Application of Hydronic Radiant and Beam Systems

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ASHRAE

Introduction

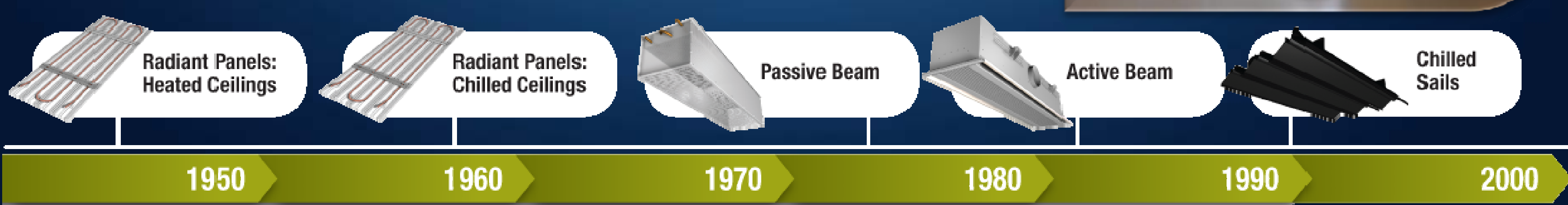
- Topics covered:
  - Theory of using water vs air
  - Discussion of water based technologies
    - Radiant panels
    - Passive beams
    - Active beams
    - Chilled sails
  - Application examples

Introduction

- **Panel research started in ~90 years ago**
  - o Initially with heated surfaces
  - o Cooling started ~50 years ago
    - Died off in North America
    - Usage continued in Europe

- **Seeking more capacity**
  - o Passive chilled beams
  - o Integration with ventilation system

- **Active chilled beams**



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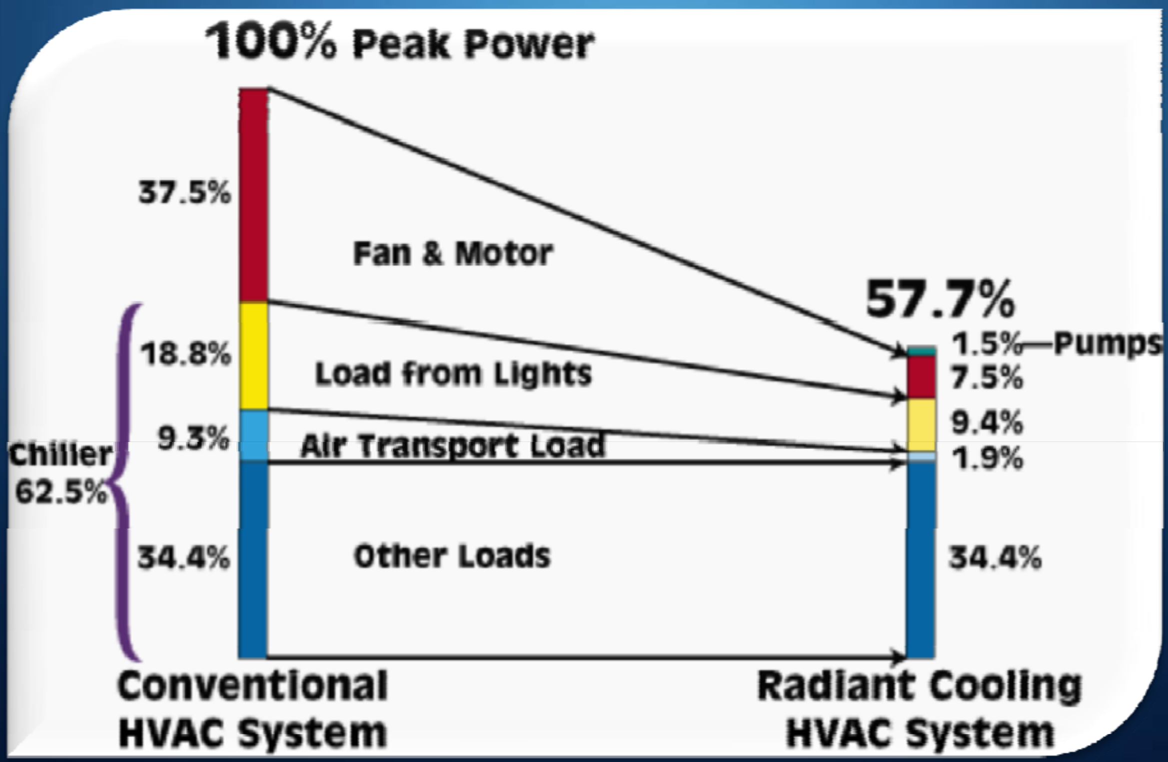
Introduction

THE GOAL

- Reduce energy consumption
- Maintain thermal comfort



CBS Newsletter, Fall 1994 http:/eetd.lbl.gov/newsletter/CBS_NL/n14/RadiantCooling.html

Introduction

The Opportunity

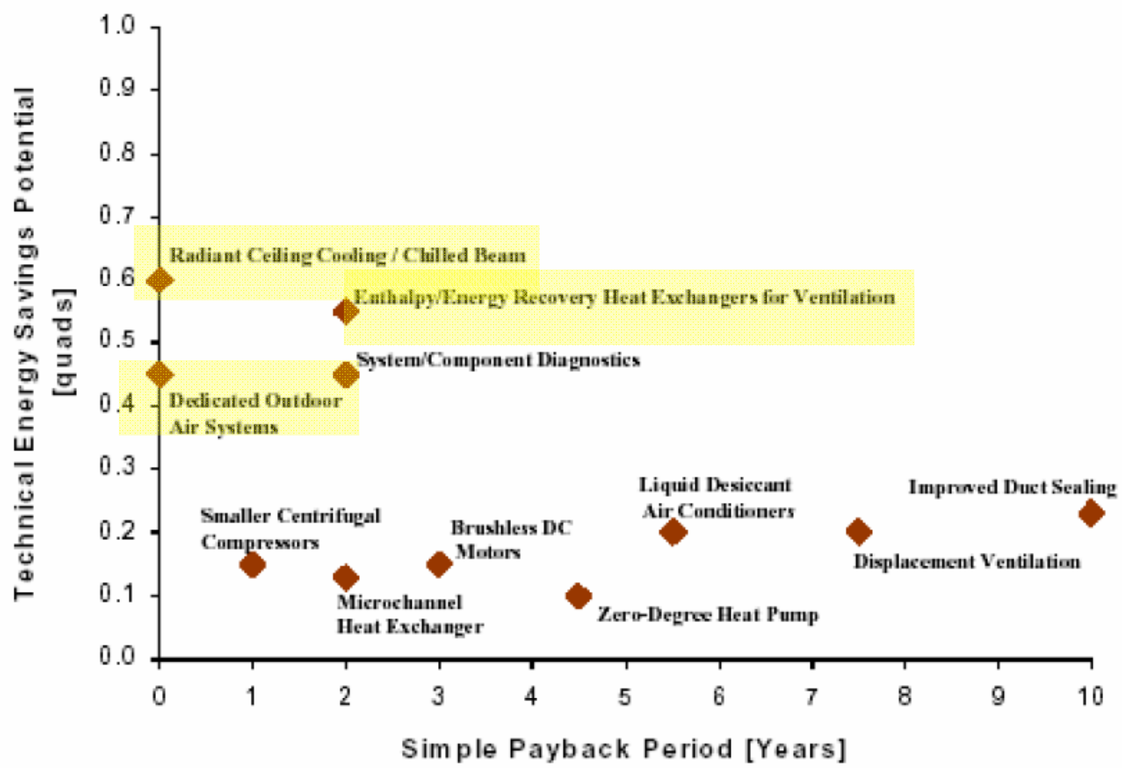


Figure 5-2: Estimated Technical Energy Savings Potential and Simple Payback Periods for the 15 Options

Roth, K. W., et al., Energy Consumption Characteristics of Commercial Building HVAC Systems, Volume III: Energy Savings Potential, Technical Report, prepared by TIAX, LLC for U.S. DOE, July 2002. (NTIS Order No. PB2002-107657)

Theory

Why water?

- Ability of fluid to transfer energy:

$$q = m\ \rho\ Cp\ \Delta T$$

	ρ [kg/m³]	C_p [kJ/kg K]	Sum [kJ/m³ K]
Air	1.23	1.005	1.236
Water	999	4.186	4182

- Water holds ~3400x more energy per volume than air.

Theory

Why water?

- Size of piping vs duct
  - Compare 100,000 Btu/hr of transported energy

	ΔT basis	Volume flow rate	Duct/pipe size
Air	20°F	4600 cfm	26” (1200 fpm)
Water	6°F	33 gpm(US)	2” (<4 fps)

- Energy consumption

	Volume flow rate	Energy consumption
Air	4600 cfm	2.5 – 3.0 kW
Water	33 gpm(US)	0.27 – 0.33 kW

Theory

Sensible only application

- Design to avoid condensation – why?
  - Avoid dripping into the occupied zone below
  - Avoid dust build up on wet surfaces
  - Avoid condensate trays/piping/pumps

Theory

Sensible only application

- Design to avoid condensation – how?
  - Unit is designed for sensible cooling only
  - Latent removal through ventilation air only
  - Positive pressure
  - Commissioning of infiltration
  - Design controls to handle humidity change
  - Design system based on expectations

Theory

Sensible only application

- Design to avoid condensation – how?
  - Design:
    - Dew point + 2°F
    - Avoid or design for high latent load applications
    - Use dry air – DOAS
  - Exceeding dew point limit
    - Condensation process begins at dew point > surface temperature
    - Speed of process depends on environmental conditions

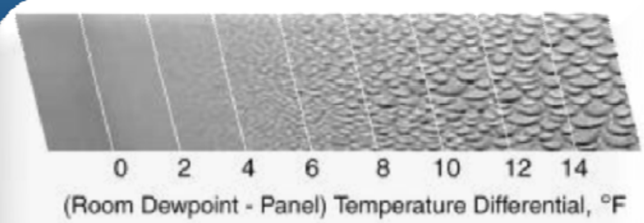


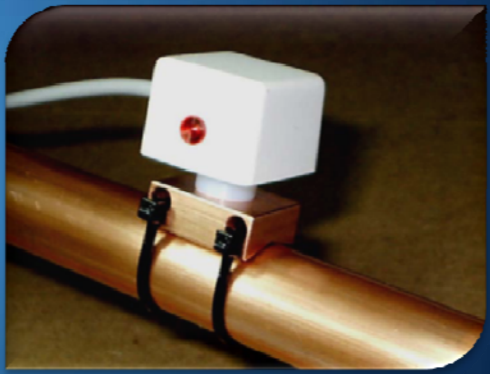
Figure 6 Condensation formation on a panel after 8.5 hours.

Mumma, Stanley; 2002; Chilled Ceilings in Parallel with Dedicated Outdoor Air Systems: Addressing the Concerns of Condensation, Capacity, and Cost; *ASHRAE Transactions 2002, Vol 108, Part 2*, pp220-231

Theory

Sensible only application

- Design to avoid condensation – how?
  - Sensing:
    - Room humidity sensors
    - Condensation detection on piping
  - Strategies
    - Water on/off
    - Entering water temperature reset
    - Supply air water content



Systems – Radiant Panels

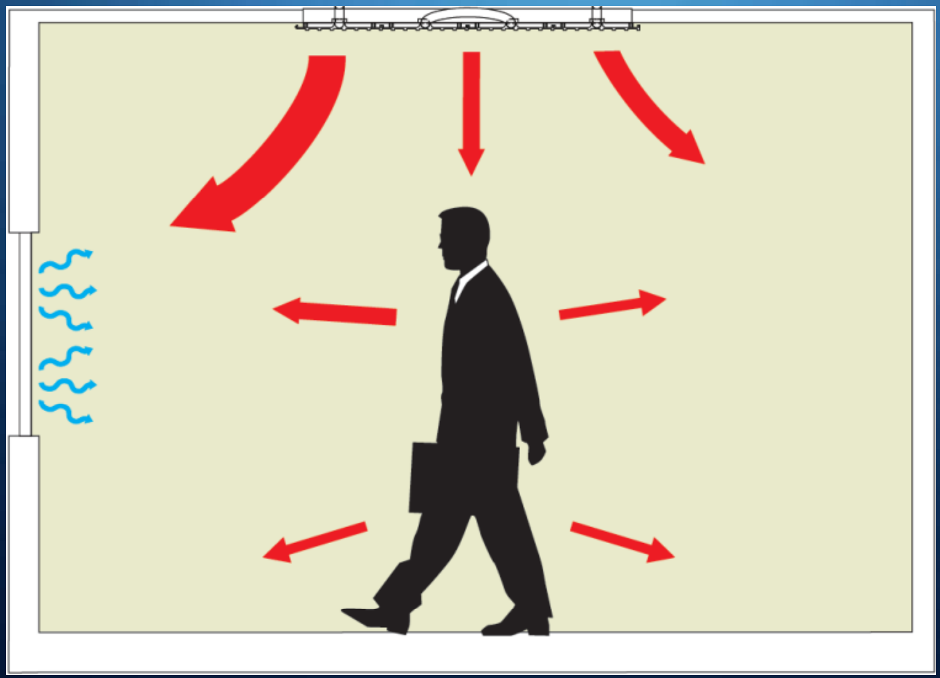
Purpose:

Passive cooling or heating device using surface temperature modification to provide thermal comfort.

