slabs separated from structural slabs by insulation — referred to as embedded surface systems (ESS).

This study documented the variety of design and control approaches currently used, highlighting themes and variations in common practice. The interviews revealed that there are many different approaches to designing and controlling buildings with these systems. The report also summarizes best practices as reported by these experts, noting areas where such expert insights will be of value to other practitioners. Interview findings are reported objectively, based on only the interviewee responses, and include limited commentary from the research team. Key findings include the following:

- There are some consistent themes among all interview responses. These include: importance of a high performance building envelope and managing internal loads, requirement of supplemental cooling, the challenges of the slow responsiveness in radiant slab control, and the use of the self-regulation feature of the radiant slab in design.
- Interviewees described a variety of design strategies and had unique preferences for their typical TABS design. These topics included: building types and space types where TABS should be applied, the choice and design of chilled water plants for buildings with radiant cooling, the design and zoning of ventilation systems, the design of supplemental cooling systems, the use of two-position valves, modulating valves, or pumps for radiant zone control, the choice of space temperature set points, and the control of changeover between slab heating to slab cooling.
- In practice, though most designers were aware of the potential benefits, they omit significant potential energy performance improvements, such as precooling, load-shifting, reduced plant sizes, lower cooling/higher heating water temperatures, and waterside economizing, due to lack of design tools, existing successful case study examples, availability of reliable controls to achieve the design intent, and project-specific constraints.

A separate research report describing all details of the expert interviews was prepared by Paliaga et al. (2017). The report represents a deliverable for the project and is contained in Appendix G: TABS Radiant Cooling Design & Control in North America: Results from Expert Interviews.

2.1.2. Cooling load and design sizing report

The current standard procedure for design sizing of cooling systems is not well suited for design of buildings with radiant cooling. There are several reasons that the standard design procedure for radiant cooling systems (ASHRAE Systems & Equipment 2016 Chapter 6: Radiant Heating and Cooling) is flawed, including that the current standard definition of space cooling load (ASHRAE Fundamentals 2017 Chapter 18: Nonresidential Cooling and Heating Load Calculations) omits fundamental principles that are essential to the operation of radiant cooling. This report identified several specific shortcomings with the current standard cooling load definition and with the standard cooling system design sizing procedure. We explain the fundamental flaws with each, discuss why addressing these shortcomings is especially important to the optimal design and operation of radiant cooling systems, and provide general recommendations for how the procedures ought to be improved. The issues and recommendations presented in this report were informed by several research tasks conducted as part of this project. In addition to identifying specific flaws with standard cooling load and design sizing procedures, we also discuss how each aspect of our research has provided evidence about or potential solutions to each issue.

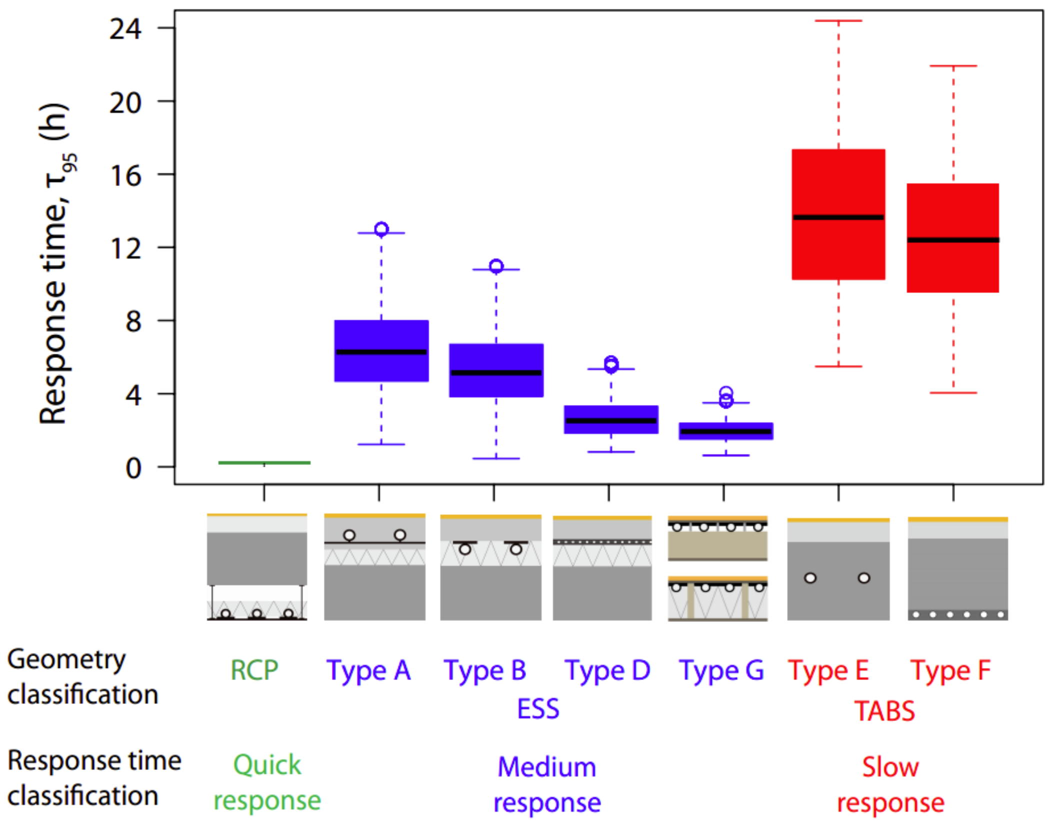
This research report was prepared by Woolley et al. (2018b). The report represents a deliverable for the project, Final Cooling Load and Design Sizing Report, and is contained in Appendix H: Cooling Load and Design Sizing Report. Many of the findings from this report informed the research team's recommendations contained in the Codes and Standards Report described in Chapter 5.

2.1.3. Thermal response time of radiant systems

Radiant system design and control standards and guidebooks currently classify radiant systems as a function of their structure and geometry. The assumption was made that design solutions, testing methods, and control strategies of radiant systems can be more clearly described and classified based on their thermal parameters. In this study, the research team used the thermal response time to evaluate the dynamic thermal performance of radiant systems. Response time (τ_{95}) is defined as the time it takes for the surface temperature of a radiant system to reach 95% of the difference between final and initial values when a step change in control of the system is applied as input. The state space and thermal resistance models were used to calculate the response time for different radiant system types with a variety of configurations and boundary conditions. The team performed 56,874 simulations. Concrete thickness, pipe spacing, and concrete properties have significant impact on the response time of thermally activated building systems, while pipe diameter, room operative temperature, water temperature and water flow regime do not. The results showed that $\tau_{95} < 10$ min for radiant ceiling panels; $1 < \tau_{95} < 9$ h for embedded surface systems; $9 < \tau_{95} < 19$ h for thermally activated building systems.

A preliminary radiant system classification scheme based on thermal response time is proposed (see Figure 12).

Figure 12: Thermal response time for different radiant system types



A separate technical paper describing the study was prepared and published (Ning et al. 2017). The paper is contained in Appendix I: A Novel Classification Scheme for Design and Control of Radiant Systems Based on Thermal Response Time.

2.2. Simplified Tool for Implementing Controls of Radiant Slab Systems

2.2.1. Simplified design and operation tool for radiant systems

The CBE Rad Tool is an interactive web-based design tool for the early design of high thermal mass radiant systems (Figure 13). The primary aim of this design tool is to provide an interface for estimating the performance of high thermal mass radiant systems under steady-state conditions (for both heating and cooling) and transient conditions (on the cooling design day). The transient analysis is based on 2.5 million pre-simulated cases on a summer cooling design day using EnergyPlus as the dynamic simulation engine. High thermal mass radiant systems have a slow response time to control changes because it must heat or cool a substantial amount of thermal mass (e.g., building's structural slab) before any noticeable effect in the thermal environment of the spaces. It has been shown that it can take over two hours for embedded surface radiant systems (ESS) and over nine hours for thermally activated building radiant systems (TABS) to change the surface temperature to a new setpoint (Ning et al. 2017). Thus, it is important to use transient tools, such as the CBE Rad Tool, that considers high thermal mass radiant systems' start time and duration of operation to properly calculate the space and hydronic plant heat extraction rates. The CBE Rad Tool allows designers to consider the impact of innovative control strategies such as nighttime cooling plant operations. See functional specifications (below) for full details of the tool.

