

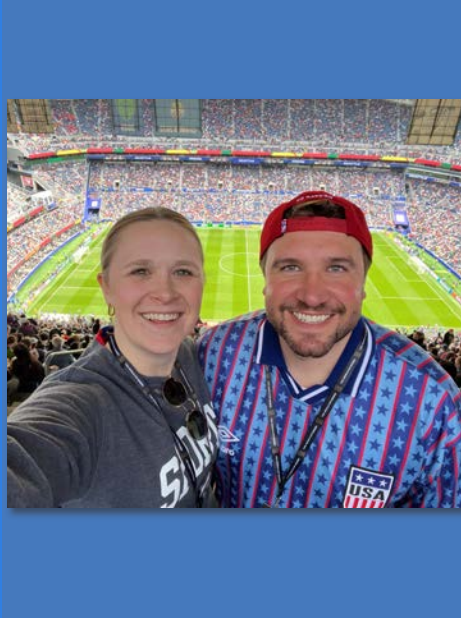


Taking Passive Building to New Heights: Scaling from Single-Family to Multifamily Housing

Greta Tjeltveit | August 4, 2026

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Building Science Specialist



Considerations in Greater Seattle & Western Washington

An aerial photograph of the Greater Seattle area. In the background, the city skyline is visible with several prominent skyscrapers. The middle ground shows a dense residential area with many houses. In the foreground, there's a body of water, likely a lake or a bay, with some houses and trees along the shoreline. The background features a range of mountains, some with snow or light-colored rock. The overall tone is somewhat muted, with a dark overlay.

- Area becoming less of a “moderate” climate
- Wildfire smoke events
- Mold/moisture
- Affordability

AGENDA

Building Form

Owner Goals

Performance Metrics

Risk Management

Insulation & Thermal Bridging

Airtightness Testing Methods

Ventilation Approaches

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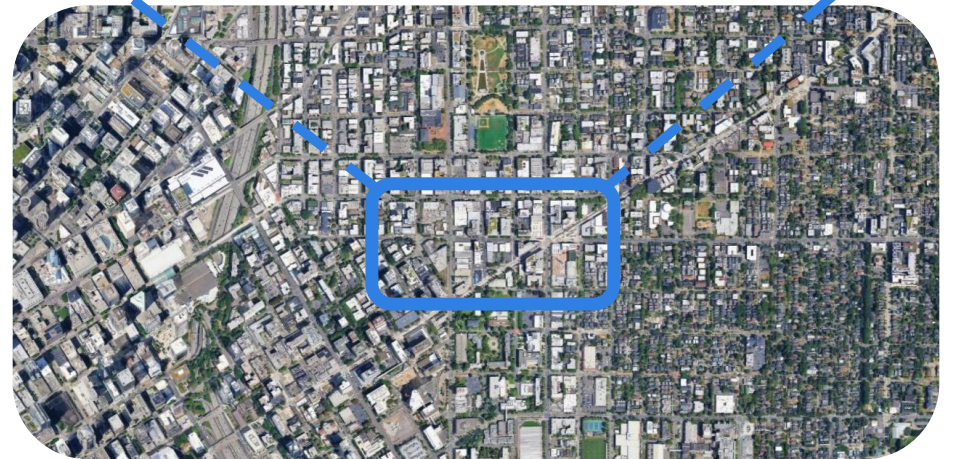
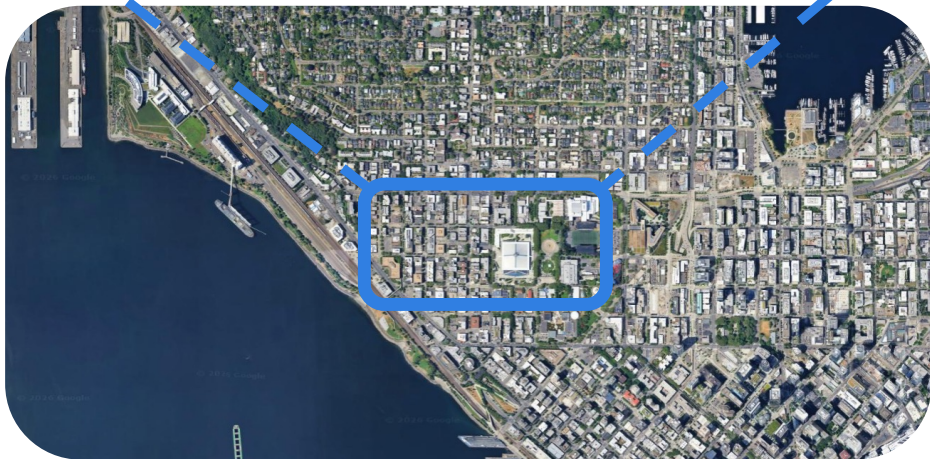
Building Form