Primarily radiant heat transfer.

Systems - Radiant Panels

- What is radiant heat transfer?
  - Electromagnetic waves
  - Intensity based on temperature and distance/view factor
  - Space/distance is the medium
  - Exchange is based on relative surface temperature



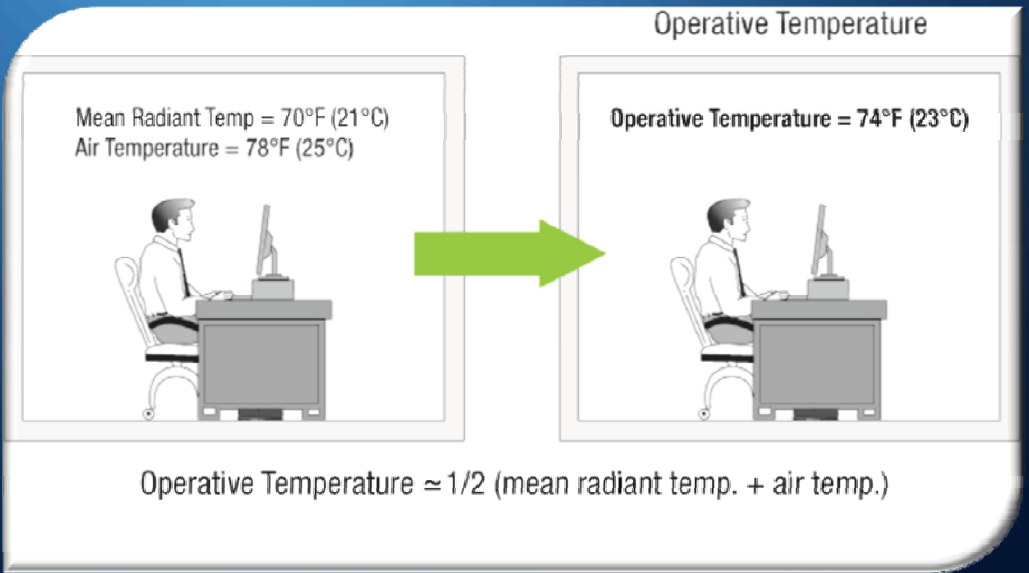
Systems - Radiant Panels

- Background
  - Roman hypocaust – radiant heating – ~300 BC
  - Middle East – radiant cooling - ~800 AD
  - Southwest US – adobe houses – thermal mass
  - Modern research
    - Heating
    - Cooling
  - Modern cooling initially failed
  - Resurgence for energy and thermal comfort

Systems – Radiant Panels

Radiant Thermal Comfort

- Comfort perception
  - Radiant plays key role in comfort
  - Optimum at 60% radiant, 40% convection (ASHRAE App. ch 53)
  - Average of mean radiant & air temperatures – operative temperature



Mean Radiant Temperature

$MRT^4 = T_1^4F_1 + T_2^4F_2 + \ldots T_n^4F_n$

T = surface temperature [°R]

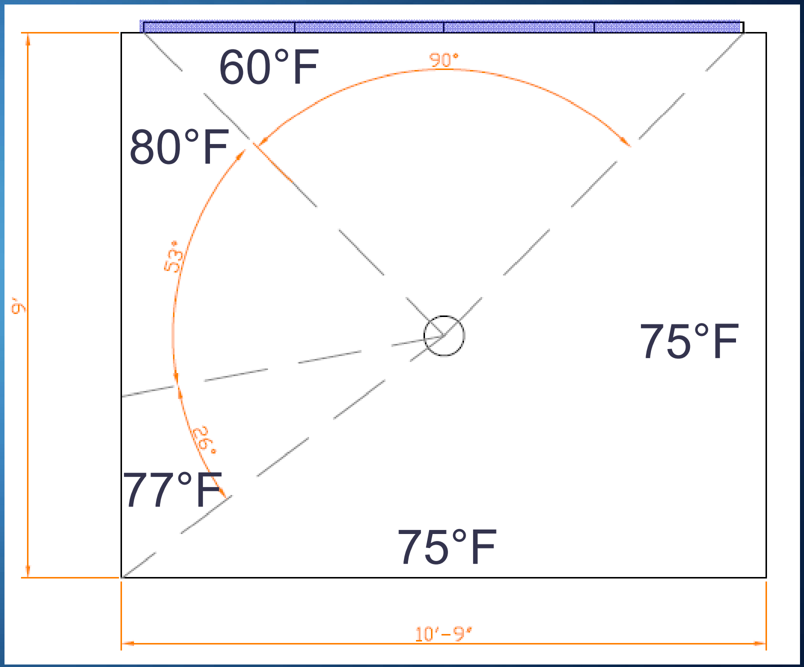
F = angle factor

MRT (cooling example) = 72°F

for T_o = 75°F, T_{air} = 78°F

Limitation:

- 2D analysis, provides good check
- Best method is view factors (Fundamentals)
- Significant analysis with modelling programs



Mean Radiant Temperature

$MRT^4 = T_1^4F_1 + T_2^4F_2 + \ldots T_n^4F_n$

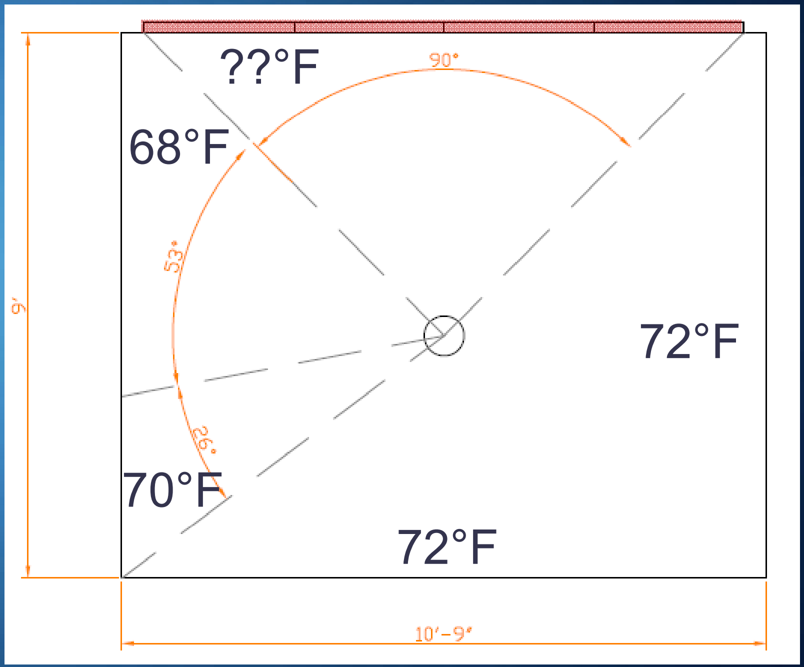
T = surface temperature [°R]

F = angle factor

for T_o = 75°F, T_{air} = 70°F

MRT (heating example) = 80°F

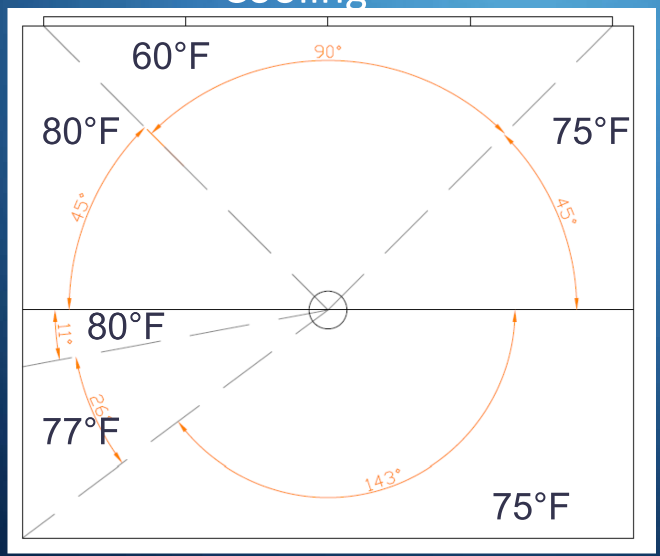
Panel surface temperature = 105°F



Radiant Asymmetry

- Limited based on thermal comfort (ASHRAE 55) (< 5% PPD)
  - Heating – 9°F
  - Cooling – 25°F

Cooling



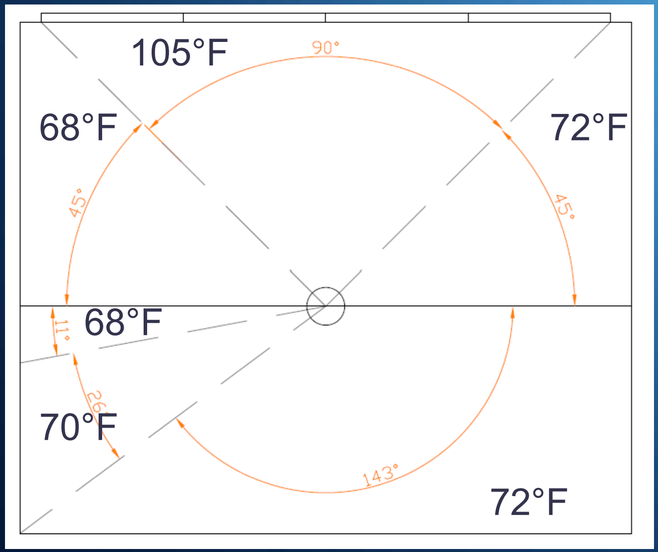
MRT top = 69°F
MRT bottom = 76°F
Asymmetry = 7°F

