

Kohta Ueno

Building Science Experts' Session
Special Use Facilities



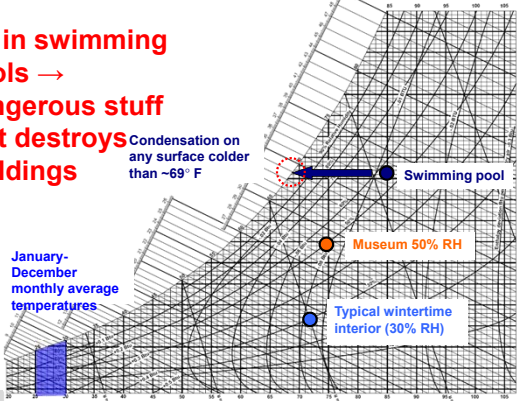
Swimming Pools: Basics & Assemblies



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Swimming Pool Conditions

Air in swimming pools → dangerous stuff that destroys buildings




Condensation on any surface colder than -69°F

Swimming pool

Museum 50% RH

Typical wintertime interior (30% RH)

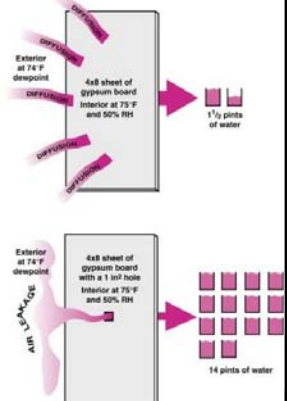

January-December average monthly temperatures



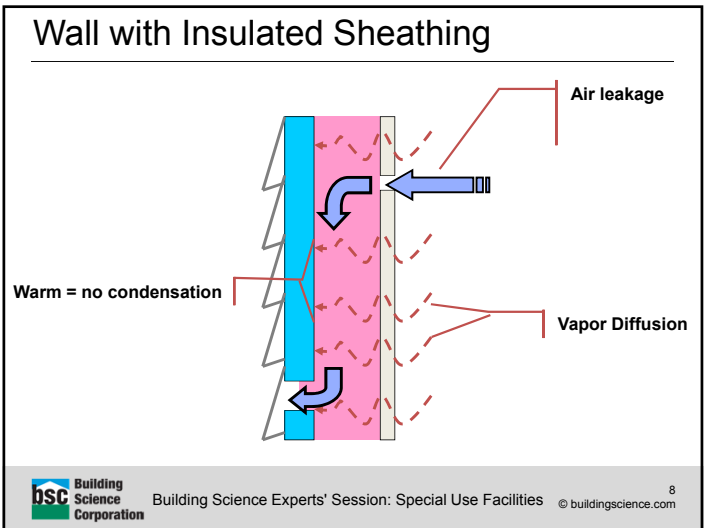
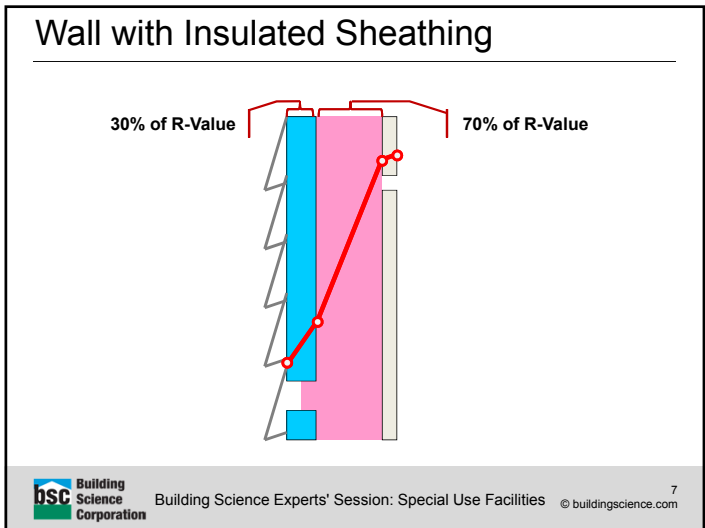
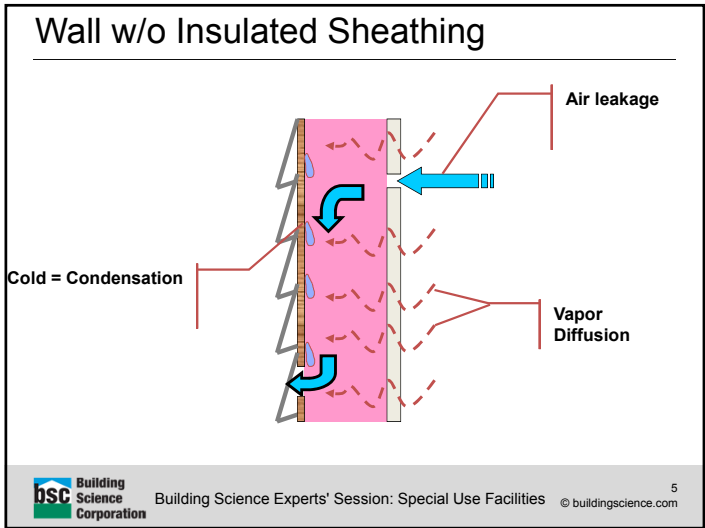
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Vapor Diffusion vs. Air Leakage