- External Factors
- Form Complexity
- Compactness & Occupancy Density

External Factors – SF Site



External Factors – MF Site

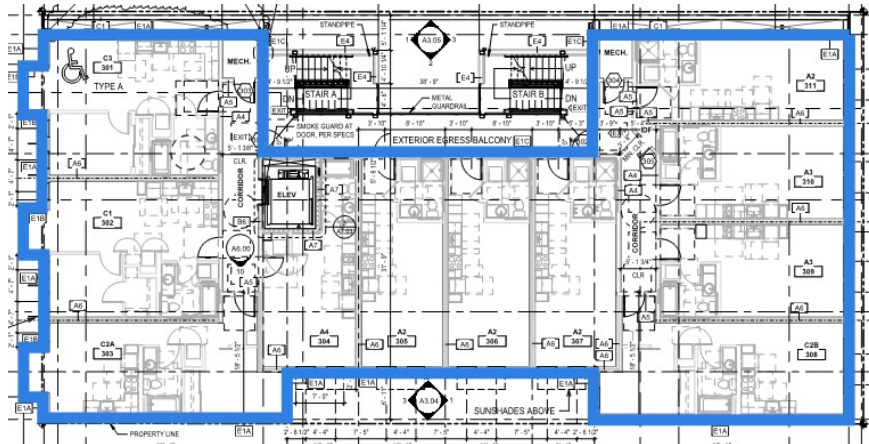


External Factors – SF Zoning & Code

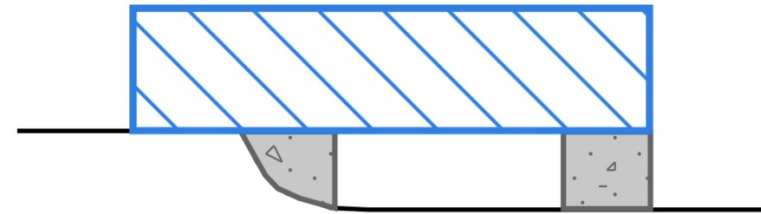
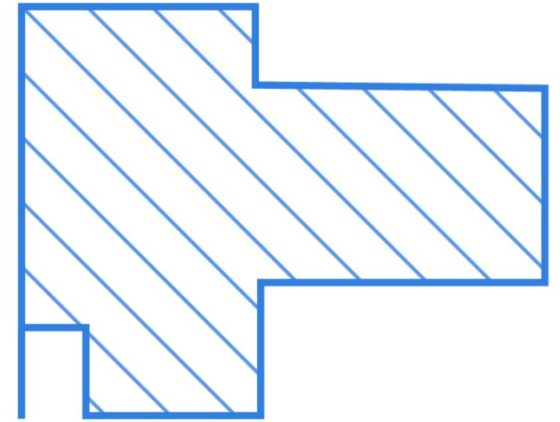


External Factors – MF Zoning & Code

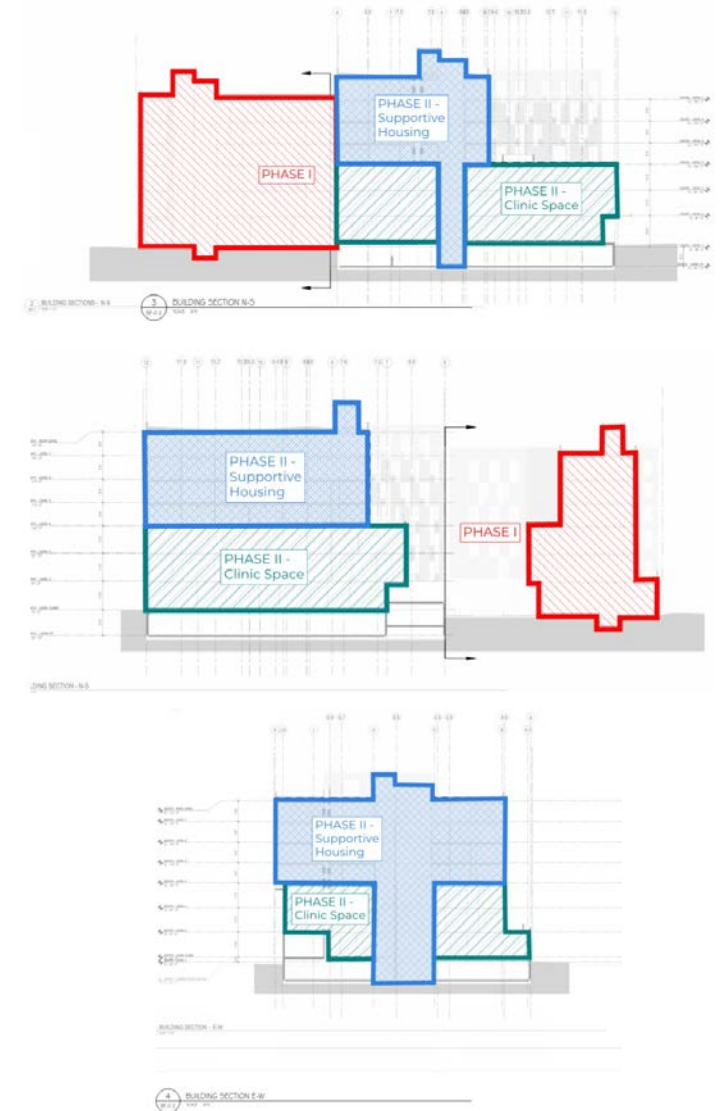
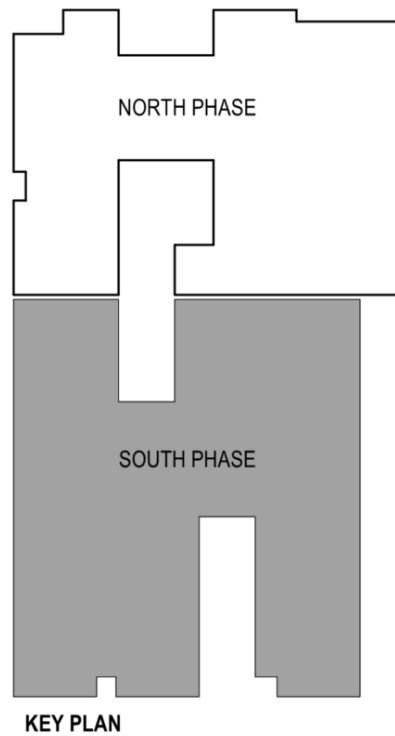
- ▶ Seattle's Early Design Guidance:
 - ▶ Driven by neighborhoods
 - ▶ Façade modulation*



Form Complexity - SF



Form Complexity - MF



Compactness & Occupancy Density

Project	SF/MF	Units/Total Bedrooms*	Cond. Floor Area (sq.ft.)	Volume (cu.ft.)	Enclosure Surface Area (sq.ft.)	Occupancy Density (sq.ft./person*)	Enclosure-to-Volume
FPR	SF	1 unit/3 bds	3,462	42,505	8,880	866	0.209
L125	MF, a	90 units/66 studios, 24 1-bds	59,336	702,380	60,238	659 – 520	0.086
HPS	MF, a	92 units/92 studios	44,596	482,863	57,482	485	0.119
EPH	MF, lux	69 units/32 studios, 36 1-bds	33,879	243,806	39,439	491 – 326	0.162
SCH	MF, lux	45 units/5 studios, 35 1-bds, 5 2-bds	29,490	342,296	32,550	590 – 328	0.095