Systems – Radiant Panels

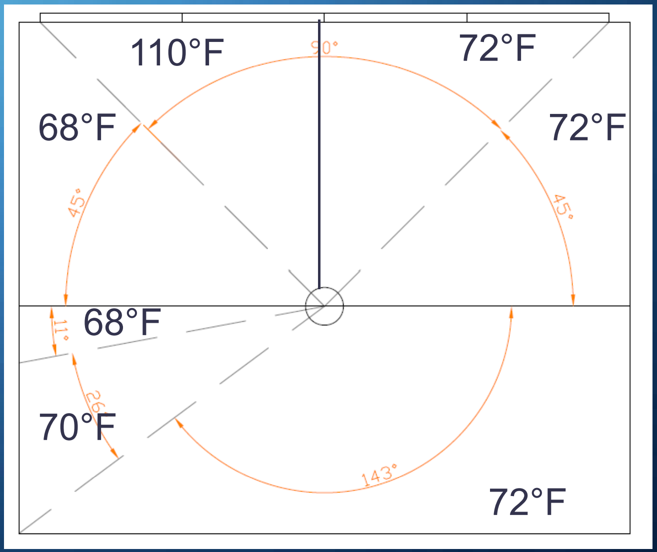
Radiant Asymmetry

- Heating can be more of a challenge

Heating



MRT top = 88°F
MRT bottom = 72°F
Asymmetry = 16°F

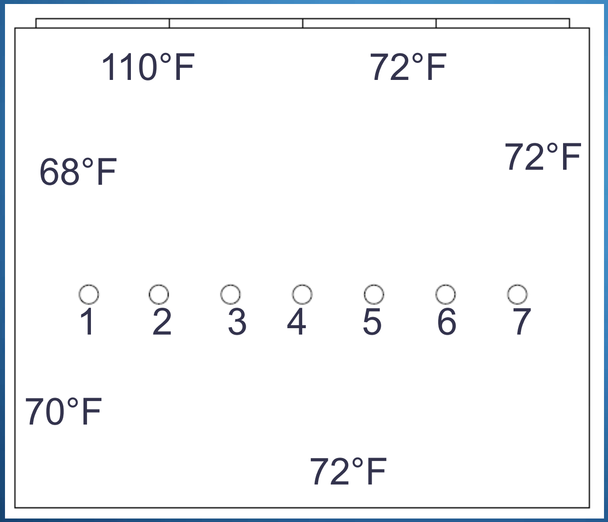


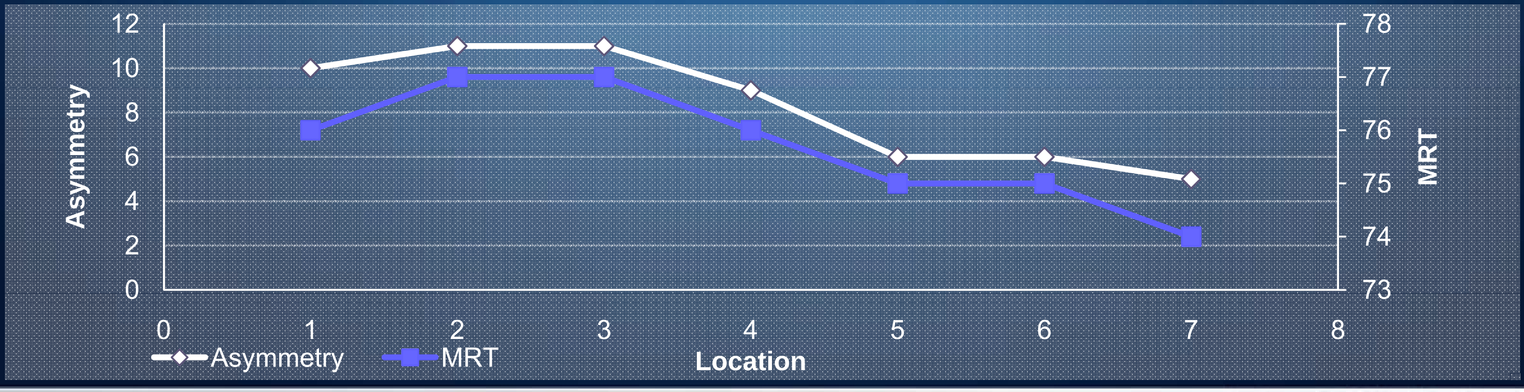
MRT top = 81°F
MRT bottom = 72°F
Asymmetry = 10°F

Systems – Radiant Panels

Radiant Asymmetry

- Heating can be more of a challenge





Radiant Panel Performance

- Standardized test methods
  - ASHRAE 138 – not catalogued by anyone
  - EN 14037 – heating
  - EN 14240 – cooling
- Standardized tests not catalogued by many
  - EN standard is European
  - Standardized tests underperform real performance
    - No surface temperature variations
    - Minimal natural convection only
    - Conservative performance for safety

Systems – Radiant Panels

Radiant Panel Performance

- Calculations
  - ASHRAE Systems - Panel Heating and Cooling
    - Radiant

$$q_r = 0.15 \times 10^{-8}[(t_p + 459.67)^4 - (\text{AUST} + 459.67)^4]$$

    - Convective
      - Heated ceiling (natural)

$$q_c = 0.041 \frac{(t_p - t_a)^{1.25}}{D_e^{0.25}}$$

      - Cooled ceiling (natural)

$$q_c = 0.39 \frac{|t_p - t_a|^{0.31}(t_p - t_a)}{D_e^{0.08}}$$

    - Based on
      - no forced air convection (ie: displacement, non-occupied hours)
      - Panel surface temperatures and AUST

Radiant Panel Performance

- Calculations
  - Forced convection
    - Radiant

$$q_r = 0.15 \times 10^{-8}[(t_p + 459.67)^4 - (\mathrm{AUST} + 459.67)^4]$$

    - Convective

Ceiling	$T_s > T_{air}$	$h_c = [(0.704 \cdot \Delta T^{0.133} / D_h^{0.601})^3 + (2.0 \cdot \mathrm{ACH}^{0.39})^3]^{1/3}$	$(\mathrm{W/m^2K})$
		$h_c = [(0.234 \cdot \Delta T^{0.133} / D_h^{0.076})^3 + (0.35 \cdot \mathrm{ACH}^{0.39})^3]^{1/3}$	$(\mathrm{Btu/h \cdot ft^2 \cdot F})$
	$T_s < T_{air}$	$h_c = [(2.12 \cdot \Delta T^{0.33})^3 + (2.0 \cdot \mathrm{ACH}^{0.39})^3]^{1/3}$	$(\mathrm{W/m^2K})$
		$h_c = [(0.308 \cdot \Delta T^{0.33})^3 + (0.35 \cdot \mathrm{ACH}^{0.39})^3]^{1/3}$	$(\mathrm{Btu/h \cdot ft^2 \cdot F})$

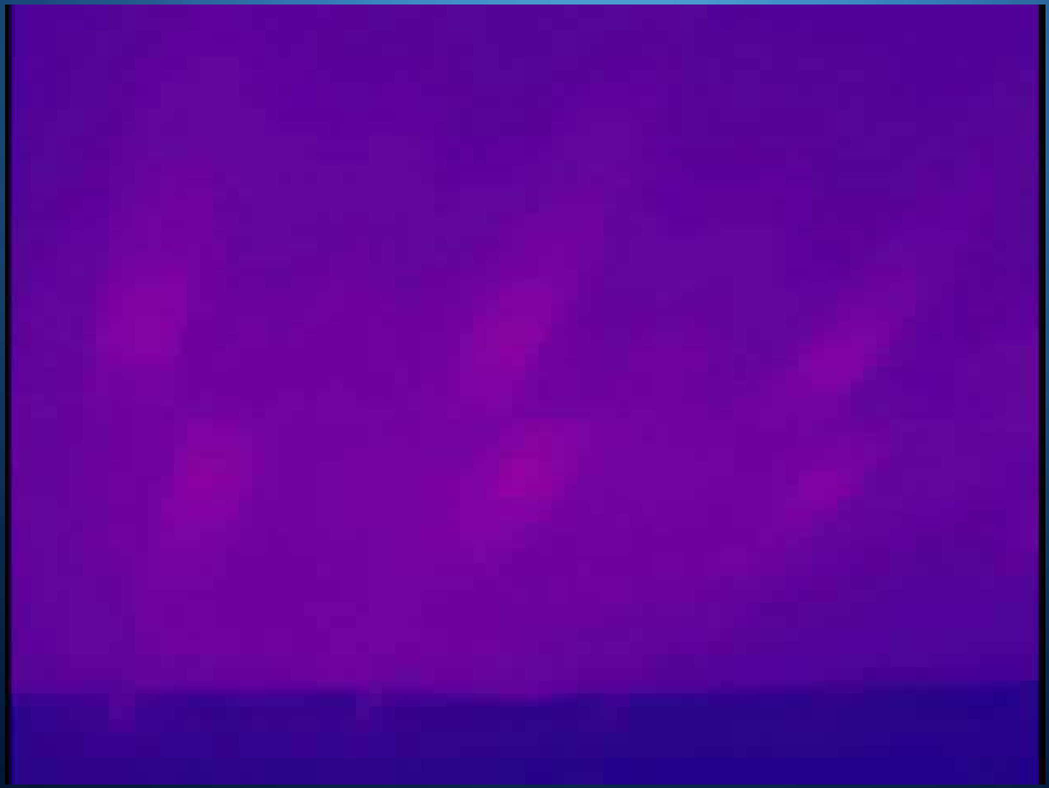
Novoselac A., Burley B.J., Srebric J., *New convection correlations for cooled ceiling panels in room with mixed and stratified airflow*, HVAC & Research, Vol 12, n° 2, April 2006, pp 279-294

    - Based on:
      - High induction diffusers throwing between (not over) the panels
      - Air change rates
      - Panel surface temperatures and AUST

Systems – Radiant Panels

System response

- Depends on layout, flow rate
- Typical response – 5 min.

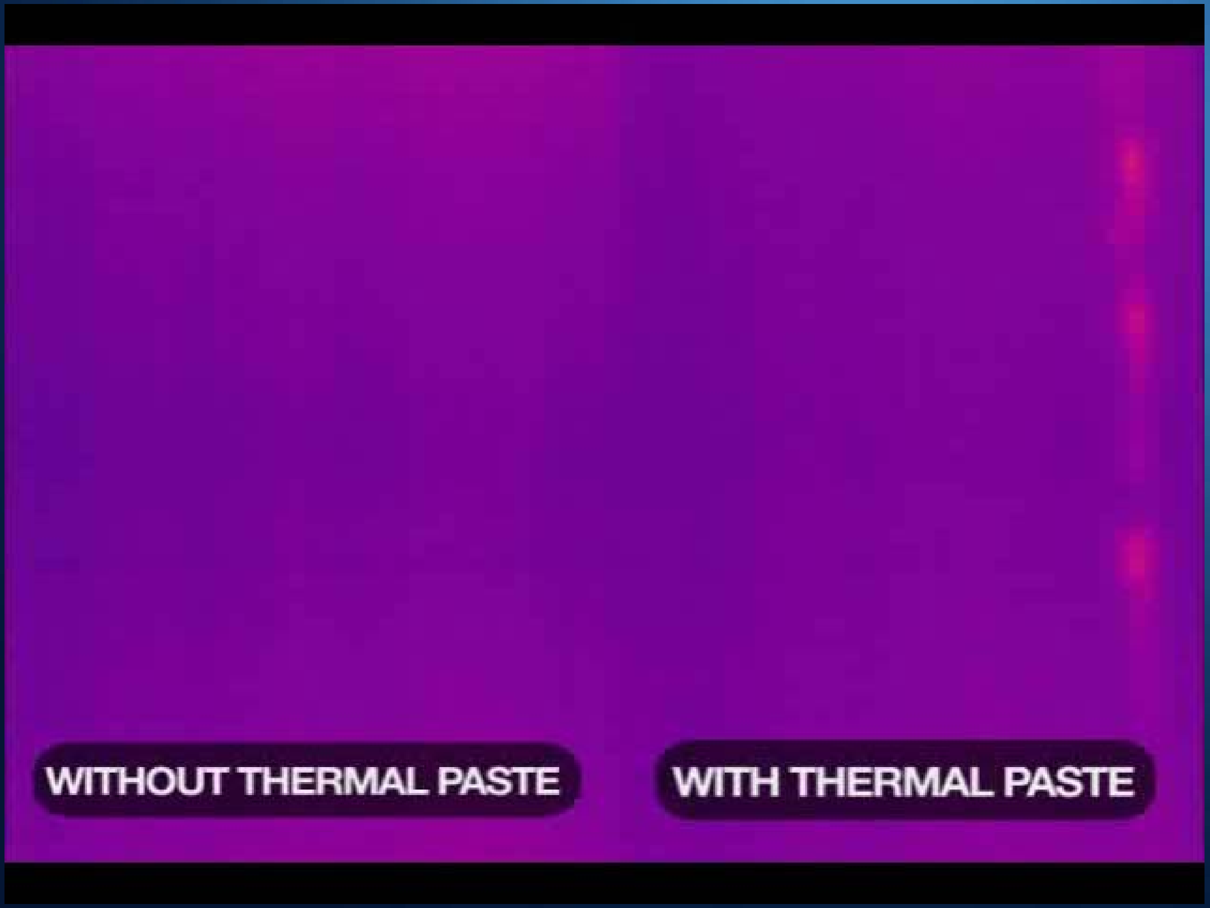


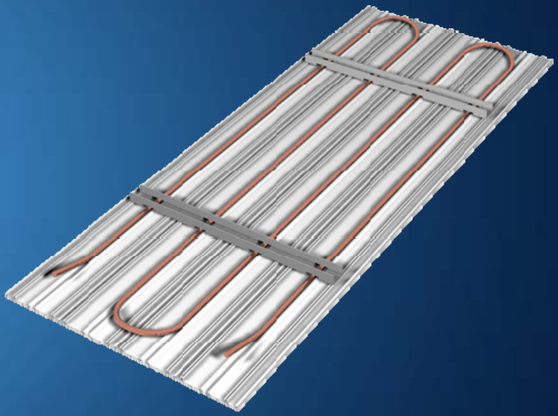
Time lapse IR video – 25 minutes, 0.5 gpm, 12 panels at 2’x6’ 4 pass

