BUILDING SCIENCE LIVE
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Failing Forward: Learning from Forensic Investigations

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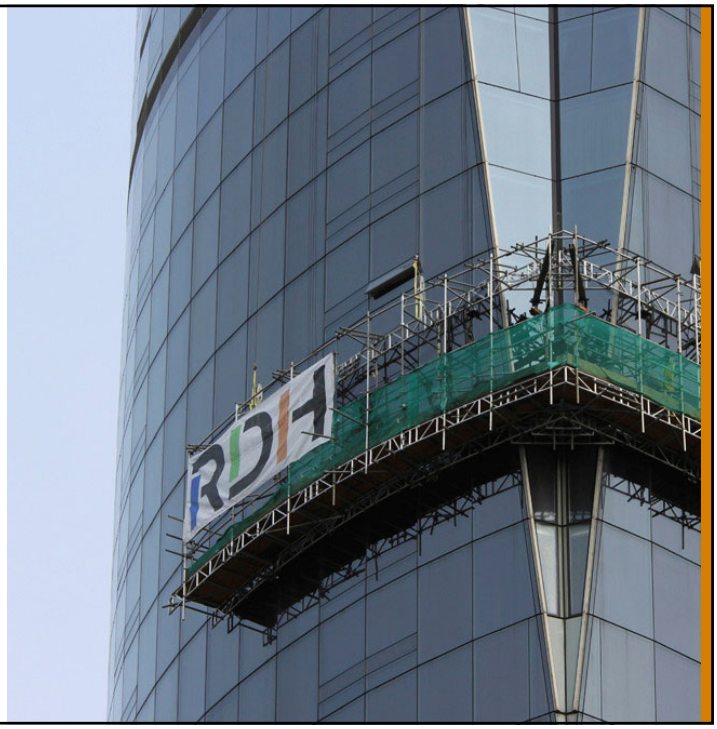

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What are Forensic Investigations?

- "the application of professional engineering principles and methodologies to investigating failures and incidents, usually to determine causation". From: *Forensic Engineering Investigations*, PEO 2016.
- Why?
  - Stop damage
  - Inform repair design
  - Assess responsibility

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Process & Approach

- Failures and buildings are highly individual
- However, standard investigation and analysis processes should be considered in developing your plan
- Some good advice available

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Forensic Standards

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First Step… Collect Data

- Go to site, get photos, ask people
  - Beware others' conclusions, witnesses are unreliable
- Observations
  - Extent, patterns
  - *Your senses, experience, and building science knowledge are the most important tools*
- Diary of project, dates of problems
- Design documents, materials, systems, contractor, trade, designer, owner
  - Contract drawings, shop drawing etc. often have changes!

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Assessment / Interpretation

- **Experience**
  - Have we seen similar failures before?
  - What factors are the same?
  - What factors are different?
  - Be open to new failure modes!

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Assessment / Interpretation

- **Science,** basic principles
  - Allows for reliable relative comparisons
    - E.g. Air leakage vs. diffusion
  - Can often *rule out* causes / mechanisms
    - E.g. HVAC vs. capillary pressures and rain leaks
- **Calculations** and simulations
  - Always approximate, sometimes useful
  - Often done poorly

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Assessment / Interpretation

- **Develop hypotheses to explain observations**
  - Compare evidence to hypothesis being tested
    - Some evidence is more reliable than others
    - Extraordinary claims require extraordinary evidence
- **Provide some estimate of confidence of your conclusions**
  - … and what might be done to improve it

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Case study

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Case Study: High-Rise Condensation

- Simplified in this presentation, focus on one part of building
- Federal Courthouse
- Upstate New York (cold)
- Precast concrete

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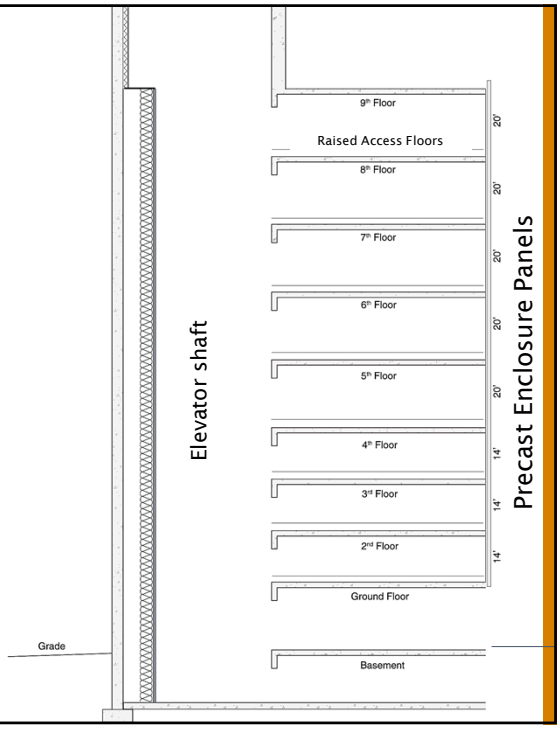
Problems

- Construction underway
- "Water is cascading down our elevator shaft!"



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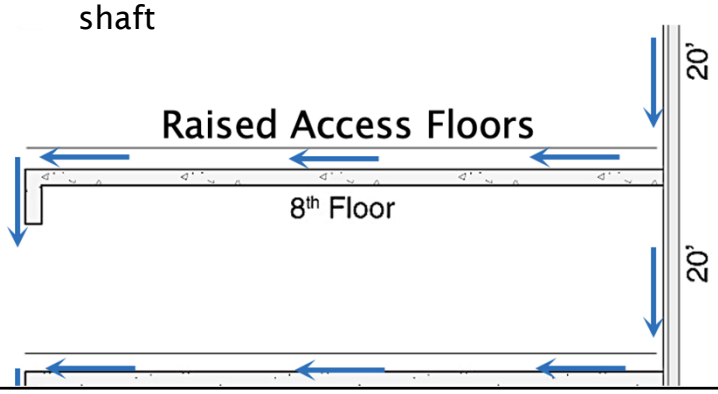
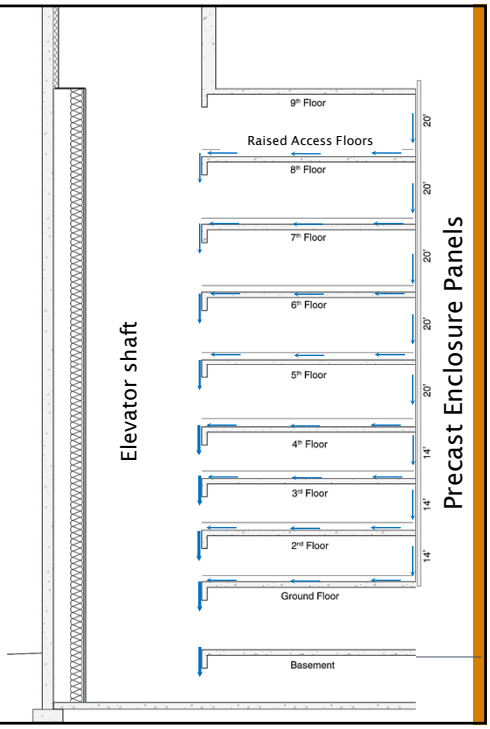
Problems

- Construction underway
- Late January problem:
  - water running down wall, onto floor, under raised access floor into elevator shaft





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Field Investigation

- High indoor humidity
- Long cold snap, followed by warming
- Good air barrier
- … but convection

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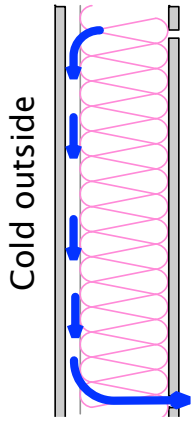
Convection Loop

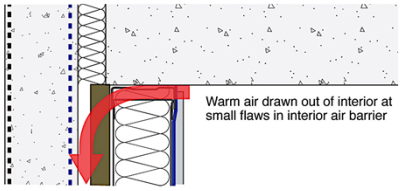
- Air gap intentionally provided in design!
- Imperfect air seal at upper and lower levels allowed

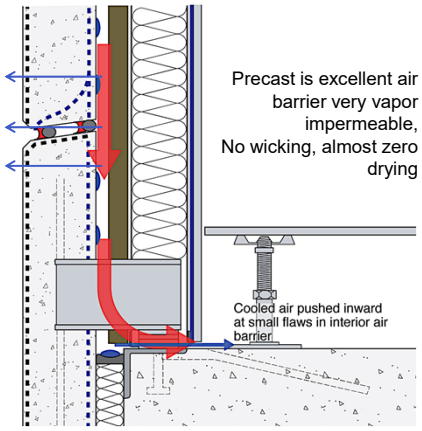


Cold air falls
so…
in cold weather:

- **Cavity air pushes into building at bottom**
- **Drags warm indoor air into cavity at top**

Experience has shown this to be a common problem





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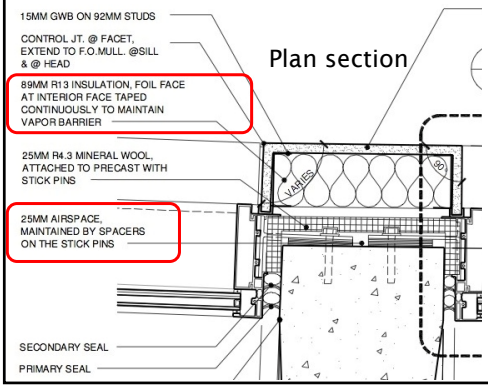
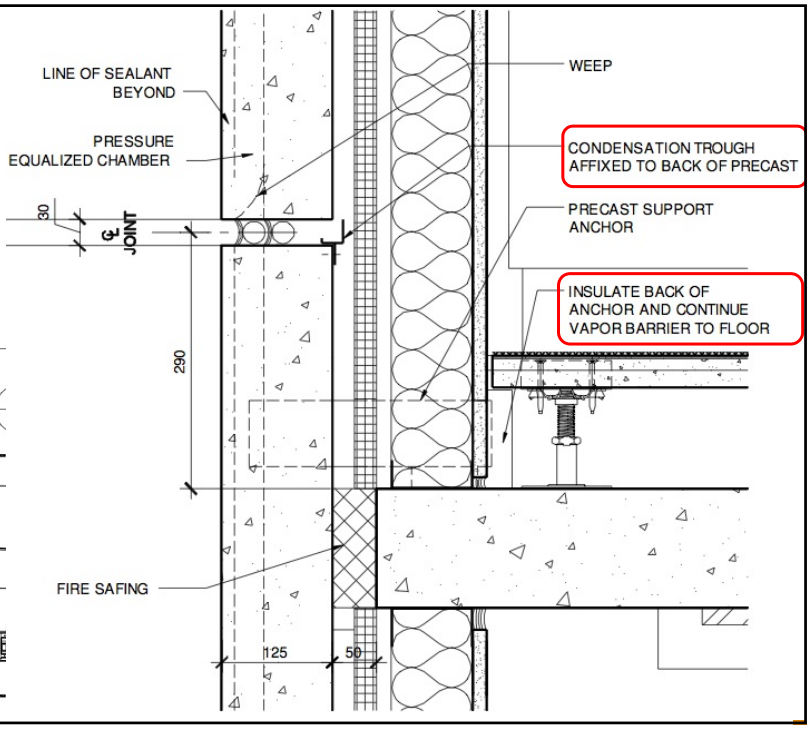
Design Drawings – Ellipse Wall

A vapor barrier is not an air barrier
…and vice versa





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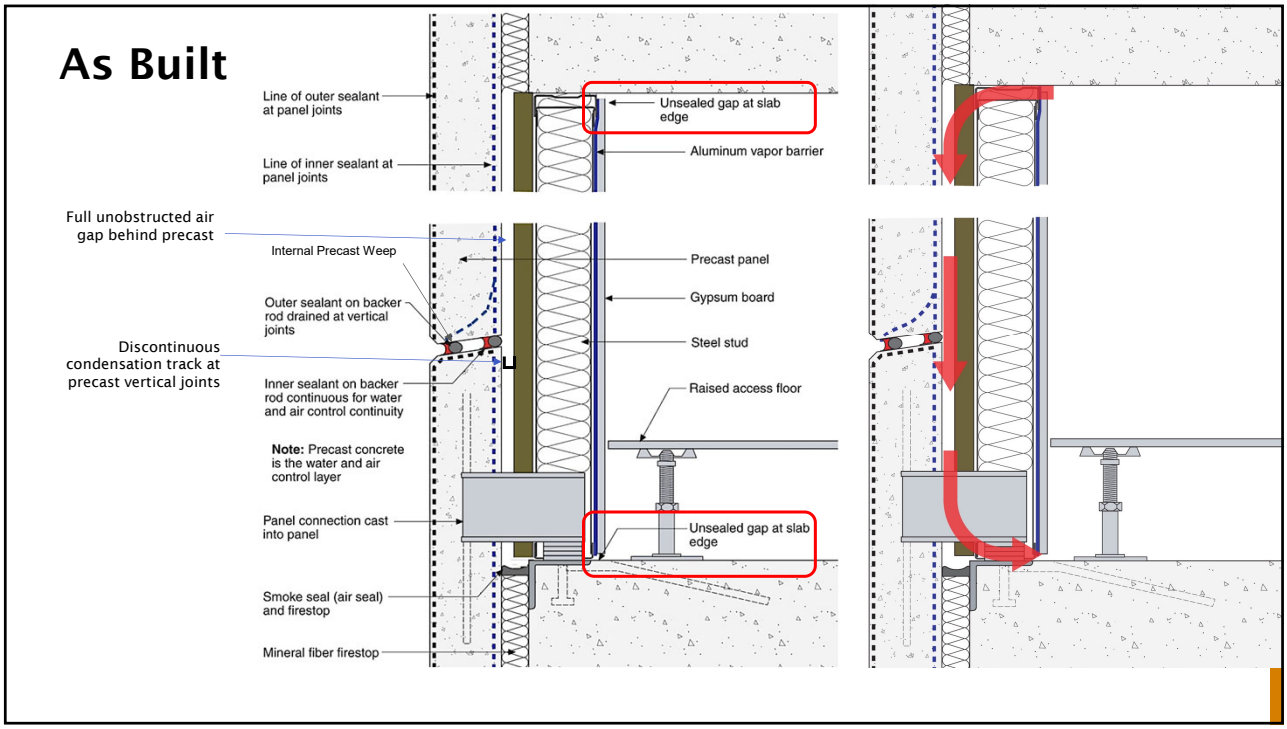
As Built
Line of outer sealant at panel joints
Line of inner sealant at panel joints
Unsealed gap at slab edge
Aluminum vapor barrier
Full unobstructed air gap behind precast
Internal Precast Weep
Outer sealant on backer rod drained at vertical joints
Discontinuous condensation track at precast vertical joints
Inner sealant on backer rod continuous for water and air control continuity
Note: Precast concrete is the water and air control layer
Panel connection cast into panel
Smoke seal (air seal) and firestop
Mineral fiber firestop
Precast panel
Gypsum board
Steel stud
Raised access floor
Unsealed gap at slab edge