Figure 13: Image of online CBE Rad Tool

The CBE Rad Tool is available online at: [radiant.cbe.berkeley.edu/.](radiant.cbe.berkeley.edu/)

2.2.2. Simplified design and operation tool for radiant systems functional specifications

As part of the Rad Tool, the research team developed a detailed online "help" function that serves as the functional specifications. These specifications document the methods and assumptions used to develop the tool. The first section of the specifications references the steady-state calculations while the second section references the transient calculations. There is also a third section that describes how a user can request a custom radiant zone for their own analysis. The team also provides an example model in EnergyPlus so that designers can easily run their own simulations. This includes a publicly available sequence of operations for specifying the control strategy developed in this project (see Section 2.2.4). Lastly, the team provides the EnergyPlus code to simulate these control sequences in an EnergyPlus model. The Rad Tool functional specifications document is a deliverable for the project and is contained in Appendix J: Simplified Design and Operation Tool for Radiant Systems Functional Specifications. The document is also available online at: radiant.cbe.berkeley.edu/doc/rad_tool_documentation.html.

2.2.3. Energy simulations studies report

Summary

This report is a deliverable for the project and summarizes energy simulation sensitivity studies that were conducted within Tasks 3 and 5. EnergyPlus was used as the simulation engine for all studies completed. The purpose of the energy simulation research in Task 3 was to assess viable approaches for controlling high thermal mass radiant systems as a function of a range of factors, including start time and duration of system operation, other operating conditions such as supply water temperature, internal loads, and representative California climates. The results of the simulation studies have supported three key tasks within the EPIC Radiant project:

- Development of a simplified design and operation tool that captures the majority of these design and control improvements while still remaining feasible to implement within existing building management systems. This online tool (CBE Rad Tool) is described in Sections 2.2.1 and 2.2.2.
- The newly developed control strategies have been implemented in two of the field study buildings. The findings from these control intervention studies are described in the Field Study Reports for the SMUD East Campus Operations Center in Sacramento, CA, and the David Brower Center in Berkeley, CA (See Sections 3.2 and 3.3).
- As part of the cost comparison study, energy simulations were used to compare the energy performance of the radiant vs. VAV building.

Two conference papers and one research report have been written describing the results of the energy simulation studies. Brief descriptions of these papers are presented below.

A new control strategy for high thermal mass radiant systems

This paper presents a new controller for high thermal mass radiant systems that can be implemented within a typical Building Automation System. We illustrate its performance using an EnergyPlus model representing a single zone, middle floor of an office building in Sacramento, California. The results of a small sensitivity analysis show that when compared to common practice in the US this approach reduces electricity cost and energy consumption by up to 40% and 35%, respectively, while maintaining comparable comfort conditions in the zone. Furthermore, this design & control approach could eliminate the need for a chiller in most California climate zones for typical office design loads (Raftery et al. 2017). This paper is included in Appendix K: A New Control Strategy for High Thermal Mass Radiant Systems.

How high can you go? Determining the highest supply water temperature for high thermal mass radiant cooling systems in California

Cooling demands are a major driver of energy consumption in buildings, and is mostly performed using systems based on the refrigeration cycle, an energy and cost intensive process. To investigate the potential of eliminating the refrigeration cycle from a building design in Californian climates, we created a single zone EnergyPlus model that uses a high thermal mass radiant system as the primary conditioning system, and that meets California's energy code requirements. On the cooling design day, we randomly selected the start and number of hours of radiant system operation, lighting and plug load power densities, and occupant density for a set of models to determine the supply water temperature (SWT) that maintained comfortable temperatures. About 67% of tested models required SWT at or above 18 ˚C indicating that high thermal mass radiant systems have a high potential to use less energy and lower cost cooling devices like evaporative cooling towers in most California climates (Duarte et al. 2018a). This paper is included in Appendix L: How High Can You Go? Determining the Highest Supply Water Temperature for High Thermal Mass Radiant Cooling Systems in California.

Comparison of energy costs for radiant vs. VAV systems

As part of the cost comparison study (Section 4.5), energy models of the two designs (radiant and VAV) were developed in EnergyPlus to evaluate the corresponding energy and comfort performance. In the VAV system model, the controls are generally based on the recently published ASHRAE Guideline 36 (ASHRAE, 2018), which provides high performance sequences of operation for VAV systems that have been widely acknowledged in the building industry. However, for the hybrid radiant slab and DOAS system, there are no well-established control sequences readily available. Some of the control approaches commonly used in the industry appear to be quite energy inefficient. As a result, it was expected that the energy simulation findings would tend to favor the VAV system.

The annual simulation results show that the total site HVAC energy use is 16.2% higher for the radiant system (2.9 kBtu/ft$_2$) than the optimized VAV design (2.5 kBtu/ft$_2$). The VAV design has significantly lower cooling energy use and benefits from the opportunity for free cooling from the airside economizer with mild San Francisco weather. The radiant design has lower heating energy use but slightly higher fan energy use, compared to the VAV design. DOAS fan are commonly expected to use less energy than VAV fans because of the much lower design airflows but, in fact, the opposite is generally true due to the fact that VAV systems generally operate for the majority of time at lower part loads.

A report describing all results of the study was written by Feng and Cheng (2018) and is included as Appendix M: Comparison of Construction and Energy Costs for Radiant vs. VAV Systems in the California Bay Area. The report contains further discussion of opportunities to improve the energy performance of radiant systems. With current design practice leaving some of these opportunities on the table, it is important for radiant designers to incorporate into their system designs many of the practical solutions described in this report. For example, in mild climates, such as the Bay Area in California, radiant designs should take advantage of the benefits of free cooling as much as possible either with airside or waterside economizers. The information contained in this Final Report and its appendixes is available to further improve the energy efficiency of radiant system design and operation.

2.2.4. Sequences of operations

The research team prepared a detailed set of sequences of operations for high thermal mass radiant systems. These sequences were implemented in the two field study buildings described in Chapter 3. These sequences are also publicly available for use by any building engineer or operator with a high thermal mass radiant system. The sequences have been written up as a deliverable for the project, Final Sequences of Operations Report and are attached as Appendix N: Sequences of Operations for High Thermal Mass Radiant Systems.

The intent of these sequences of operation is to use slowly adjusted slab temperature setpoints to control radiant system operation to maintain comfort in the zone. The strategy operates based on a slab temperature measurement and uses information from the zone temperature during the occupied period to make minor adjustments to the slab setpoint for the next day. The strategy constrains the radiant system to take advantage of thermal inertia and condition the slab only during certain periods of time. For a given project, this allows designers to select for either: more efficient and cost effective operating hours (e.g., system only operates at night), longer operating hours to yield smaller heating or cooling plant sizes (e.g., system sized assuming 18 or 24-hour operation on the design day), or aim to provide a more uniform daily range of comfort conditions (e.g., time pre-cooling such that it approximately accounts for the slab time constant and the peak loads). Additionally, the sequences include selectable options for project- and zone-considerations, such as: on/off vs. pulse width modulated zone valve controls; sequences for zone supplemental heating and cooling systems; and slab temperature setpoint resets.

CHAPTER 3:
Field Studies and Control Demonstrations in Radiant Slab Buildings

The goal of this task was to conduct detailed field studies of three buildings with radiant slab systems to highlight issues identified in design, construction, and operation. In the first field study, the research team had a unique opportunity in the ARTIC building to investigate the impact of direct solar radiation on the performance of a chilled radiant floor system. The second and third field studies were more typical radiant slab office building designs and the team focused on demonstrating and further evaluating the newly developed control method (see Chapter 2) for high thermal mass radiant systems in these buildings.

3.1. Field Study #1: Anaheim Regional Transportation Intermodal Center (ARTIC), Anaheim, CA

The ARTIC building is a 67,000-ft^2 (6,200-m^2) bus and train station in Anaheim, California. The station started operation in 2014. This unique building was designed by HOK and Parsons Brinckerhoff. BuroHappold Engineering designed the mechanical system. In 2015 ARTIC was awarded LEED Platinum status and become the first station in the world to reach this status.

ARTIC has several unique features. The tubular steel-framed structure has a compound curved shell covered with a 200,000-ft^2 (19,000 m^2) ethylene tetrafluoroethylene (ETFE) roof system. This transparent roof allows diffuse sunlight to illuminate the building interior. Besides light in the visible spectra, the transparent ETFE roof allows short and long-wave infrared radiation to penetrate the building (Figure 14).

