New Findings on Radiant System Comfort and Energy Performance

Fred Bauman, P.E., FASHRAE

CENTER FOR THE BUILT ENVIRONMENT

Presentation outline

Radiant systems research at Center for the Built Environment (CBE)

- Overview
- Satisfaction with thermal comfort and indoor environmental quality (IEQ)
- Energy performance
- Laboratory experiment: Practical guidance to address acoustic quality of chilled radiant ceilings

Acknowledgments

CBE

- Paul Raftery
- Stefano Schiavon
- Carlos Duarte
- Jonathan Woolley
- Jovan Pantelic
- Lindsay Graham

EPFL

- Caroline Karmann

Taylor Engineering

- Hwakong Cheng

TRC Energy Services

- Gwelen Paliaga
- Jingjuan (Dove) Feng

New Buildings Institute

- Cathy Higgins

ARTIC, Anaheim ↑
David Brower, Berkeley ↗
SMUD, Sacramento →
IDeAs Z^2, San Jose ↘
Delta HQ, Fremont ↓

Overview: EPIC* radiant systems project

Project Title

- Optimizing radiant systems for energy efficiency and comfort

Project Overview

- Start date: September 2015
- End date: April 2019
- Budget: $3.2M
  - $2.9M – California's EPIC Grant Program
  - $300K – 10% match funding (CBE: $240K; Price Industries: $60K)
- Research team: CBE, Taylor Engineering, TRC,
  New Buildings Institute, Price Industries

http://www.cbe.berkeley.edu/research/optimizing-radiant-systems.htm

**Electric Program Investment Charge (EPIC)*

Anaheim Regional Transportation Intermodal Center (ARTIC), Anaheim, CA.

Radiant project scope of work

1. Fundamental laboratory studies
2. Collect data from radiant buildings as real world examples
   - Indoor environmental quality surveys
   - Energy use data
   - Cost study
3. Develop web-based design and operation tool
4. Conduct three detailed field studies in radiant slab buildings
5. Propose changes to Title 24 and ASHRAE standards and handbooks

Summary of accomplishments

Publications

- 10 peer-reviewed journal papers
- 3 conference papers
- 11 research reports
- 9 radiant case studies

Key outcomes

- 6 laboratory studies
- 4 detailed case studies, including 2 controls interventions
- Online Rad Tool design tool with documentation
- Radiant buildings database and online map

Contributors

- 6 CBE researchers, 7 graduate students and 5 visiting scholars
- Taylor Engineering, New Buildings Institute, TRC, Armstrong and Price Industries

Student funding

- Supported 4 PhD students and 3 MS students
- 3 PhD dissertations (1 complete, 2 underway)
- 3 MS theses

Satisfaction with thermal comfort and indoor environmental quality

Background: Literature review

Do radiant systems provide better thermal comfort than all-air systems?

73 papers found

8 judged conclusive

Karmann, C., S. Schiavon, and F. Bauman. 2017. Thermal comfort in buildings using radiant vs. all-air systems: A critical literature review. *Building and Environment*, 111, 123-131. https://escholarship.org/uc/item/1vb3d1j8

Study overview

Objective

- Compare temperature and acoustic satisfaction results from surveys in 60 buildings

Approach

- Conduct occupant surveys in radiant buildings
- Select previously surveyed all-air buildings to be used for comparison (similar building characteristics)

Collect occupant and energy data from real buildings

Developed online radiant map with over 400 projects:
bit.ly/RadiantBuildingsCBEv2

Indoor environmental quality (IEQ)

Occupant IEQ Survey

- 9 categories
- 7-point Likert scale from very dissatisfied to very satisfied

Overall building
Lighting
Overall workplace
Office furnishings
Acoustic quality
Office layout
Air quality
Thermal Comfort

How satisfied are you with the temperature of your workspace?

Very dissatisfied	Dissatisfied	Somewhat dissatisfied	Neither satisfied nor dissatisfied	Somewhat satisfied	Satisfied	Very satisfied

Indoor environmental quality (IEQ)

Occupant IEQ Survey

- 9 categories
- 7-point Likert scale
  from very dissatisfied to very satisfied

Data collection and building selection

Radiant buildings

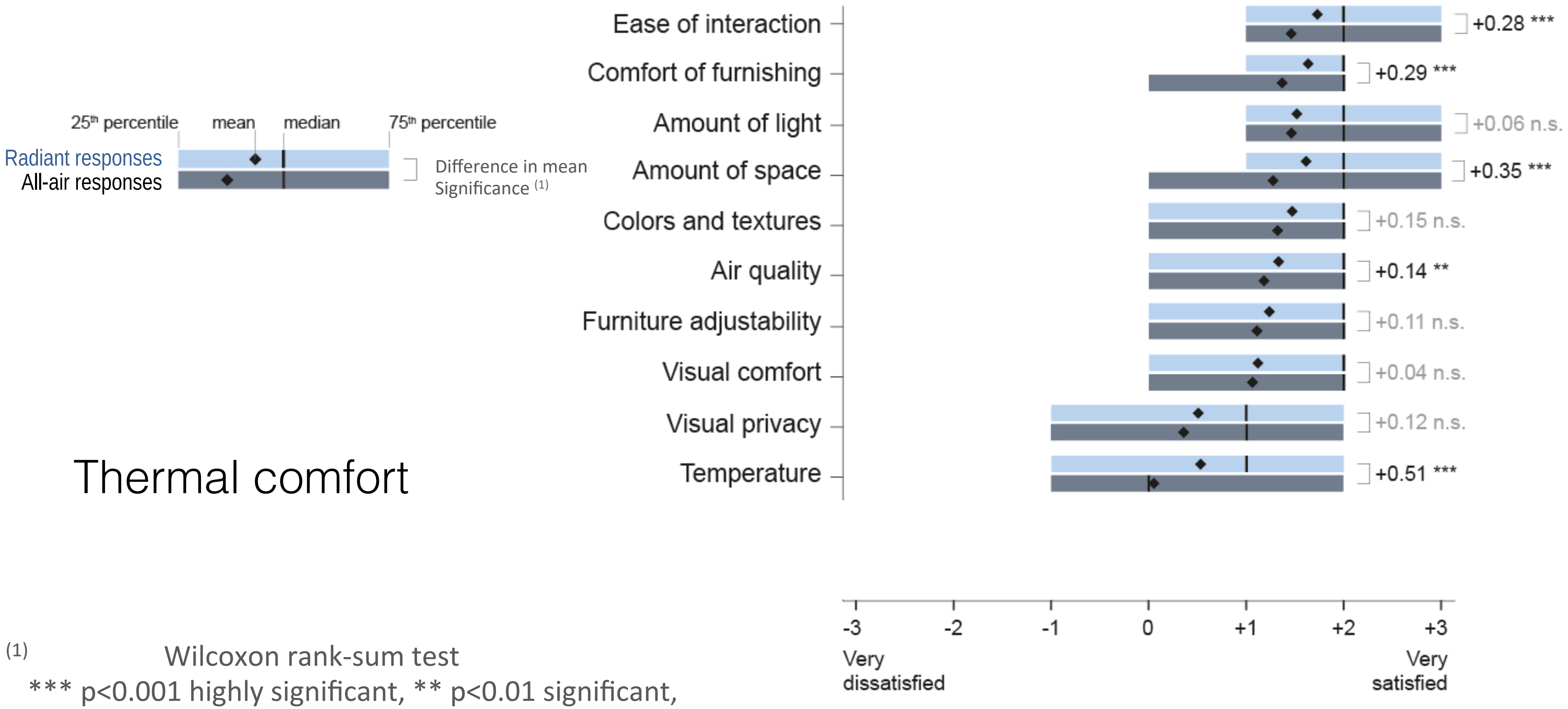
- 26 buildings (20 buildings newly surveyed)

Criteria for selecting all-air buildings

- Offices, educational or government buildings (only office spaces surveyed)
- Located in the U.S. or Canada
- Use active mechanical cooling systems
- Building age (completed or major renovation)
- Building size

Dataset	All-air subset	Radiant subset	Total
Buildings	34 (57%)	26 (43%)	60
Occupant responses	2247 (58%)	1645 (42%)	3892