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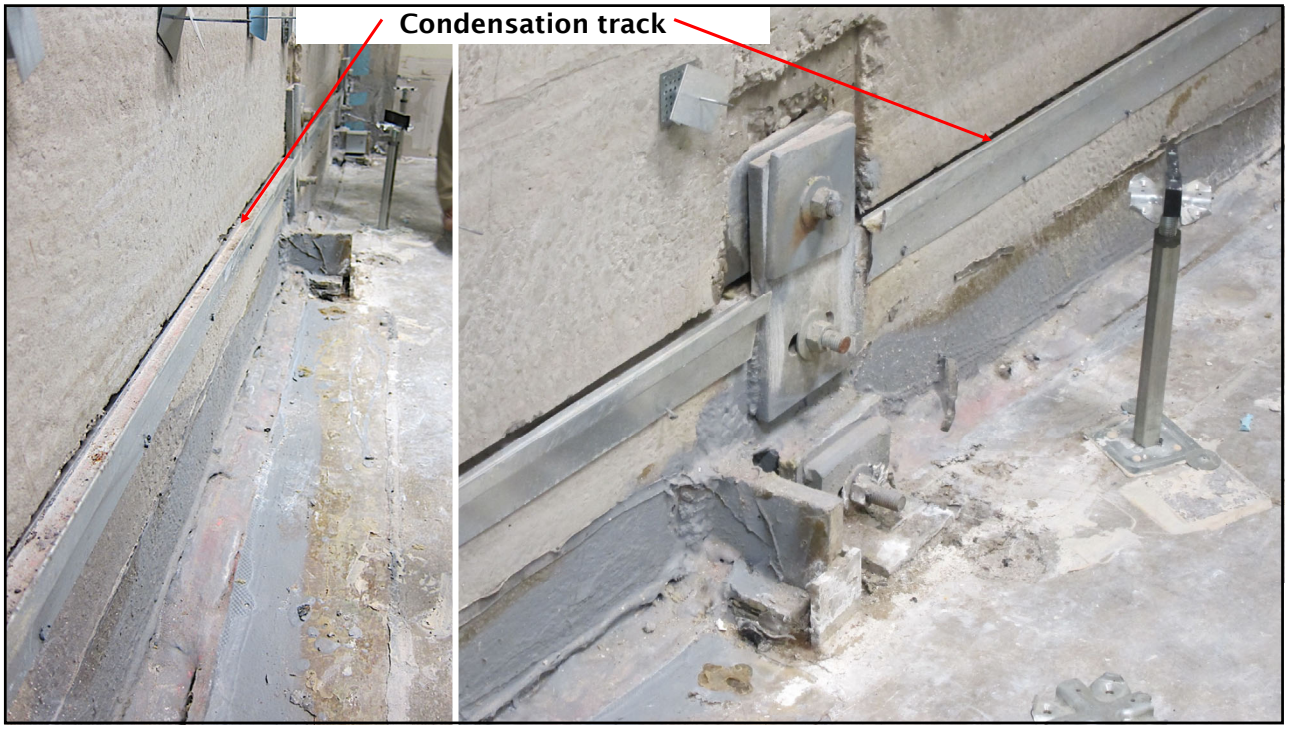
Condensation track

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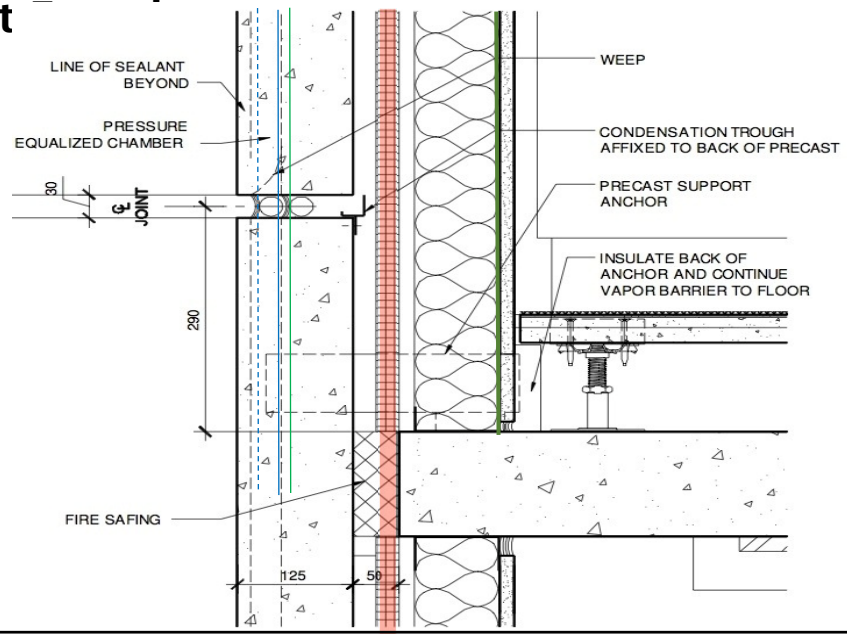
Component



Air
Rain
Thermal
Vapor

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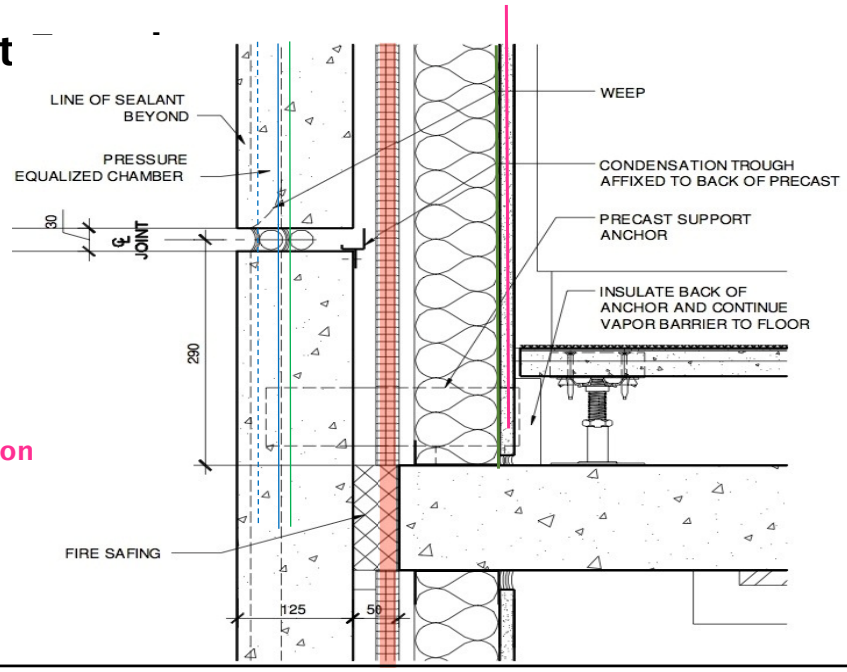
Component



Air
Rain
Thermal
Vapor
Convection

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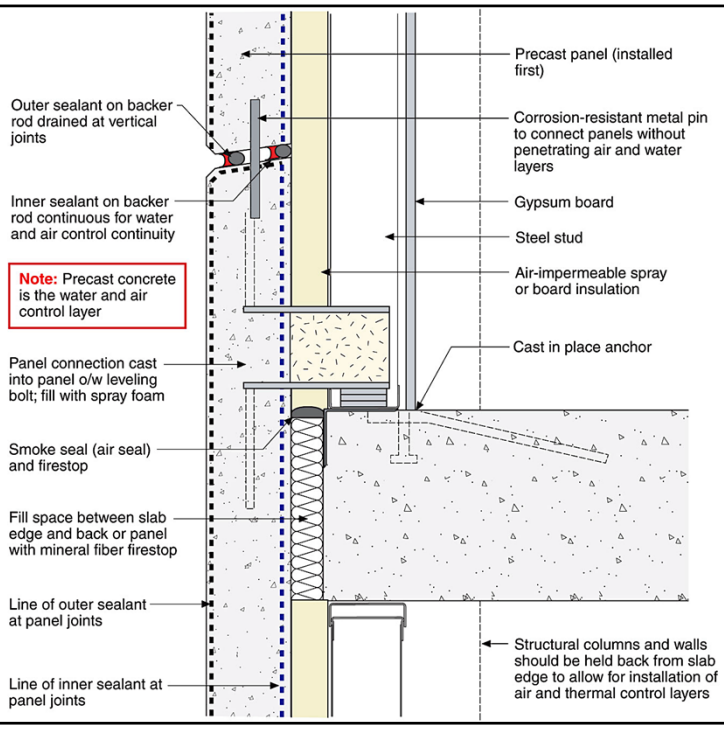
An Aside

→Proper best practice design



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Cracks present widely along bottom
Raised access tiles removed

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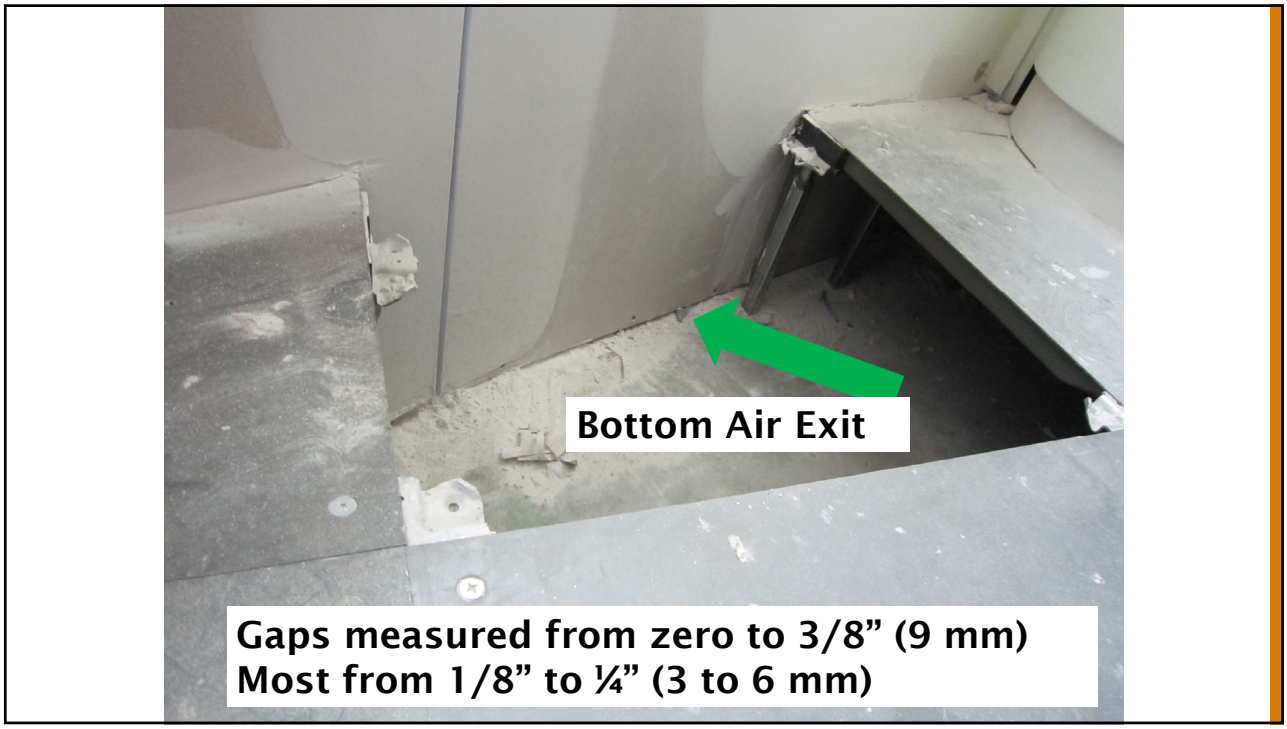
Bottom Air Exit
Gaps measured from zero to 3/8" (9 mm)
Most from 1/8" to ¼" (3 to 6 mm)