The ARTIC ETFE roof design and transparent glass walls had a critical impact on the choice of the HVAC system. The solar irradiance influences large areas of the floor, hence the designers from BuroHappold decided to implement a radiant floor cooling system (see Figure 15). The radiant floor extracts solar heat flux from the floor surface almost immediately. The radiant floor cooling system was the subject of the field study investigation. The research team conducted its measurements during October and November 2016.

Measurements of the chilled floor slab performance were conducted on a section of a large second-floor balcony in front of a restaurant from October 19 - November 9, 2016. Air temperature sensors were placed at 3 locations, on the railing, on the wall of the shop, and on the pillar on the façade. We measured the operative temperature in 2 locations, on the wall of the shop and the pillar. The floor heat flux was measured in 3 locations with strategically distributing sensors on the floor areas affected by the sun at different times during the day. We measured solar heat flux with a pyranometer at one location in the middle of the floor. This location was the best estimate of the average floor exposure to the sun.

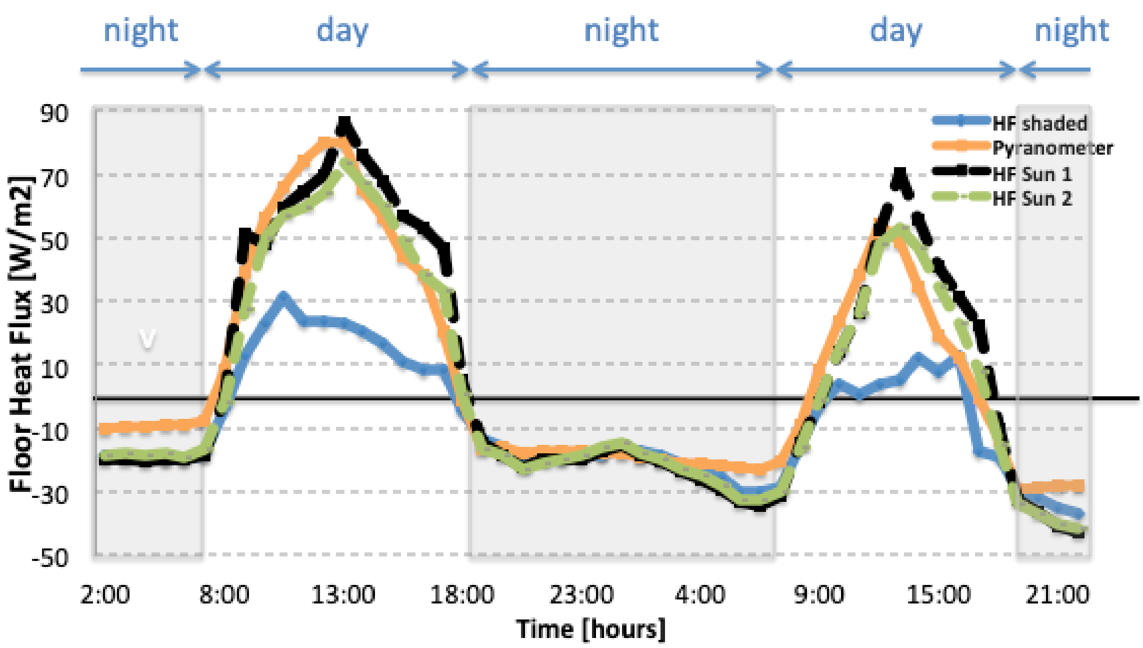
Figure 14: Anaheim Regional Transportation Intermodal Center (ARTIC)

Credit: archdaily.com

Figure 15: Interior photograph of ARTIC, Anaheim

Figure 16 shows heat flux measurement results for October 19-20, 2016, two consecutive warm sunny days. The peak solar gain on the floor measured by the pyranometer was 80 W/m2 (25 Btu/h-ft2), matching very closely with the radiant floor peak heat extraction flux (measured by heat flux sensors in the solar illuminated areas) of 86 W/m2 (27 Btu/h-ft2). This indicates that the radiant floor effectively extracts solar heat penetrating through the ETFE roof and glass walls and confirms that the radiant floor is an effective system in spaces with direct solar exposure. The peak heat flux in the shaded regions of the floor was only 30 W/m2 (9.5 Btu/h-ft2), matching the cooling capacity recommended by ISO-11855 (ISO 2012) for non-solar-exposed radiant surfaces. Results from the ARTIC field study show the same trends as those observed in the experiment conducted in FLEXLAB (Section 1.2.1). Sun-exposed regions had much higher cooling capacity than the shaded regions, more than 2 ½ times greater in ARTIC.

Figure 16: Field measurement results for ARTIC, Anaheim



Radiant floor exposure and heat flux in the shaded and sun-exposed regions; Oct. 19-20, 2016.

Full details of the field study are reported by Pantelic et al. (2018b). The report represents a deliverable for the project and is contained in Appendix O: Final Field Study #1 Report: Anaheim Regional Transportation Intermodal Center (ARTIC), Anaheim, CA.

3.2. Field Study #2: Sacramento Municipal Utility District (SMUD) East Campus Operations Center, Sacramento, CA

The SMUD East Campus Operations Center (ECOC) is a 51-acre facility located in Sacramento, California. The campus includes a diverse set of building types and uses, including the study site: a 200,000 ft$_2$ LEED Platinum certified office building that incorporates numerous energy efficient technologies and design strategies. The building, shown in Figure 17, has five above-ground floors and one underground floor, for six stories in total. The design team included architect RNL, MEP and design engineer Stantec, and general contractor Turner Construction, along with other subcontractors.

Figure 17: Photograph of SMUD East Campus Operations Center, Sacramento

Credit: HRGA Architecture

The office building is part of a campus with a central plant that distributes hot and chilled water to the various buildings and services for space heating and cooling and hot water needs. The office building uses radiant as the primary heating and cooling system with a dedicated outdoor air system (DOAS) for ventilation, distributed through overhead mixing diffusers. Conference spaces have active chilled beams that simultaneously provide ventilation and cooling and have a faster response time than the radiant system. The active chilled beams are well-suited for the intermittent and potential high-density occupancy in conference rooms. Ventilation is demand controlled and provides heat recovery (with a thermal wheel), which can save energy during Sacramento's cool winter.

In addition to the radiant heating and cooling, the open office spaces have ceiling fans to provide thermal comfort and overhead air distribution (DOAS) for ventilation, as seen in Figure 18. The DOAS system provides constant volume and constant temperature fresh air at 65 ˚F. The DOAS was not upsized to provide supplemental cooling; however, it was sized to provide 25% more ventilation than code minimum for improved air quality with cooling as an ancillary benefit.

Figure 18: Interior photographs of SMUD East Campus Operations Center, Sacramento

Left: Open office space with radiant ceiling, ceiling fans and overhead mixing diffusers for ventilation only. Right: Ceiling fan over open office cubicle.

In 2018, we rewrote the Siemens PPCL control code entirely for the zone controllers and implemented the proposed sequences of operation developed as part of this research project. The earlier 2014 control improvements made by CBE were used as the baseline (Bauman et al. 2015). The following section describes the new sequences.

The primary zone control loop in the SMUD building uses a pulse-width modulating controller that controls the radiant zone manifold valve as a two position valve (on/off) to maintain the slab temperature at its setpoint (the baseline control operated the valves as modulating valves). The pulse-width modulated controller opens the valve fully for 5 minutes (approximately the length of time required to flush all of the water in a PEX circuit loop at the design flow rate) and then closes for a period determined by a proportional band. This approach allows for better control at low flow conditions (which is where these systems operate most of the year) than modulating valves and reduces pumping power (Tang et al., 2018). It would allow reduced first costs for both valve and wiring in a new design scenario. A secondary cascading control loop uses a proportional controller to reset the slab temperature setpoint on a daily basis. The secondary control loop of the proposed strategy resets the slab temperature setpoint using the error between the maximum/minimum zone air temperature during the preceding occupied hours and the comfort setpoint for cooling/heating. The intent of the proposed radiant control strategy is to slowly adjust slab temperature setpoints based on information from the zone air and slab temperature, as opposed to based solely on the zone air temperatures. As part of the new controls, the water temperature setpoint for the radiant loops in cooling was increased from 58 to 62 ˚F.