Credit: Built Work Photography

Owner Goals

Building Form

Owner Goals

Performance Metrics

Risk Management

Insulation & Thermal Bridging

Airtightness Testing Methods

Ventilation Approaches

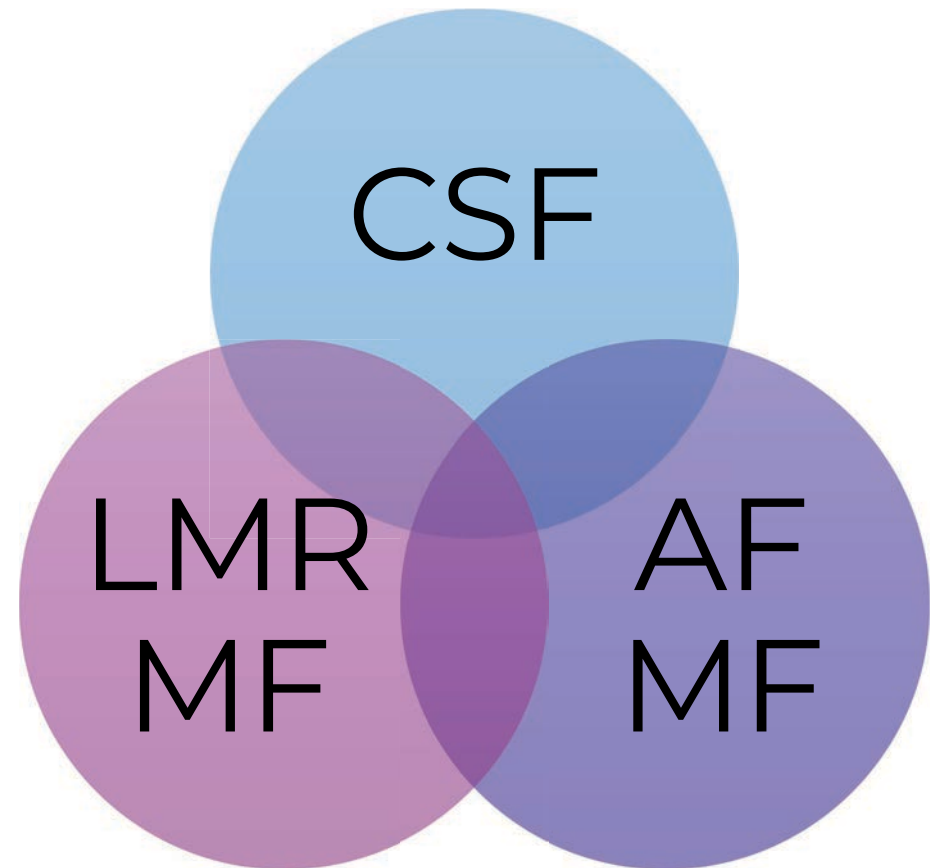
Risk Management

Owner Goals

- Mission & Values
- Financial Drivers & Incentives
- Market Value & Resident Experience

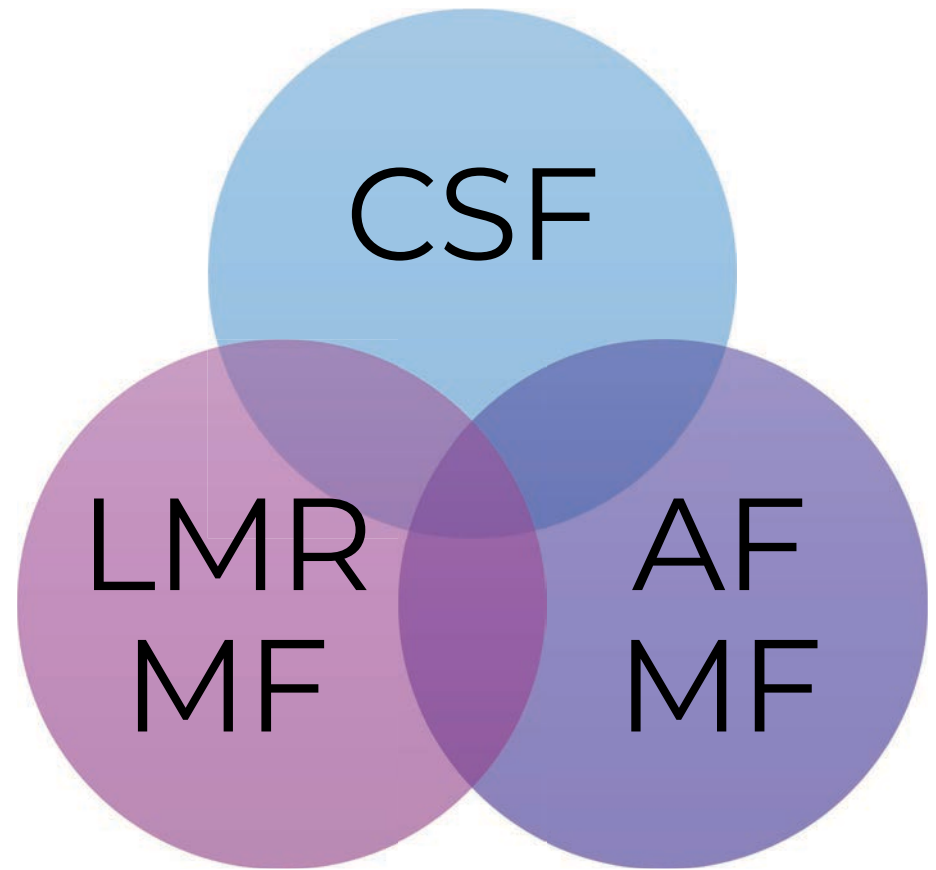
Mission & Values

- ▶ Custom Single-Family (CSF):
 - ▶ Sustainability
- ▶ Luxury & Market-Rate (LMR MF) Multifamily:
 - ▶ Marketability
- ▶ Affordable Multifamily (AF MF)
 - ▶ Funding & lower operating costs