Results

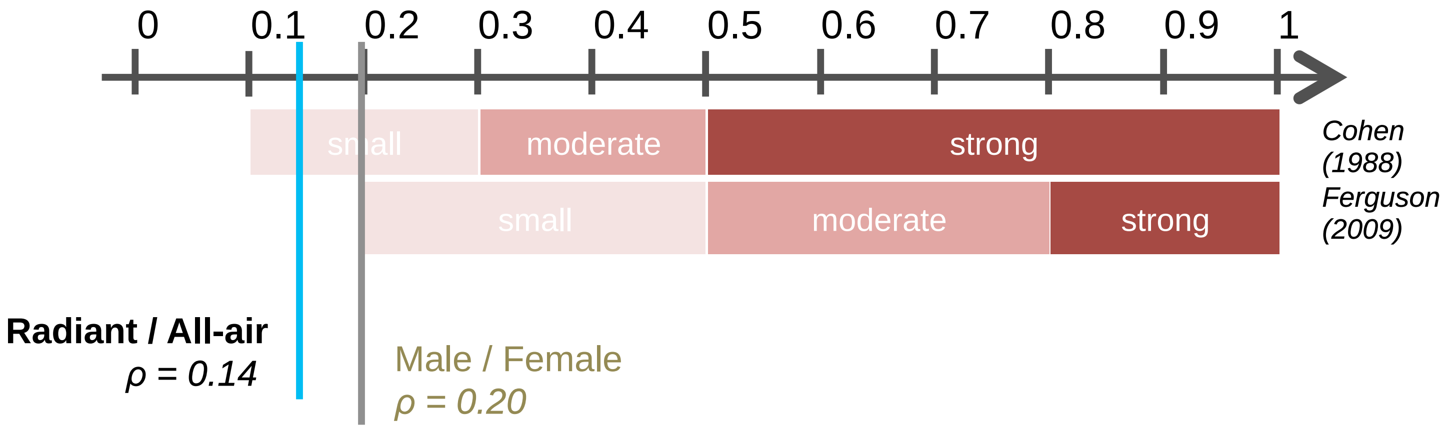


Thermal comfort

(1) Wilcoxon rank-sum test
*** p<0.001 highly significant, ** p<0.01 significant,
* p<0.05 less significant, n.s. not significant

Results: Thermal comfort

Spearman's ρ

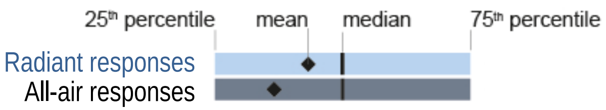


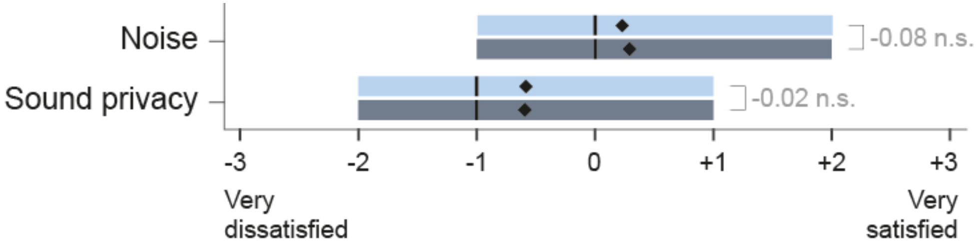
Cliff's ∂

Probability of higher temperature satisfaction

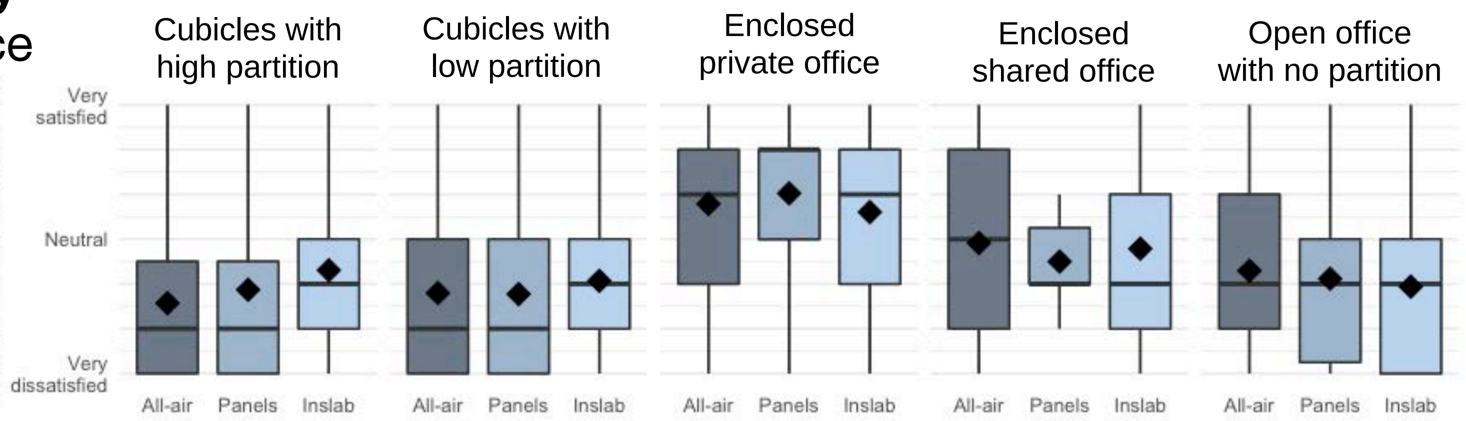
$$\partial = P(\text{radiant} > \text{all-air}) - P(\text{all-air} < \text{radiant})$$

Results: Acoustical comfort





Sound privacy
by type of office
& system



Conclusions

- Occupants of radiant and all-air buildings have equal IEQ, with a tendency towards improved temperature satisfaction in radiant buildings.
- A randomly selected occupant has a 16% higher chance to have higher comfort in a radiant system vs. an all-air system.
- Occupants of radiant and all-air buildings have equal acoustic satisfaction (noise and sound privacy).

Publication

- Karmann, C., S. Schiavon, L. Graham, P. Raftery, and F. Bauman. 2017. Comparing temperature and acoustic satisfaction in 60 radiant and all-air buildings. *Building and Environment*, 126. December. www.escholarship.org/uc/item/3nh8q2bk

Energy performance

New report: Energy performance of radiant buildings

How well do real world examples of radiant buildings perform in terms of energy?

Objective

- Document energy performance of as many North American buildings with radiant systems as possible and compare to benchmarks

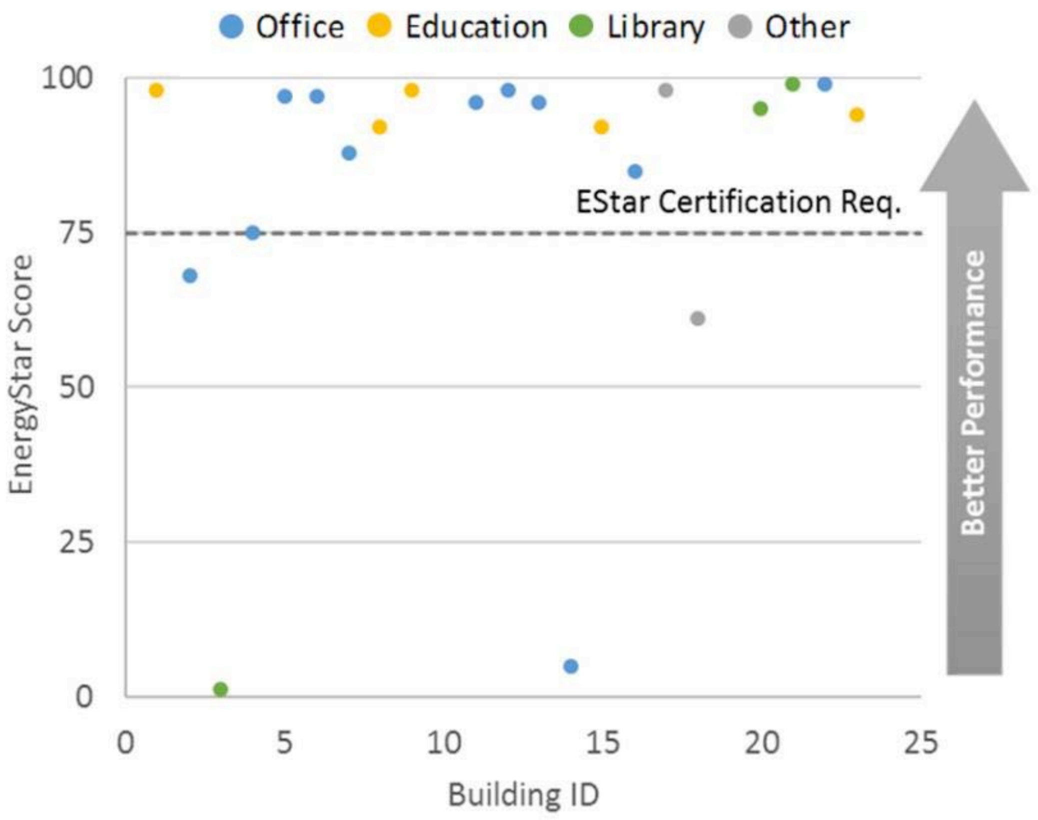
Approach

- Collected building description and 1 year's utility data from 23 representative radiant buildings
- Compared with national benchmarks, including:
  - Commercial Buildings Energy Consumption Survey: CBECS
  - EnergyStar