In addition, the radiant control strategy allows the building operator to select a time interval to condition the slab. The strategy constrains the radiant system to take advantage of thermal inertia and condition the slab only during that period of time. The building operator can select for either: more efficient and cost effective operating hours (nighttime hours in cooling mode), longer operating hours[1] to reduce the chiller or other system plant device cooling/heating load (greater than 16 hours), or aim to provide a more uniform daily range of comfort conditions by timing the conditioning of the slab such that it approximately coincides with the peak space heating/cooling loads, taking into account the typical lag time (e.g., 3-5 hours). In this field study, we chose to test and demonstrate two different options for operating hour strategies. More detailed information about the proposed radiant control strategy can be found in (Raftery et al. 2017) and in the publicly available Sequences of Operation Report described in Chapter 2.

Option A, Daytime Lockout: Allow the TABS system to operate only during nighttime hours from 8 pm to 6 am, with the system locked out entirely during occupied hours. This is a full pre cooling and pre-heating strategy, where the radiant system never operates at the same time with occupancy or the operation of the DOAS system.

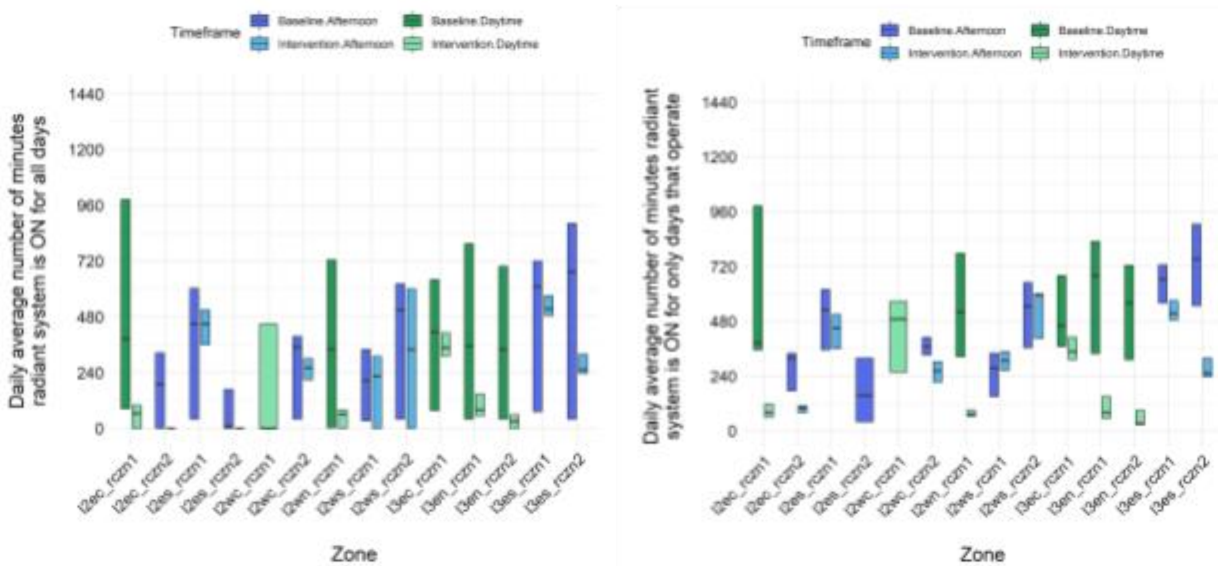
Option B, Afternoon Lockout: Allow the TABS system to operate only during the early morning and early afternoon, from 4am to 2pm, with the system locked out from 2pm to 4am. This will shift cooling use from the hot afternoon (peak periods). It should provide a slightly more uniform comfort condition during the day. In other words, the range between the minimum and maximum temperature in the zone should be slightly smaller than with the existing baseline controls, and significantly smaller than in Option A.

Overall, the new sequences of operation were able to maintain zone air temperatures within the defined comfort setpoints for significantly more hours than the existing baseline controls. These new sequences were able to do so using a 4 °F higher supply water temperature and while significantly reducing the operating time of the radiant system. Perhaps most importantly, the sequences allow the operator (or designer) to lockout the operation of the radiant system during certain periods of the day, and this field study demonstrates that the sequences automatically adjust to maintain comfortable conditions without requiring manual trial and error by the operator to identify new setpoints. This allows operators to choose the times of the day the radiant system performs cooling and heating, minimizing energy consumption, demand, and/or energy operating costs as appropriate for their building and cooling or heating systems.

To assess the control sequence performance across all zones during the intervention and ability to reduce energy consumption, we compare the average number of minutes per day the system called for the valve to each zone to open. As seen in Figure 19, most zones called for cooling for less time under the new control strategies, which reduces operating time and has the potential for energy savings.

[1] Additionally, it is possible to stagger the operation hours of multiple zones in a building in order to spread out the plant loads over the daily period. This can reduce peak loads on the plant significantly.

Figure 19: Daily number of minutes that radiant system is ON



Daily number of minutes that radiant system is actuating the manifold valve in each radiant zone to ON, during all days in dataset (left) and only for days when the manifold turned ON (right).

Full details of the field study are reported by Raftery et al. (2018). The report represents a deliverable for the project and is contained in Appendix P: Final Field Study #2 Report: Sacramento Municipal Utility District (SMUD) East Campus Operations Center, Sacramento, CA.

3.3. Field Study #3: David Brower Center, Berkeley, CA

The David Brower Center (DBC), shown in Figure 20, is a LEED Platinum, four-story mixed-use building located in downtown Berkeley, California. DBC was designed by the architecture firm Mithun formerly WRT/Solomon E.T.C and mechanical design firm Integral Group, formerly Rumsey Engineers. DBC's program consists of offices, conference center, auditorium, restaurant, and gallery with a total conditioned space of 38,600 ft^2 and 3,300 ft^2 of unconditioned space. The restaurant, auditorium, and gallery are located in the first floor and office spaces are mainly in floors two through four. Its main tenants are nonprofit environmental organizations with current total building occupancy of about 150 people.

Figure 20: Photograph of David Brower Center's east and south facades

Credit: Tim Griffith

The heating, ventilation, and air-conditioning (HVAC) system includes a thermally activated building system (TABS: PEX tubing embedded in the structural slab) for the primary heating and cooling in the office spaces. Ventilation is provided by a 100% outside air underfloor air distribution (UFAD) system, as well as natural ventilation through operable windows. Carbon dioxide (CO_2) sensors are used to provide demand control and provide minimum outdoor air ventilation rates in the occupied spaces. Heating and cooling in the first-floor gallery and meeting rooms are provided by an overhead air distribution system served by water-to-air heat pumps. The radiant system serves only the 2nd – 4th floors.

Two gas condensing boilers provide hot water to the radiant system, air handling units (AHUs), and heat pumps. Hot water production is available 24 hours a day. DBC does not have a chiller for chilled water production. Instead, a cooling tower with a heat exchanger provides cooled water to the radiant system and AHUs. Cooling towers operate at a fraction of the energy consumption and cost of chillers. However, cool water production from a cooling tower is heavily dependent on the outdoor climate conditions. The outdoor wet-bulb temperature is an important driver for the effectiveness of the cooling tower. The lower the outdoor wet-bulb temperature, the lower the chilled water temperature that the cooling tower can produce. The lowest wet-bulb temperatures are usually found during nighttime hours as shown in the building site climate data section below. Thus, only high thermal mass HVAC systems that are within suitable climates can use cooling towers to provide the cooling demand in the building. The research team recently demonstrated that using cooling towers coupled to TABS to provide cooling in the building is suitable within most California climates (Duarte et al., 2018a).