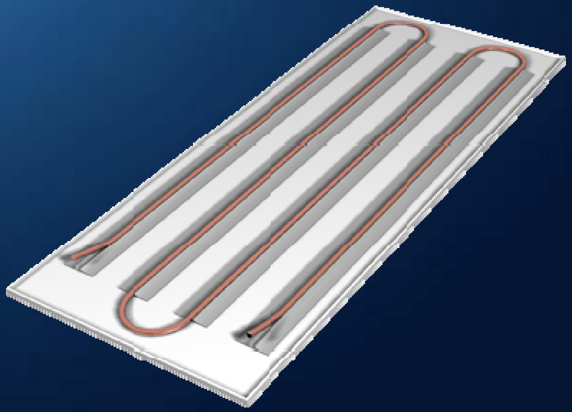
Systems – Radiant Panels

System response

- Surface contact of components







Systems – Radiant Panels

Typical Operating Conditions

	Cooling	Heating
EWT	Dew point + 2°F	90-140-200°F
Water ΔT	2 – 6°F	10-20°F

- Series or parallel piped
- Series piped between multiple panels

Systems – Radiant Panels

- General Guidance
  - Heating
    - High heating surface temperatures can be uncomfortable
    - Generally a ceiling surface temperature of max 120°F
    - High surface temperatures acceptable with little occupancy
      - Perimeters
      - Spaced out to prevent a blanketed hot surface
    - Air temperature across panel < panel temperature
  - Cooling
    - Radiant asymmetry problems rare
    - Maintain surface temperatures above dew point
    - Spread out the load
    - Air temperature across panel > panel temperature

Systems – Radiant Panels

- General Guidance
  - Use operative temperature for thermal comfort
    - Minimize SAT ΔT, or
    - Minimize air volume
  - Offset variations in surface temperatures
    - Hot/cold walls/ceilings
    - High solar gain
  - Use panels to activate building mass
  - Off hour temperature stabilization
  - Requires 4”-6” of clearance
  - Integrate ceiling components (sprinklers, PA, lighting)

Systems – Radiant Panels

- Minimize ventilation
- Work with operable windows
- Offset high solar gain
- Activate building mass

Systems – Radiant Panels

- Low ventilation requirement
- Maintain comfort

Systems – Passive Beam

Purpose:

Passive cooling device using natural convection to provide cooling.

Dependent on temperature differential between air and water.

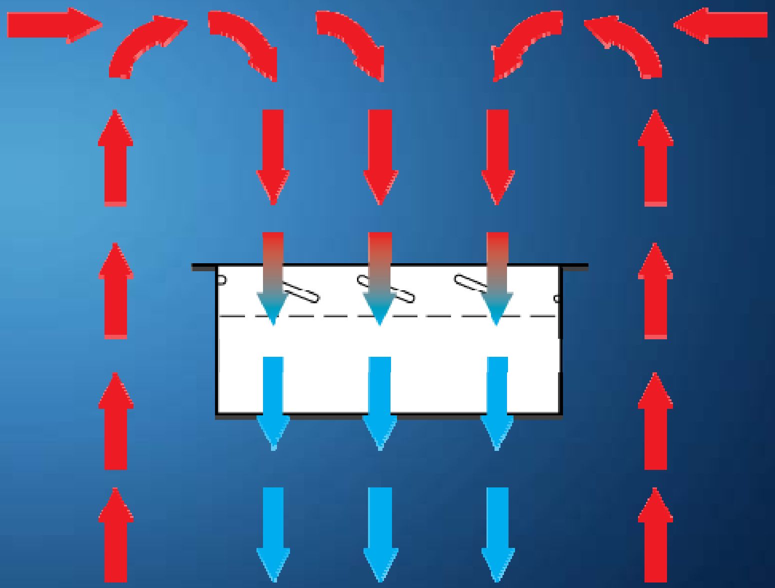
Systems – Passive Beam

- Background
  - First installations in 1980s
  - Concentrated passive cooling
  - Displacement ventilation

Systems – Passive Beam

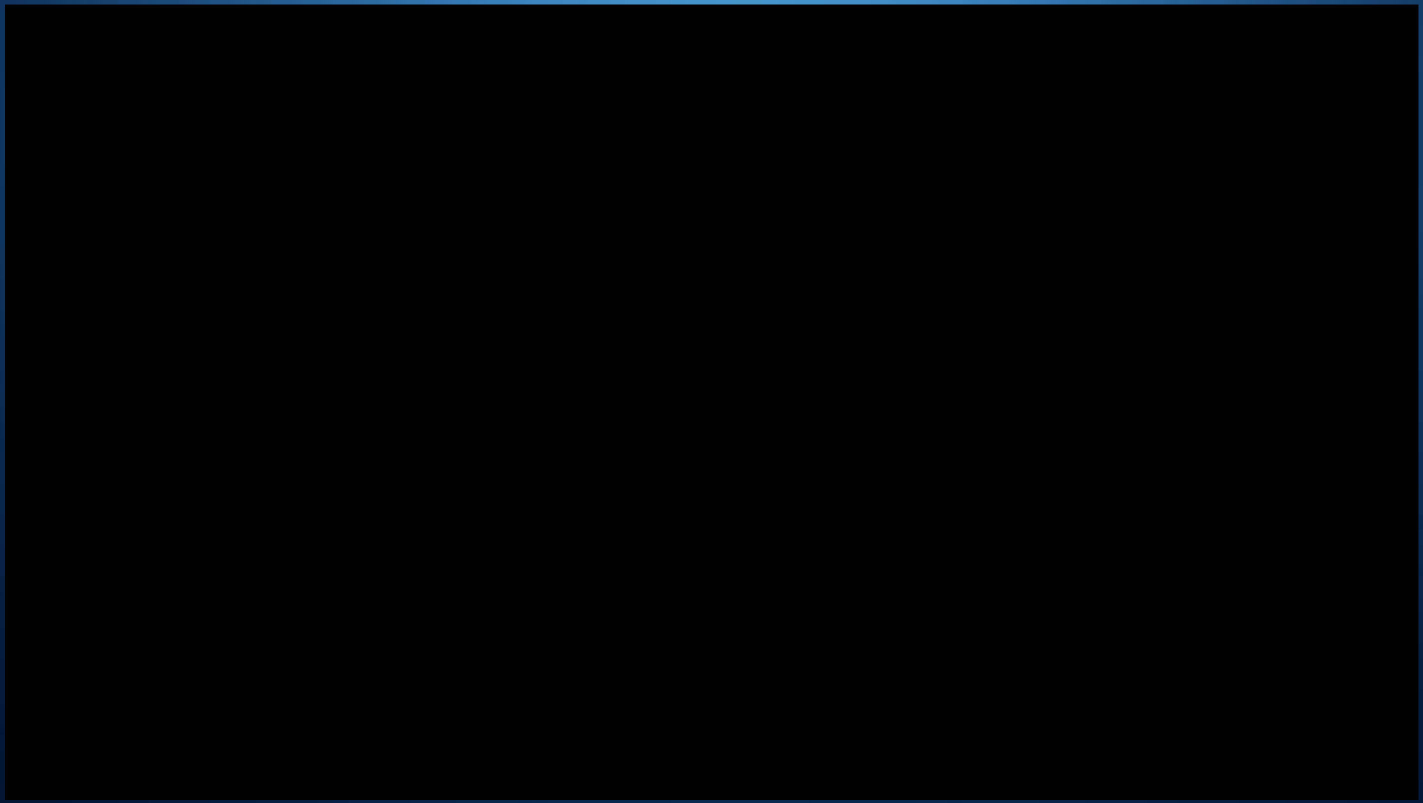
Operation

- Warm air pools in ceiling space
- Air cools on contact
- Cooling is density driven
- Velocity related to cooling capacity.



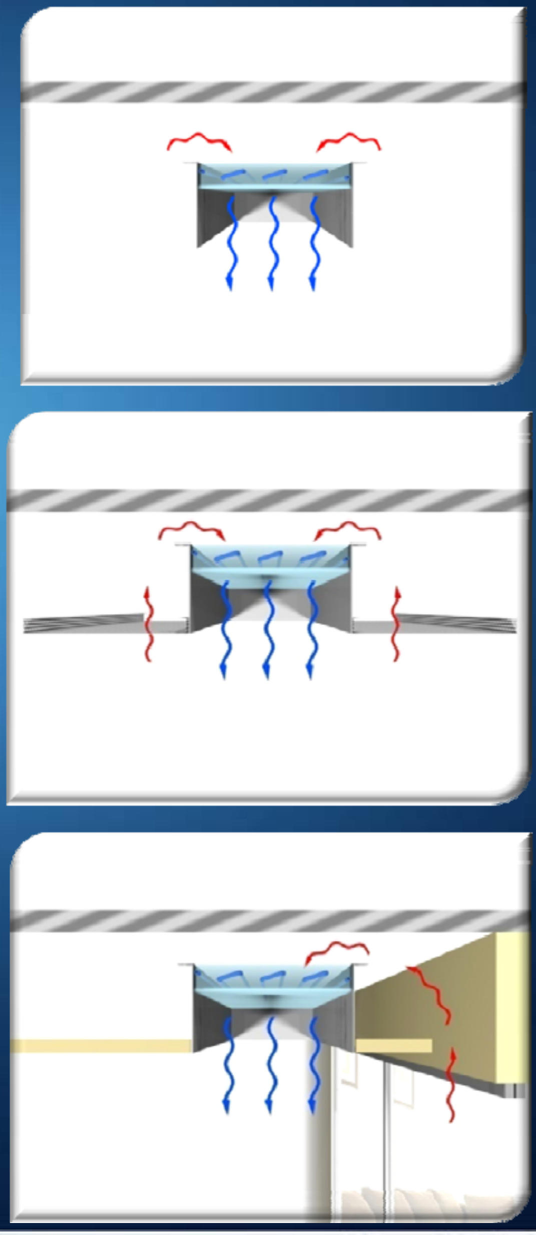
Systems – Passive Beam

- Passive beam
  - 12” x 48” beam in 24”x48” grid ceiling



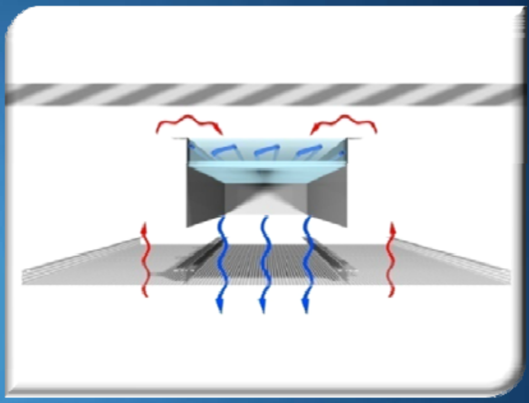
Systems – Passive Beam

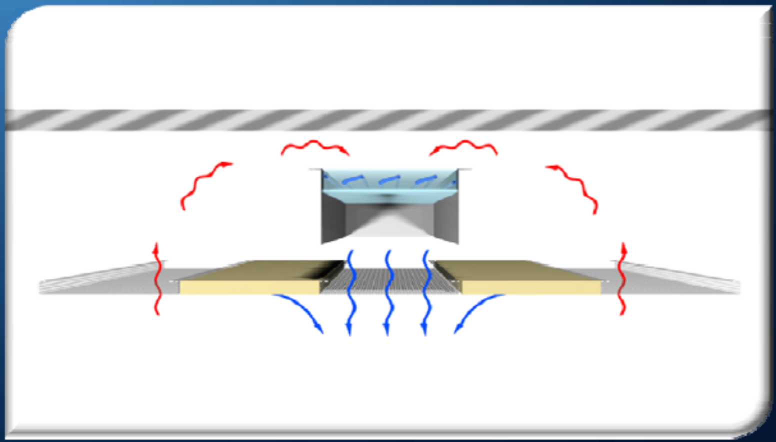
- Application
  - o At least ¼ of width above beam for air flow
  - o Free area ≥ ½ the area of the beam face
  - o Perimeter applications
    - Offset from the heat source
    - May need to capture the warm current