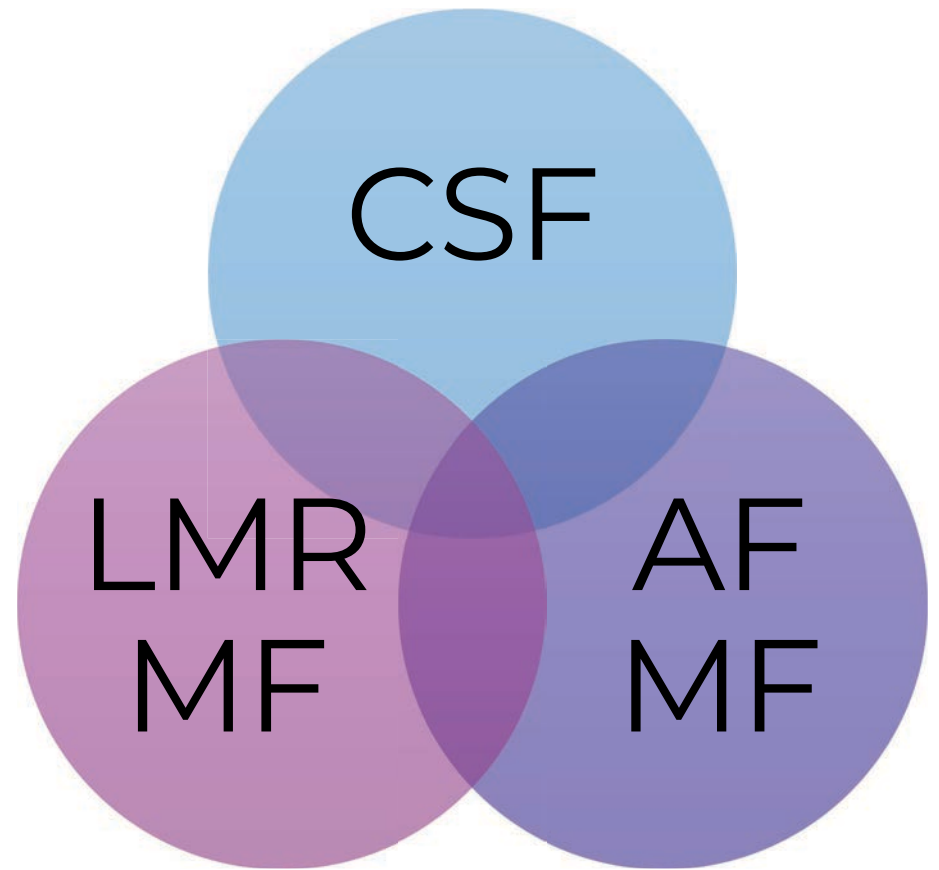
Financial Drivers & Incentives

- ▶ Federal Incentives & Tax Credits
 - ▶ IRA, 45L, 179D, Low-Income Housing Tax Credit (LIHTC)
- ▶ C-PACE Financing
- ▶ Fannie Mae Green Building Loans
- ▶ Energy Star rebates
- ▶ Regional Funding
- ▶ Expedited Permitting Incentives
- ▶ Floor Area Ratio (FAR) bonus
- ▶ Phius as a WA State Energy Code Compliance Path for SF projects



Market Value & Resident Experience

- ▶ Indoor air quality
- ▶ Wildfire smoke resilience
- ▶ Comfort
- ▶ Lower utility bills
- ▶ Competitive marketing advantage
- ▶ Additional amenity space and/or solar PV area enabled by optimized mechanical systems



Performance Metrics

Building Form
Owner Goals

Performance Metrics

Risk Management
Insulation & Thermal Bridging
Airtightness Testing Methods
Ventilation Approaches

Performance Metrics

- What Are We Optimizing?
- Every Metric Has Assumptions
- Building Performance Should Measure Outcomes, Not Just Inputs

What Are We Optimizing?

- ▶ Lower operational energy
- ▶ Lower carbon emissions
- ▶ Affordability
- ▶ Housing more people
- ▶ Healthy, resilient buildings



Every Metric Has
Assumptions
(and Blind Spots!)



Building Performance Should Measure Outcomes, Not Just Inputs

- ▶ Tracking actual energy use
- ▶ Public display of energy use
- ▶ Better understanding occupant behavior
- ▶ WSEC outcome-based performance pathway



Risk Management

Building Form
Owner Goals
Performance Metrics
Risk Management

Insulation & Thermal Bridging
Airtightness Testing Methods
Ventilation Approaches

Risk Management

- **Design & Certification Risk**
- **Construction & Quality Risk**
- **Operational & Ownership Risk**

Design & Certification Risk

- ▶ Single-family:
 - ▶ Smaller projects have less "buffer"—localized issues can represent a much larger percentage of the enclosure.
 - ▶ Owners are often personally invested in certification and performance.
 - ▶ Performance assumptions should remain realistic for construction teams.
- ▶ Multifamily
 - ▶ Certification is often tied to:
 - ▶ Funding
 - ▶ Incentives
 - ▶ Code compliance pathways
 - ▶ Missing certification can have significant financial consequences.
 - ▶ Larger teams and more complex schedules increase coordination risk.
 - ▶ Energy modeling assumptions and construction tolerances become increasingly important.
 - ▶ Need realistic safety factors and margins for airtightness, ventilation, and energy targets.

Construction & Quality Risk

- ▶ Single-family:

- ▶ Defect (air leak, moisture issue, installation error) can affect a much larger percentage of the building.
- ▶ Fewer systems generally make issues easier to identify and correct.



- ▶ Multifamily:

- ▶ Larger projects have more redundancy but significantly more interfaces.
- ▶ Greater coordination among trades.
- ▶ More opportunities for inconsistencies between units.
- ▶ Larger enclosure means localized defects may represent a smaller percentage of the whole, but can still affect many occupants if widespread.
- ▶ Importance of QA/QC, testing, balancing, commissioning, and verifier involvement.