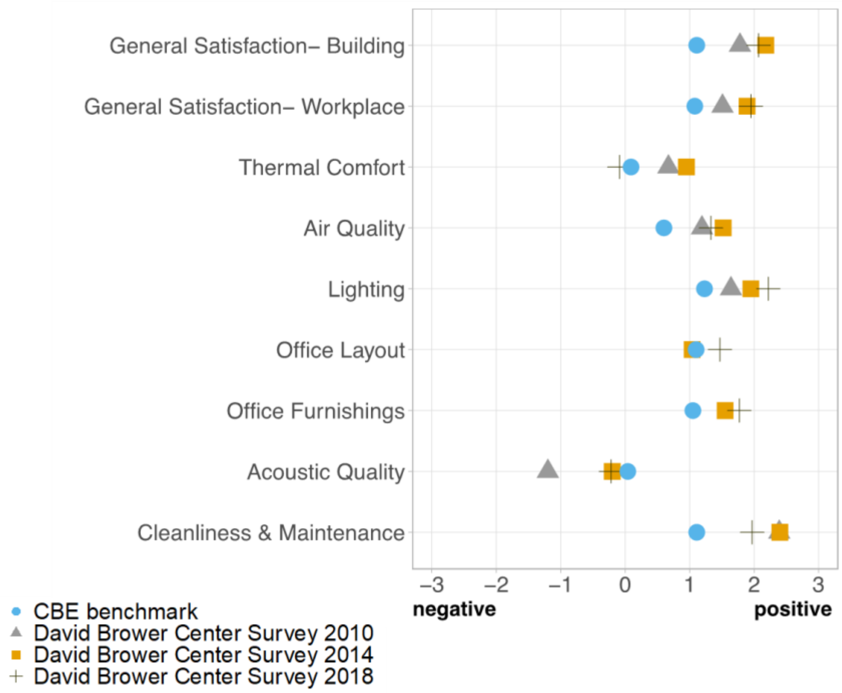
The field study implemented a new control strategy that was introduced in all 15 zones in three phases over a three-month period. To assess the performance of the controls, the study team compared the zone dry-bulb air temperatures and system operating time to a baseline period from two prior years. Overall, the intervention control strategy was able to maintain zone dry-bulb air temperatures within the defined comfort setpoints for significantly more hours compared to the baseline control strategy; a reduction in the total discomfort hours (hours outside of the comfort zone) from 8.8% to 2.9%.

The intervention control strategy also significantly decreased the amount of time it actuated the radiant manifold valve to the open position when compared to the baseline control strategy. Perhaps most importantly, the sequences allow the operator (or designer) to lockout the operation of the radiant system during certain periods of the day, and this field study demonstrates that the sequences automatically adjust to maintain comfortable conditions without requiring manual trial and error by the operator to identify new setpoints. This allows operators to choose the times of the day the radiant system performs cooling and heating, minimizing energy consumption, demand, and/or energy operating costs as appropriate for their building and cooling or heating systems.

In addition to the controls intervention, the research team conducted an occupant satisfaction survey in the Brower Center during May 2018. This was the third time that the CBE survey has been administered in the building (previous surveys were taken in 2010 and 2014). Figure 21 shows the mean response scores on the 7-point satisfaction scale for the seven core categories and two overall satisfaction questions from the survey. Also shown for comparison is the CBE benchmark database for each category at the time this current survey was collected. The results show that DBC has consistently scored higher than the benchmark for most categories. The exceptions are in the acoustics category and recently in the thermal comfort category.

The building experienced a period without a dedicated building operator during a transition in personnel. This coincided with the period immediately preceding and including the time when the most recent survey was implemented. We hypothesize that this may in part be the cause of the lower satisfaction with thermal comfort shown in Figure 21. The research team plans to administer a follow-up survey one year later to assess occupant satisfaction with the new control strategies that have been implemented in the building after the survey was completed in May 2018.

Figure 21: CBE occupant satisfaction survey results at David Brower Center



	DBC 2010	*DBC 2014*	*DBC 2018*
General Satisfaction– Building	*1.78*	*2.18*	*2.07*
General Satisfaction– Workplace	*1.51*	*1.89*	*1.95*
Thermal Comfort	*0.67*	*0.95*	*-0.09*
Air Quality	*1.19*	*1.52*	*1.33*
Lighting	*1.64*	*1.95*	*2.22*
Office Layout	-	*1.04*	*1.47*
Office Furnishings	-	*1.55*	*1.77*
Acoustic Quality	*-1.20*	*-0.20*	*-022*
Cleanliness & Maintenance	*2.39*	*2.40*	*1.97*

Full details of the field study are reported by Duarte et al. (2018b). The report represents a deliverable for the project and is contained in Appendix Q: Final Field Study #3 Report: David Brower Center, Berkeley, CA.

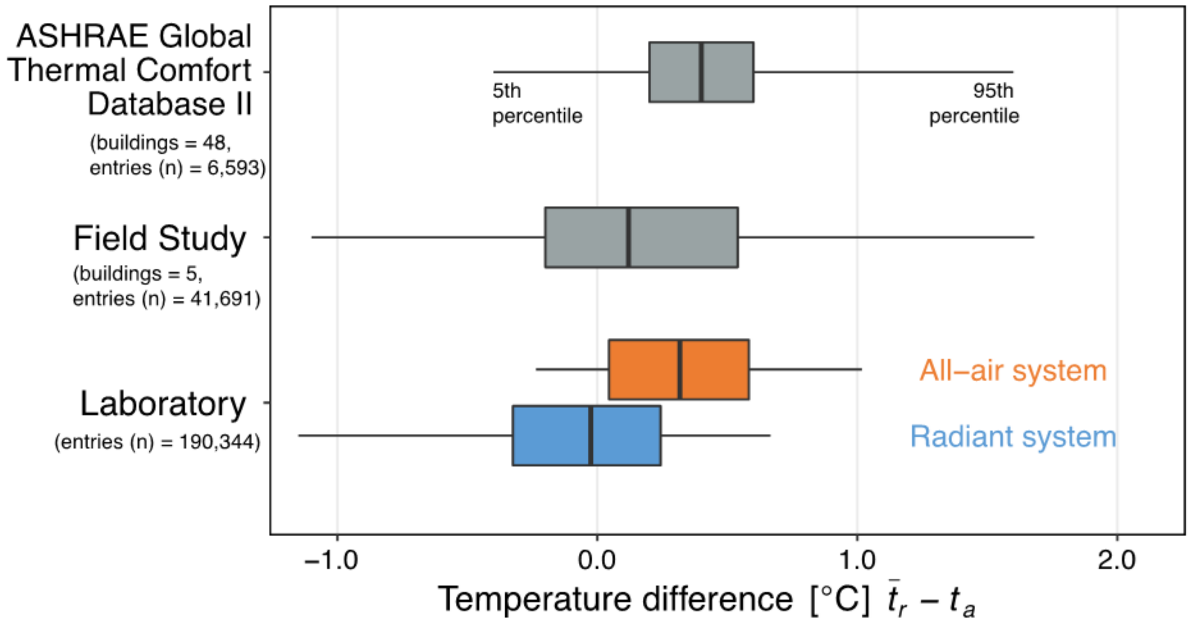
3.4. Comparison of mean radiant and air temperatures

Although not a deliverable for this project, during the field study activities, we assessed the difference between mean radiant temperature ($\bar{t_r}$) and air temperature (t_a) in conditioned office buildings to provide guidance on whether practitioners should separately measure $\bar{t_r}$ or operative temperature to control heating and cooling systems. The results of this study are included below.

We used measurements from 53 field studies in office buildings and five test conditions from a laboratory experiment, including both radiant and all-air spaces. Under typical office conditions, the median absolute difference (e.g., disregarding direction of the difference) between $\bar{t_r}$ and t_a was 0.4 °C (with interquartile range = 0.4 °C), and more specifically, the median difference shows that $\bar{t_r}$ was 0.4 °C (with interquartile range = 0.4 ˚C) warmer than t_a in this dataset. In the radiant cooled laboratory tests, $\bar{t_r}$ was significantly ($p<0.05$) cooler than t_a (average difference -0.1 °C) while in the all-air cooled laboratory tests $\bar{t_r}$ was significantly ($p<0.05$) warmer than t_a (average difference +0.3 °C). While these observations are significant, the effect sizes are negligible to small based on Cohen's d and Spearman's rho. These observations indicate that $\bar{t_r}$ and t_a are typically closer in radiantly cooled spaces than in all-air cooled spaces. The results suggest that t_a measurements are sufficient to estimate $\bar{t_r}$ under typical office conditions, and that separately measuring $\bar{t_r}$ or operative temperature is not likely necessary to improve thermal comfort, especially in buildings with radiant systems. Furthermore, spatial and temporal variations in t_a can be greater than the difference between $\bar{t_r}$ and t_a at any one location in a thermal zone, thus we expect that such variations have a greater impact on occupant thermal comfort than the differences between $\bar{t_r}$ and t_a.

A technical paper on the above study has been prepared by Dawe et al. (In press) and will be submitted for publication. Figure 22 presents the graphical abstract from the paper.

Figure 22: Measured relative temperature difference (Dawe et al. (In press))



We can assume mean radiant temperature is equal to air temperature

CHAPTER 4:
Energy Analysis, Cost Assessment, and Occupant Surveys

The goal of this task was to increase empirical evidence and documentation of the a) energy performance, b) cost, and c) occupant perception of the indoor environment with radiant systems in order to compare radiant systems with other buildings, establish the basis for more accurate potential energy savings estimates, and provide design firms and owners real world project examples. The research team conducted a large outreach to identify as many buildings as possible having radiant systems, and gathered and analyzed data for energy performance and occupant satisfaction.