Report

- "Energy Performance of Commercial Buildings with Radiant Heating and Cooling"

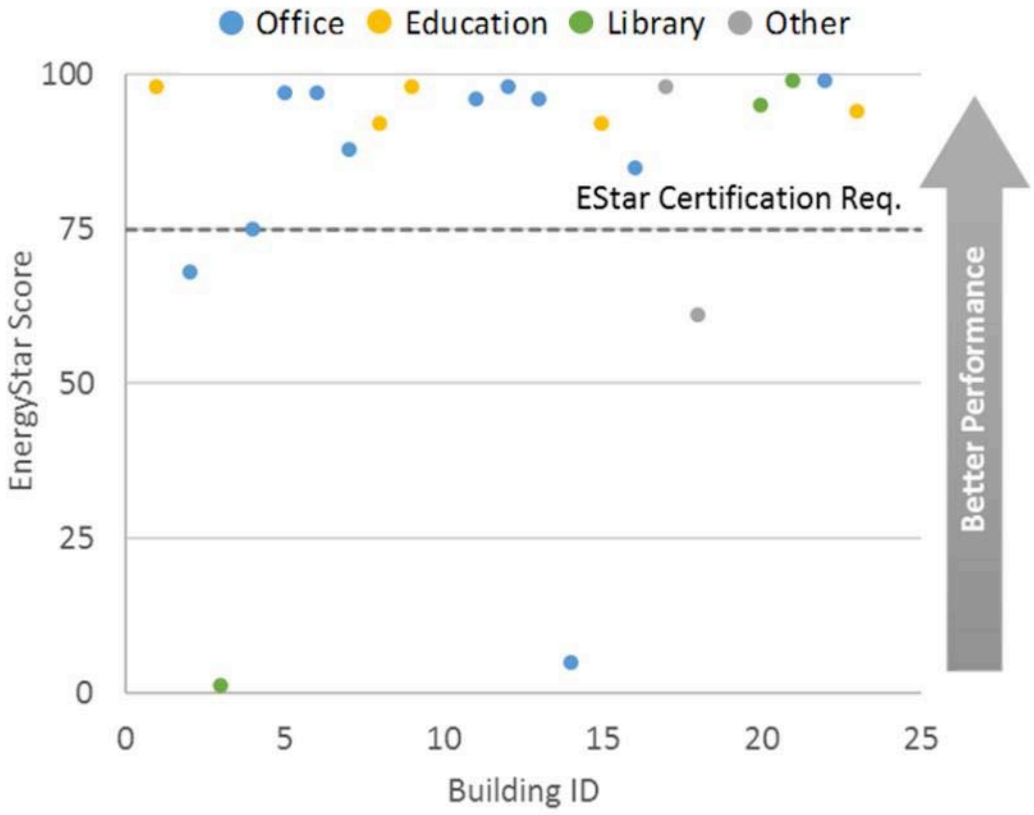
https://escholarship.org/uc/item/34f0h35q



New report: Energy performance of radiant buildings

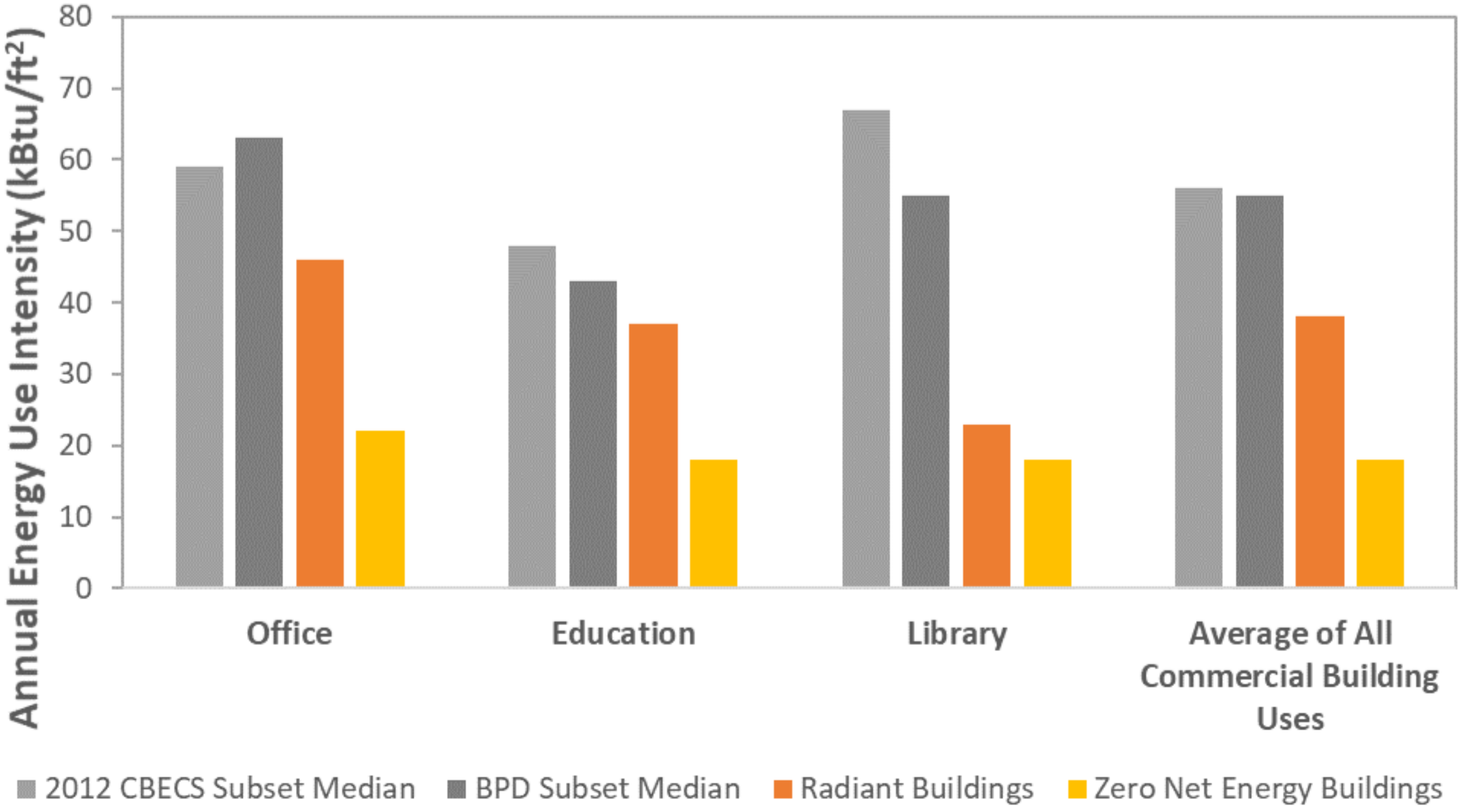
Key takeaways

- Two-thirds of the research dataset buildings have EnergyStar scores above 90
- All but four buildings (81%) had EnergyStar scores at or above 75, meaning that they qualify for EnergyStar certification



Key findings: Energy performance of radiant buildings

The median annual Energy Use Intensity (EUI, kBtu/ft^2) for radiant buildings is **significantly better** (lower) than typical buildings.