Systems – Passive Beam

- Application
  - Perforated ceiling
    - Offset spreads out cool air, reduces velocity
    - Metal ceiling cools, acts like radiant panel
    - Free area should be within 20’ of beam





Systems – Passive Beam

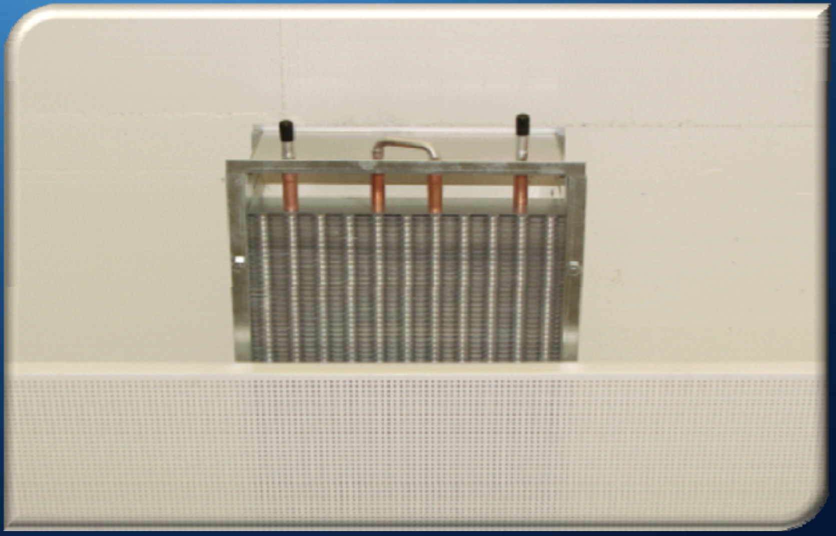
- General Guidance
  - Allow warm air to rise
  - Higher temperature air = higher capacity
  - Velocities above 50 fpm at ~250 Btu/hr ft
  - Avoid locating over heat sources
    - Offset to prevent collisions
    - May chill sedentary occupants
  - Acts like DV air
  - Avoid disturbing air flow patterns
    - Move cooled below beam
  - Maintain cooling without primary air

Systems – Passive Beam

Typical Operating Conditions

	Cooling	Heating
EWT	Dew point + 2°F	n/a
Water ΔT	2 – 6°F	n/a

- Parallel or series piped



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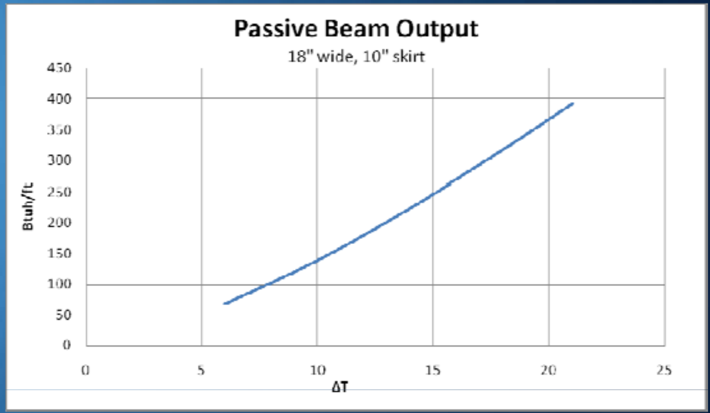
Passive Beam Performance

- Standardized test methods
  - EN 14518
- Catalogued based on MWT – T_{air}
  - Relates to Btu/hr ft
- Capacity corrections:
  - Skirt height
  - Unit width
  - Free space above unit
  - Return below the unit > 50% free area – no correction
  - Free area > 60% for supply – no correction
  - Perforation hole size (larger is better)



Systems – Passive Beam

- Lower supply air requirement
- Maintain cooling with high temperature source water

Systems – Passive Beam

- Works together with DV to provide cooling
- Provides cooling minimum visibility

Systems – Active Beam

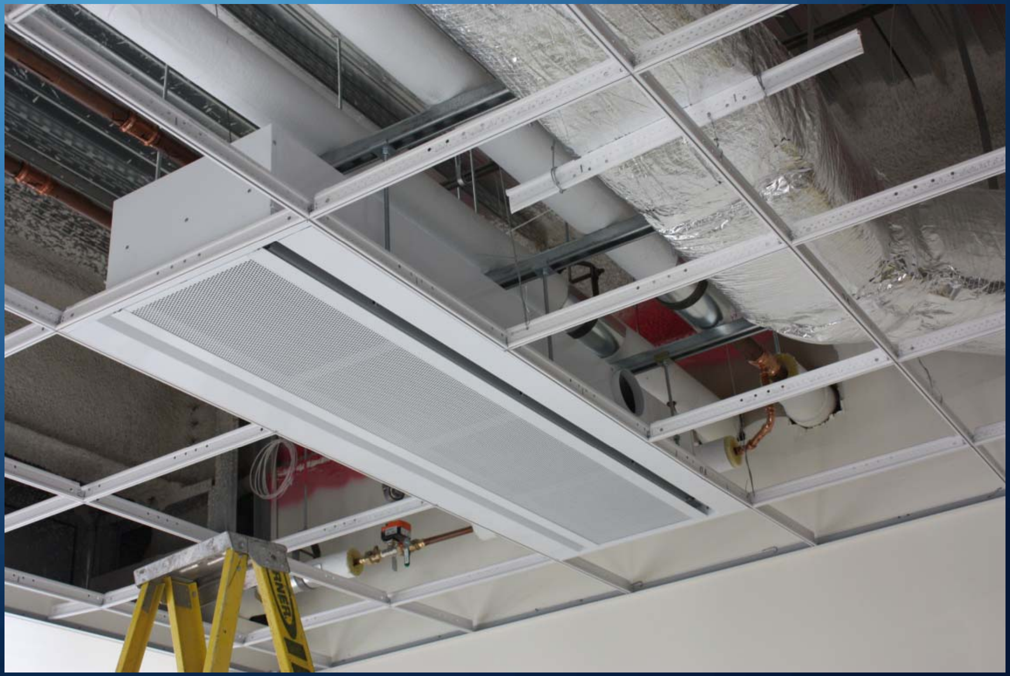
Purpose:

Active cooling device using minimal primary air inducing secondary air to provide cooling / heating.

Dependent on temperature differential between air and water.

Systems – Active Beam

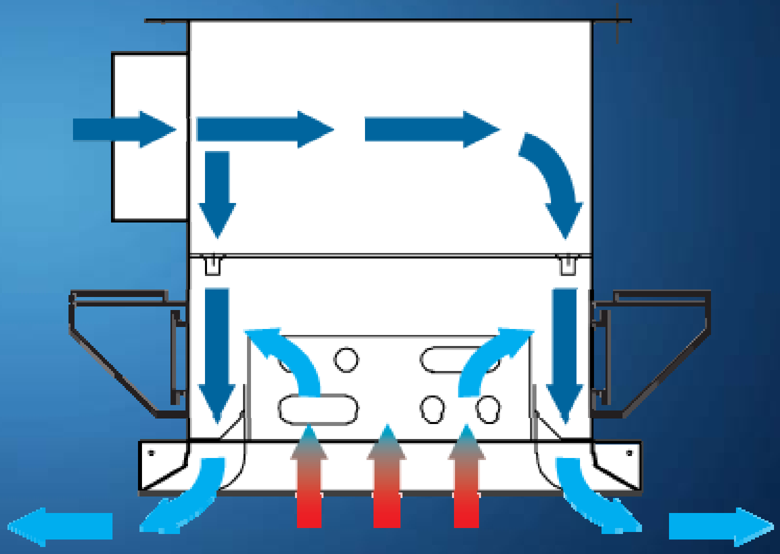
- Background
  - Original theory with induction units - old
  - Installations in 1990s in Europe
  - Extension of the passive beam



Systems – Active Beam

Operation

- Primary air
  - Minimal amounts
  - Forced through nozzles
- Secondary air
  - Drawn up through coil
- 2 or 4 pipe

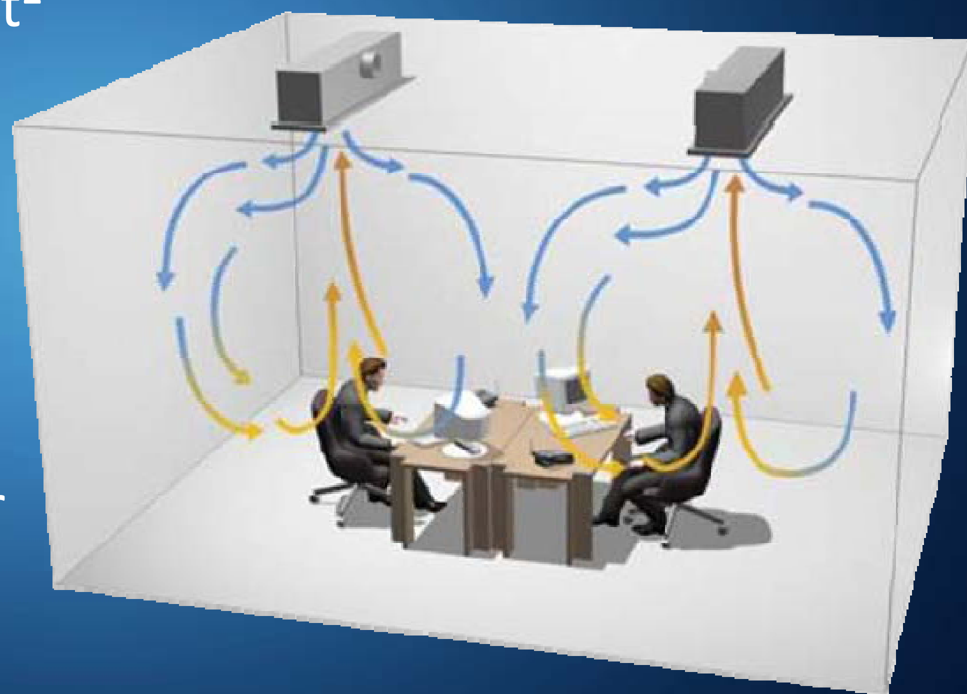


Systems – Active Beam

- Active beam
  - 12” x 48” beam in 24”x48” grid ceiling

Systems – Active Beam

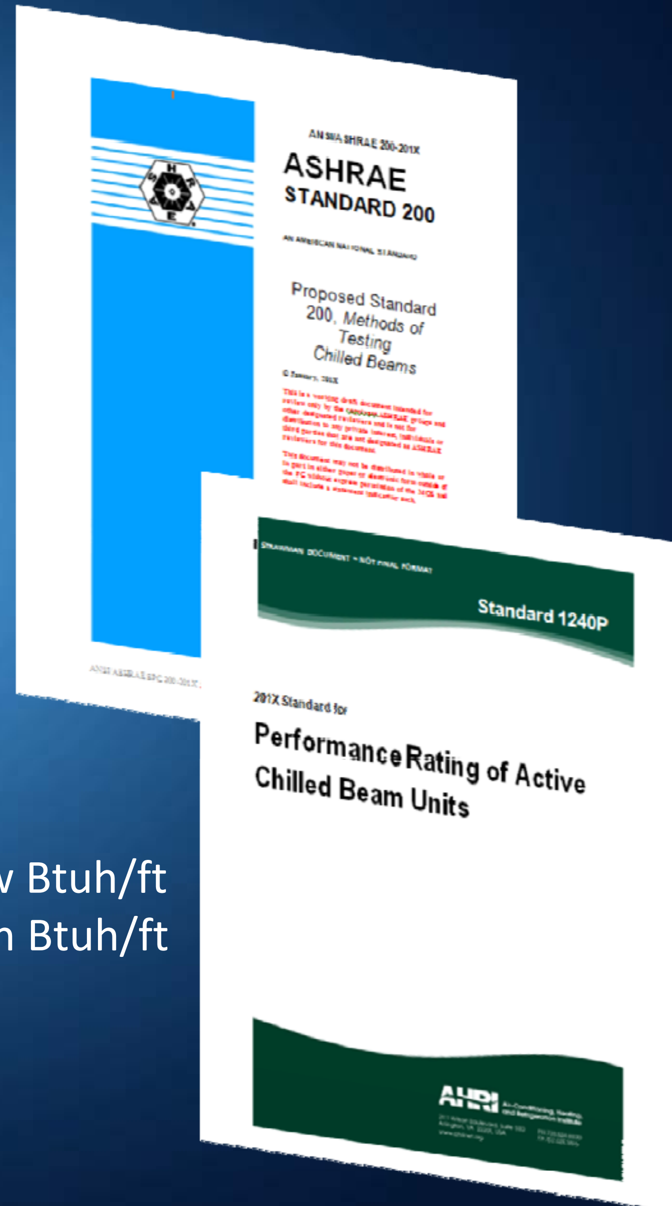
- Application
  - Typically 35-40 Btu/hr ft^2 without draft
  - Flexible design
  - Types
    - 1 way
    - 2 way
    - 4 way
  - Use thermal plumes for capacity