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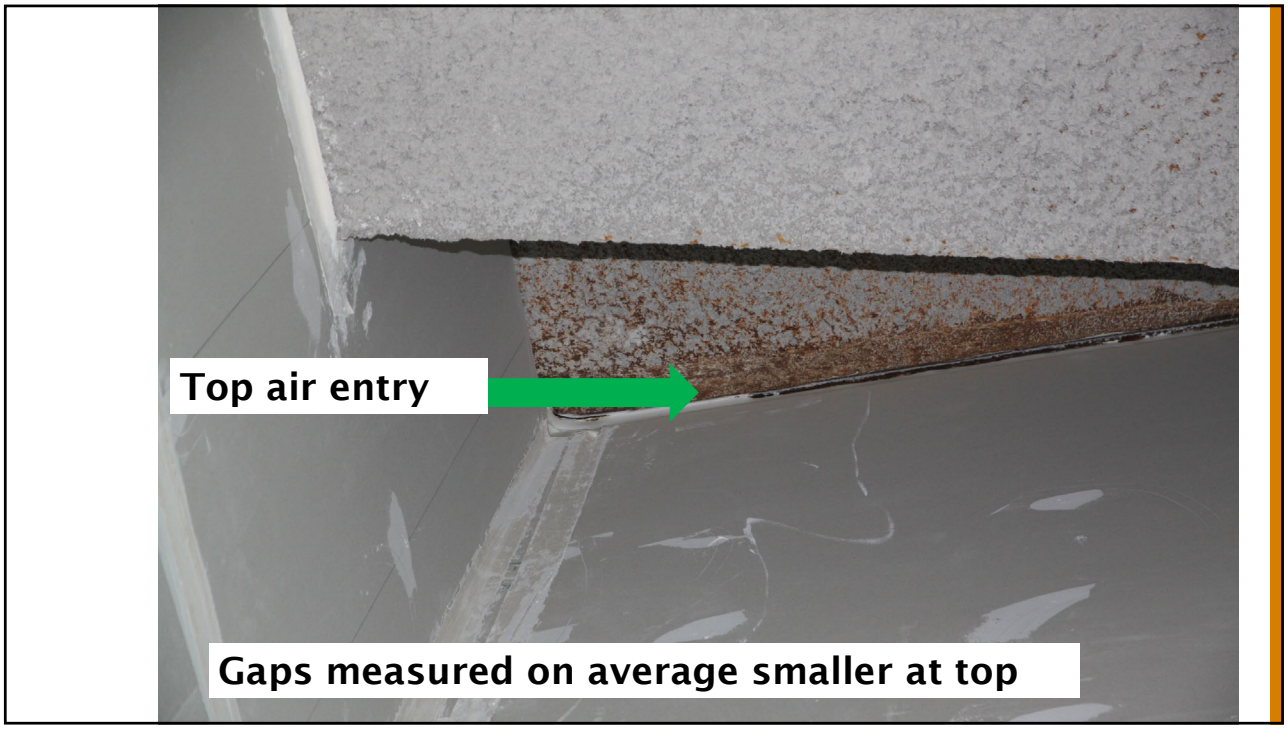

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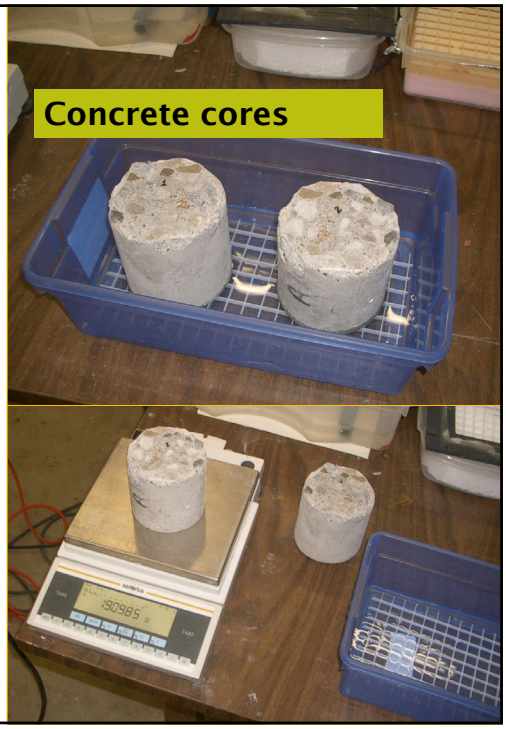
Laboratory testing

- Lab tests can be used to:
  - Prove/disprove theories
  - Confirm material assumptions
  - Feed computer models
- In this case, simple tests
  - Material, not system tests
  - Water uptake test (cores)
  - Vapor permeance test



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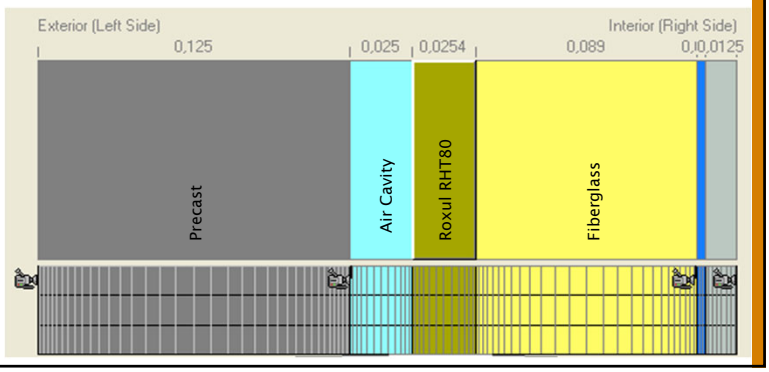
Computer modeling

- "All models are wrong, some are useful"
- Goals
  - Explain / replicate observed performance
  - Model repair strategies
  - Explore risk factors
- WUFI 1D used in case study



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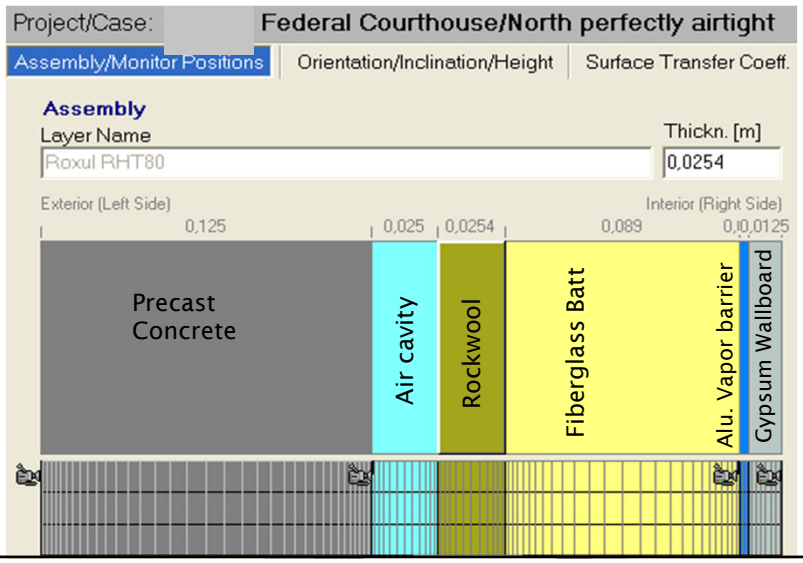
Detailed View of Wall Model



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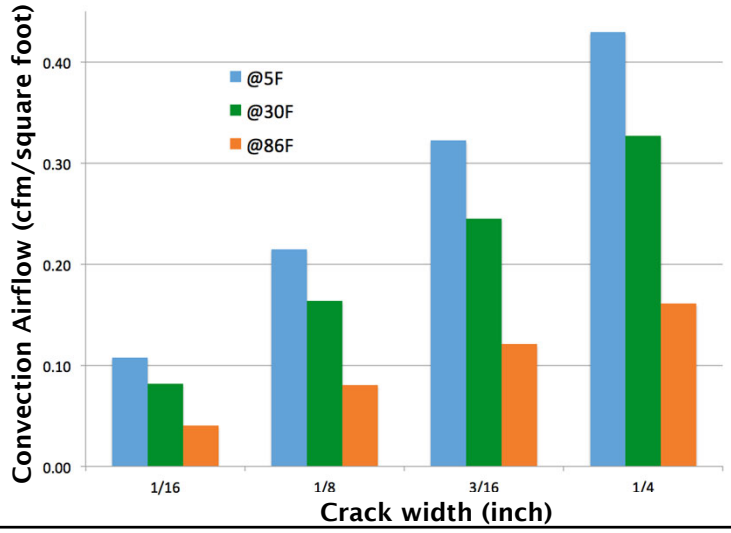
Airflow Through Cracks

→ Simple calculations based on "sharp-edged orifice"



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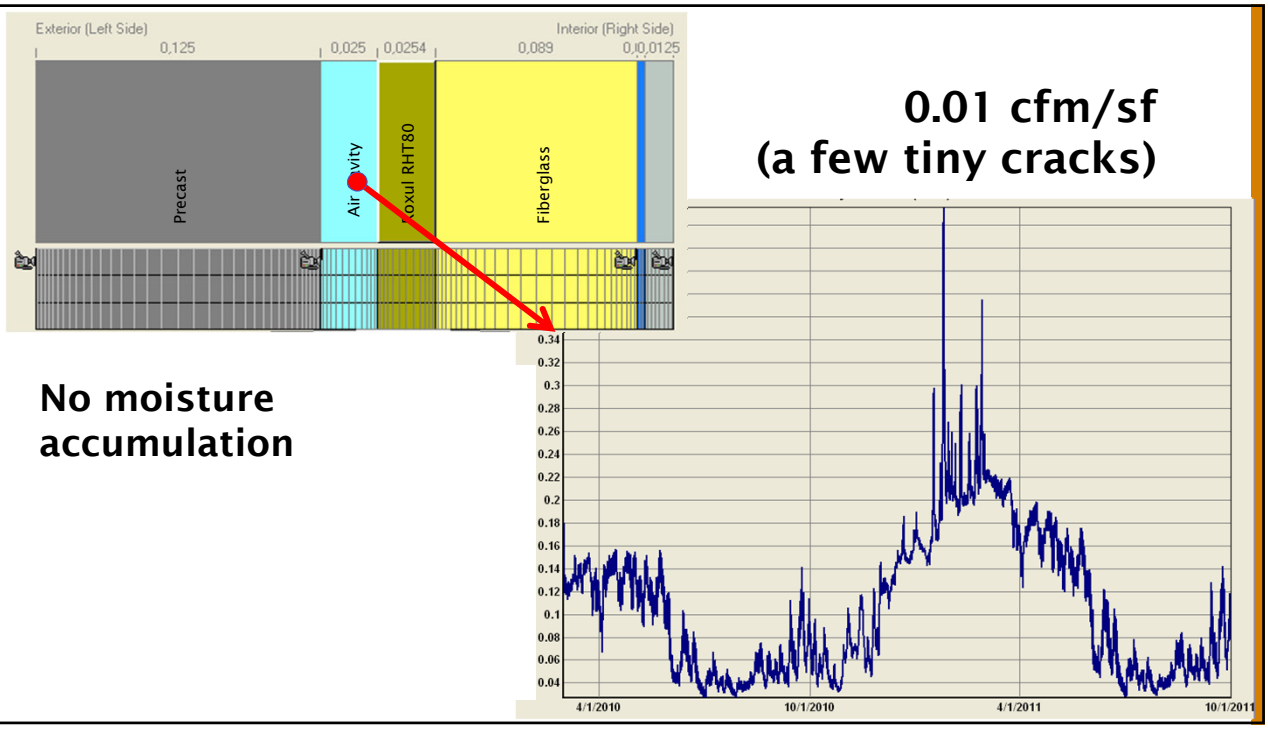

0.01 cfm/sf
(a few tiny cracks)

No moisture accumulation

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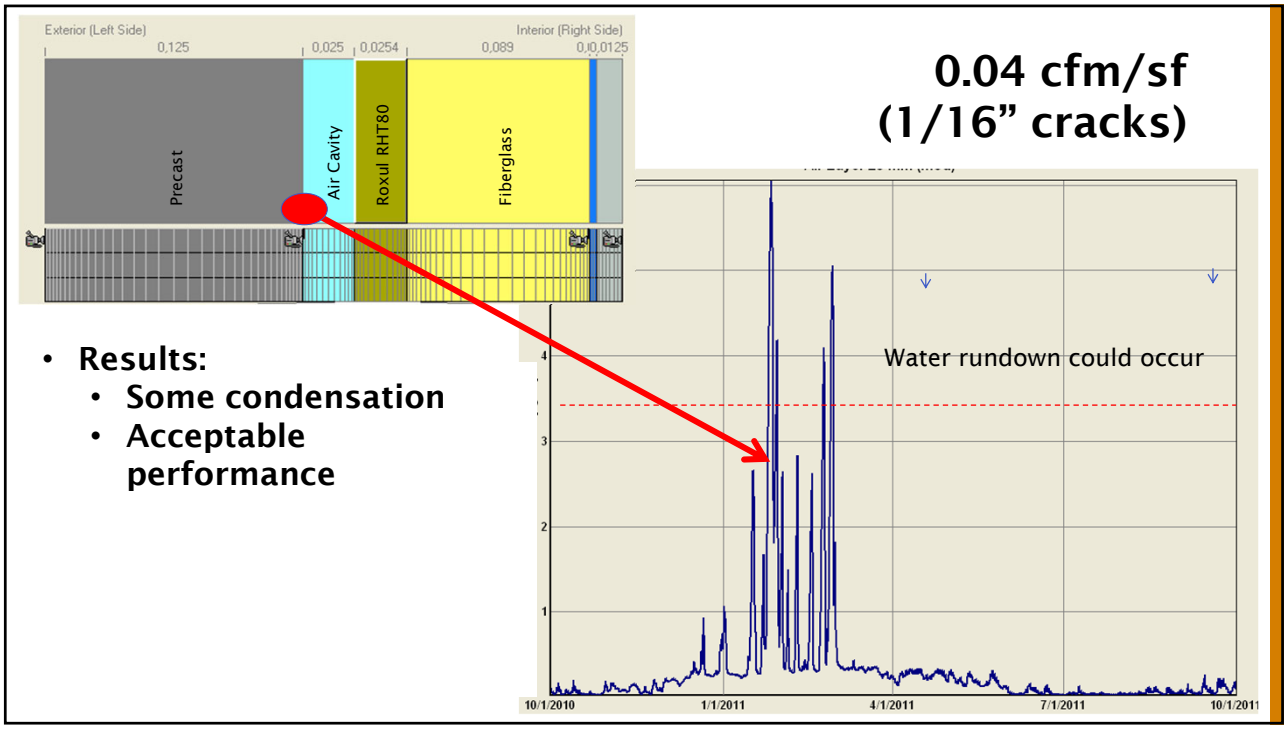