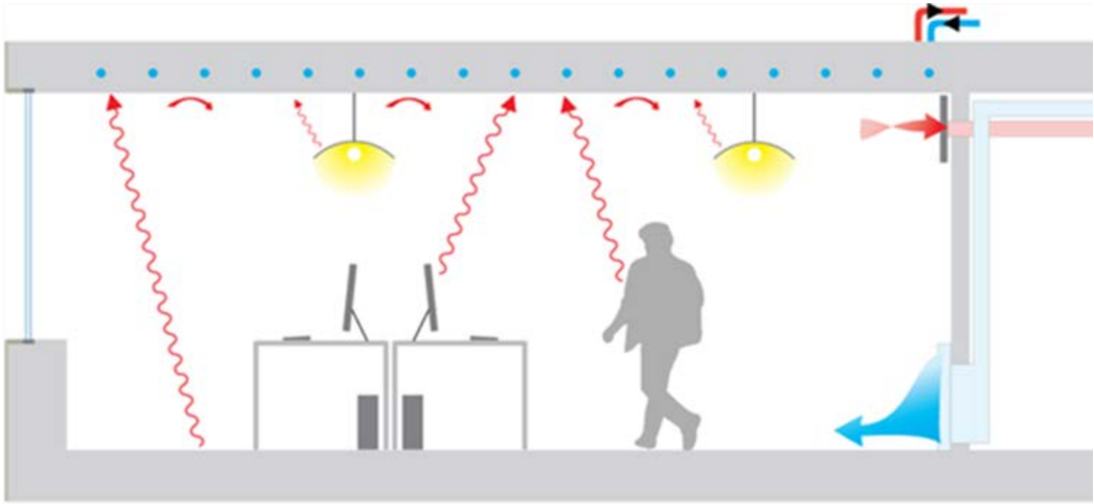
Laboratory Experiment

Practical guidance to address acoustic quality of chilled radiant ceilings

Background: Exposed concrete ceilings

- Radiant spaces have previously shown lower occupant satisfaction with acoustics
- Exposed concrete is highly sound reflective

Concrete ceiling (Brower Center)
Image: Tom Griffith



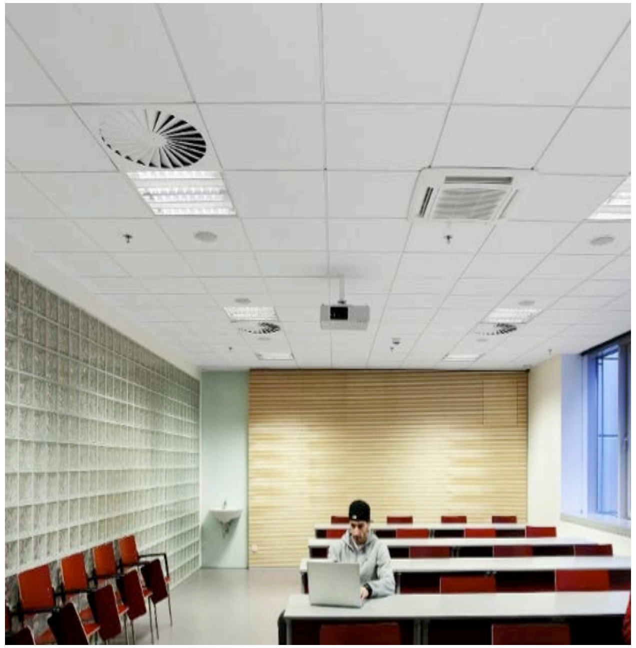
Radiant system

Background: Exposed concrete ceilings

Effect of acoustical clouds on:

- Cooling capacity of radiant ceiling
- Acoustical reverberation

Acoustical *clouds*
Image: Armstrong



Acoustical *tiles*
Image: Armstrong

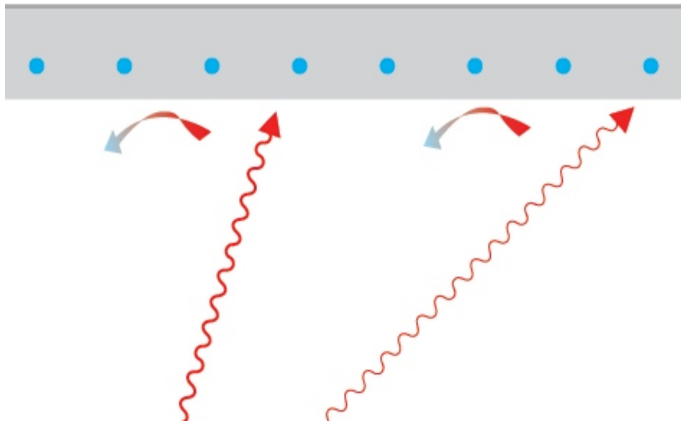
Laboratory study overview

Objective

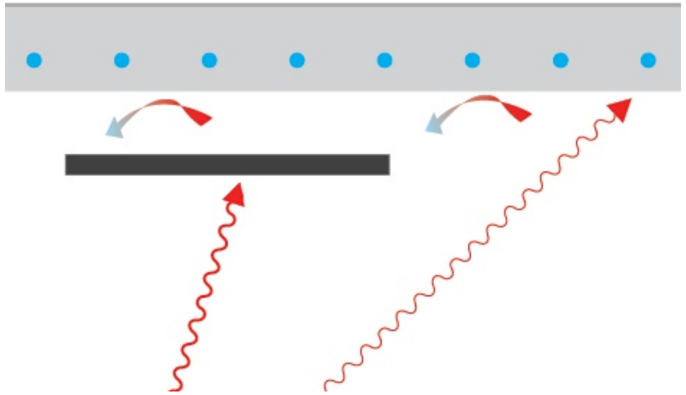
- Study cooling performance of a radiant chilled ceiling as a function of
  - Coverage by acoustical canopies
  - Use of fans
- Study acoustical performance of a radiant chilled ceiling as a function of coverage by acoustical canopies

Methods: Joint lab study

- Cooling capacity tests (at Price Labs)
- Acoustical tests (at Armstrong World Industries)