- Vapor Diffusion**
 - more to less vapor
 - no air flow
 - flow through tiny pores
- Air Convection**
 - more to less air pressure
 - flow through visible cracks and holes
 - vapor is just along for the ride

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"Perfect Wall"

The diagram illustrates a wall cross-section with a blue insulation layer on the left. Red dashed arrows represent air leakage and vapor diffusion moving from left to right. A blue arrow indicates air flow being blocked by the wall. Text labels include: '~100% of R-Value' pointing to the insulation, 'Warm = no condensation' on the left side, 'Air leakage' at the top right, and 'Vapor Diffusion' at the bottom right.

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The Perfect Wall

- Structure (protected)
- Air-water-vapor barrier ("Control layers")
- Insulation
- Ventilated gap ("Rainscreen")
- Exterior cladding

The diagram shows a wall cross-section with three main layers from left to right: 'Cladding' (a vertical brick-like pattern), 'Control layers' (a thin vertical line), and 'Structure' (a thick vertical grey block). A blue arrow points from the cladding towards the structure, passing through the control layers.

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The "Perfect" Wall: Higher Performance

This diagram shows a multi-layered wall assembly. From left to right, the layers are: Brick veneer/stone veneer, Drained cavity, Exterior rigid insulation — extruded polystyrene, expanded polystyrene, isocyanurate, rock wool, fiberglass, Membrane or trowel-on or spray applied drainage plane, air barrier and vapor retarder, Concrete block, Metal channel or wood furring, Gypsum board, and Latex paint or vapor semi-permeable textured wall finish. A blue double-headed arrow at the bottom is labeled 'Vapor Profile'.

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The Commercial Steel Frame Wall

This diagram shows a wall assembly for a commercial steel frame. From left to right, the layers are: Brick veneer/stone veneer, Drained cavity, Exterior rigid insulation — extruded polystyrene, expanded polystyrene, isocyanurate, rock wool, fiberglass, Membrane or trowel-on or spray applied drainage plane, air barrier and vapor retarder, Non paper-faced exterior gypsum sheathing, plywood or oriented strand board (OSB), Uninsulated steel stud cavity, Gypsum board, and Latex paint or vapor semi-permeable textured wall finish. A blue double-headed arrow at the bottom is labeled 'Vapor Profile'.

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Wood Frame Perfect Wall

Existing wood framing
 Cementitious plaster
 1/2" exterior plywood sheathing
 Self-adhered membrane (air, water and vapor barrier)
 4" rigid foil-faced polyisocyanurate insulation (two layers of 2" insulation); tape horizontal and vertical joints
 1x3 wood furring
 Furring attached with 6" heavy-duty flat head coated screws spaced vertically at 24" o.c.
 Shiplapped siding
 1/2" vented mesh
 Insect screen closure at base of wall
 Metal flashing

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Conceptual Pool Enclosure

Vented roof
 All structural loads, okay, not the trusses but you know what I mean
 Thermal control layer outside of air and vapor control layers
 Continuous air control and vapor control layer outside of structure
 Ventilated cladding
 All services inside, air, not some, air and I really mean it

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Roof-to-Wall Connection

- Perfect wall
- Vented roof
- All mechanicals inside shell
- Thermal bridging at steel truss
- Roof-to-wall air/vapor barrier connection

Truss
 Metal roof
 Fully-adhered roofing membrane
 Roof sheathing
 Metal roof deck
 Gypsum board air control layer
 Liquid applied vapor control layer
 2x4 timber truss
 Vented soffit
 2x continuous wood thermal break
 Sheat metal closure strip
 Surface-mounted fixtures
 Metal cladding
 Nail channel
 Thermal control layer
 Water control/air control/vapor control layer
 Service space
 Interior lining
 Dropped ceiling

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Cathedral Vented Roof

- "Perfect wall" built on a slope

Roof sheathing
 Shingles
 Roofing paper
 Minimum R-50 rigid insulation in two or more layers with horizontal and vertical joints staggered
 Plywood roof sheathing
 Roofing membrane (vapor permeable liquid applied or roofing felt)
 Vented space
 Air control layer/vapor control layer
 Wood decking
 Timber rafter or exposed joist

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Low-Slope ("Flat") Roof

- Only works for Climate Zone 4 and warmer

Labels in diagram: Fully-adhered roofing membrane, Coverboard and hygric buffer, Rigid insulation (min. two layers; joints offset), Screw attachment, Gypsum sheathing (paperless), Fully-adhered air control layer/vapor control layer, Metal deck.