Operational & Ownership Risk

- ▶ Single-family:
 - ▶ Homeowner is effectively the facility manager
 - ▶ Success depends on:
 - ▶ Understanding the systems
 - ▶ Replacing filters
 - ▶ Routine maintenance
 - ▶ Knowing when to call professionals
- ▶ Multifamily
 - ▶ Dedicated maintenance staff or facility manager
 - ▶ Greater reliance on:
 - ▶ O&M manuals
 - ▶ Staff training
 - ▶ Maintenance budget



Insulation & Thermal Bridging

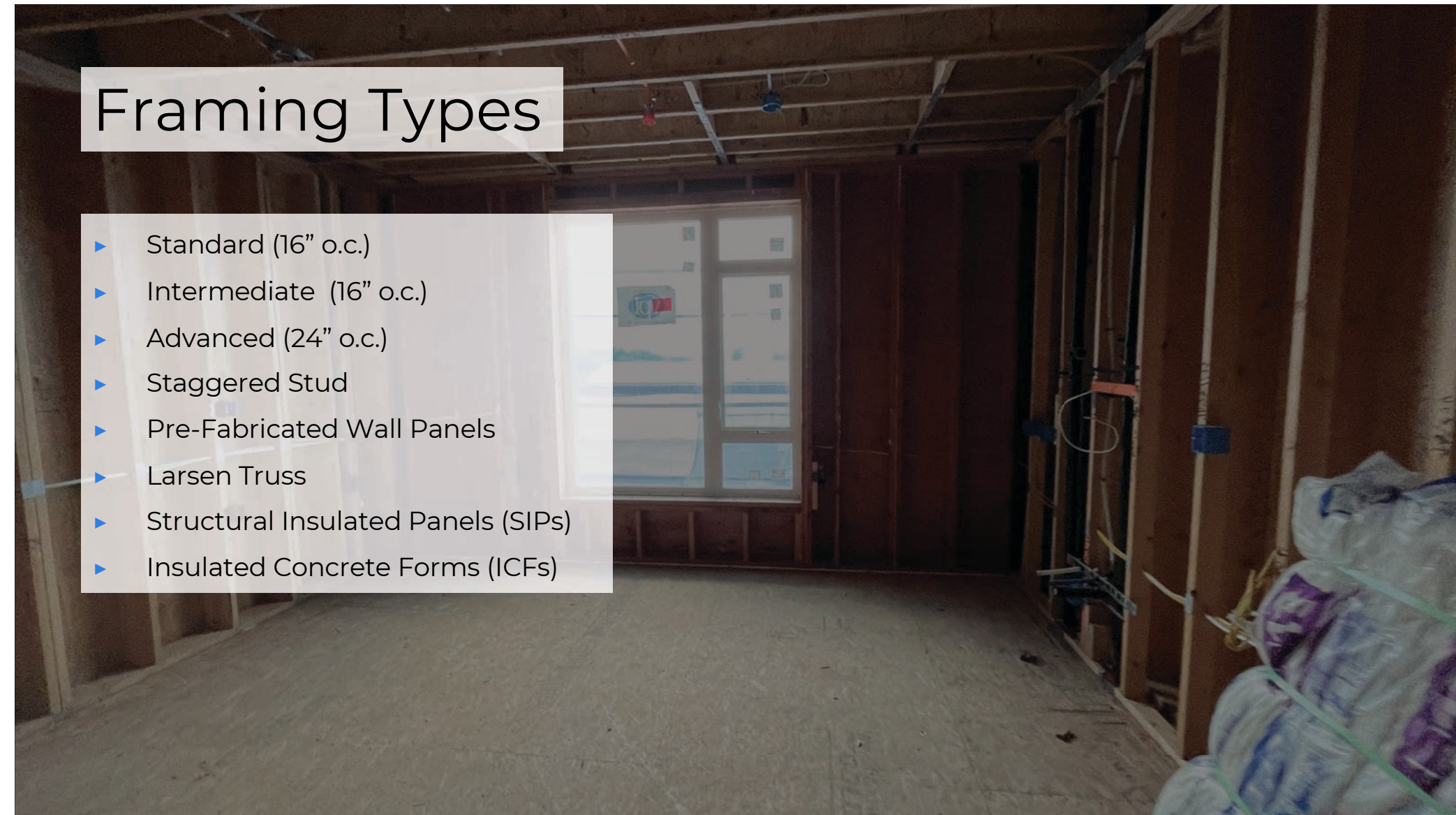
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Insulation & Thermal Bridging

- Framing Types
- Occupancy-Driven
Insulation Selection
- As-Built Framing Factors

Framing Types

- ▶ Standard (16" o.c.)
- ▶ Intermediate (16" o.c.)
- ▶ Advanced (24" o.c.)
- ▶ Staggered Stud
- ▶ Pre-Fabricated Wall Panels
- ▶ Larsen Truss
- ▶ Structural Insulated Panels (SIPs)
- ▶ Insulated Concrete Forms (ICFs)



Occupancy-Driven Insulation Selection

- ▶ SF:
 - ▶ Lower occupancy and appliance density = fewer internal heat gains and requires a more robust thermal enclosure
 - ▶ 2x6 (16" o.c.) with dense-pack cellulose insulation + 3" ext. insulation
- ▶ MF:
 - ▶ Higher occupancy density and internal heat gains doesn't require as robust of a thermal enclosure
 - ▶ 2x8 (16" o.c.) with blown-in fiberglass insulation – no cont. ext. insulation

Sheathing

As-Built Framing Factors

- ▶ Background
- ▶ Gap in Knowledge
- ▶ Methodology
- ▶ What We Looked At
- ▶ Results
- ▶ Analysis
- ▶ Lessons Learned