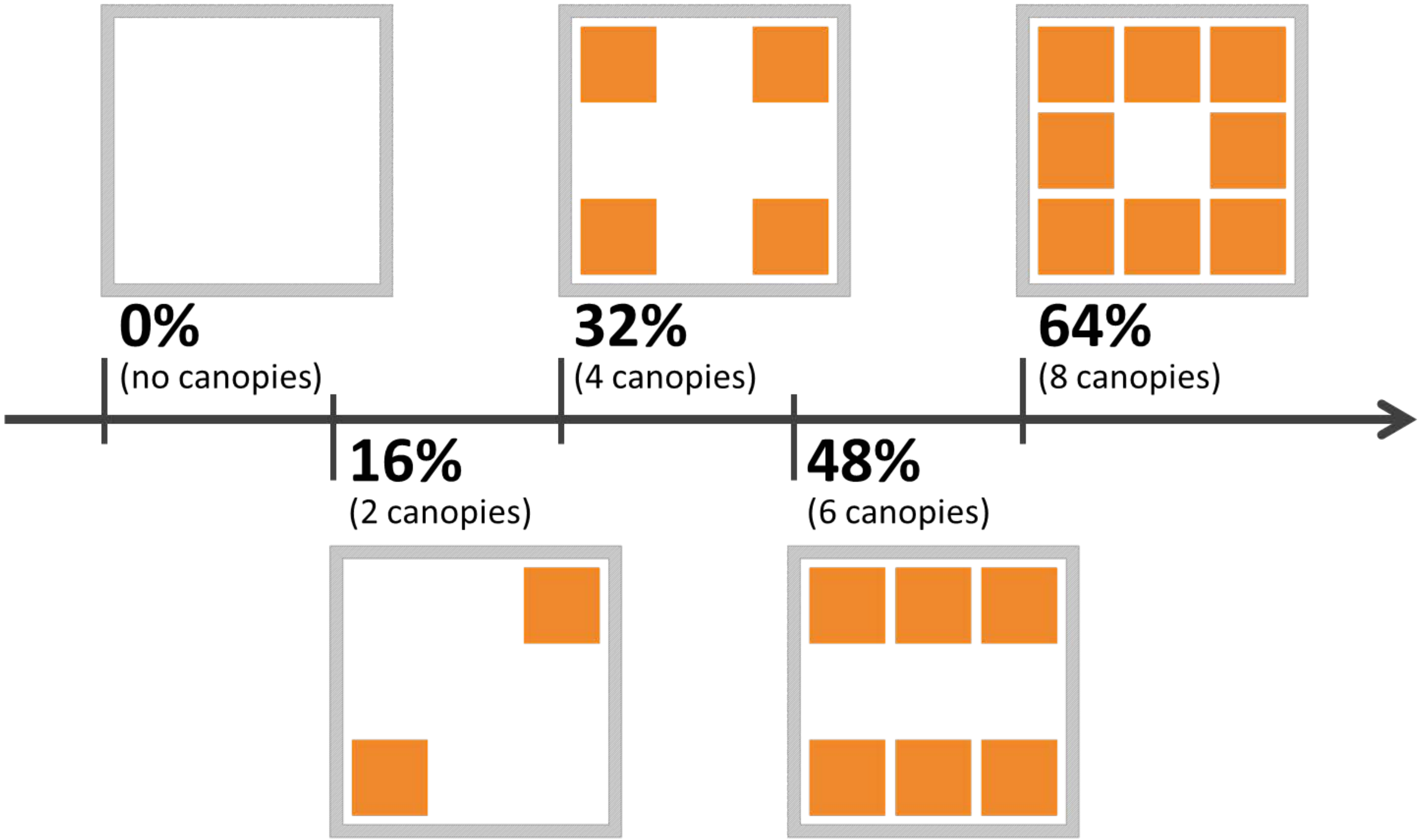


Schematic section of a radiant slab



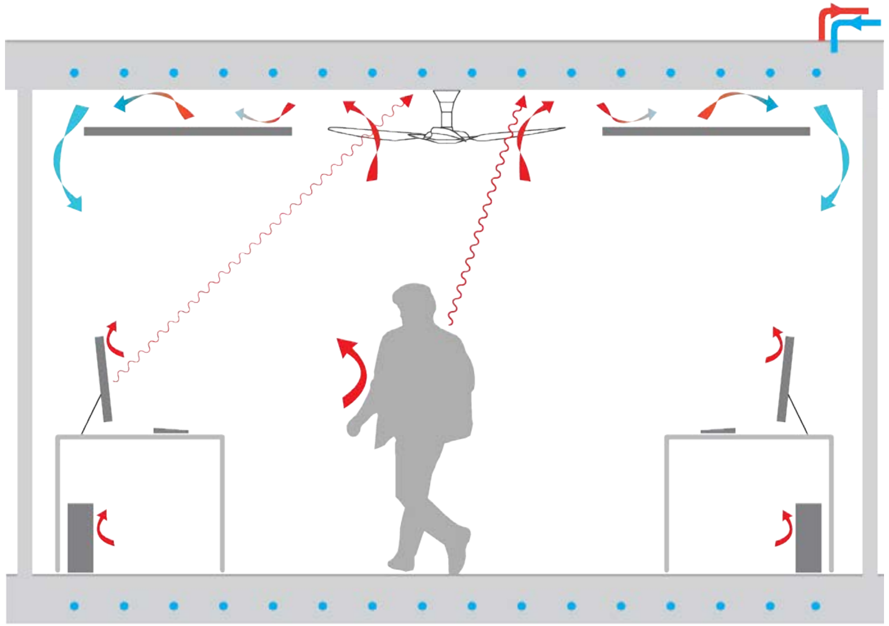
Schematic section of a radiant slab with acoustical canopy

Test configurations: Acoustical coverage

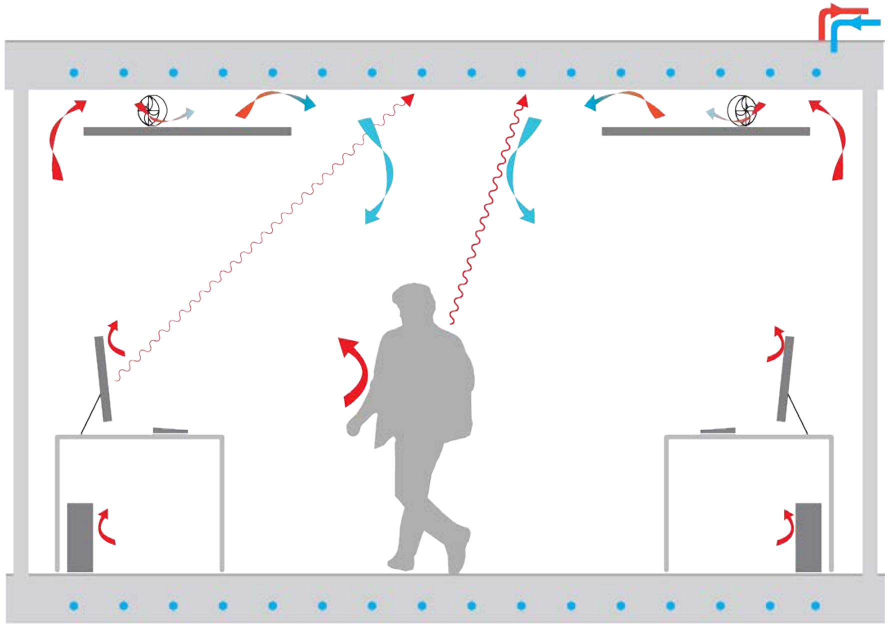


Test configurations: Fans

- No fan (reference case)
- Ceiling fan blowing up and down between the canopies
- Small fan hidden above the canopies



Central ceiling fan



Small fans hidden above the canopies

Acoustical testing set-up

Objective

- Determine the minimal acoustical coverage for acceptable acoustic quality

Approach

- Acoustical tests in a reverberant room (Accredited by NVLAP)

Experimental set-up

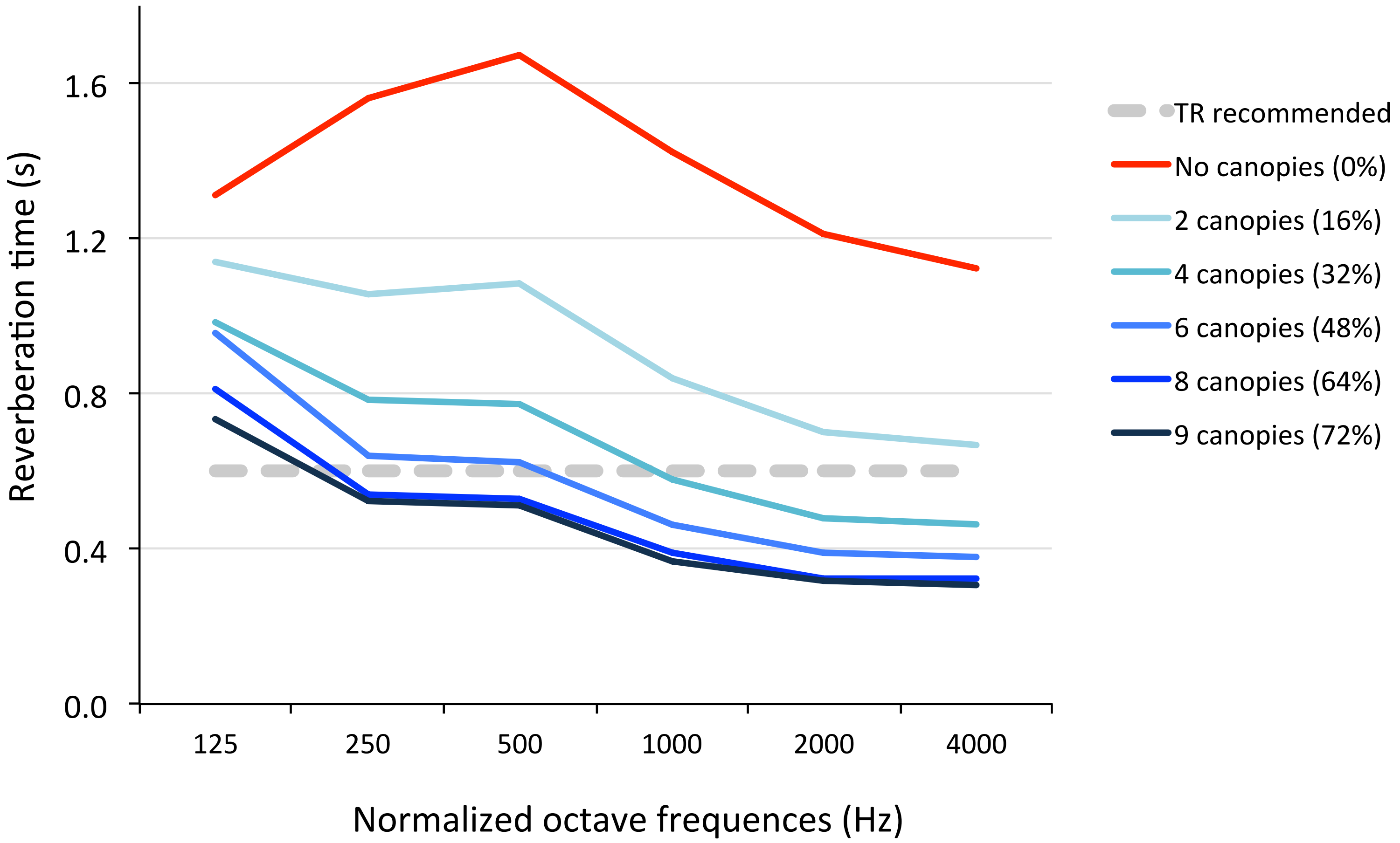
- Acoustical clouds tested upside down
- Plenum 16”, Spacing 6”
  Arrays of 4, 6, 8, and 9 clouds