- **Results:**
  - **Some condensation**
  - **Acceptable performance**

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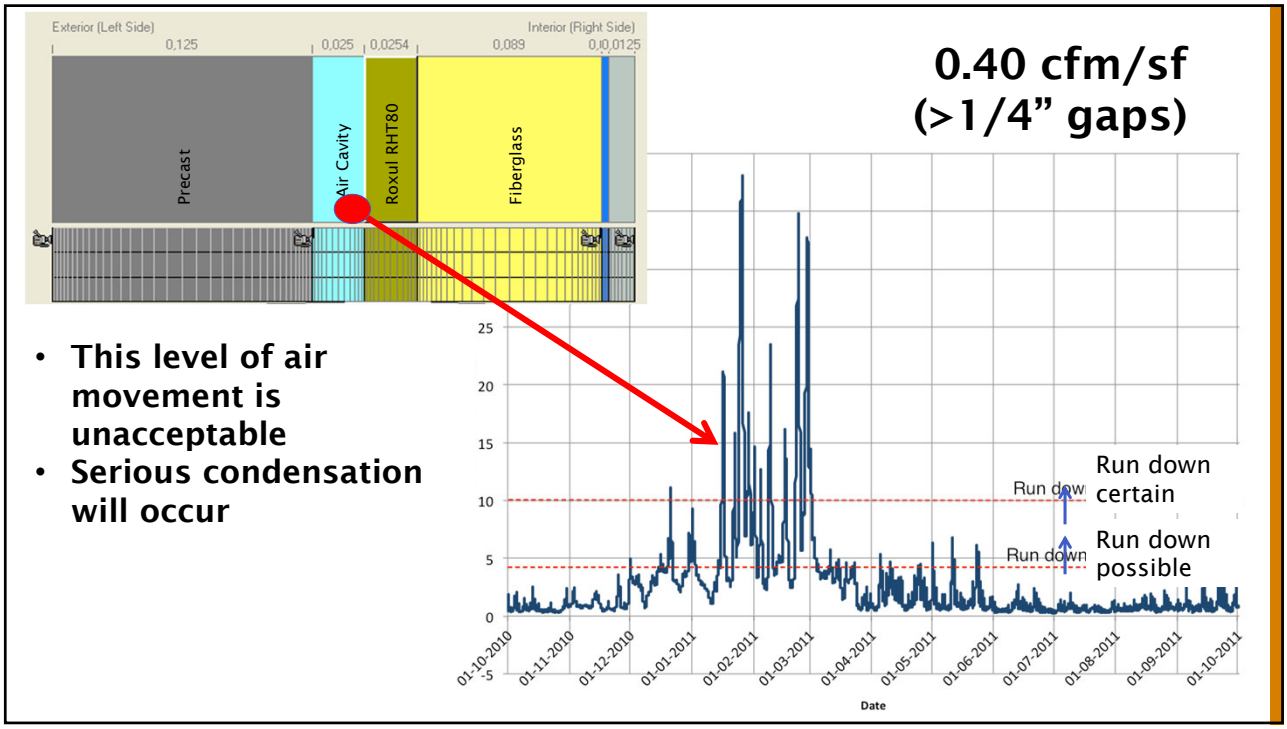

- **This level of air movement is unacceptable**
- **Serious condensation will occur**

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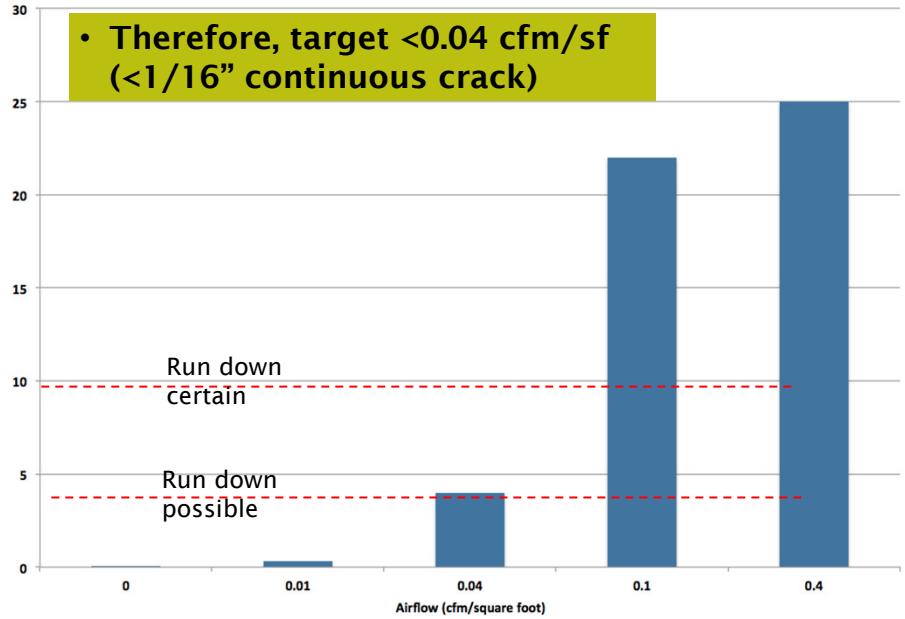
Summary of Simulations

- **Therefore, target <0.04 cfm/sf (<1/16" continuous crack)**



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Modeling results

- **Model can predict problem observed**
  - Building science calculations & simple lab testing needed of course
- **Perfect airseal is not needed for repair**
  - Define performance requirements and inspection protocols
- **Manage cold weather humidity inside**
  - Requires HVAC and operational integration

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Solutions

→After forensic investigations we usually need to fix the building!

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Appropriate solutions

→Options: Do Nothing, Repair, Replace, Modify operation, etc.

→Good, better, best

→Advise the client of pros and cons

→Can't always do the best repair

→Always present ideal/best as an option for comparison

→Cost, schedule, disruption, etc. normally involve

→Consider consequence of doing nothing?

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Affordable solutions
Note: This repair has been successful for almost ten years

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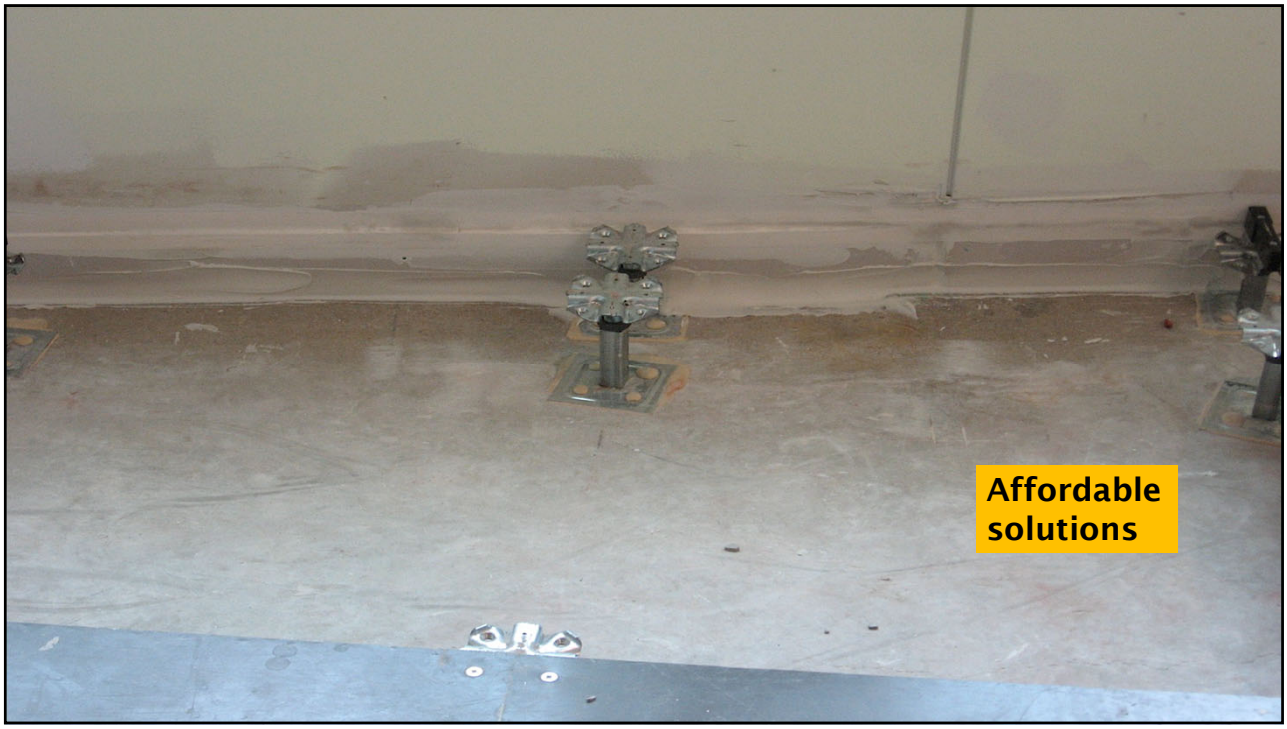
Affordable solutions

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Forensic Conclusions

- General procedures and approaches are available
  - Almost every project requires modification
- Senses, experience, and building science knowledge are the most important tools
  - Fancy widgets are sometimes nice, never sufficient
- Blend site observations, calculations, lab work, modeling to develop sensible reliable solutions
  - Different projects demand different solutions

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Break for Questions

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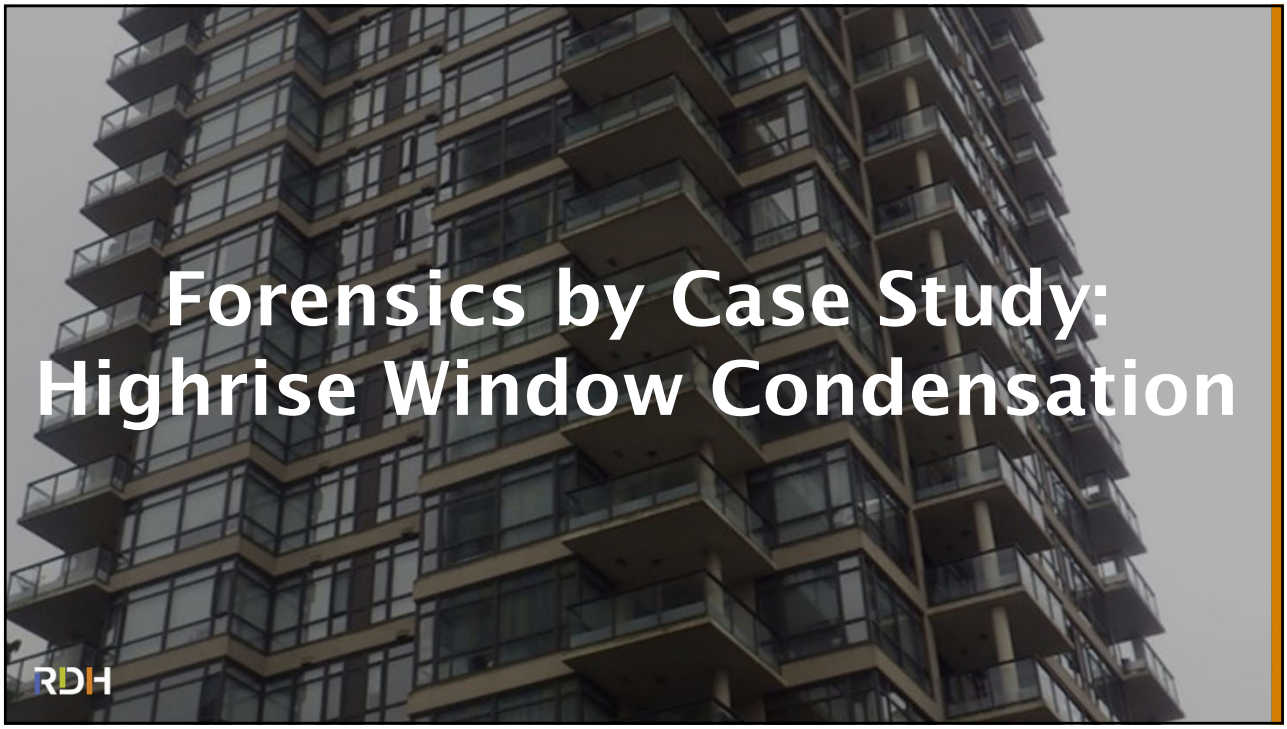