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Low-Slope ("Flat") Roof

- For Climate Zone 5-ish

Labels in diagram: Fully-adhered roofing membrane, Coverboard and hygric buffer, Intermediate plywood layer; joints sealed, Screw attachment to intermediate plywood layer, Screw attachment to structural deck, Rigid insulation, Gypsum sheathing (paperless), Fully-adhered air control layer/vapor control layer, Metal deck.

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Inverted Membrane Roof

- Entirely safe: "perfect wall" as roof
- Top side could be ballast, pavers, "green roof"

Labels in diagram: Ballast, Filter fabric, Control layers, Roof structure.

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Inverted Membrane Roof

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Labels in diagram: Ballast, Filter fabric, Control layers, Roof structure.

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All-Foam Roof: How Thick?

TABLE R402.1.2
INSULATION AND FENESTRATION REQUIREMENTS BY COMPONENT*

CLIMATE ZONE	FENESTRATION U-FACTOR ¹⁾	SKYLIGHT ²⁾ U-FACTOR	GLAZED FENESTRATION SHGC ^{3), 4)}	CEILING R-VALUE	WOOD FRAME WALL R-VALUE	MASS WALL R-VALUE ⁵⁾	FLOOR R-VALUE	BASEMENT ⁶⁾ WALL R-VALUE	SLAB ⁷⁾ R-VALUE & DEPTH	CRAWL SPACE ⁸⁾ WALL R-VALUE
1	NR	0.75	0.25	30	13	3/4	13	0	0	0
2	0.40	0.65	0.25	38	13	4/6	13	0	0	0
3	0.35	0.55	0.25	30	20 or 13+5 ⁶⁾	8/13	19	5/13 ⁷⁾	0	5/13
4 except Marine	0.35	0.55	0.40	49	20 or 13+5 ⁶⁾	8/13	19	10/13	10, 2 ft	10/13
5 and Marine 4	0.32	0.55	NR	49	20 or 13+5 ⁶⁾	13/17	30 ⁸⁾	15/19	10, 2 ft	15/19
6	0.32	0.55	NR	49	20+5 or 13+10 ⁶⁾	15/20	30 ⁸⁾	15/19	10, 4 ft	15/19
7 and 8	0.32	0.55	NR	49	20+5 or 13+10 ⁶⁾	19/21	38 ⁸⁾	15/19	10, 4 ft	15/19

- 2015 IECC example (residential R-values)
- R-49 = 7.8 inches polyisocyanurate

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All-Foam Roof: How Thick?

TABLE R402.1.4
EQUIVALENT U-FACTORS*

CLIMATE ZONE	FENESTRATION U-FACTOR	SKYLIGHT U-FACTOR	CEILING U-FACTOR	FRAME WALL U-FACTOR	MASS WALL U-FACTOR ²⁾	FLOOR U-FACTOR	BASEMENT WALL U-FACTOR	CRAWL SPACE WALL U-FACTOR
1	0.50	0.75	0.035	0.084	0.197	0.064	0.360	0.477
2	0.40	0.65	0.030	0.084	0.165	0.064	0.360	0.477
3	0.35	0.55	0.030	0.060	0.098	0.047	0.091 ¹⁾	0.136
4 except Marine	0.35	0.55	0.026	0.060	0.098	0.047	0.059	0.065
5 and Marine 4	0.32	0.55	0.026	0.060	0.062	0.033	0.050	0.055
6	0.32	0.55	0.026	0.045	0.060	0.033	0.050	0.055
7 and 8	0.32	0.55	0.026	0.045	0.057	0.028	0.050	0.055

- 2015 IECC Table R402.1.4 equivalent U-values
- U-0.026 = R-38.5 continuous = 6.2 inches polyisocyanurate
- Walls ~3-4 inches polyisocyanurate typical

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Swimming Pools: Residential Pool Case Study

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Roof-to-Wall Connection

Self-adhered or liquid-applied vapor barrier membrane on ceiling gypsum board or sheathing (non-finish layer)

Metal hat channel/z-furring or wood furring strips to create service cavity (wiring, electrical boxes). Size based on required dimensions for services.