Reverberant room, NRC testing

Armstrong “Soundscapes Shapes” canopies

Results: Reverberation time

Acceptable acoustical quality (reverberation time) was achieved with 6 canopies (48% coverage)



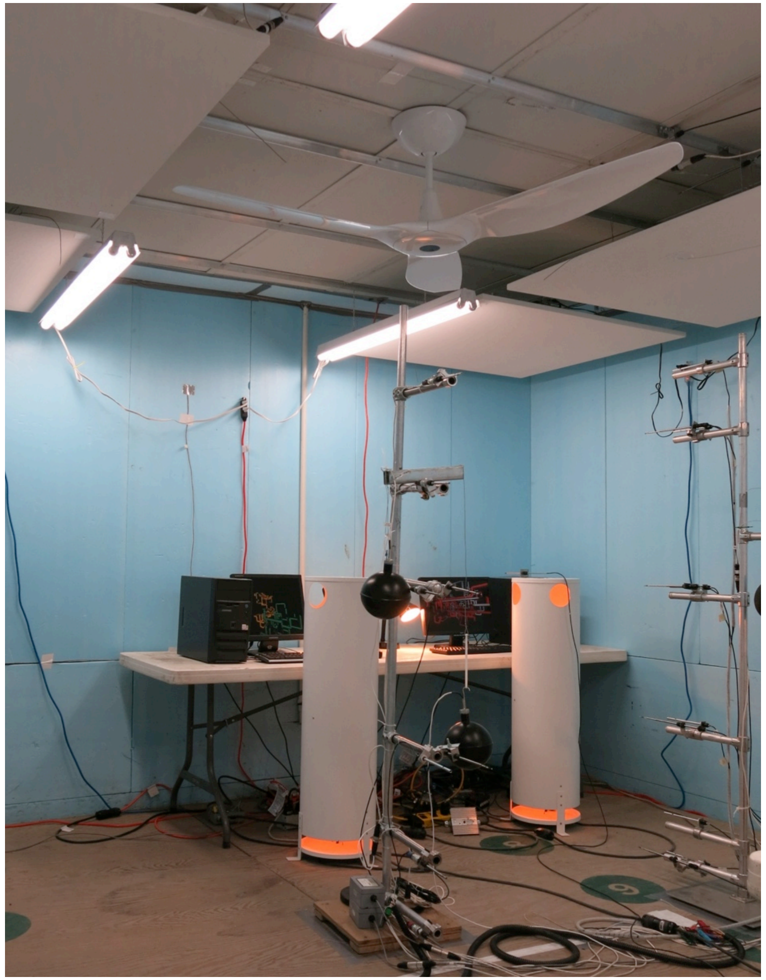
Cooling testing set-up

Hydronic test chamber

- Room 14 x 14 x 10 ft
- 8 in. thick R-40 insulation
- Radiant panels
  (8.2 ft ceiling height)
- EN14240 compatible
  (standard for cooling capacity testing of radiant panels)