Systems – Active Beam

Active Beam Performance

- Standardized test methods
  - EN 15116
  - ASHRAE – in development
- Catalogued based on MWT – T_{air}
  - Based on nozzle configuration
- Capacity considerations
  - Nozzles
    - Pressure drop
    - Trade-off:
      - Small nozzles = high Btuh/cfm, low Btuh/ft
      - Large nozzles = low Btuh/cfm, high Btuh/ft
  - Primary air temperature
    - High primary air temperature



General Guidance

- Minimize air, maximize water
- Increasing air/ft increases capacity
  - increased induction = increased cooling/heating capacity
  - increased throw = increased ΔP = increased noise
- Constant volume typical, VAV possible
- Location
  - 12’ ceiling
  - Thermal plumes
- Temperature control with water
- EWT < 140°F
- Low height

Systems – Active Beam

General Guidance

- Maintenance

Beam Maintenance Costing - 20 year period

source: Rehva, Chilled Beam Application Guildebook, REHVA Guidebook 5, 2004, p10

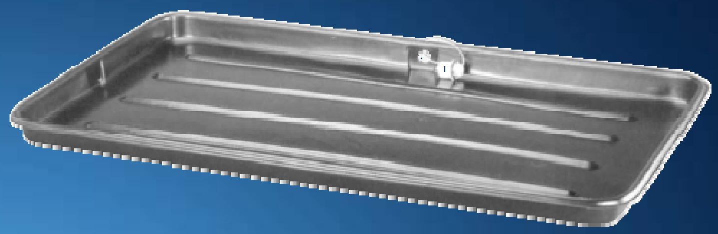
Maintenance of Fan Coil Terminal Units over 20 years

Number of FC Terminal units	150	
Filter change		
Number times per year	2	
Cost per filter	$25	
Hours per filter	0.25	
Labour cost per hour	$20	
		$180,000
Condensate system cleaning		
Number times per year	1	
Hours per terminal	0.25	
Labour cost per hour	$20	
		$15,000
Terminal unit motor replacement		
Cost per motor	$200	
Hours per motor	2	
Labour cost per hour	$20	
		$36,000
Total per 20 year span		**$231,000**

Maintenance of Chilled Beams over 20 years

Number of chilled beams	300	
Number of years per cleaning	5	
Hours per beam	0.25	
Labour cost per hour	$20	
		$6,000
		$6,000

General Guidance



- Condensation trays?
  - o Consider ASHRAE 62.1
    - Inspected for growth – min 1x annually (+$)
    - Cleaned if growth found (+$)
    - Connected to a removal system (+$)
    - Field tested or certified slope
    - Coils expected to be wet need MERV6 filter – loss of capacity
    - Wet coils attract dust caking and required cleaning (+$)
  - o Consider health
    - Biological growth can lead to health issues

Systems – Active Beam

Typical Operating Conditions

	Cooling	Heating
SAT	55 – 65°F	60 – 90°F
Airflow Rate	3 – 25 cfm/ft	
EWT	Dew point + 2°F	90-140°F
Water ΔT	2 – 6°F	10-20°F
Water Flow Rate	min – 0.4 gpm max – 2 gpm	
Water ΔP	0 - 10’	
Air ΔP	0.2 – 0.75” target 0.4”-0.6”	

- Parallel piped

Systems – Active Beam

- Installation
  - Threaded rod to hangers
    - Speed rail for adjustment
  - Horizontal duct entrance typical

Systems – Active Beam

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Installation

- Coil connections
  - Options:
    - Bare – Solder, Braze, press on, push on
    - NPT
  - Connection
    - Hard pipe
    - Flex hose

Design example

- 800 ft² open office space
- 8 people
- Load
  - Sensible - 28,000 Btu/hr
  - Latent - 1,600 Btu/hr
- Design point conditions
  - 75°F db/50% RH (65 gr/lb)
  - Min ventilation (ASHRAE 55) = 88 cfm

Systems – Active Beam

Design example

- Latent load:
  - Supply air
    - RTU: 55°F db/53.5°F wb; w = 58.7 gr/lb
    - DOAS w/heat recovery: 58°F db/54°F wb; w = 55.9 gr/lb
  - 1,600 = 0.68 x cfm x (65 – w)
    - RTU: at w = 58.7 gr/lb, cfm = 373
    - DOAS: at w = 55.9 gr/lb, cfm = 258

Design example

- Roughing in the beams:
  - Use an example beam, no primary air cooling
    - 8’ beam
    - Troom = 75°F
    - SAT = 75°F
    - EWT = dp + 2°F = 57°F
    - Water flow rate = 1.5 gpm
    - ΔP air = 0.5”

Nozzle config	cfm	Coil Btu/hr
A	37	2916
B	55	3161
C	90	4295
D	110	4423
E	166	4846

Systems – Active Beam

Design example

- Roughing in the beams:
  - Add air side cooling
    - 55°F db
  - Get total Btu/hr

Nozzle config	cfm	Coil Btu/hr	Air Btu/hr	Total Btu/hr
A	37	2916	799	3715
B	55	3161	1188	4349
C	90	4295	1944	6239
D	110	4423	2376	6799
E	166	4846	3585	8431

Systems – Active Beam

Design example

- Roughing in the beams:
  - Find capacity per cfm and per length

Nozzle config	cfm	Total Btu/hr	Btuh/cfm	Btuh/ft
A	37	3715	100.4	464
B	55	4349	79.1	543
C	90	6239	69.3	779
D	110	6799	61.8	849
E	166	8431	50.8	1053

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Systems – Active Beam

Design example

- Roughing in the beams:
  - Convert to total cfm and length using load
    - 28,000 Btu/hr

Nozzle config	Btuh/cfm	Btuh/ft	Total CFM	Total Length
A	100.4	464	279	60
B	79.1	543	354	52
C	69.3	779	404	36
D	61.8	849	453	33
E	50.8	1053	551	27

Systems – Active Beam

Design example

- Roughing in the beams:
  - Compare to original min cfm
    - Std RTU: min cfm = 373

Nozzle config	cfm	Total Btu/hr	Btuh/cfm	Btuh/ft	Total CFM	Total Length
A	37	3715	100.4	464	279	60
B	55	4349	79.1	543	354	52
C	90	6239	69.3	779	404	36
D	110	6799	61.8	849	453	33
E	166	8431	50.8	1053	551	27

Systems – Active Beam

Design example

- Roughing in the beams:
  - Compare to original min cfm
    - DOAS w/ heat recovery (higher primary air temp)
      - » min cfm = 258

Nozzle config	cfm	Total Btu/hr	Btuh/cfm	Btuh/ft	Total CFM	Total Length
A	37	3595	97.2	449	288	62
B	55	4171	75.8	521	369	54
C	90	5947	66.1	743	424	38
D	110	6443	58.6	805	478	35
E	166	7894	47.6	987	589	28

Systems – Active Beam

Design example

- Compare and decide

	RTU-1	RTU-2	DOAS-1	DOAS-2
Length - nominal [in]	96	96	120	120
Width - nominal [in]	24	24	24	24
Height - nominal [in]	10	10	10	10
Primary Airflow [cfm]	85	80	47	50
Nozzle Configuration	C	C	A	A
Airside Pressure Loss [in wc]	0.46	0.41	0.51	0.56
Sound Power [NC]	25	23	-	-
Cooling				
Indoor Air Temperature [F]	75.0	75.0	75.0	75.0
Supply Air Temperature [F]	55.0	55.0	58.0	58.0
Water Flow Rate [gpm]	1.12	1.78	2.52	1.46
Water Supply Temperature [F]	57.0	57.0	57.0	57.0
Capacity, water-side [BTUh]	3772	3876	3804	3752
Capacity, air-side [BTUh]	1836	1728	863	918
Total Beam Capacity [BTUh]	5608	5604	4667	4670
Summary				
Quantity	5	5	6	6
Total cfm	425	400	282	300
Total Btu/hr	28,041	28,022	28,002	28,017
Total length	40	40	60	60

Systems – Active Beam

- Operates as linear slot diffuser
- Integrates with tile grid, drywall

Systems – Active Beam

- 1 way throw
- Located at bulkhead

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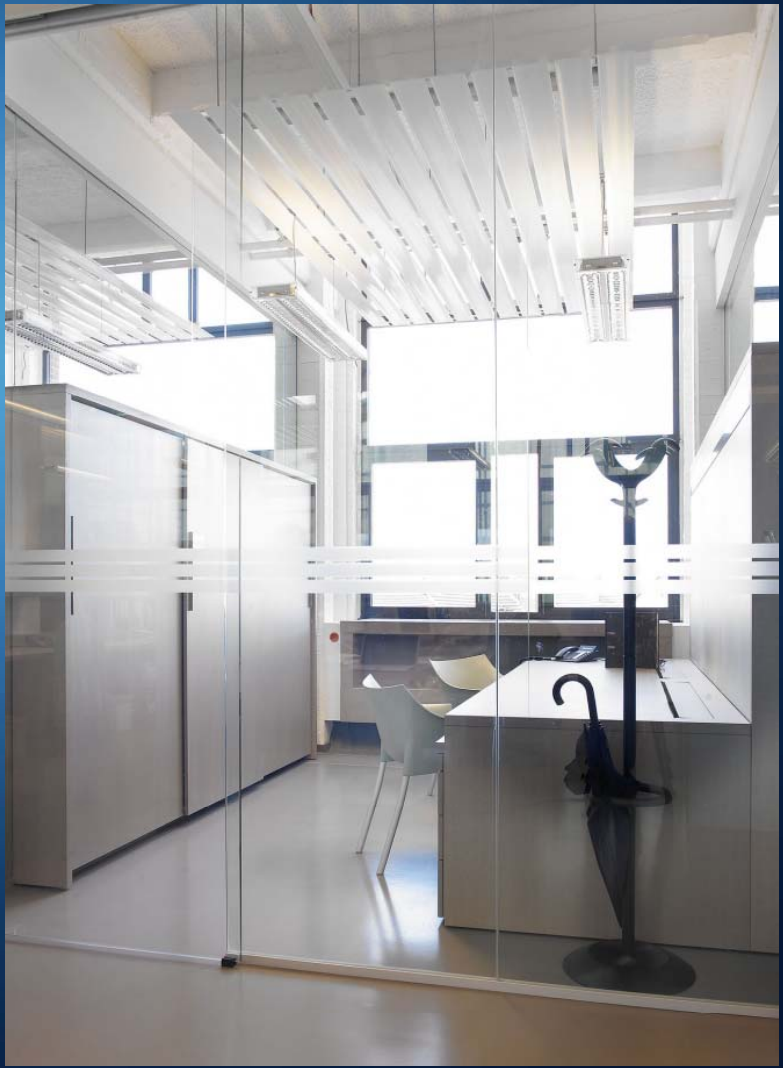
Systems – Chilled Sail

Purpose:

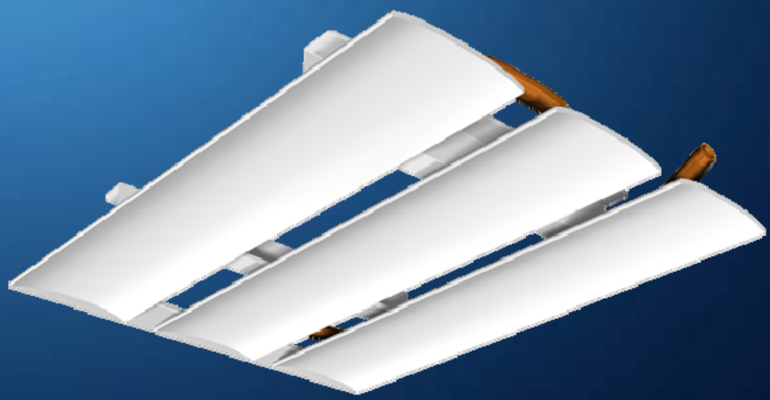
Passive cooling device combined radiant and convective cooling

Cross between radiant panel and passive beam.