Chase with HVAC ductwork inboard of vapor barrier membrane in soffit (sample placement)

See roof-wall connection detail below

Interior gypsum board finish; non-paper faced recommended (DensArmor Plus or equal). Latex paint (non vapor barrier)

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Roof-to-Wall Air Barrier Connection



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Interior & Exterior Air-Vapor Barrier



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Interior & Exterior Air-Vapor Barrier



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Swimming Pools: Closed Cell Spray Foam?

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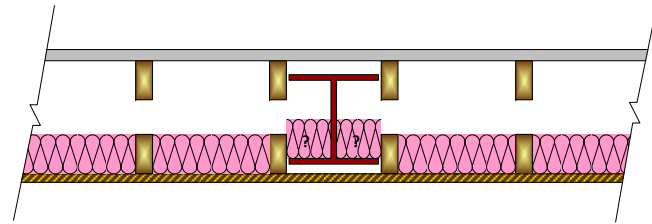
Failed Pool & Architectural Constraints



- “The pool building can’t be a different size than the matching opposite wing.”

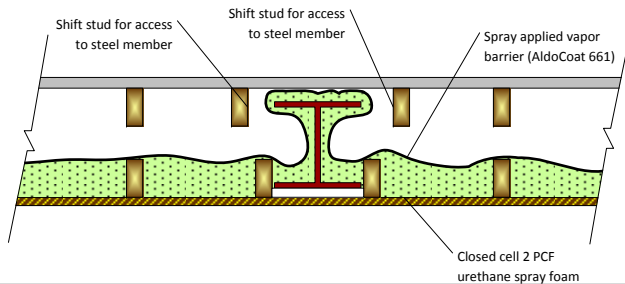
Failed Wall

- Double wall, fiberglass batts, interior plaster



Spray Foam Wall Retrofit

- ccSPF covered with vapor barrier
- Steel “buried” in ccSPF
- Permeable WRB, ventilated rainscreen



Vapor-Permeable Adhered Membrane



- Excellent air barrier
- Ventilated rainscreen—drying of sheathing
- Continued up cathedral roof assembly

Interior Vapor Barrier Coating

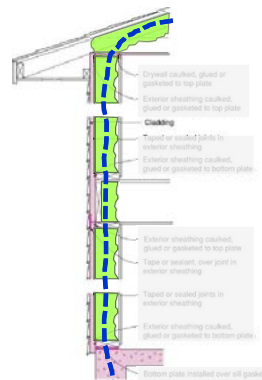
- Applied to interior of ccSPF
- Needed or not?
 - 5.5" ccSPF = 0.3 perms.
 - Class I (under 0.1 perm) recommended
- Continuity of coating (air barrier)
- Problem: compatibility (real or perceived) between ccSPF & coating
 - Solution: same manufacturer for both
- Many Class I materials-VOCs, interior use IAQ

Thermal Bridging at Steel

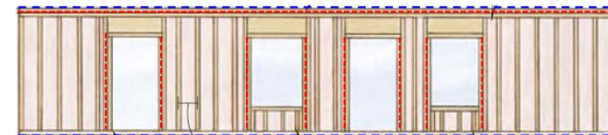


- Steel for hanging interior finishes or mechanicals
- "Bury" foam where possible, come inboard
- Still has risks

Spray Foam as an Air Barrier



Spray Foam as an Air Barrier




- Spray foam doesn't air seal where it isn't there!
- Wood-to-wood connections

Spray Foam as an Air Barrier



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Spray Foam as an Air Barrier


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Spray Foam Pool Enclosure: Takeaways

- Can work if “backed into a corner”
- Not recommended solution/best practice
- Risks from air leakage (imperfections in spray foam if not caught by other layer)
- Annoyances of vapor barrier coating
- Risks from thermal bridging


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Swimming Pools: Case Studies & Failures


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Case Study: Roof-Wall Air Barrier

- Academic pool building stripped, re-insulated, reclad
- Climate Zone 6A
- Efflorescence staining in first winter



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Case Study: Roof-Wall Air Barrier

- "Perfect wall"