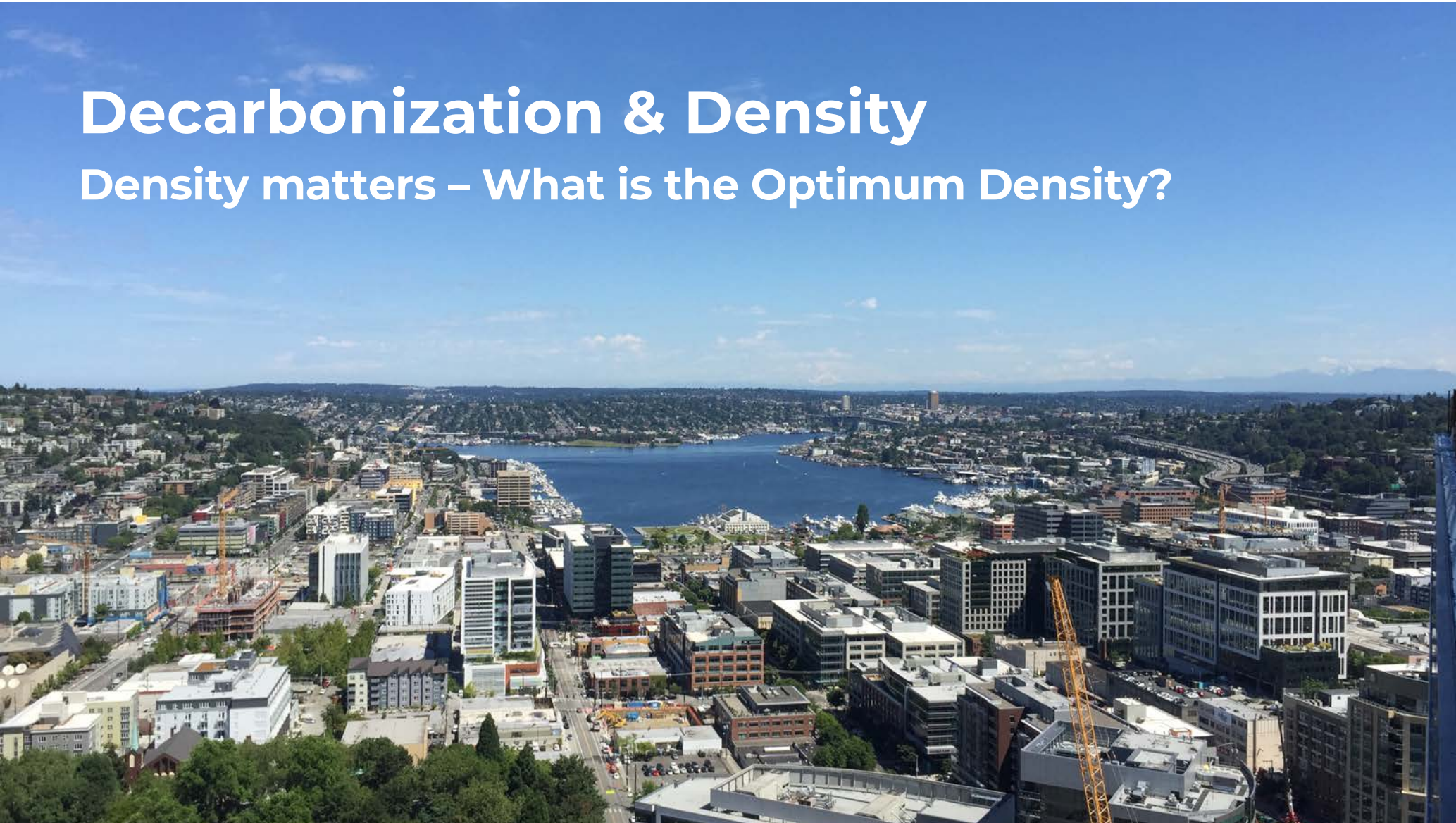


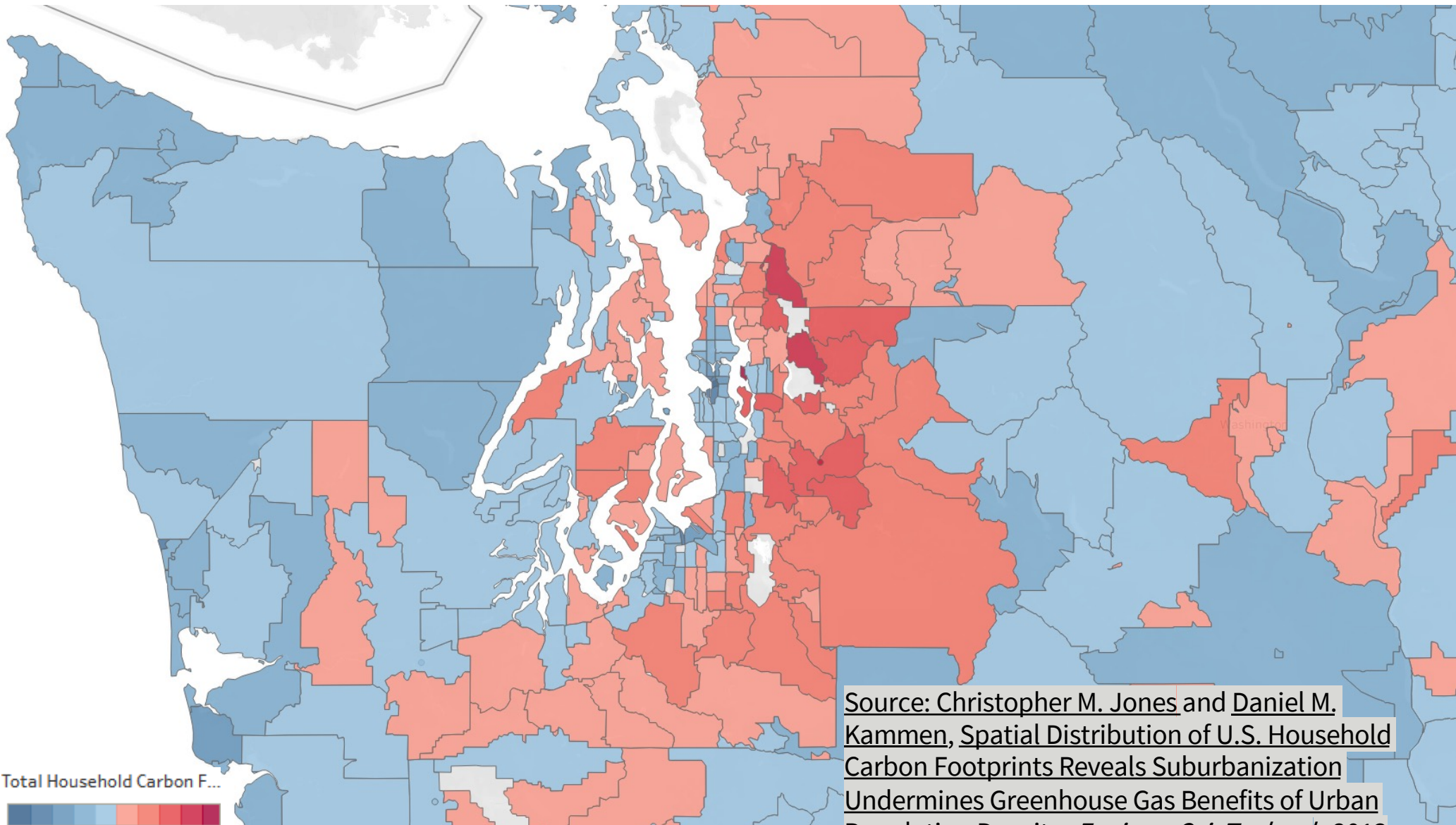
High Level Summary

- ▶ **Framing factor definition** = the fraction of the total building component (wall or roof) area that is framing
- ▶ WA State Energy Code wall framing factors are assumed to be between **13-19% for walls**
- ▶ We surveyed **5 buildings** = 4 affordable housing mid-rises + 1 market rate mid-rise
- ▶ Surveys defined “modules” and counted extra studs to define **as-built framing factors**
- ▶ Framing factors were between **13-41% above** WA State Energy Code assumptions
- ▶ We analyzed the impact of additional framing in terms of:
 - Excess annual energy demand
 - Annual carbon emissions
 - Material cost of lumber not structurally required

Decarbonization & Density

Density matters – What is the Optimum Density?