Systems – Chilled Sail

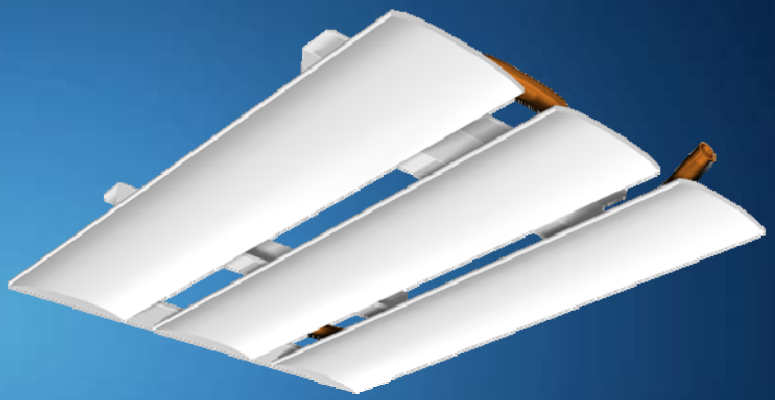
- Background
  - o Installations from late 1990
  - o Blend of radiant and convection
    - More cooling
    - Reduce draft risk

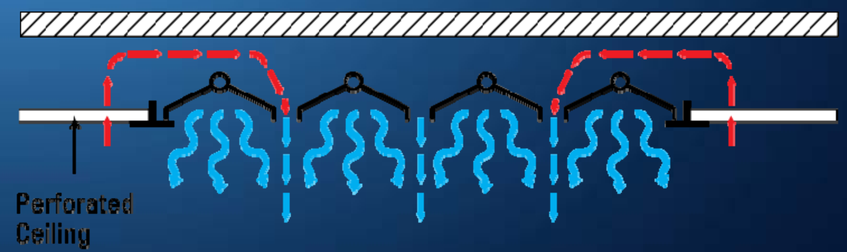


Systems – Chilled Sail

Operation

- Warm air contacts cool elements
- Surface temperature activated for radiant exchange





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Systems – Chilled Sail

- Chilled sail
  - 24” x 48” exposed sail

Systems – Chilled Sail

- Application
  - Combined with other ventilation sources
  - Flexible design
  - Types
    - Exposed
    - Concealed
  - Increases total cooling capacity in area

Systems – Chilled Sail

General Guidance

- Minimize air, maximize water
- Takes advantage of operative temperature
- Active building mass
- Locate over occupants
- Higher surrounding temperatures increase convection
- Ventilation
  - Works best with DV
  - Blow O/H cool air elsewhere
- Heating is application specific
- > 60% of ceiling space reduces capacity

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Systems – Chilled Sail

Typical Operating Conditions

	Cooling	Heating
EWT	Dew point + 2°F	Application specific
Water ΔT	2 – 6°F	Application specific

- Parallel or series piped

Design Example

- Single occupant office
  - 10’x10’
  - Exposed ceiling deck, sails at 9’
  - Latent load = 220 Btu/hr
  - Sensible load = 3,500 Btu/hr
  - Min ventilation = 20 cfm
  - SAT = 45°F db/45°F wb (w = 44.3 gr/lb)
  - T_{room} = 77°F db/63.6°F wb (w = 67.1 gr/lb, dp = 56°F)
  - $T_{operative}$ = 75°F
  - EWT = 58°F

Systems – Chilled Sail

Design Example

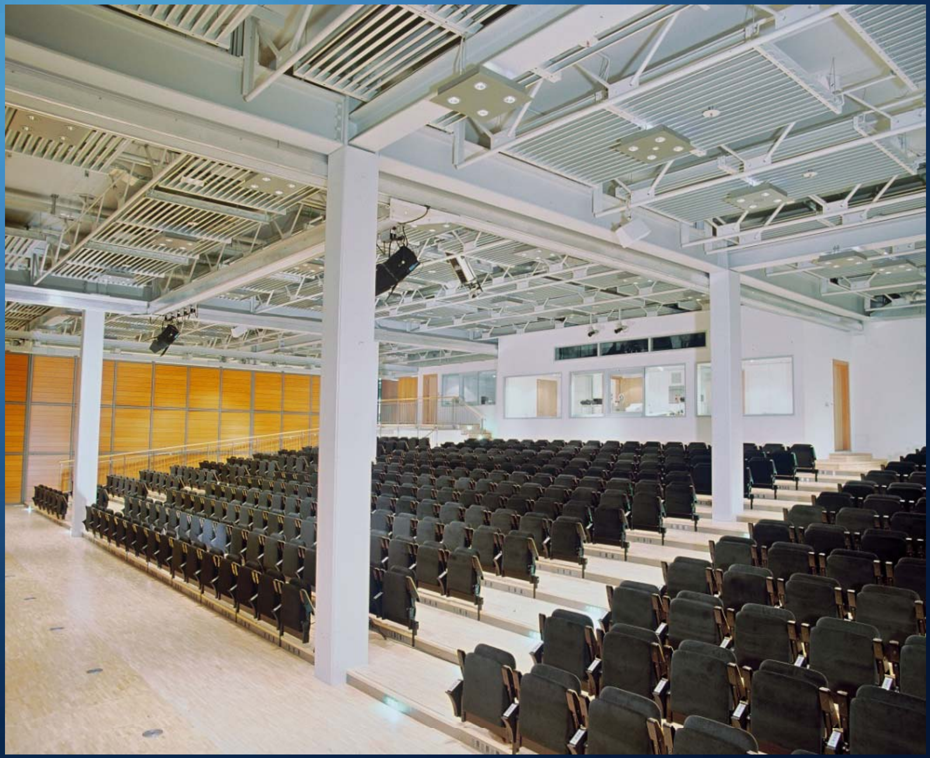
- Sail capacity = 50.7 Btu/hr ft^2
  - Troom = 77°F
  - EWT = 58°F
- Air sensible capacity
  - Q = 1.08 x cfm x ΔT = 1.08 x 20 x (77-45) = 691 Btu/hr
- Air latent capacity
  - Q = 0.68 x cfm x Δw = 0.68 x 20 x (67.1-44.3) = 310 Btu/hr
- DP < EWT
- Remaining sensible load
  - 3,500 – 691 = 2809 Btu/hr
  - At 50.7 Btu/hr ft^2 = 55 ft^2
  - Use 3 @ 2.5'x 8' (60 ft^2)

Systems – Chilled Sail

- Classroom environment with operable windows
- Maintain comfort with minimum air

Systems – Chilled Sail

- High radiant exchange with ceiling sail
- Displacement ventilation air supply



Review of technology

Comparison of technologies

Based on common operating conditions

	Panels	Sails	Passive Beam	Active Beam
Cooling	Up to 30 Btuh/ft²	50-55 Btuh/ft²	100 – 500 Btuh/ft	400 – 1000 Btu/ft
Heating	> 90 Btuh/ft²	Application specific	None	500 – 1400 Btu/ft
Ventilation	None	None	None	Integrated

Review of technology

Review of applications

	Panel	Sail	Passive beam	Active Beam
Office	good	good	good	good
Laboratory	good	good	good	good*
Classroom	Fair	good	good	fair
Renovation	good*	good*	good*	good*
Healthcare	good	?	?	?

Systems design

“Low grade” energy sources

Cooling water	Heating Water
Ground source heat pump	Ground source heat pump
Zone to zone heat pump	Condensing boiler
Dehumidification leaving water	Solar
Economizer	
Evaporative Cooling	
Open pond	

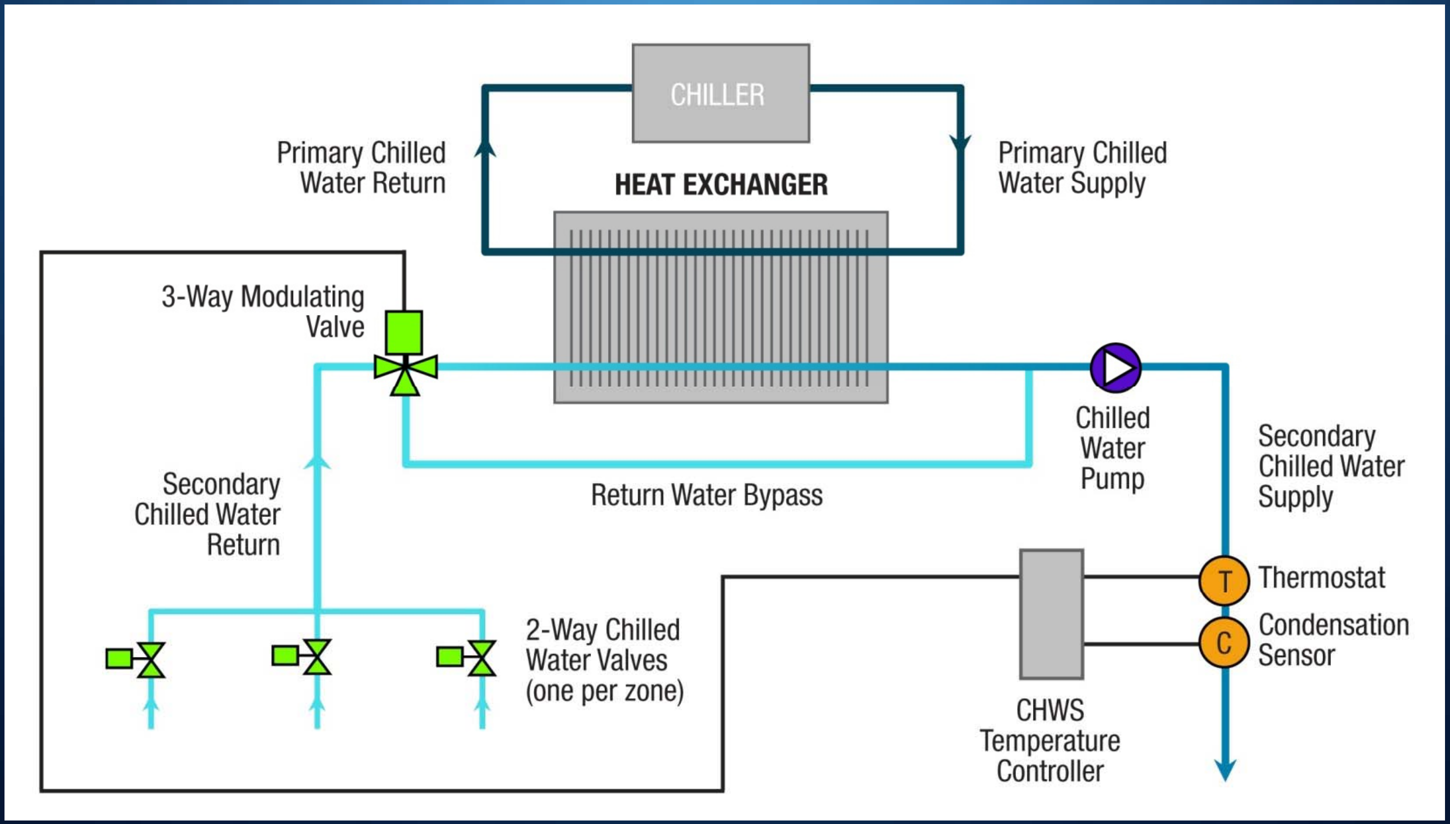
Costing Comparisons

Variations from average design

Higher	Lower
Piping	Ducting
Valving	Fan and dehumidification equip.
Hydronic components	Plenum depth (fl. to fl. height)
Additional chiller (?)	Support infrastructure
Cooling/heating technology (?)	Riser/mechanical space
	Chiller operating cost
	“low grade” energy usage
	Annual maintenance
	Architectural ceiling (visible sail)