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Condensation Issues

- Condensation at window interior surfaces experienced since building was new
- Condensation at interior surface of windows, inside the insulating glass units (IGUs)
- Mold growth at the walls and ceiling surfaces near the windows

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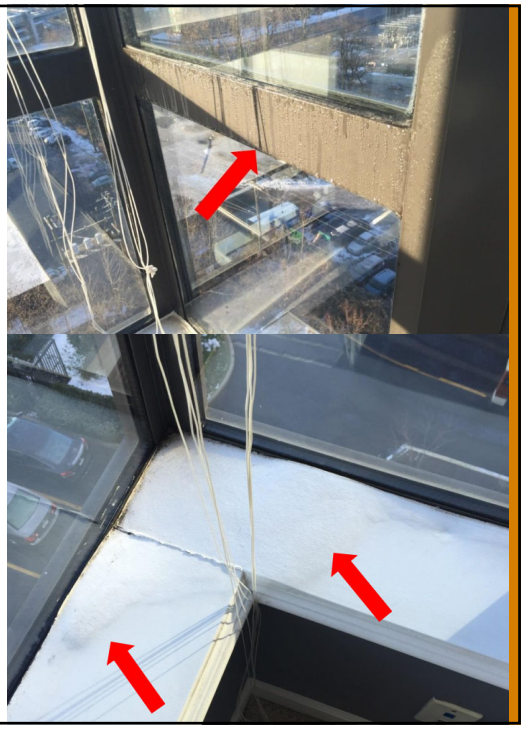
Previous Work by Others

- Severe condensation issues noted in Five Year Performance Review
- Extent and severity of issues documented in forensic investigation reports by 2 other consultants
- Window system, installation configuration, and interior conditions noted as cause.
- RDH retained to provide a 2nd opinion



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Previous Work by Others

- Previous two consultants:
  - Missing thermal breaks at window frames
  - Air leakage around window frames
  - Failed perimeter seal of insulating glass units (IGUs), leading to condensation between the window panes (1)
  - Problematic window installation detail - window frame offset from the plane of the wall insulation
  - Several suites found with higher relative humidity levels, though suites with normal RH found to have some condensation
  - Fungal growth at interior wall/ceiling surfaces
  - No testing or review of HVAC system

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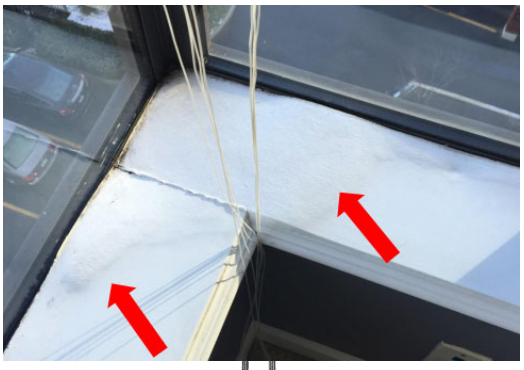

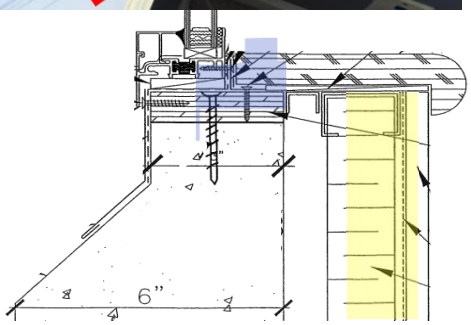

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Previous Work by Others

- Consultant 1 recommendations:
  - Strategy 1 – Occupant lifestyle change/review ventilation
  - Strategy 2 – Retrofit existing operable windows due to (perceived) lack of thermal break **$275K**
  - Strategy 3 – Replace IGUs with warm edge technology (WET) **$4.5M**
  - Strategy 4 – Replace all windows **$6.7M**

5. CLOSURE

Strategy 1 should be implemented regardless, at least as far as educating occupants about what steps they can take to avoid compounding the incidence of condensation at this building.

However, because of the construction deficiencies noted with the window installation, the incidence of condensation at this building will continue to be greater than if these concerns were addressed. Strategy 4 is the only approach that will appreciably reduce (but not eliminate) condensation accumulation and damage.

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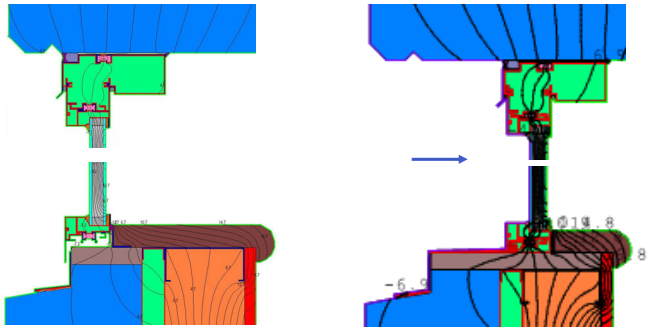
Previous Work by Others

→ Follow-up thermal modelling of window sill explored moving the window inwards



EXISTING PROPOSED

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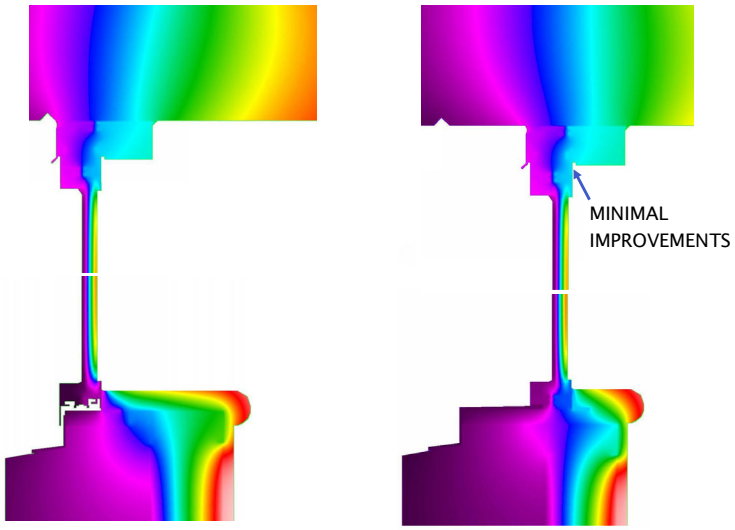

EXISTING PROPOSED

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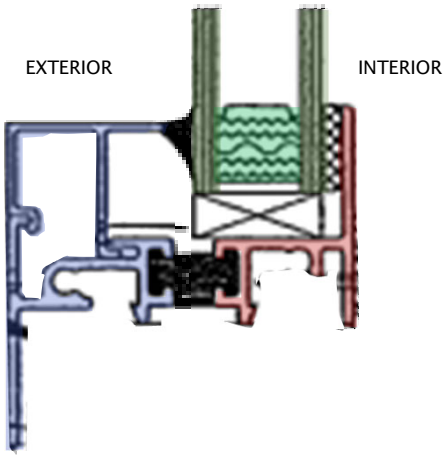
Existing Window System

- Allied Windows thermally broken aluminium frame window with “warm edge technology” insulating glass units
- Frames use thermal break to separate exterior from interior components
- Glass panes use thermally optimized spacer to improve thermal performance



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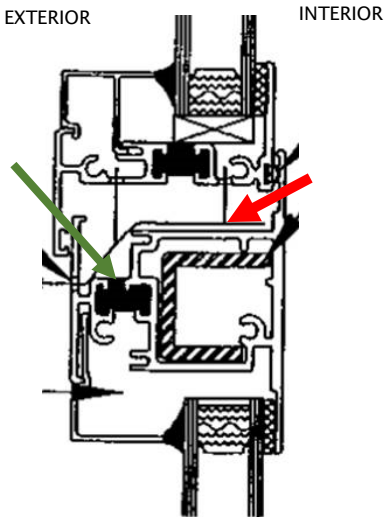
Window System

- Shop drawings show thermal break at all mullions, including horizontal mullion previously reported to have a missing thermal break



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RDH 2nd Opinion Review & Findings

- IGUs reviewed and tested for signs of failure
- Interior surfaces reviewed for damage due to wetting from both condensation and possible leakage
- Discussion with owners experiencing severe condensation

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RDH Initial Review & Findings

- No failed IGUs found through visual review/testing
  - Glazing units are not systemically failing and do not need to be replaced
  - Some small percentage will fail and should be replaced under warranty
- Signs of severe condensation visible on glass surfaces
- Damage to interior window sills
- Condensation most severe in bedrooms
- Attempts to improve suite ventilation with fans unsuccessful
- Fairly standard window system and installation detail—though not ideal, it works on many other projects in BC

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RDH Initial Review & Findings

- Severe condensation on interior surface of the thermally optimized IGUs, rather than just the window frame:
  - Is an indicator that interior moisture levels are a significant causal factor
  - Rules out glazing replacement as a valid repair solution
- Severe condensation on thermally broken aluminum mullions indicates that window replacement alone may not resolve the condensation issue in all suites
- Thermal modeling indicates negligible condensation resistance improvements by retrofitting the existing window installation

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Recommendations

- Integrate mechanical, building enclosure, and occupant investigations together into one investigation that is developed to determine the exact cause of the problems
- Then perform and test mock-ups to confirm performance

Repair strategies should only be developed once causation has been determined

- Consultant 1 - recommendations:
  - ~~Strategy 1 – Occupant lifestyle change/review ventilation~~
  - ~~Strategy 2 – Retrofit existing operable windows due to (perceived) lack of thermal break. $ 275K~~
  - ~~Strategy 3 – Replace IGUs with warm edge technology (WET) $4.5M~~
  - ~~Strategy 4 – Replace all windows $6.7M~~

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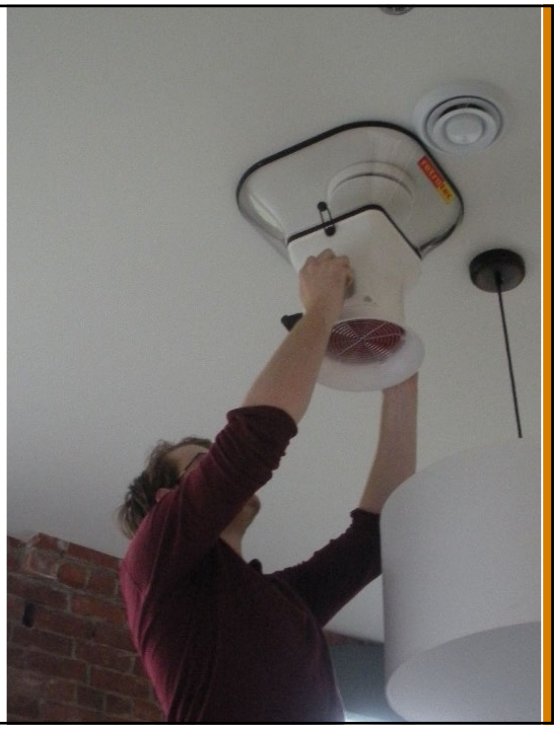
RDH Full (Proper) Forensic Investigation – Steps 1 & 2

1. **Owner Survey:**
   - → Gather up-to-date information on the occurrences and severity of condensation

2. **Ventilation System Operation & Window Leakage Testing:**
   - → Air Testing of the mechanical system suite ventilation performance, including flow rate and condition of supply air to suites
   - → Water Testing of façade to rule out possibility of bulk water leakage causing increased ambient moisture levels and benchmark suite ventilation rates



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RDH Full Investigation – Step 3

3. **Advanced Monitoring:**
   - → Installation of complete monitoring system in at least 4 suites (3 condensation and 1 control suite) in order to measure/monitor:
     - → Window temperature and condensation occurrences
     - → Ambient temperature/Relative Humidity/Carbon Dioxide
     - → Ventilation/exhaust air flow at suite entry and bathrooms
     - → Outdoor ambient conditions

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Example Sensor Installations

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Example Suite Sensor Layout Plan

- T/RH/Surface T
- T/RH/CO2
- T/RH/Fan Operation
- T/RH/Pressure - Corridor
- T/RH - Exterior

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RDH Full Investigation – Steps 4 - 6

4. **Data Analysis:** Data from monitoring retrieved and analyzed to determine the main causal factors resulting in condensation
5. **Recommendations & Trial Repairs/Mock-up:** Formulate and implement a test repair strategy to minimize the condensation risk
6. **Follow Up Testing & Monitoring:** Continued shorter-term monitoring of suites with test repairs to determine effectiveness of the repair strategies

Repair strategies might include:

- → Increasing the quality and quantity of ventilation air to suites to lower RH (HVAC or individual HRV)
- → Improving heating of interior window surfaces
- → In situ thermal improvements at window to wall interface
- → Automation of exhaust fans

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Outline

- → Survey Results
- → Ventilation Testing
- → Initial Monitoring Data
- → Ventilation Testing Results
- → Trial Repairs
- → Full Monitoring Data & Findings
- → Window Review & Findings
- → Energy Benchmarking
- → Recommendations for Next Steps