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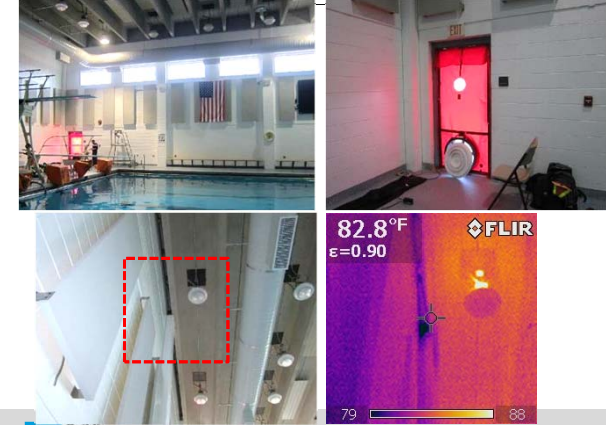
Case Study: Roof-Wall Air Barrier

- Excellent roof (air-vapor barrier below)



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Case Study: Roof-Wall Air Barrier



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Case Study: Roof-Wall Air Barrier

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Run Pools at Negative Pressure

- Contains moisture (outside to inside air leakage)
- Contains odors (pool attached to rest of building)
- Tighter construction = smaller fan needed
- ASHRAE ~ -12 Pa recommended

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Room Pressure Indicator

- "Ball in the wall" (medical, animal labs, etc.)

ADI NEGATIVE PRESSURE ROOM

(AIRFLOW DIRECTION INTO ROOM)

- RED BALL ROLLS IN DIRECTION OF AIRFLOW.
- TUBE TILTS DOWN TOWARDS OUTSIDE OF ROOM FOR FAILSAFE MODE & CHECKING.
- TO CHECK, OPEN DOOR & RED BALL SHOULD GO TO OUTSIDE OF ROOM.
- NORMAL OPERATION: WITH DOOR CLOSED, RED BALL SHOULD GO INTO ROOM.

BALL-IN-THE-WALL®
(888) 334-4545
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Case Study: Pressurized Pool

- Recently rebuilt NH resort pool

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Case Study: Pressurized Pool

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Case Study: Pressurized Pool

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Case Study: Pressurized Pool

- Reused existing mechanical system (ventilation-based dehumidification, not refrigerant-based)
- Pool running at ~+25 Pascals (up to +40 Pa)

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Case Study: Pressurized Pool

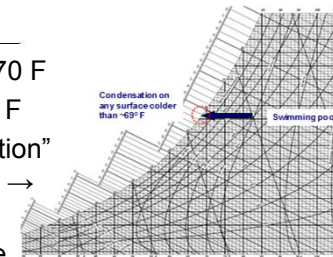
- Pool conditioning system improperly configured
- Pressurized pool + greater airtightness → concentrated air leakage condensation

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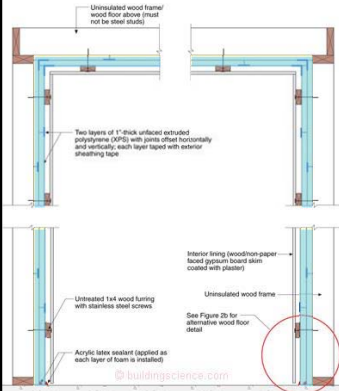
Swimming Pool: Pool-to-Interior Walls

Interior-to-Pool Walls

- Dewpoint of pool air is ~70 F
- Interior typically at 68-75 F
- “Cold-weather condensation” when outdoors is “warm” → relatively low risk
- Condensation & moisture resistant assemblies recommended
- Double glazed for pool-to-interior windows (eliminates window fogging), or blowing heat
- Airtightness—connection to exterior air barrier

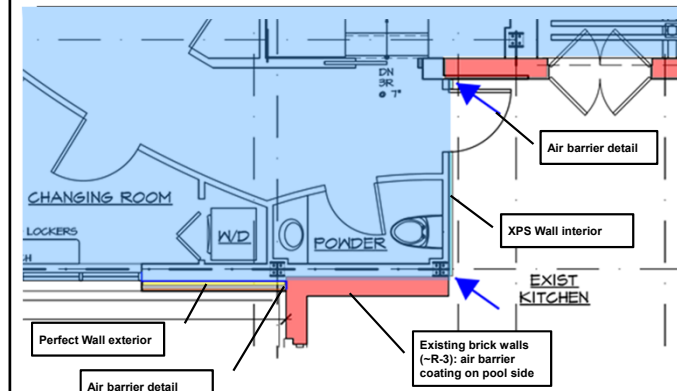


Wine Room Enclosure Assembly



- XPS on one side of empty stud frame
- Taped joints for air barrier continuity
- Furring for interior finishes
- Challenges at ceiling: mechanical penetrations & sequencing
- ccSPF also an option