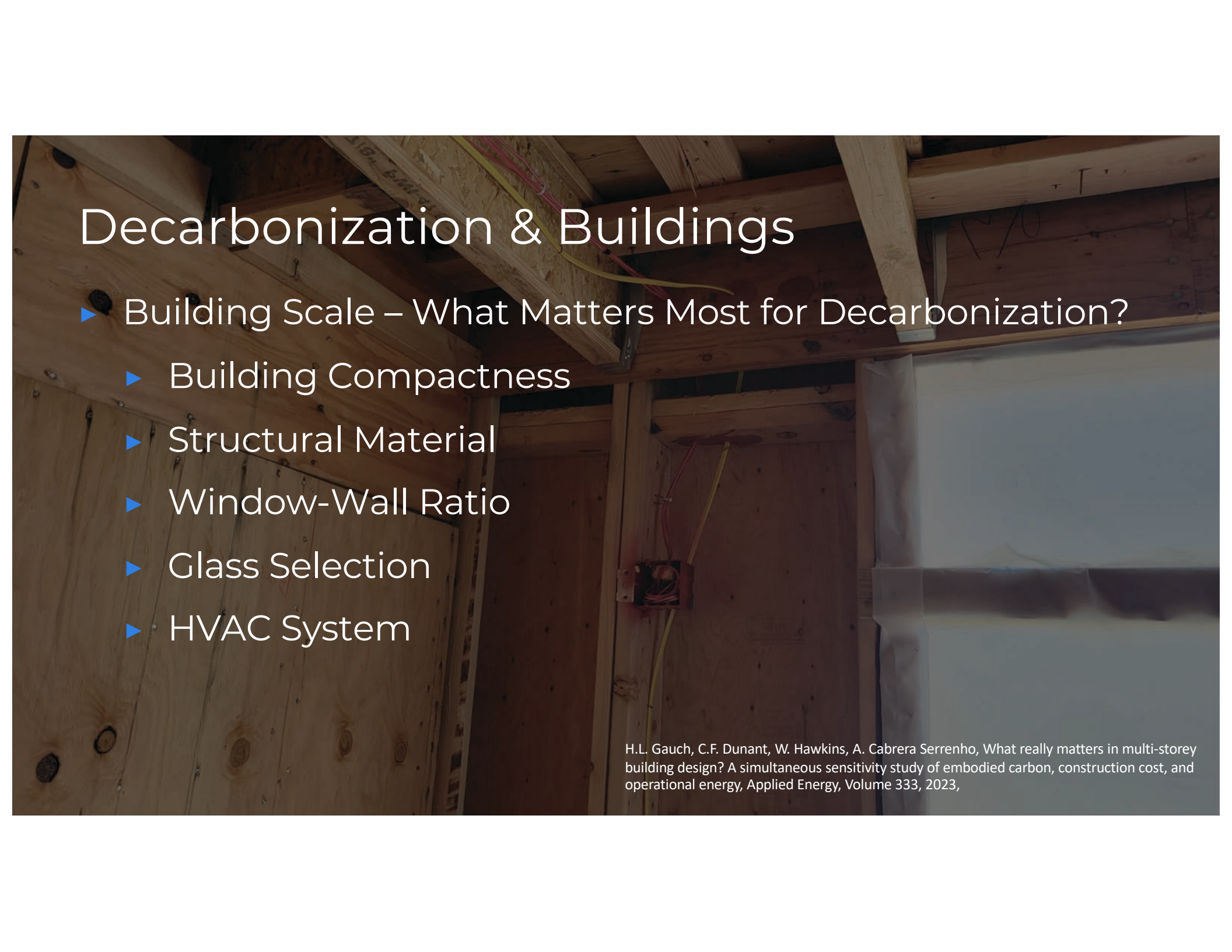




Decarbonization & Density

- ▶ Density matters – What is the Optimum Density?
 - ▶ High Density High Rise (e.g. Manhattan)
 - ▶ Low Density High Rise (e.g. Le Corbusier's Radiant City)
 - ▶ High Density Low Rise (e.g. Paris)
 - ▶ Low Density Low Rise (e.g. Urban/Suburban Sprawl)

Pomponi, F., Saint, R., Arehart, J.H. *et al.* Decoupling density from tallness in analysing the life cycle greenhouse gas emissions of cities. *npj Urban Sustain* 1, 33 (2021)

The background of the slide is a photograph of a building's internal wooden structure. It shows a network of light-colored wooden beams and panels, some of which are covered with white protective plastic. A small electrical box with wires is visible on one of the vertical studs. The lighting is somewhat dim, highlighting the textures of the wood.