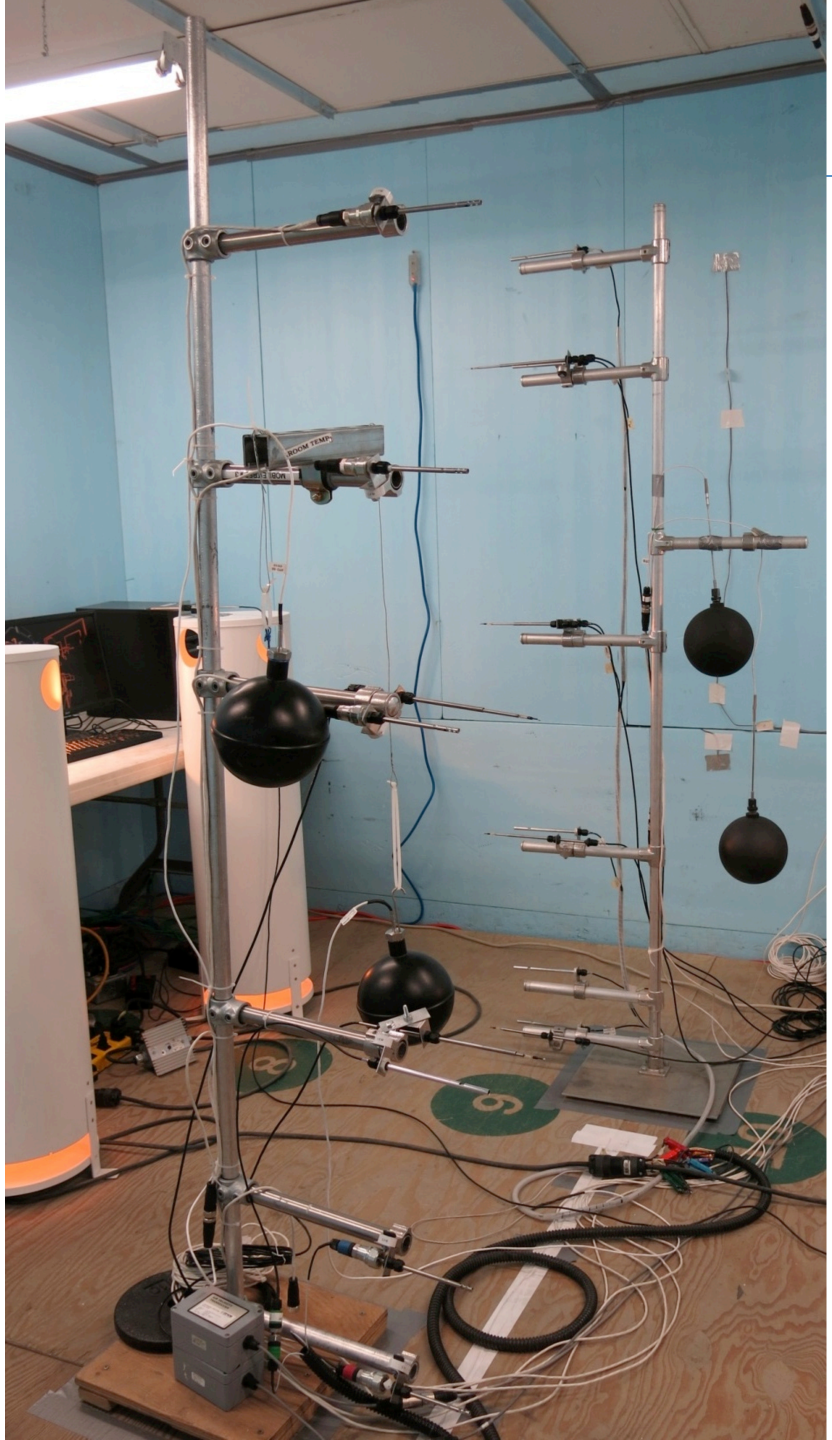
Experimental set-up

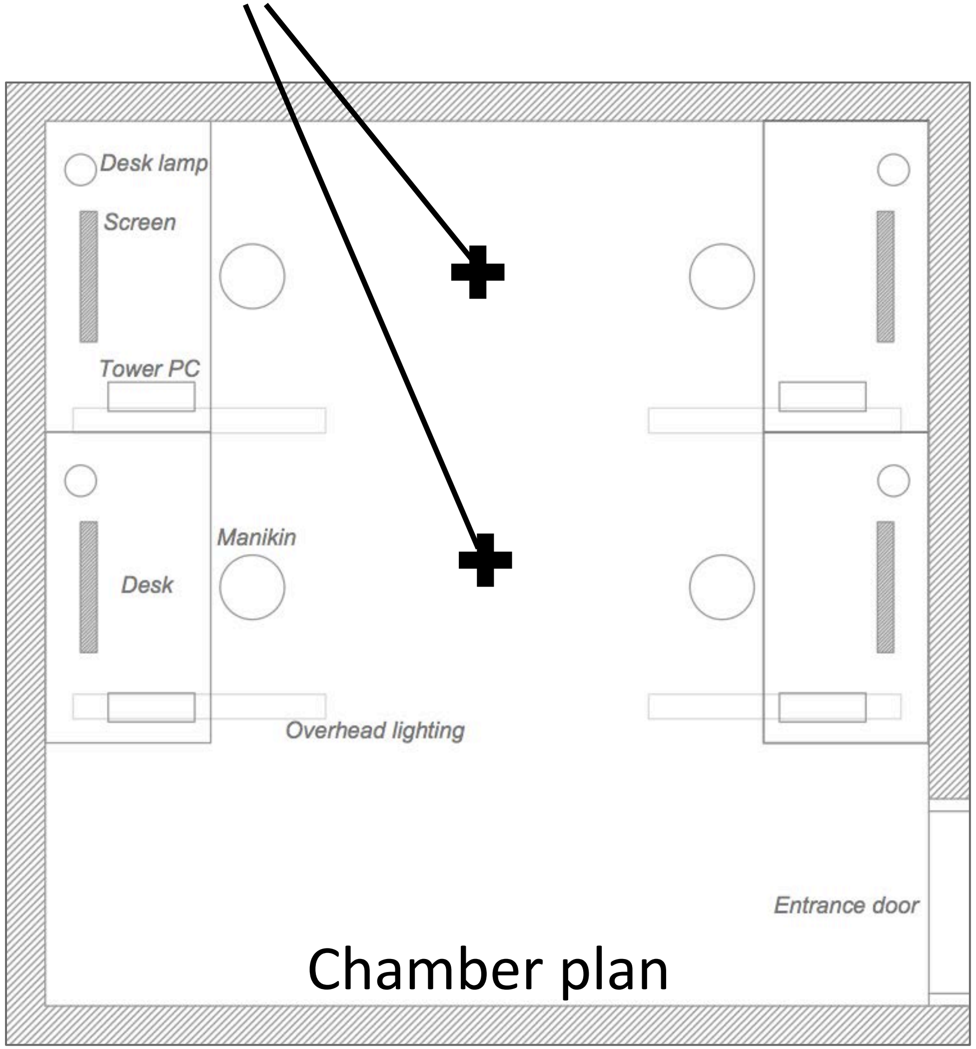
- Simulated workstations
- Cloud combinations (fans/canopies)