Interior-to-Pool Wall



Swimming Pool: Takeaways

Pool Enclosure Takeaways

- Air inside pool is “dangerous stuff”
- Perfect wall/roof/slab enclosure ideal
- Contain with negative pressurization (exhaust)
- Pool dehumidification system
 - Limit interior to 50-60% RH. Must run 24/7/365
 - Pool covers will reduce the load
- Windows will always condense (unless triple)
 - Detail assuming interior condensation
- Air leakage testing at air barrier completion
 - Quality control for air barrier failures
 - Can estimate size of required exhaust fan (~ -12 Pa)


Museums

Werner Otto Hall (Harvard)-1991

- Was demolished after 19 years of service
- Pressurized / 50% RH
- Wintertime condensation, walls soaked through
- Icicles from parapets
- Glass block efflorescence
- Harvard sued architect & contractor in 1996
- Repairs done; still demolished in 2010



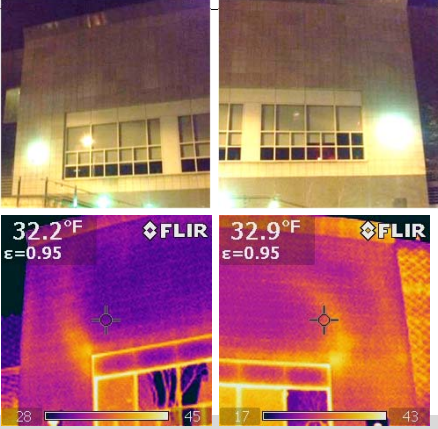
Werner Otto Hall (Harvard)-2008



- Metal panel cladding, sealed joints
- Creates its own weeps!

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Werner Otto Hall (Harvard)-2008




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Museum Storage Building (Insulated Metal Panel)

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Museum Storage Building

- Constant humidified 50% RH (art storage)
- Insulated metal panel (IMP) walls and roofs, simple design
- Climate Zone 6A
- Dripping from ceiling during early fall commissioning
- Dripping stopped with RH dropped to 20%
- Seasonal problems



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IMPs and the Perfect Wall

- BSI-090: Joseph Haydn Does The Perfect Wall
- Perfect air/vapor barriers on both sides of panel

Water control layer, air control layer, vapor control layer and thermal control layer: insulated metal panel

Uninsulated steel stud cavity

Gypsum board

Latex paint or vapor semi-permeable textured wall finish

Exterior face (water control layer, air control layer, vapor control layer)

Thermal control layer

Vapor Profile

Interior face (air control layer and vapor control layer)

Insulated metal panel

Vapor Profile

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IMP Wall Panel Joints

- Double sealant joint
- Thermal break at panel edge
- Drained and “flushed” joint (rain has to push uphill at horizontal joints)

Non-Skinning Butyl Tube (Vapor Sealant) IMP7100
1/4" Uniform Bead (minimum) at location specified

Exterior seal providing continuity of the exterior air control layer and vapor control layer

Interior seal providing continuity of the interior air control layer and vapor control layer

Flushed and drained joint

Direct contact between thermal control layers of adjacent panels provides continuity of the thermal control layer

Wall Member

Exterior Concealed Wall

Max at Interior of Joint

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IMP Roof Panel Joints

- Standing seam w. double sealant joint, thermally broken
- Ridge detail (ccSPF)
- Panel end lap details
- Dripping coming from end laps

Standing seam provides continuity of the water control layer

Exterior seal providing continuity of the exterior air control layer and vapor control layer

Direct contact between thermal control layers of adjacent panels provides continuity of the thermal control layer

Interior seal providing continuity of the interior air control layer and vapor control layer

Detail at High End of Panel

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Minor Thermal Bridging at Roof Clips

- “Grid of dots” on ceiling
- Attachment clips bridge through most of insulation
- Not the source of dripping problems

Field Applied Clip Sealant IMP7412 underside of Clip Tab

Field applied Seam Sealant IMP7406

Panel Clip

Cold Form Member or Parallel Strut Shape and Orientation May Vary

Minimum Bearing Surface

172.7F

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Depressurization Testing

- Depressurized to -60 Pa
- Infrared flow visualization (warm weather outdoors)
- Recommended as quality control during construction



Depressurization Flow Visualization

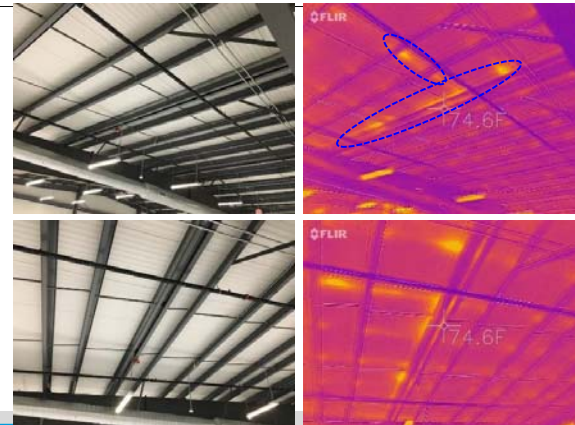


Depressurization Flow Measurement



- Some seams airtight, others leaky
- Airflow 100-300 FPM/feet per minute
- Not obvious from visual inspections