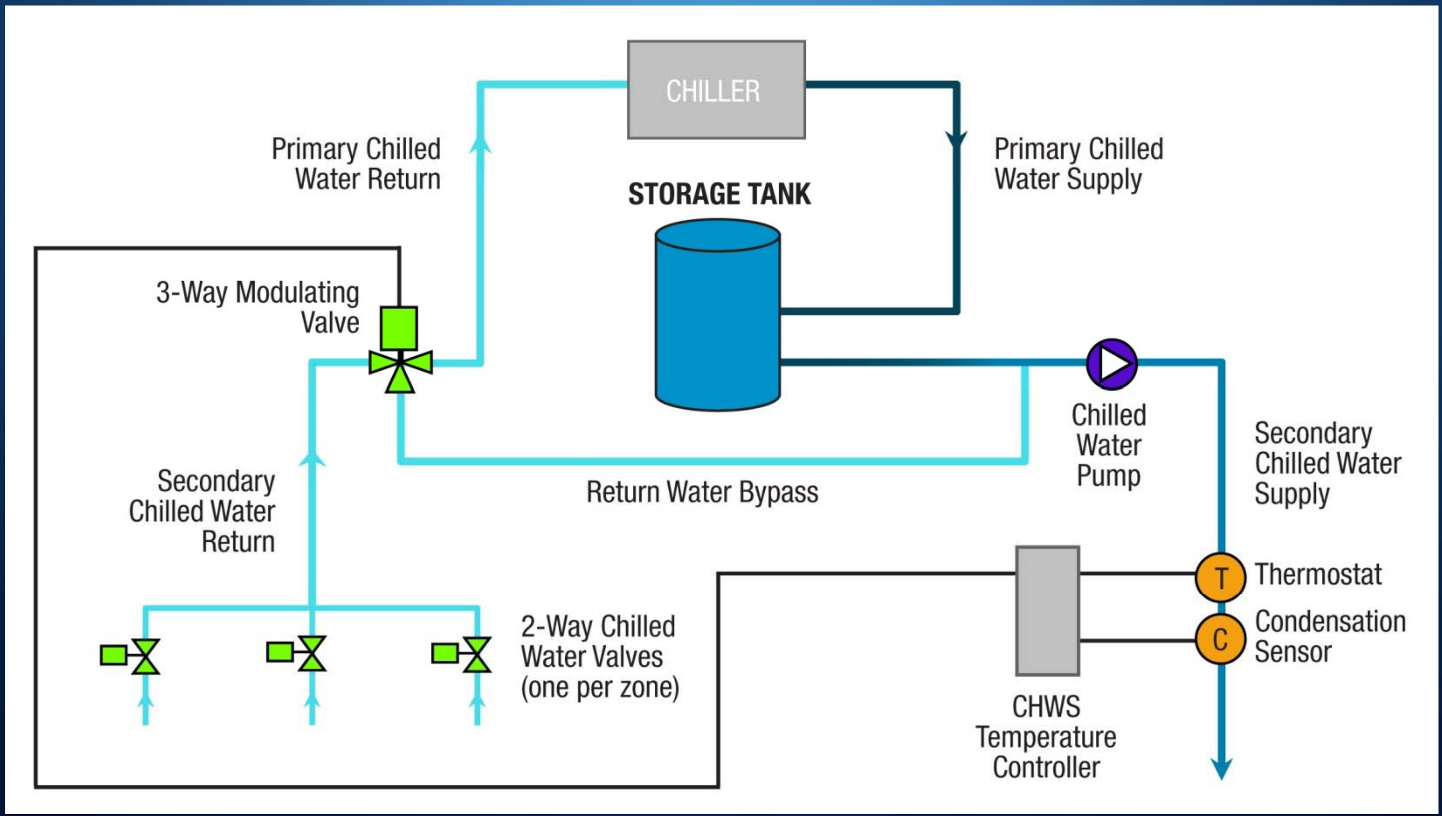
System Design

Piping – shared chiller



System Design

Piping – staging tank



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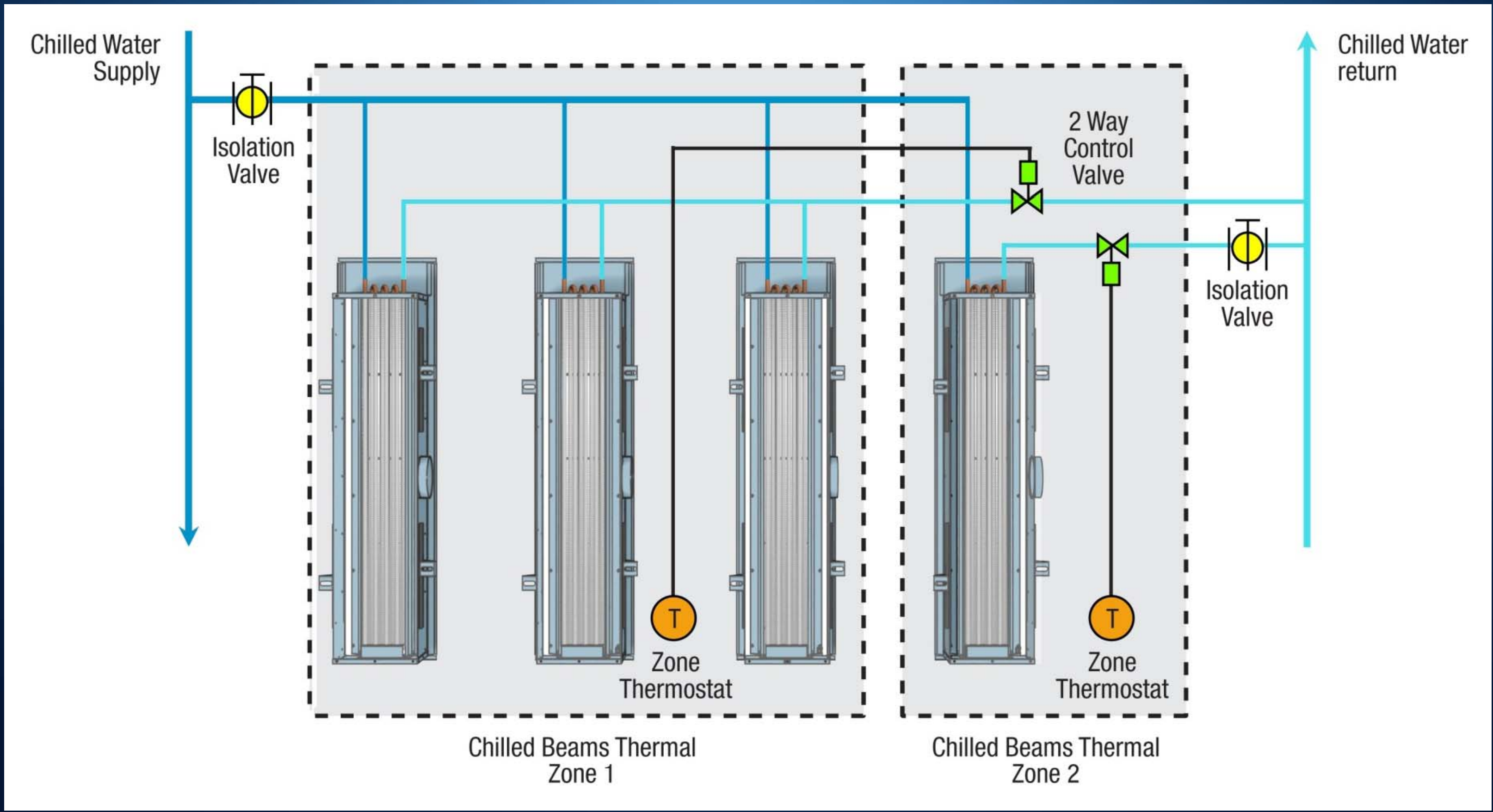
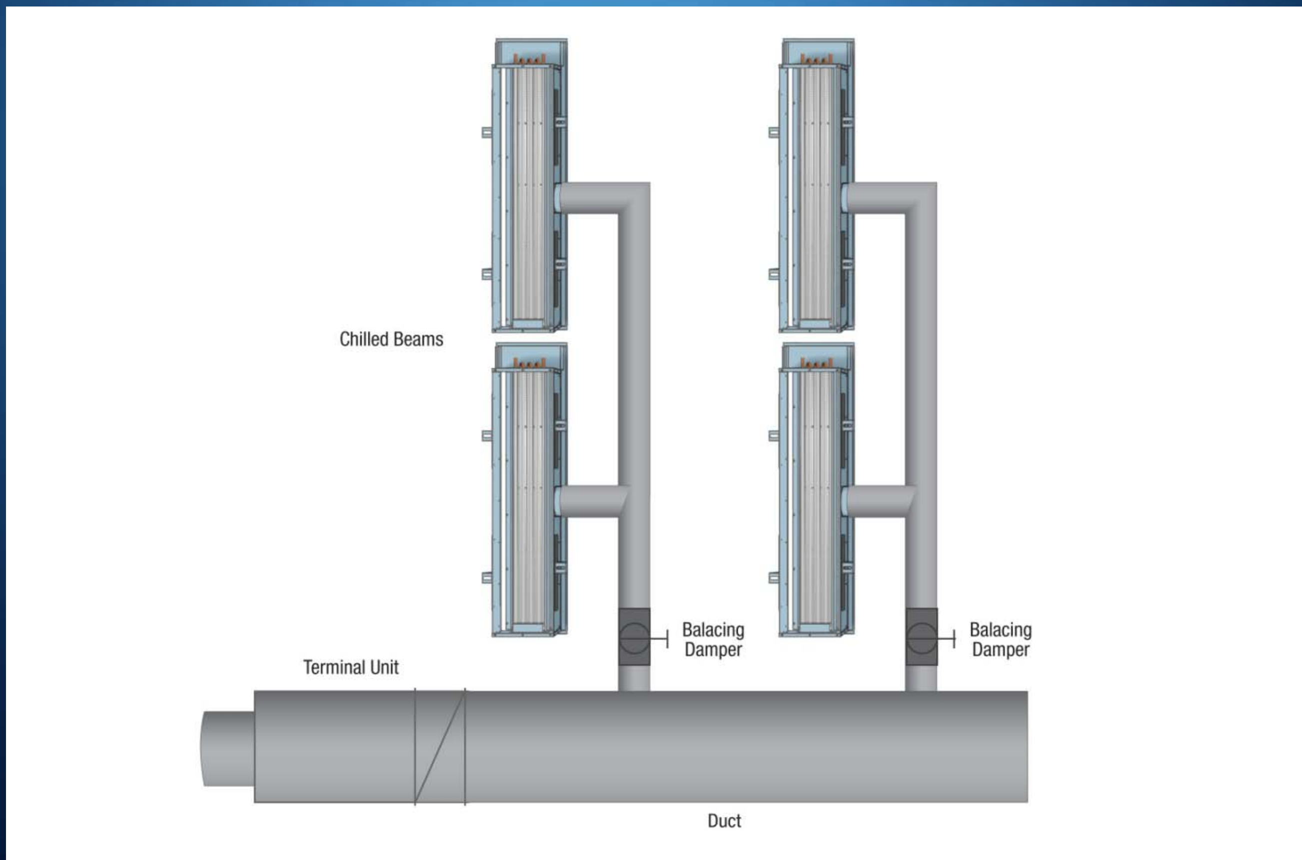
System Design

Piping – supply and control



System Design

Ducting



System Design

Commissioning

- Water flow rates
- Nozzle configuration (active beam)
- Plenum pressure = cfm (active beam)

QUESTIONS?