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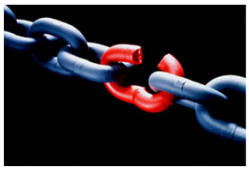
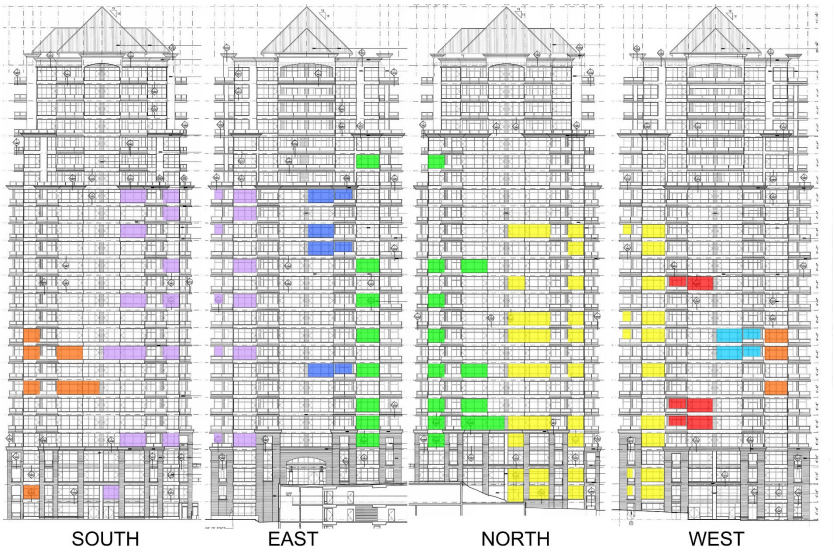
Survey Results – Reported Severe Condensation





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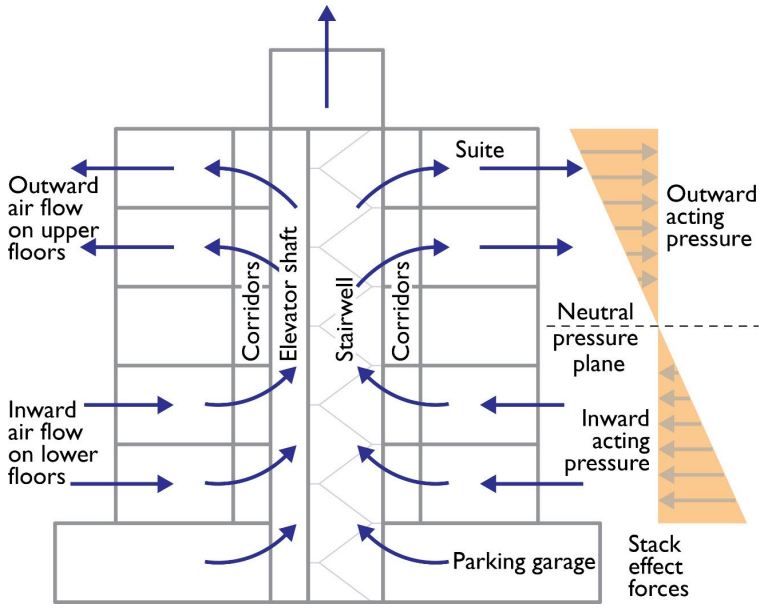
Ventilation Issues – Stack Effect

- Ventilation is hindered by improper HVAC balancing and stack effect forces
- Static HVAC balancing only works perfectly when not heavily influenced by stack effect.



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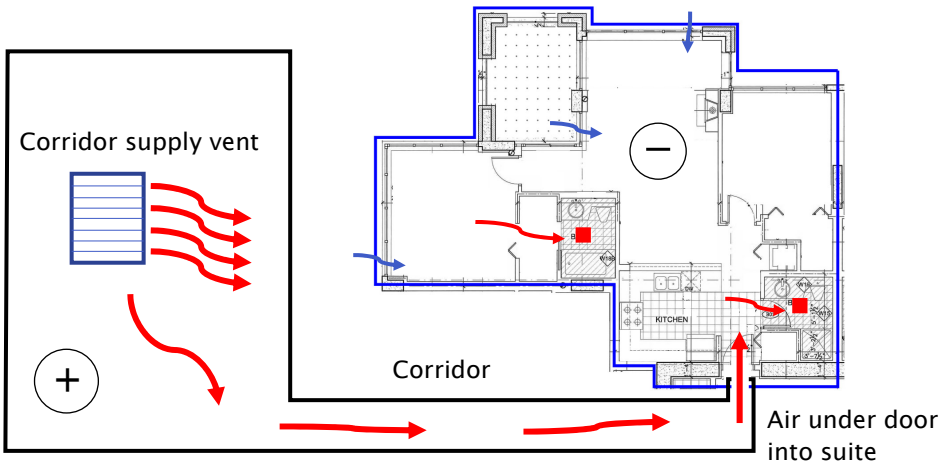
Ventilation Mechanism – Pressurized Corridor



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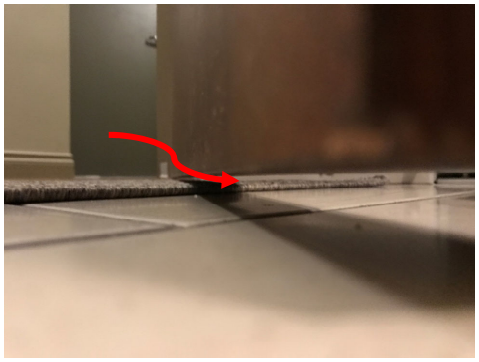
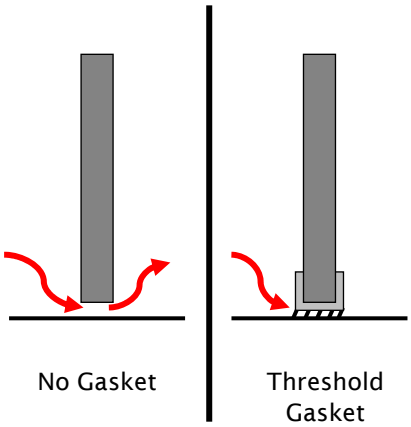
Ventilation Mechanism – Door Undercuts

→ Air can only enter suite with positive pressure and open path for airflow





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Ventilation System Testing

→ Ventilation and door airflow, exhaust fan airflow



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Ventilation Testing Results

Corridor Ventilation Rates

Floor 5	Floor 7	Floor 9	Floor 16
~60 CFM	~60 CFM	~97 CFM	**~127 CFM**

Entry Door Pressure & Airflow – Single Point

502	702	902	Control 1602
-5.5 Pascals	-0.7 Pascals	-0.8 Pascals	6 Pascals
(4.5 CFM)	(14 CFM)	(5.9 CFM)	**47 CFM**
threshold gasket	no gasket	no gasket	no gasket

(ASHRAE=30-50 cfm)

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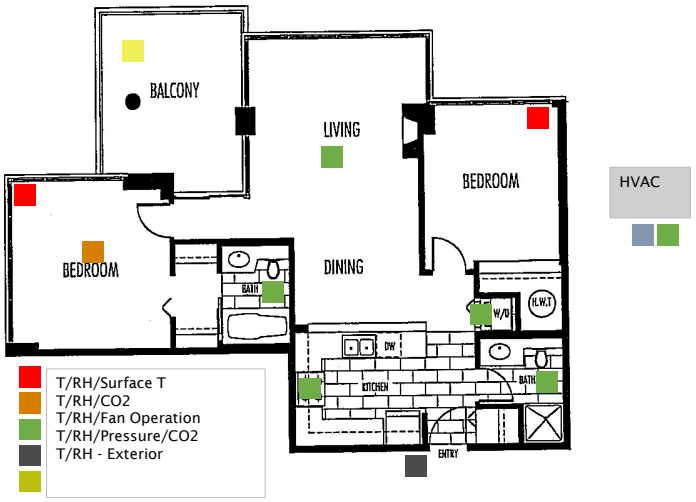
Sensor Installation

- Four #02 suites
- 3 test suites with condensation
- 1 control suite with no condensation



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Sensor Installation

- Ambient temperature, relative humidity, CO2

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Sensor Installation

→ Suite pressure, fan operation

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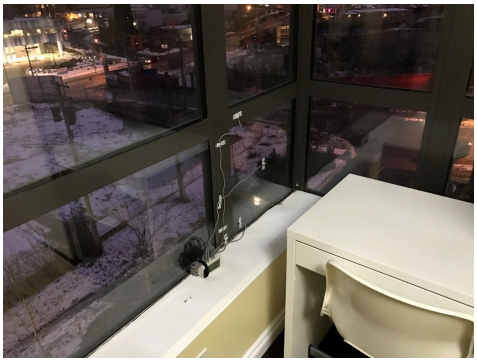
Sensor Installation

→ Window surface temperatures



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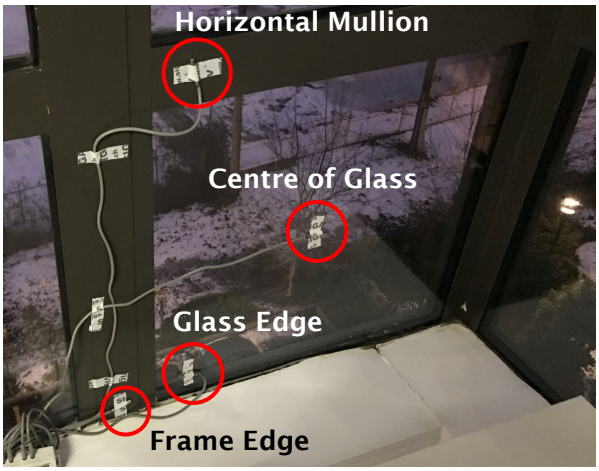
Sensor Locations

→ Window surface temperature sensor locations



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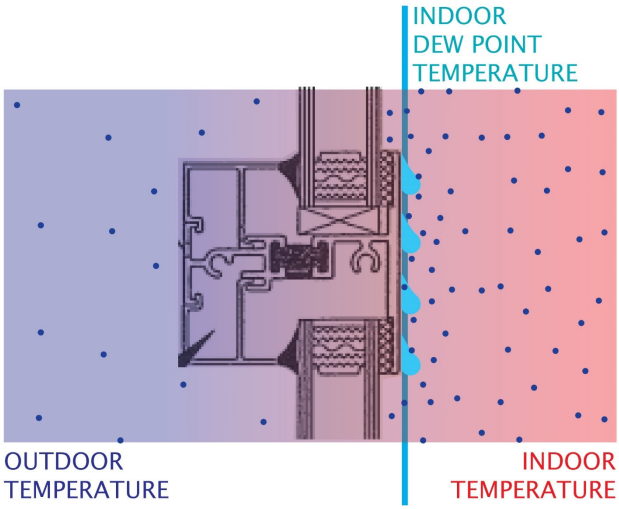
Condensation Process



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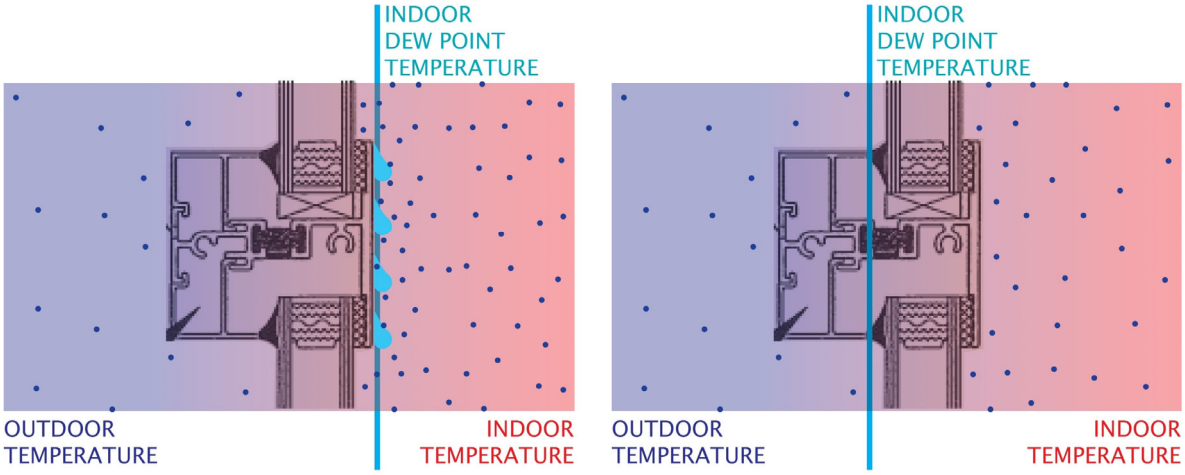
Remediation Option 1 – Reduce Dew Point Temp



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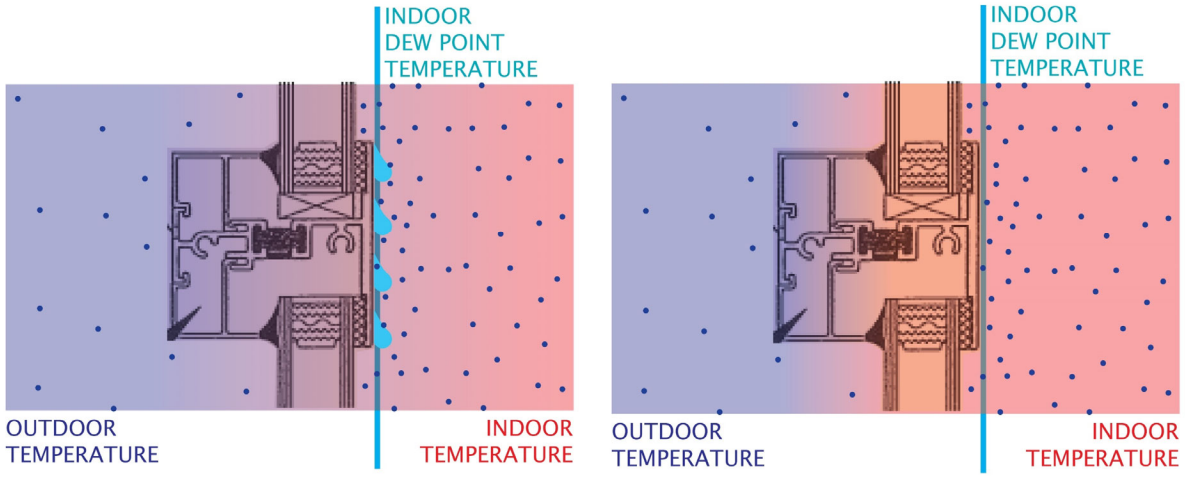
Remediation Option 2 – Warm Surfaces