As part of this task, researchers developed an expanded database of over 400 commercial buildings using radiant cooling and heating. All buildings from the database are displayed on an online interactive map located here: bit.ly/RadiantBuildingsCBEv2 (see Figure 23). A report was written summarizing the results and trends from this radiant map dataset, which focuses primarily on North America (United States and Canada) (Talami et al. 2017). The report is attached as Appendix R: Recent Trends in Radiant System Technology in North America.

Figure 23: Online radiant map available at bit.ly/RadiantBuildingsCBEv2

4.1. Energy Performance

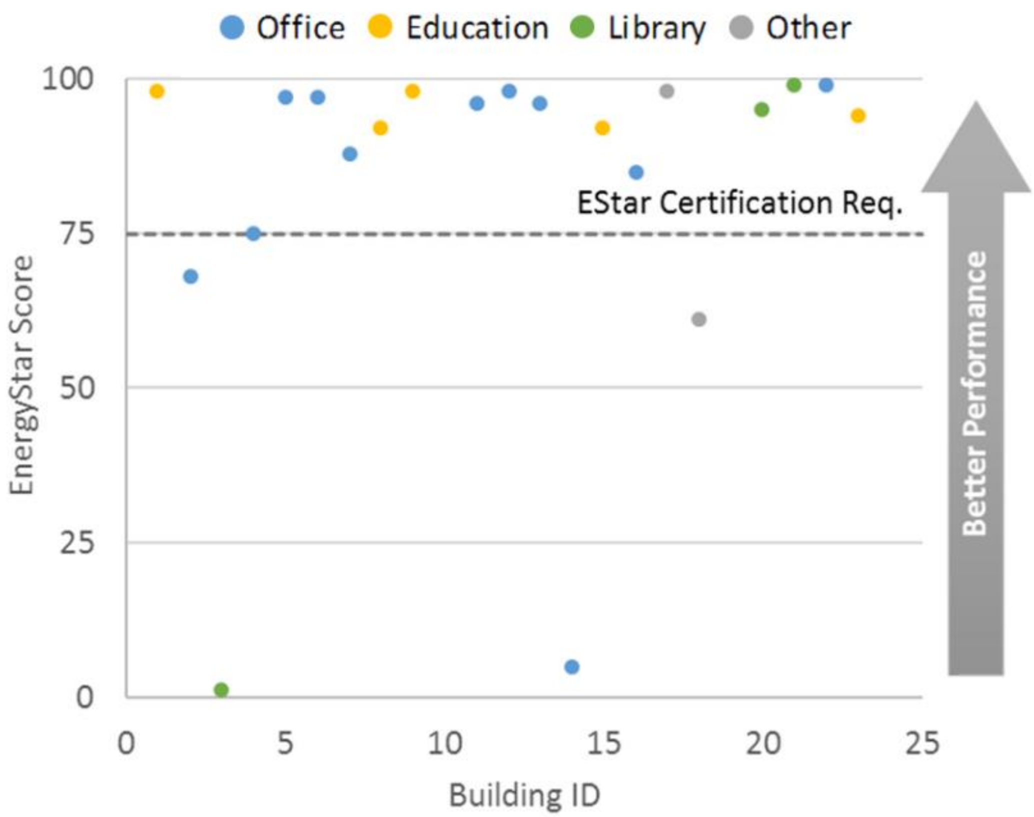
Radiant systems can contribute to significant energy savings due to relatively small temperature differences between the room set-point and cooling/heating source, and the efficiency of using water rather than air for thermal distribution. High thermal mass radiant systems can also offer peak demand reduction with load shifting strategies. Although a radiant system is not the sole driver of good energy performance it can be an important part of an integrated approach from design and technology selection through to occupancy and operations that include high performance envelope components, HVAC design and control components, including ventilation systems, operation schedules and load management.

The main goal of this project task was to determine the building characteristics of projects with radiant heating and cooling and assess their real world energy use compared to standard benchmarks for building energy performance. The energy use was self-reported through surveys and utility data and is based on whole building site energy use for a minimum of 12 months. The research team was able to assemble and analyze the largest database of radiant buildings to date. Complete site energy use data was obtained from 23 commercial buildings using radiant cooling and heating systems in the US and Canada.

The study found that almost all of the 23 buildings outperformed peer buildings and national benchmarks, suggesting that radiant systems are part of the integrated approach that can lead to low energy consumption in commercial buildings. Figure 24 shows the EnergyStar scores for all buildings in the radiant dataset. The EnergyStar score benchmarks an individual building against the national building stock normalized for location, type and building characteristics resulting in a score ranging from one (poor) to 100 (best). 67% of the radiant dataset buildings had EnergyStar scores above 90, which indicates that they are in the top 10% of buildings relative to their peers. Further, all but four buildings (81%) had EnergyStar scores at or above 75, meaning that they qualify for EnergyStar certification.

A separate research report describing all details of this energy performance study was prepared by Higgins and Carbonnier (2017). The report represents a deliverable for the project, Final Energy Performance Report, and is contained in Appendix S: Energy Performance of Commercial Buildings with Radiant Heating and Cooling.

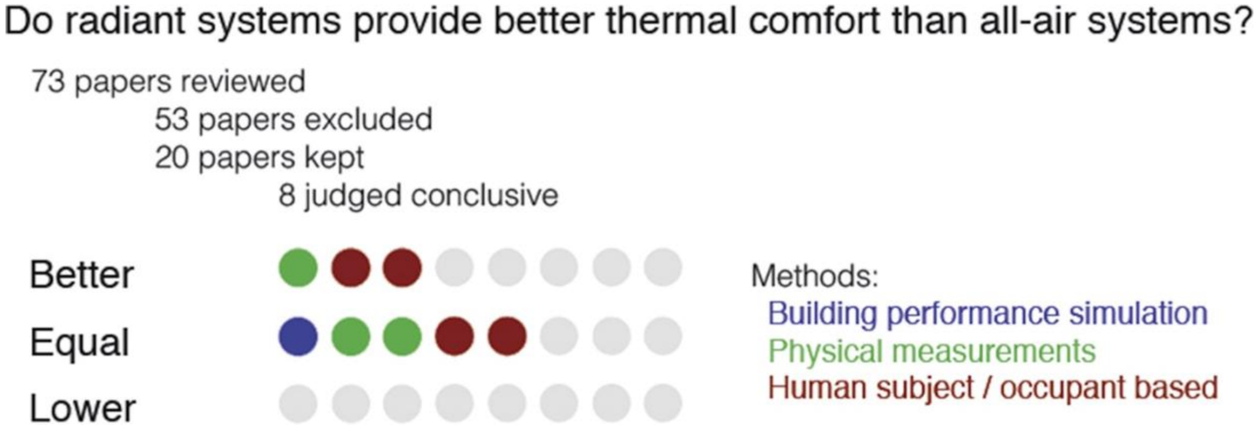
Figure 24: Calculated EnergyStar scores for analyzed buildings. Scaled from 1-100, n=21



4.2. Occupant Satisfaction with Indoor Environmental Quality (IEQ)

At the beginning of the project, one of the key questions was to determine if radiant systems provide better, equal or lower indoor environmental quality, and specifically thermal and acoustical comfort, than all-air systems. We performed a detailed literature review focusing on the thermal comfort aspect. This review identified eight conclusive studies: five studies that could not establish a thermal comfort preference between all-air and radiant systems and three studies showing a preference for radiant systems. Very few studies were based on occupant feedback in real buildings suggesting a significant research need. Overall, it was found that with only a limited number of studies available, a solid answer could not be given (Karmann et al. 2017b) (see Figure 25).