Depressurization Flow Visualization



Roof Dripping Causes

- Interior-to-exterior air leaks (from IR visualization)
- Eave (roof-to-wall) air leaks
- Interior-to-interior air leaks (like SIPS panels)
 - Convective looping

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Retrofit Details (Roof Field)

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“Bag and Sag” Roof for Comparison

- Fiberglass rolls with polyethylene facer
- Steel Z purlins
- Massive condensation in winter-unusable at 50%

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Museum Building Takeaways

- 70F / 50% RH very risky (especially cold climates)
- Insulated metal panel good solution for high-risk buildings, BUT
- Risks are at panel seams & connections
 - Building outdoors in Climate Zone 6A
- IMP seams can't be visually inspected after construction
- Air leakage testing as part of commissioning?
- Or just specify Perfect Wall?

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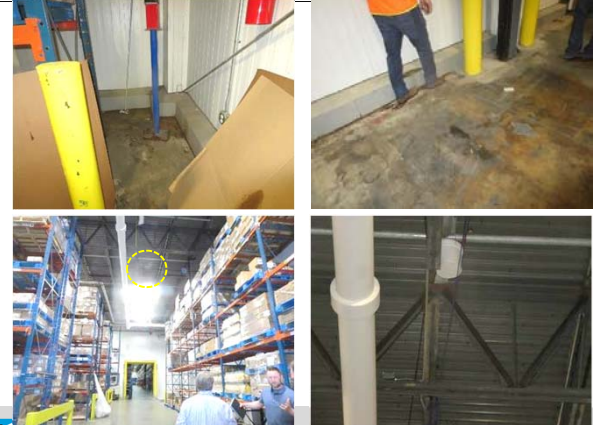
Refrigerated Warehouses

Refrigerated Warehouses

- Multiple investigations
- Refrigerated food distribution centers/warehouses
- Entire space running 0-30 F
- Typical walls IMP or IMP inboard of existing CMU
- Typical roofs metal deck, insulation, single-ply membrane



Drips from Ceiling



Icicles from Ceiling



Infrared Visualization of Air Leaks

FLIR 33.1F

FLIR 35.9F

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Infrared Visualization of Air Leaks

FLIR 34.6F

FLIR 37.3F

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Infrared Visualization of Air Leaks

FLIR 31.2F

FLIR 31.2F

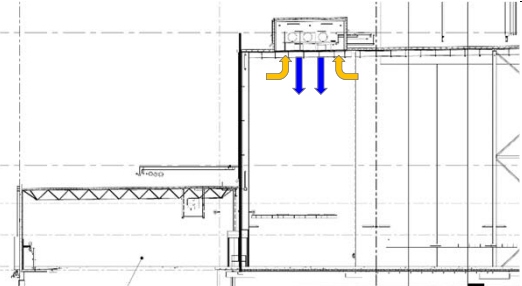
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Airflow Measurement

- Airflow below measurements limits (40 FPM)
- But no other explanation: moisture-laden air into cold spaces

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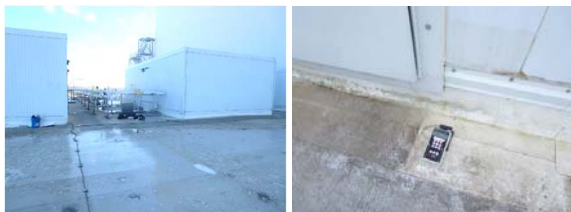
Mechanical Penthouses



- Cooling equipment in rooftop penthouse
- Penthouse acts as return plenum open to warehouse below

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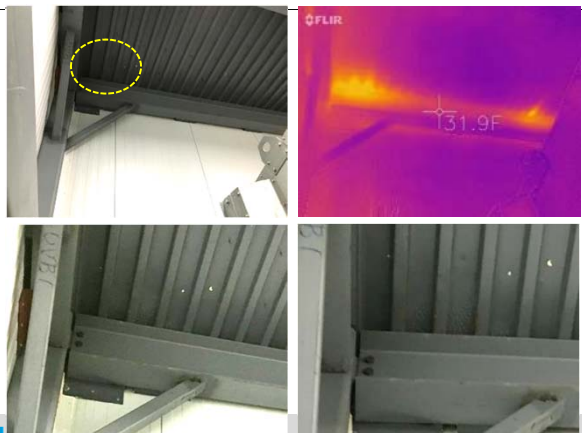
Mechanical Penthouses