Interior view of the hydronic test chamber at Price Lab, Winnipeg, MB

Location of the 2 measurement trees





Chamber plan

Internal loads simulated through workstations

Fan configurations

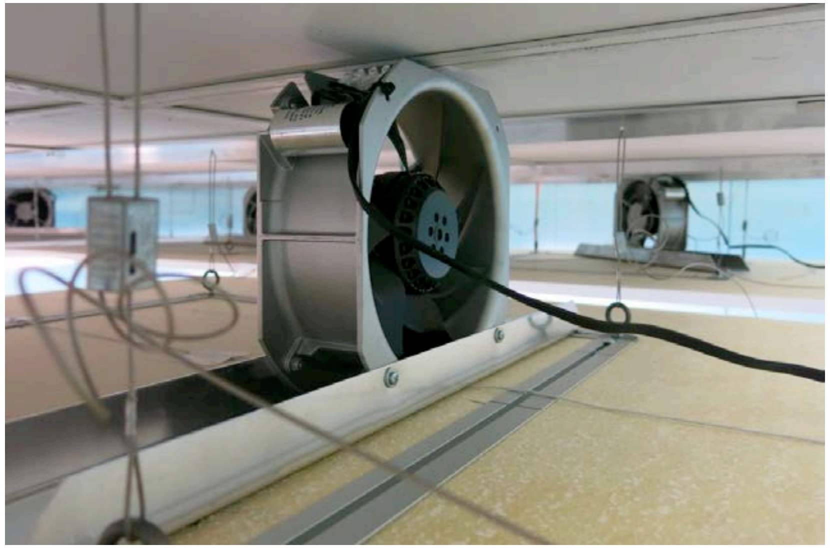
Ceiling fan variants
52-inch

Blowing up
Blowing down

Central ceiling fan

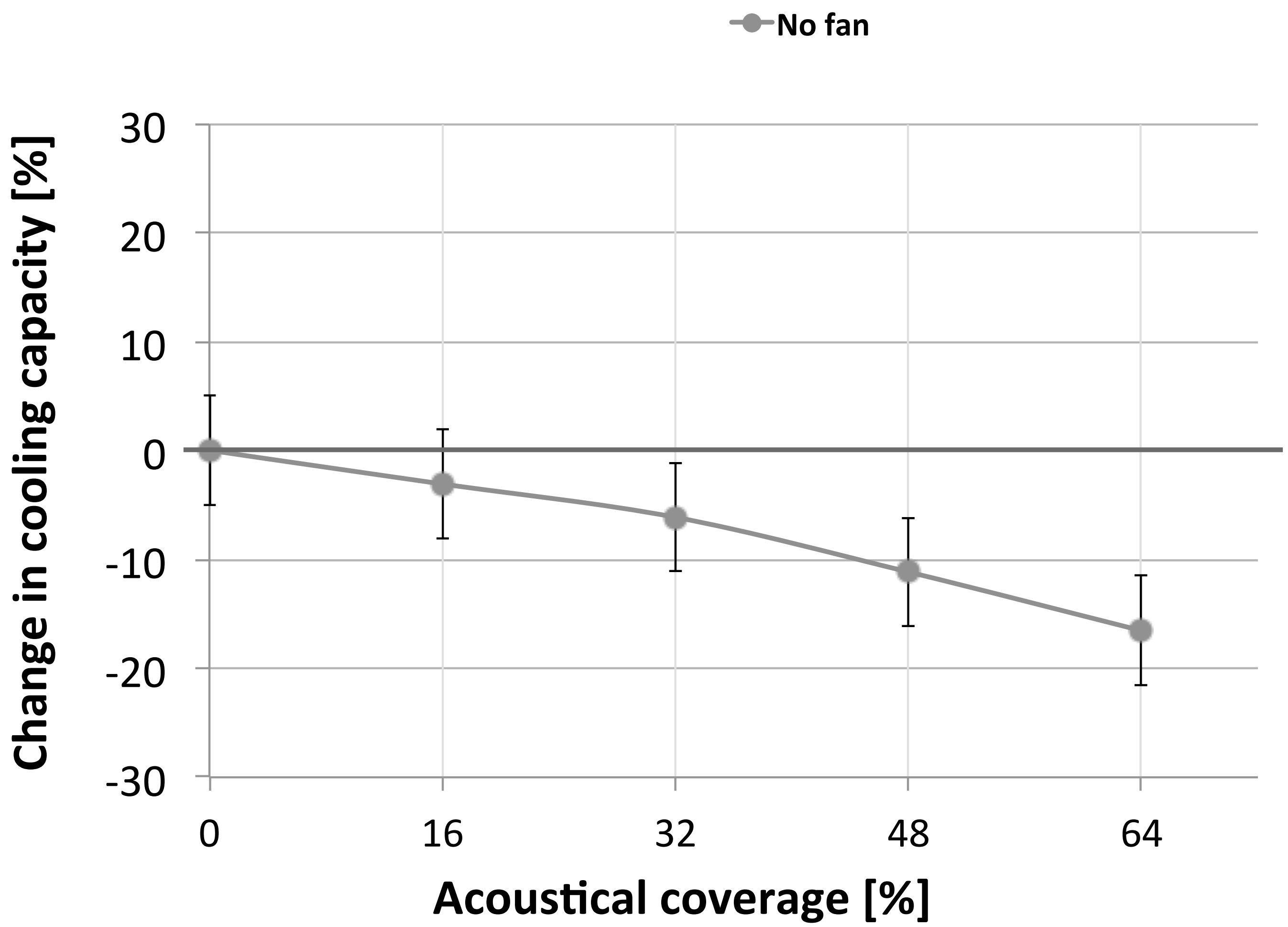
Small fans variants
8-inch

Low speed
Medium speed

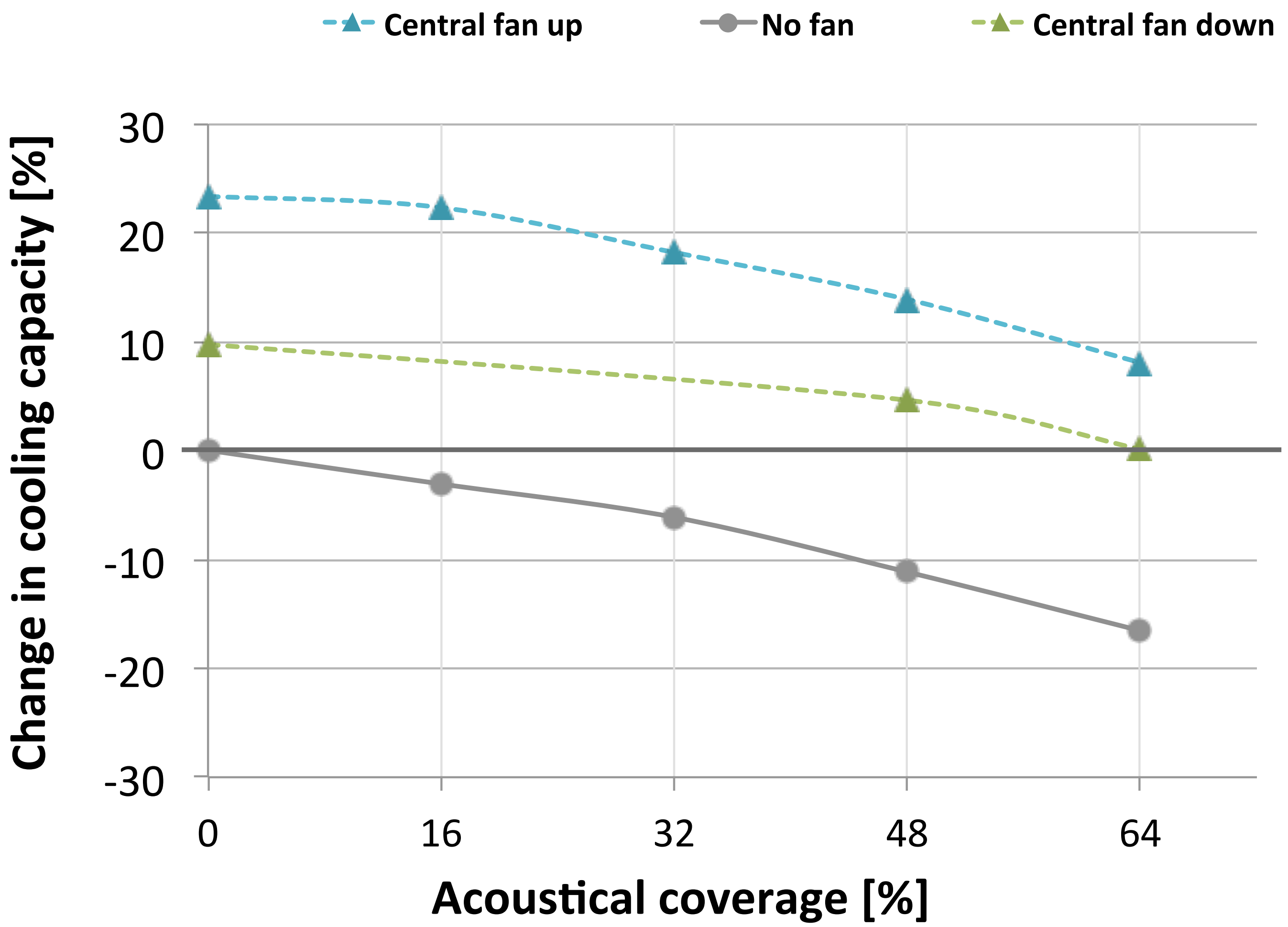


Small hidden fan (located above the canopy)

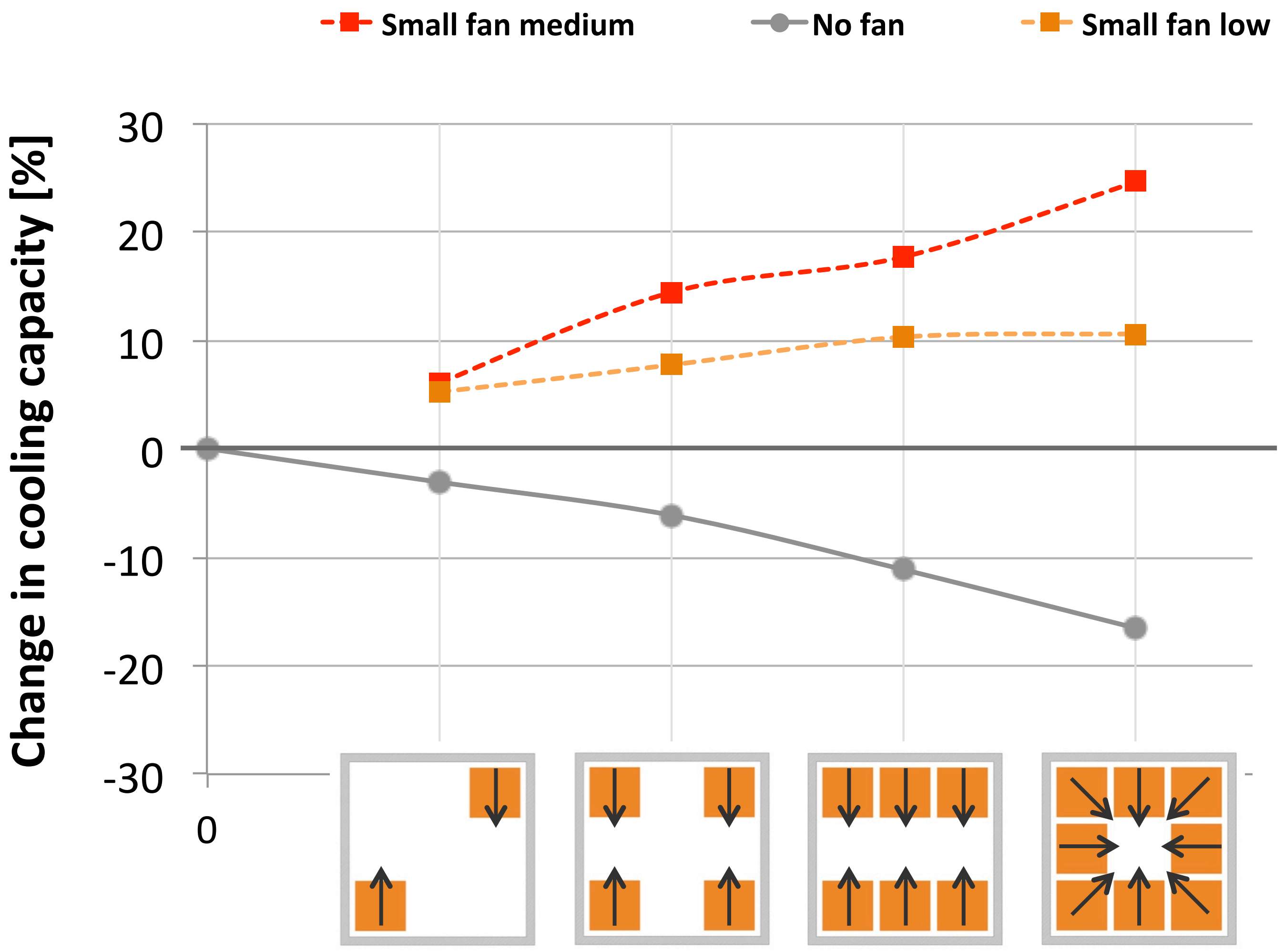
Results: Canopies without fans



Results: Canopies with ceiling fan



Results: Canopies with small fans



Conclusions

- Only minimal reduction of the cooling capacity of the radiant chilled ceiling was observed with canopies (11% cooling reduction at 48% coverage by canopies)
- Using elevated air movement is an effective strategy to compensate for the small reduction due to acoustic clouds
- The highest increase in cooling capacity reached 25.5% for the small fans at medium speed and highest coverage
- The highest increase for the cases with ceiling fan happened with no coverage:
  - It reached 22.4% for the upward blowing direction
  - It reached 12.4% for the downward direction

Publications

- Karmann et al. 2017. Cooling capacity and acoustic performance of radiant slab systems with free-hanging acoustical clouds. https://escholarship.org/uc/item/8r07k5g3
- Karmann et al. 2018. Effect of acoustical clouds coverage and air movement on radiant chilled ceiling cooling capacity. https://escholarship.org/uc/item/80h2t038

Q&A

Fred Bauman
fbauman@berkeley.edu

Radiant project website

https://cbe.berkeley.edu/project/optimizing-radiant-systems-energy-efficiency-comfort/

CBE
CENTER FOR THE BUILT ENVIRONMENT