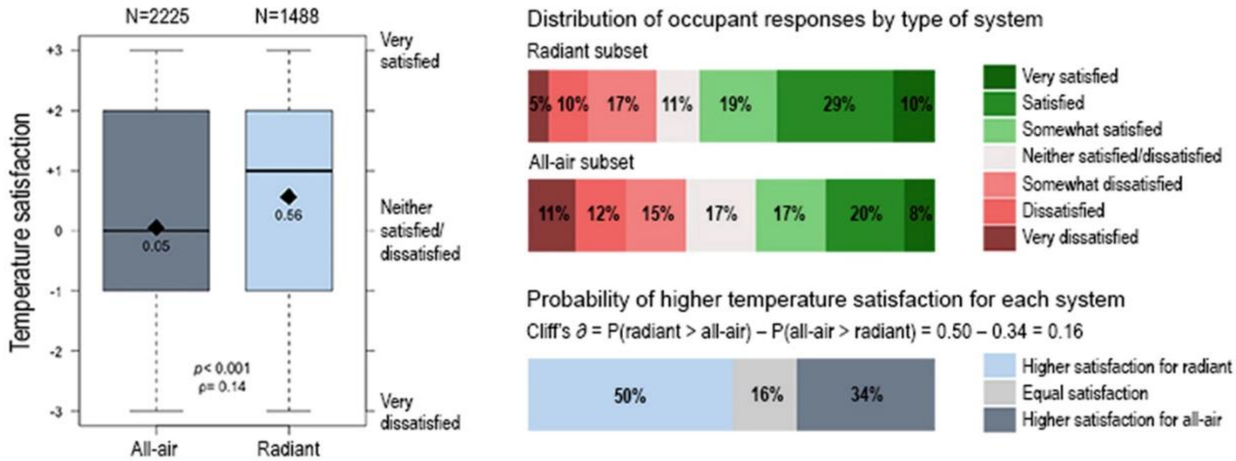
Figure 25: Graphical abstract from Karmann et al. (2017b)



To provide more relevant information to address the question on thermal comfort and other IEQ factors, the research team used the online Occupant Indoor Environmental Quality Survey administered by CBE (Zagreus et al. 2004, Frontczak et al. 2012). Following the same outreach activity described in Section 4.1, the team obtained acceptable occupant survey results from 20 radiant buildings, which were merged with existing survey data from six radiant cooled buildings. This produced survey results of 1,645 occupants in buildings with radiant systems. To our knowledge, this is the largest dataset used in a comparison of occupant satisfaction in radiant buildings. An existing database was used to extract a subset of occupant responses from all-air buildings whose key characteristics match those radiant buildings. The complete assembled comparative database consisted of indoor environmental quality survey results from 3,892 respondents in 60 office buildings located in North America; 34 of which used all-air systems and 26 of which used radiant systems as the primary conditioning system. The results indicated that radiant and all-air spaces have equal indoor environmental quality, including acoustic satisfaction, with a tendency towards improved temperature satisfaction in radiant buildings. Figure 26 presents a summary of the survey results comparing radiant and all-air buildings.

A separate technical paper describing the survey study was prepared and published (Karmann et al. 2017c). The paper represents a deliverable for the project, Final Occupant Satisfaction Report, and is contained in Appendix T: Comparing Temperature and Acoustic Satisfaction in 60 Radiant and All-Air Buildings.

Figure 26: Comparison of survey results from radiant and all-air buildings



4.3. Case Study Briefs

As part of the large database of radiant buildings compiled for the above studies, the research team selected and completed case studies for nine commercial buildings that demonstrate good performance in terms of both energy use and occupant satisfaction. Each of these radiant case studies are available as downloadable 4-page case study briefs, as highlighted in the October 2017 issue of Centerline (cbe.berkeley.edu/centerline/nine-radiant-buildings-demonstrate-energy-efficiency-and-occupant-satisfaction/). Each brief provides base information on the building characteristics, presents the individual building energy use compared to benchmarks, highlights strategies used to achieve high performance energy outcomes and, in most cases, includes results of the portion of the occupant survey related to thermal comfort. The nine case study briefs represent deliverables for the project and are included in Appendix U: Case Study Briefs.

4.4. Case Studies Report

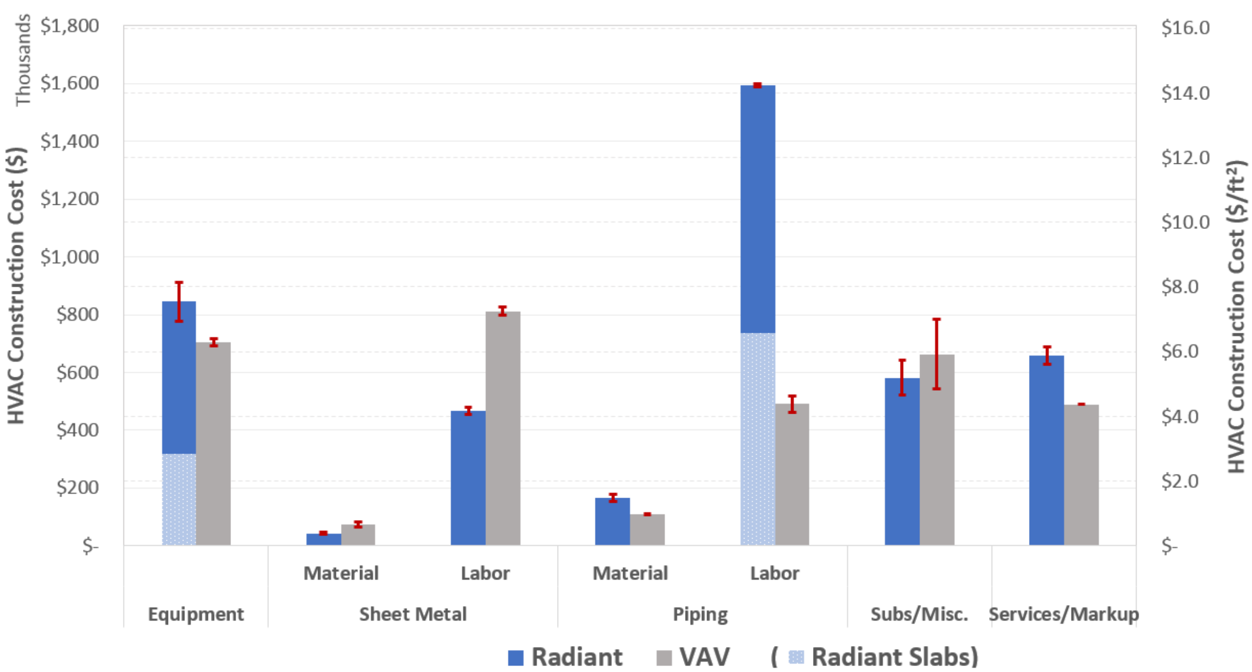
As part of the deliverables for the project, the research team prepared a Final Case Studies Report that provides an overview of the Energy Performance Report and the nine Case Study Briefs on buildings with radiant heating and cooling systems (Carbonnier et al 2017). This report is contained in Appendix V: Energy Use, Occupant Surveys and Case Study Summary: Radiant Cooling and Heating in Commercial Buildings.

4.5. Cost Comparison Study

The goal of this task was to perform a design stage cost analysis comparing a selected radiant building against an identical building with a traditional VAV system. To provide a realistic comparison, alternative radiant and variable air volume (VAV) HVAC designs were developed for an office building in California that was designed with a radiant system in real life. The building is 4-stories with primarily open-plan offices totaling 112,000 ft^2 and is designed with very low internal loads with LED lighting and plug load management. The modeled building performance has exceptionally low site energy use intensity (EUI) of approximately 12 kBtu/ft^2-yr, far below the median 55 kBtu/ft^2-yr measured performance of office buildings in the same climate zone (U.S. Department of Energy, 2018). The research team suggested control and design measures that could improve system energy efficiency by coupling the first cost comparison with predicted energy costs. Key findings from the construction costs study include:

- The total HVAC construction costs of a radiant design was $9.0/ft2 higher than the alternate VAV system.
- The cost premium associated with the radiant system is mainly due to labor for piping, which itself is $9.8/ft2 higher than that for the VAV design. Figure 27 shows a detailed breakdown comparison between the VAV and radiant designs.
- Piping labor costs are 44% of the total HVAC costs. Labor to install radiant slabs and the manifolds/changeover assemblies accounts for 46% of the total piping labor. About 13% of the total piping labor is associated with installing the hot and chilled water pipe distribution on the floors, with smaller portions attributed to the piping on the roof and the risers.
- For the radiant design studied, the HVAC equipment costs account for roughly 20% of the overall HVAC costs and the largest equipment cost is for the radiant equipment (loops, mats, manifolds) which is 40% of the equipment costs.