- Penthouses operate at negative pressures
- Penthouses are taller than rest of warehouse

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Mechanical Penthouses



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Refrigerated Warehouses and Stack Effect

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Driving Forces

The diagram illustrates three scenarios of air flow through a building. 1. Wind Effect: Wind blowing from the left creates a pressure differential across the facade, causing air to enter on the windward side and exit on the leeward side. 2. Stack Effect: Air enters through a lower opening, rises due to buoyancy, and exits through a higher opening. 3. Combustion and Ventilation: A fire source (stove) creates a low-pressure zone that draws air from the room, which then rises and exits through the roof.

Wind Effect Stack Effect Combustion and Ventilation

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Stack Effect (Winter & Summer)

The diagram compares stack effect in winter and summer. In winter, indoor air is warmer (20 C / 68 F) than outdoor air (-10 C / 14 F), causing air to rise and exit through the top, creating a negative pressure (NPP) at the bottom. In summer, indoor air is warmer (20 C / 68 F) than outdoor air (30 C / 86 F), causing air to be drawn in through the bottom and exit through the top.

Winter Conditions Summer Conditions

20 C / 68 F -10 C / 14 F 20 C / 68 F 30 C / 86 F

NPP NPP

$-P_{in} - P_{out} +$ $-P_{in} - P_{out} +$

- Theoretical open tube
- NPP = neutral pressure plane

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Stack Effect

- Stack calculated based on:
 - Temperature difference
 - Height of open "stack" (taller buildings = more stack)
- Typically a problem in cold climates/winters
 - Assume ~70F indoors
 - Cold winter @ 0F, $\Delta T = 70F$
 - Hot summer @ 100F, $\Delta T = 30F$
- Freezer warehouses are different!
 - Assume ~10F indoors
 - Hot summer @ 100F, $\Delta T = 90F$

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Stack Effect Calculation

The graph plots Stack Pressure (Pa) on the y-axis (from -30 to 10) against Outdoor Temperature (F) on the x-axis (from 10 to 110). A green line shows the theoretical stack pressure, which is positive in winter and negative in summer. Vertical dashed lines indicate Tallahassee Winter Design T (99.6%) at approximately 25 F and Tallahassee Summer Design T (0.4%) at approximately 90 F. A histogram below the graph shows the frequency of outdoor temperatures, with a shaded region between the design temperatures.

Stack Pressure (Pa)

Outdoor Temperature (F)

Frequency (# hours)

Stack Pressure (Pa)

Tallahassee Winter Design T (99.6%)

Tallahassee Summer Design T (0.4%)

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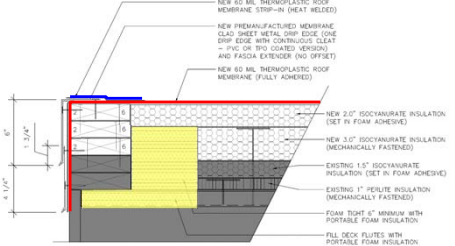
Refrigerated Warehouses Details & Solutions




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Detailing: Roof Edge



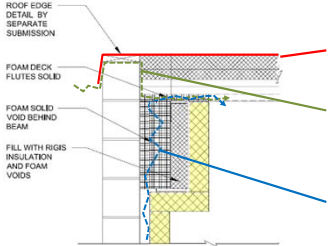
- Relies on spray foam for air seal
- Source of moisture = exterior air
- Roof membrane should be air/vapor barrier here




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Roof Edge Air Leak (CMU + IMP Wall)




- Was roof membrane detailed as air barrier?
- Reliance on ccSPF “blind” for air seal
- Problems worst at corners & transitions




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Roof Edge Detailing (IMP Only)





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Demising Walls (Roof Dam Detail)

- “Dam” detail within roof assembly
- Sealant from dam to roof membrane

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Demising Walls (Roof Dam Detail)

- Self-adhered or fluid-applied membrane
- Has to conform to deck flutes
- Has to be applied to low temperature surfaces

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Refrigerated Warehouses Takeaways

- Leakage of warm humid outdoor air can cause major problems
- Huge air pressure pulling outdoor air in at top of building, worst in summer (high ΔT , high DP)
- Can't neutralize with pressurization
- Relying on spray foam detailing problematic
- Membranes and sealants, termination bars
- Air leakage testing as quality control tool

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Questions?

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This presentation will be available at <http://buildingscience.com/past-events>

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