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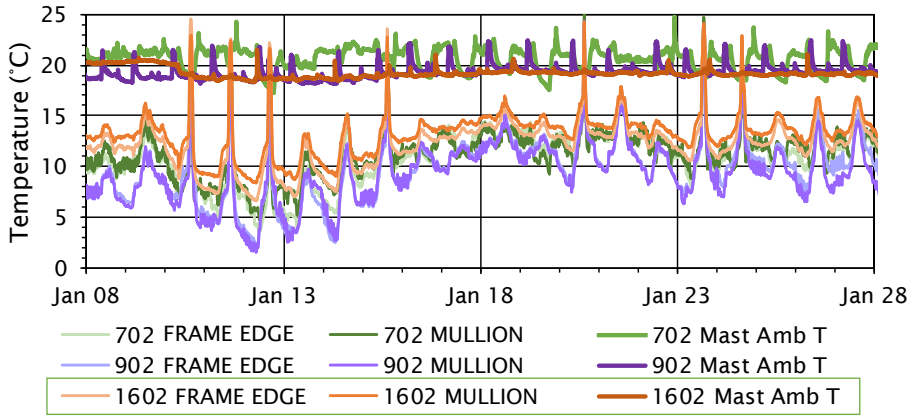
Initial Monitoring Data

Master Bedroom Ambient & Window Surface Temperatures*

*502 data not included due to occupant being away during test period



CONTROL SUITE

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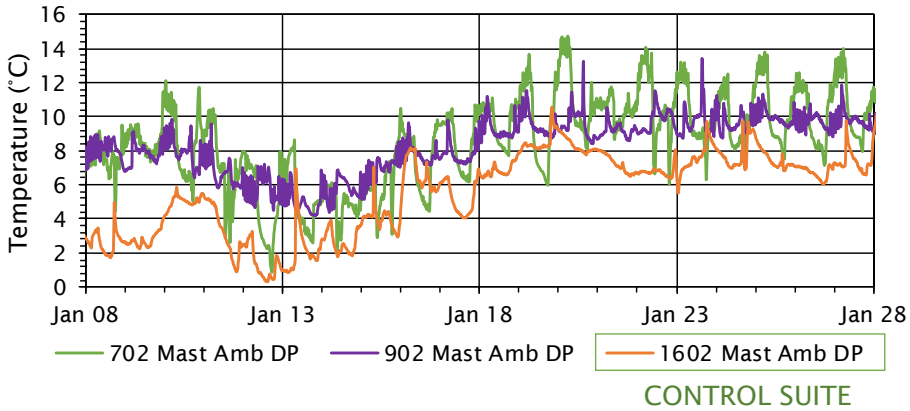
Initial Monitoring Data

Ambient Dew Point Temperatures



CONTROL SUITE

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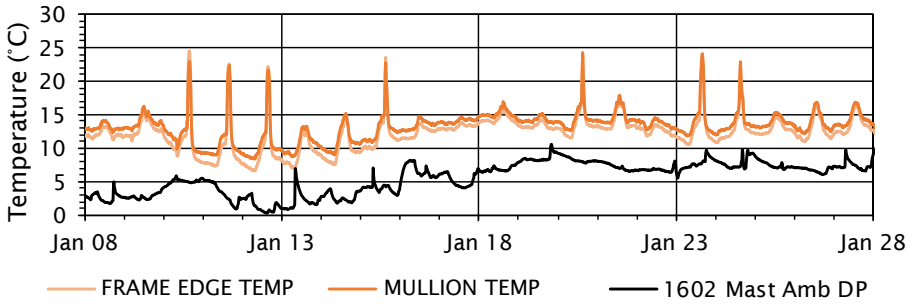
Initial Monitoring Data

1602 Control Suite Master Bedroom Conditions – **No Condensation**



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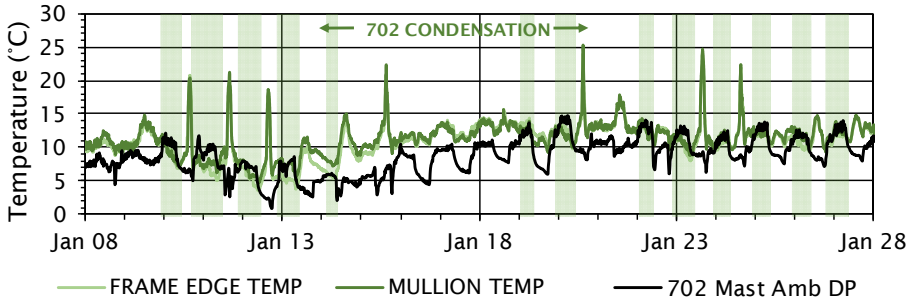
Initial Monitoring Data

702 Master Bedroom Measured Condensation Occurrences



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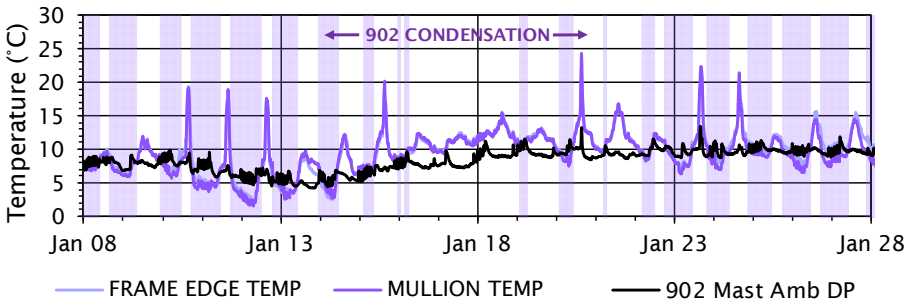
Initial Monitoring Data

902 Master Bedroom Measured Condensation Occurrences



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Initial Monitoring Data

Example of master bedroom condensation at frame

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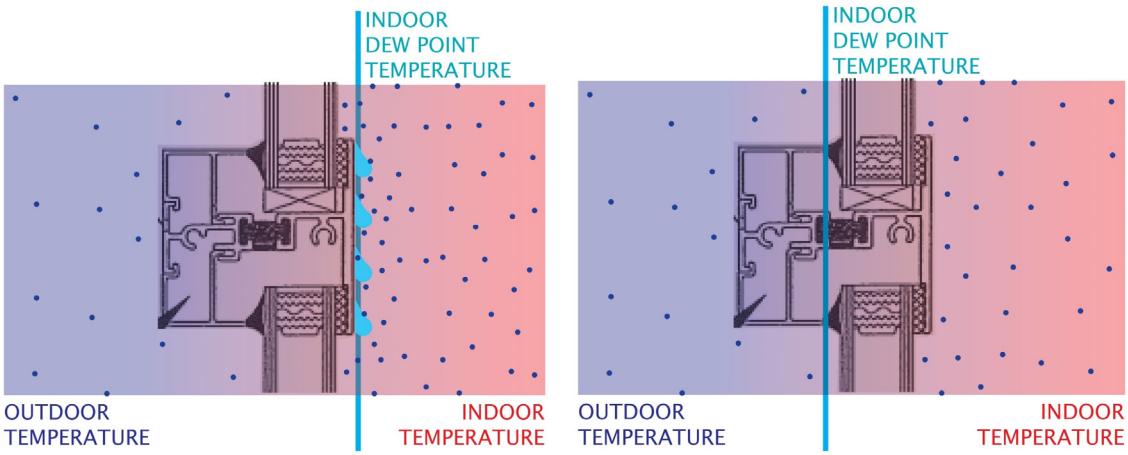
Remediation Option 1 – Reduce Dew Point Temp



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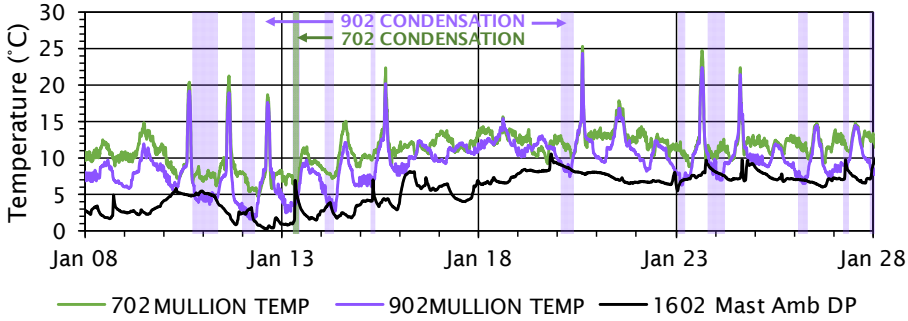
Initial Monitoring Data

702 & 902 Surface Temperatures with 1602 Dew Point Temperatures



Some condensation, but far less than before

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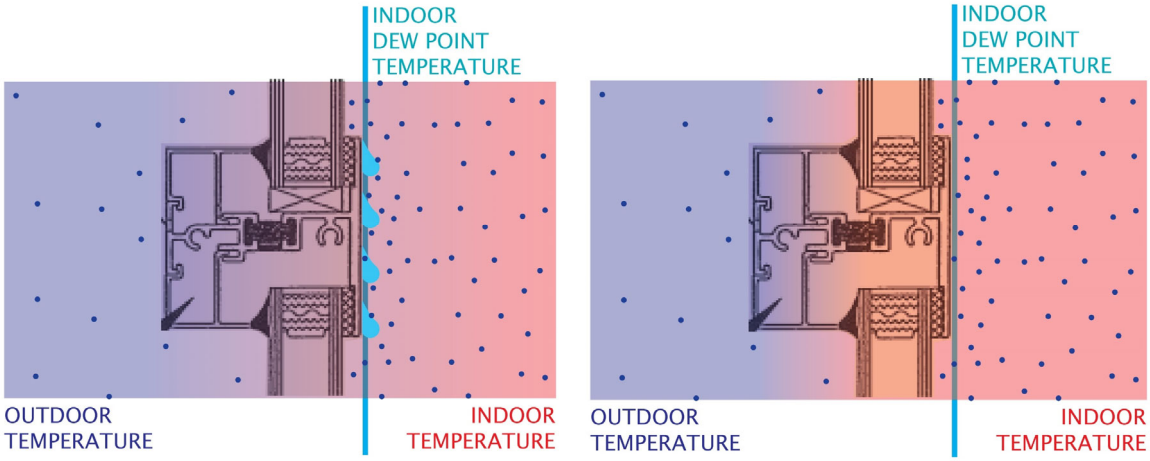
Remediation Option 2 – Warm Surfaces



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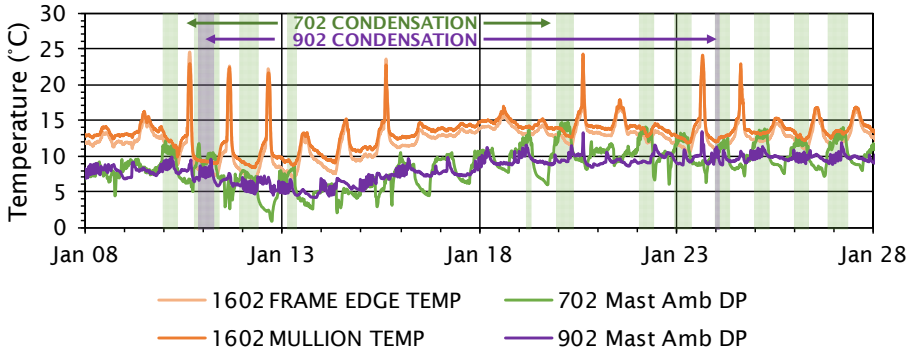
Initial Monitoring Data

1602 Surface Temp with 702 & 902 Dew Point Temperatures



Less condensation, but still occurs for Suite 702

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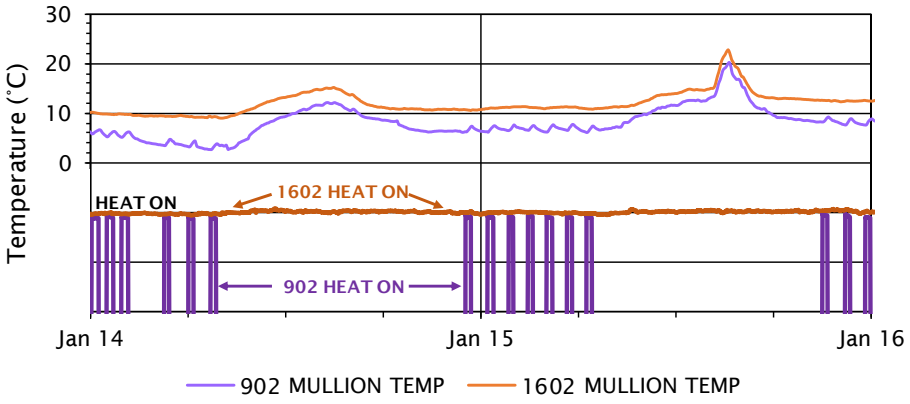
Monitoring Data – Heating Usage