Figure 27: Cost breakdown comparison between VAV and radiant designs



As expected for relatively new types of systems without large market adoptions, there is significant room for further cost reduction over current practice. The report identifies and explores many such opportunities including:

- Utilizing large radiant zones to minimize the number of radiant manifolds and zone changeover assemblies.
- Radiant mats can be used to reduce field labor cost. Labor hours to install radiant mats can be 35% to 200% lower than to install loops.

- Install radiant tube spacing at 9 inches. Dynamic simulations show that, compared to 6-in. spacing installation (a conservative common approach), it is possible to achieve very similar peak cooling capacity with 9-inch and even 12-inch spacing.
- Use multiple risers for hot water and chilled water distribution piping design instead of using a single set of piping risers. The latter relies on a single set of larger risers and long horizontal distribution runs on each floor, whereas the former employs multiple sets of smaller risers strategically located to minimize the overall amount of pipe length. The multiple risers' approach also allows smaller copper risers to be used instead of larger steel risers.
- Consider provide 4-pipe distribution to sections of the building with 2-pipe distribution continuing to groups of zones. This combination of four-pipe and two-pipe solution is a way to balance first costs with level of control – by limiting 4-pipe distribution to sections of the building that may need to be in different modes (heating or cooling) such as by orientation, or by space type and/or envelope heat transfer.

A separate research report describing all details of the cost comparison study was prepared by Feng and Cheng (2018). The report also includes a section comparing the energy performance of the two buildings (see Section 2.2.3). The report represents a deliverable for the project, Final Cost Comparison Report, and is contained in Appendix M: Comparison of Construction and Energy Costs for Radiant vs. VAV Systems in the California Bay Area.

CHAPTER 5: Codes and Standards

The goal of this task was to (1) propose changes to Title 24 to support improved modeling capabilities and help achieve significant energy efficiency goals for radiant systems in California, and (2) propose changes, as needed, to relevant ASHRAE Standards, Handbooks, and Guidelines to provide new information and guidance on radiant systems. A separate research report describing this work was prepared by Feng et al. (2018). Four separate deliverables, as originally specified in the scope of work for the project, were combined into this single report. These four deliverables include: Codes and Standards Enhancement Reports, Title 24 Code Change Report, ASHRAE Standards and Handbooks Report, and Standard Addenda. The report represents a deliverable for the project, Final Codes and Standards Report, and is contained in Appendix W: Codes and Standards Report. Selected highlights from the report are summarized below.

5.1. Title 24 Code Change Report

The current version of California Building Energy Efficiency Standards, Part 6 of the California Building Standards Code (Title 24) does not address factors specific to high thermal mass radiant systems within the body of the Standards. The alternative compliance method references some limited aspects relating to radiant systems but it is incomplete and not practically applicable, and has not yet been implemented in the associated compliance software. In addition, there are some modeling limitations for radiant systems in EnergyPlus, which is the simulation engine underlying the compliance software for the Title 24 performance approach. Updates to the Title 24 alternative compliance method are needed to ensure that modeled performance accurately reflects proposed designs, and to properly allow buildings with radiant systems to take appropriate credit for their performance. This study provided a background and roadmap of the steps needed to provide effective coverage of radiant systems for Title 24 compliance.

There are two methods for demonstrating compliance with Title 24:

- Prescriptive Method: This approach allows projects to comply by using methods known to be energy efficient and cost effective. To show compliance, each individual component of the proposed building must meet specific prescribed requirements. The prescriptive approach is inflexible but provides a simple path for compliance.
- Performance Method: This approach provides more flexibility in building design by allowing projects to trade off different factors so long as the overall simulated performance meets or exceeds that of a standard reference building, which represents the equivalent “code-minimum” building. The Alternative Compliance Method establishes the modeling rules and assumptions for the proposed and standard models.

In addition to the two compliance paths above, there are mandatory measures that apply to all projects. The mandatory measures specify minimum requirements for the envelope, heating, ventilating and air conditioning (HVAC) and water heating equipment efficiency, and other components in buildings.

Given the wide range of radiant design and control approaches and the lack of industry consensus on best practice, it is difficult to identify mandatory and prescriptive requirements that would effectively and appropriately establish minimum energy performance for all radiant systems. Further, radiant systems are generally employed in high performance buildings that aim to meet high energy efficiency targets.

Development of radiant system modeling requirements for the ACM Manual and the associated compliance software should be prioritized to address the current gap in the applicability of Title 24 to radiant systems.

The lack of capability to explicitly model radiant systems and lack of modeling rules for the associated ventilation system results in misrepresentations of the actual design, and does not allow buildings with radiant systems to take appropriate credit for their performance. Limitations in the ability of EnergyPlus to simulate certain aspects of radiant systems should be addressed through further program development.

Additionally, future efforts should evaluate opportunities for adding mandatory and prescriptive measures specific to radiant systems.

5.2. ASHRAE Standards and Handbooks Report

The overall radiant research project covered a range of topics with findings reported in formal EPIC deliverables and academic publications. Listed below are topics that are recommended to be added to the ASHRAE Standards and Handbooks.

- Provide consistent definitions for different radiant system types in ASHRAE Handbook System and Equipment, Chapter 6 (Radiant Heating and Cooling).
- Provide comfort data in real radiant buildings in ASHRAE Handbook System and Equipment, Chapter 6 (Radiant Heating and Cooling).
- Provide revised cooling load definitions and calculations in ASHRAE Handbook Fundamentals, Chapter 18 (Nonresidential Cooling and Heating Load Calculations) and ASHRAE Handbook Fundamentals, Chapter 19 (Energy Estimating and Modeling Methods).
- Provide revisions to account for effect of night cooling for buildings conditioned by radiant system in ASHRAE Handbook Fundamentals, Chapter 18 (Nonresidential Cooling and Heating Load Calculations), ASHRAE Handbook Fundamentals, Chapter 19 (Energy Estimating and Modeling Methods), ASHRAE Guideline 36-2018 (High-Performance Sequences of Operation for HVAC Systems), and ASHRAE Handbook Systems & Equipment, Chapter 6 (Radiant Heating and Cooling).
- Provide new design guidance to account for the impacts of direct solar radiation on chilled radiant floors in ASHRAE Handbook Applications, Chapter 54 (Radiant Heating and Cooling), and ASHRAE Handbook System and Equipment, Chapter 6 (Radiant Heating and Cooling).
- Provide new design guidance to account for the impacts of acoustical ceiling panels and clouds on cooling capacity of radiant ceiling slabs in ASHRAE Handbook System and Equipment, Chapter 6 (Radiant Heating and Cooling).

- Provide new design guidance to account for the impacts of air movement from ceiling and other fans on cooling capacity for both radiant ceilings and floors in ASHRAE Handbook System and Equipment, Chapter 6 (Radiant Heating and Cooling).
- Provide feedback on cost-sensitive aspects of radiant system design and suggest control and design measures to reduce costs in ASHRAE Handbook System and Equipment, Chapter 6 (Radiant Heating and Cooling). This would include recommending that radiant systems include economizers (waterside or airside) under suitable climate conditions.
- Based on the analysis comparing mean radiant temperature (MRT) and air temperature in commercial spaces, we have proposed updates to the prescriptive path in ASHRAE Standard 55-2017 (ASHRAE 2017) to estimate MRT from air temperature measurements under certain circumstances, such as in spaces without exposure to the exterior envelope.

GLOSSARY

Term/Acronym	Definition
ACEEE	American Council for an Energy-Efficient Economy
ANSI	American National Standards Institute
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
ARTIC	Anaheim Regional Transportation Intermodal Center
C	Degrees Celsius
CBE	Center for the Built Environment
CEC	California Energy Commission
COBEE	Conference on Building Energy & Environment
CPUC	California Public Utilities Commission
DBC	David Brower Center
DOAS	Dedicated outdoor air system
DTU	Technical University of Denmark
EPIC	Electric Program Investment Charge
ETFE	Ethylene tetrafluoroethylene
EUI	Energy use intensity
F	Degrees Farenheit
HVAC	Heating, ventilating, and air-conditioning
IEQ	Indoor environmental quality
LED	Light-emitting diode
LEED	U.S. Green Building Council's Leadership in Energy and Environmental Design
MEP	Mechanical, electrical, and plumbing
NBI	New Buildings Institute
PIER	California Energy Commission Public Interest Energy Research
PLEA	Passive and Low Energy Architecture

SMUD	Sacramento Municipal Utility District
TAC	Technical advisory committee
TAG	Technical advisory group
VAV	Variable air volume

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