902 & 1602 Surface Temperatures & Heater Use



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Curtains vs. Blinds

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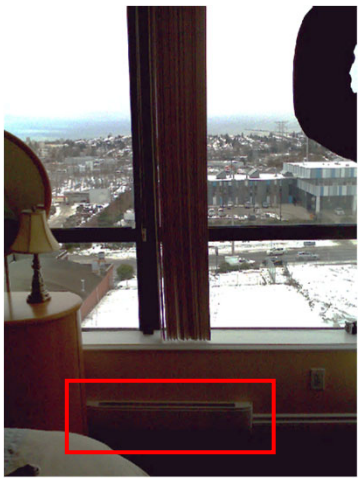
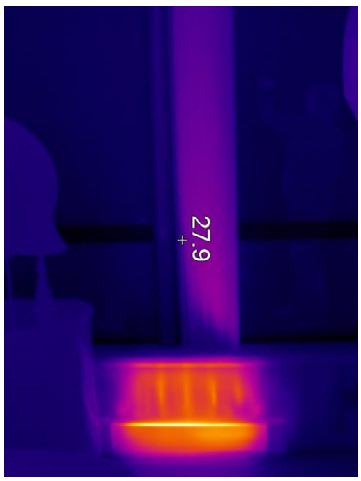
Heating From Baseboard Heater - Limited





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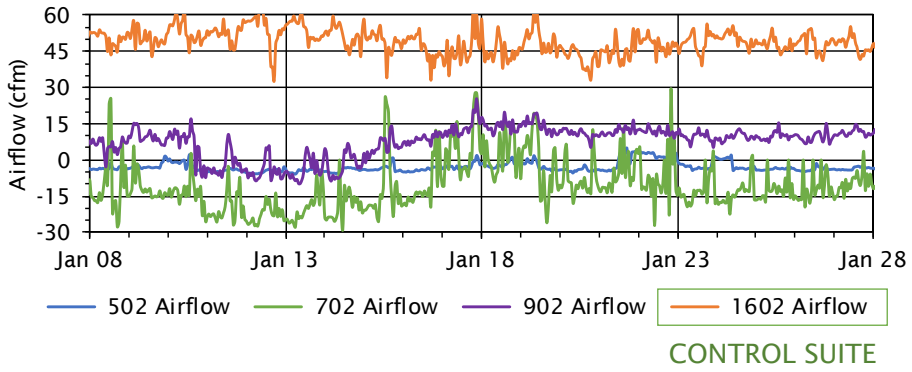
Initial Monitoring Data - Ventilation

Entry Door Airflow May Indicate Condensation Potential



CONTROL SUITE

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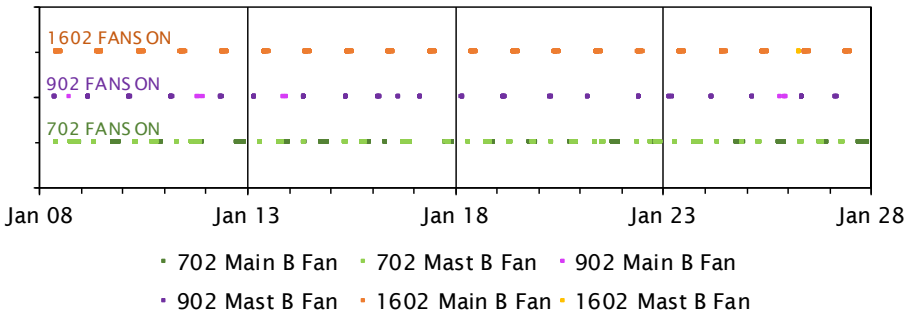
Initial Monitoring Data - Ventilation

Bathroom Fan Operation – All use fans regularly



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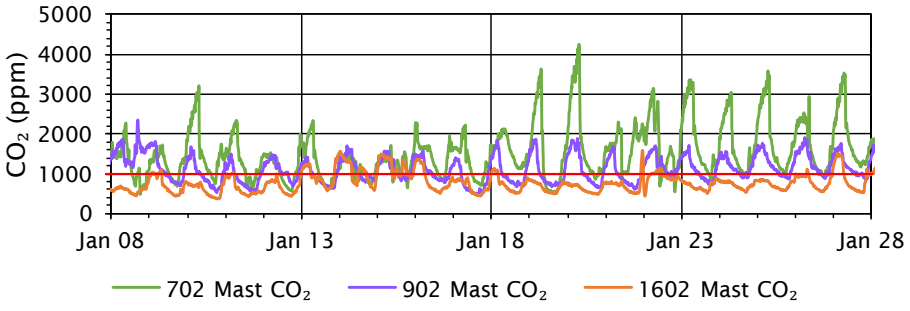
Monitoring Data - Ventilation

Carbon Dioxide Levels – 702 & 902 higher than expected (ASHRAE Box= 1000 ppm)



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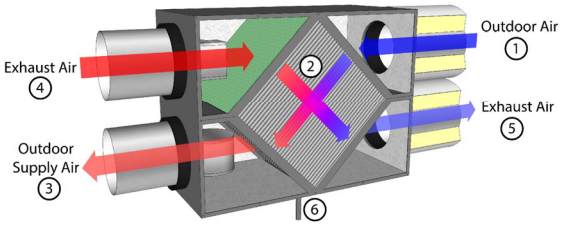
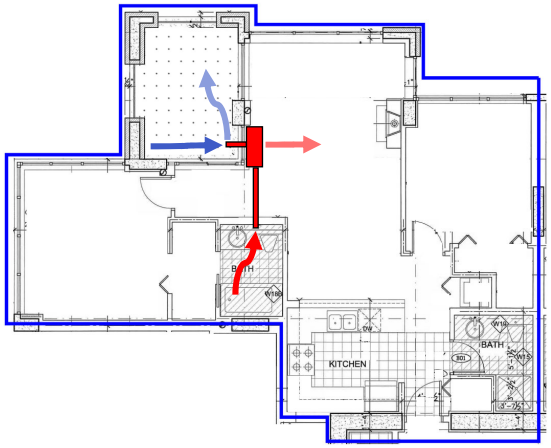
Trial Repairs – Improved Ventilation Mechanism

Heat Recovery Ventilator



Approx. 40 CFM



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Trial Repairs – Heat Recovery Ventilator

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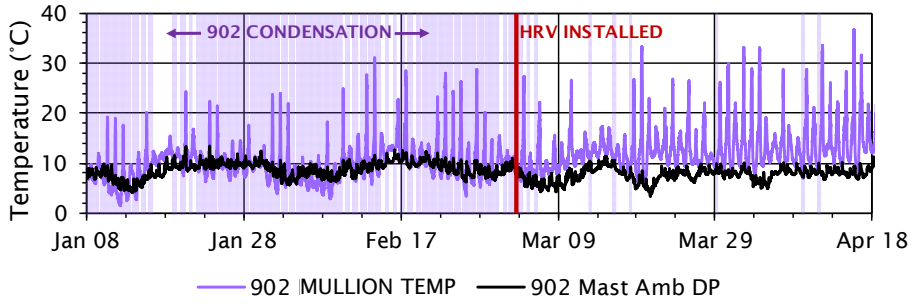
Monitoring Data

902 Condensation Occurrences Pre- & Post-HRV Retrofit



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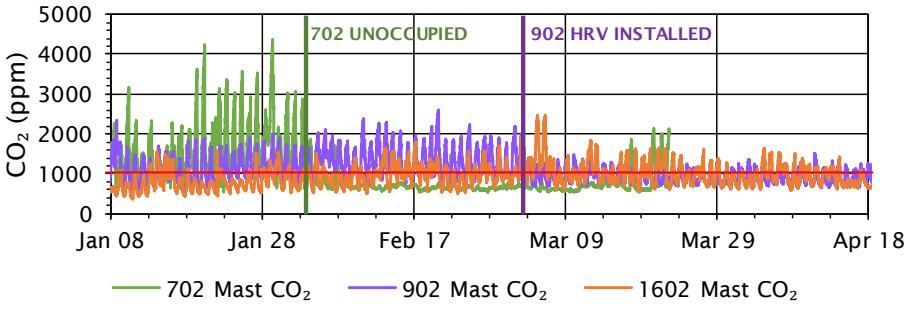
Monitoring Data

CO2 Levels Pre- & Post-HRV Retrofit*

*Occupant of Suite 702 moved out during test period, no HRV installed



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Monitoring - Findings

- Control suite received approximately recommended ventilation levels, had no signs of condensation, and maintained healthy CO2 levels
- Suites with no or minimal ventilation corresponded with condensation issues and had high CO2 levels, even with regular bathroom fan use
- Applying effects of ventilation to pre-HRV data shows far less condensation occurrences, though some condensation still may occur during cold periods
- All suites had similar ambient conditions, but highly varied window surface temperatures due to occupant behavior, heater use, window coverings

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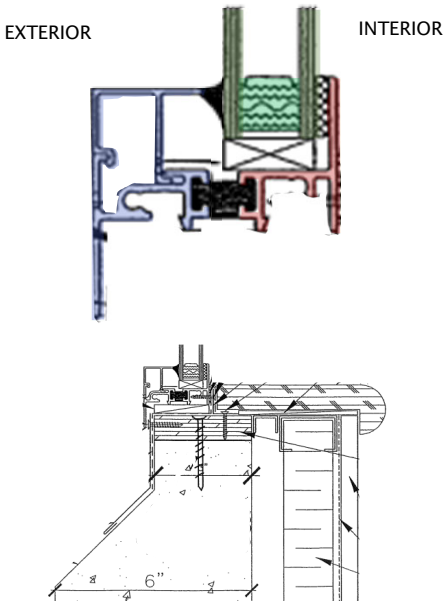
Window Review - Findings

- Windows are not great, but not the worst
- Window moisture leakage not reported to date
- Windows use thermally improved glass units, thermal breaks, and are installed in a standard arrangement at the sill
- Operable vents are not airtight and should receive adjustments and new gaskets



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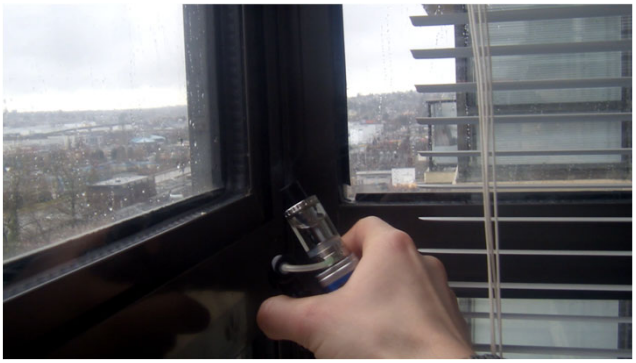
Window Review



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Window Review – Adjustments & New Gaskets

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HRV Retrofit Design: 2 Bed 2 Bath (16 Suites)

DUCT RUN – CEILING BULKHEAD

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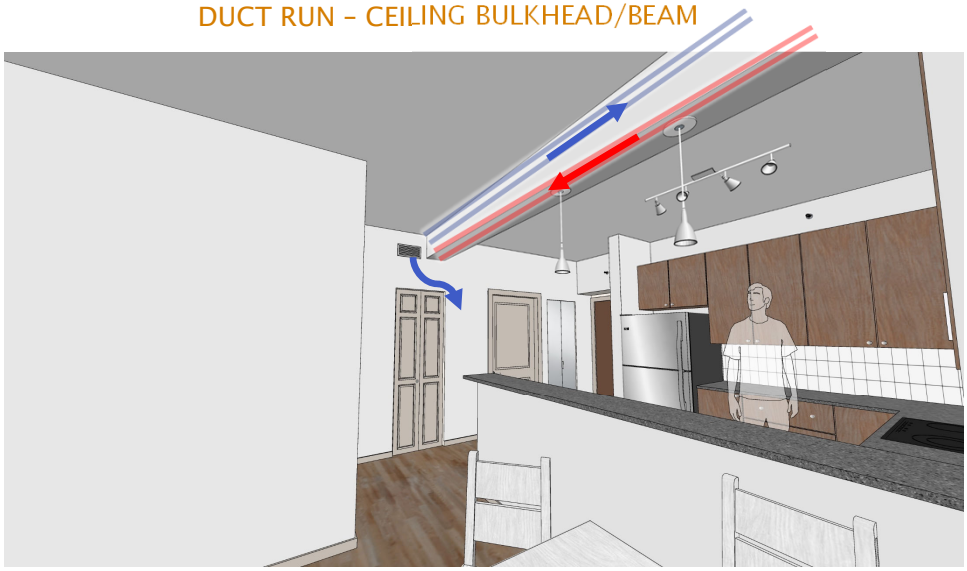
HRV Retrofit Design: 2 Bed 2 Bath Type A

DUCT RUN – CEILING BULKHEAD/BEAM



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Forensic Investigation and Repair

- Install HRVs in all suites up to Floor 20 and add gasket to seal entry doors
- Modify existing ventilation system to prioritize corridors and suites on upper floors
- Service operable windows
- Take steps to further minimize condensation risk in suites
  - Maintain minimum heating levels to keep interior surfaces warm
  - Open blinds when not in use
  - Encourage ventilation/airflow within suite
- Cost: **$1.3-1.6 M**

VS

Forensic Guessing and Repair

- Consultant 1 - Recommendations:
  - Strategy 1 – Occupant lifestyle change/review ventilation
  - Strategy 2 – Retrofit existing operable windows due to (perceived) lack of thermal break **$275K**
  - Strategy 3 – Replace IGUs with warm edge technology (WET) **$4.5M**
  - Strategy 4 – Replace all windows **$6.7M**
- Don't be Dogbert !

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FAILING FORWARD

Discussion + Questions

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