Decarbonization & Buildings

- ▶ Building Scale – What Matters Most for Decarbonization?
 - ▶ Building Compactness
 - ▶ Structural Material
 - ▶ Window-Wall Ratio
 - ▶ Glass Selection
 - ▶ HVAC System

H.L. Gauch, C.F. Dunant, W. Hawkins, A. Cabrera Serrenho, What really matters in multi-storey building design? A simultaneous sensitivity study of embodied carbon, construction cost, and operational energy, Applied Energy, Volume 333, 2023,

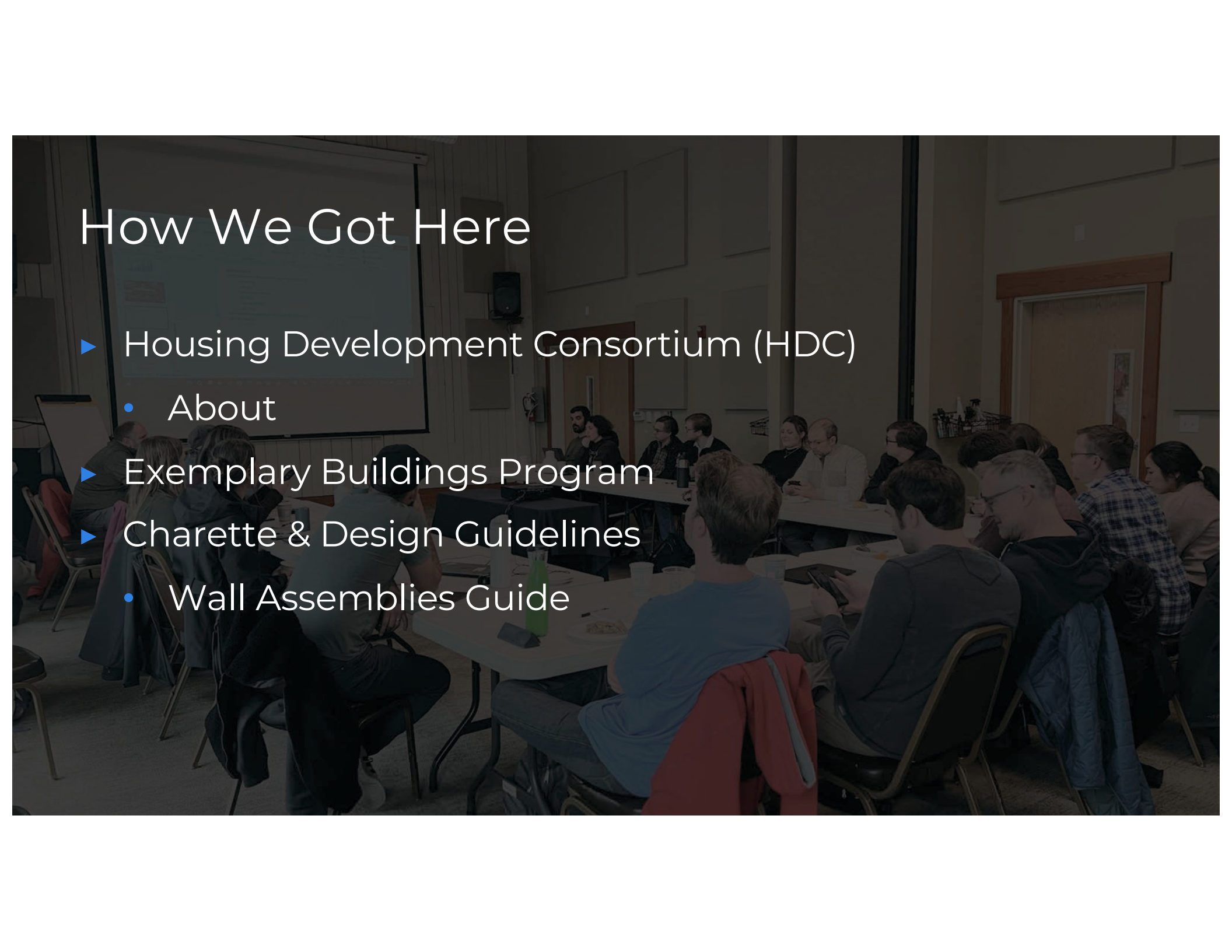


Building Scale: Typical Multifamily Construction Costs in Seattle

- ▶ ROUGH typical percentages of total construction cost:
 - ▶ Concrete (Div 03) ~6%-16%
 - ▶ Framing Package (Div 06) ~7%-14%
 - ▶ Enclosure (Div 07) ~7%-9%
 - ▶ Windows & Doors (Div 08) ~1.5%-5%
 - ▶ HVAC (Div 23) ~3%-6%

Why wood framing is Important

- ▶ Efficient Wood Structures Make Efficient Buildings
- ▶ Efficient Wood Structures Have A Triple Bottom Line:
 - Planet: Energy Efficiency (Operational AND Embodied)
 - Prosperity: Construction Cost Efficiency
 - People: More Housing Affordability

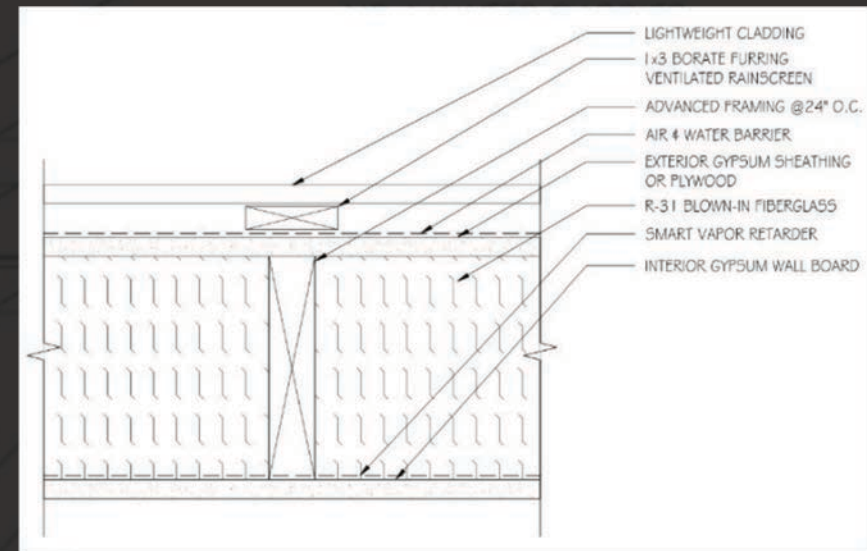
A group of people are seated at long tables in a room, facing a large screen. The screen displays a presentation with the title 'How We Got Here' and a list of topics. The room has a high ceiling and large windows. The people are engaged in the presentation, with some looking at the screen and others looking at their devices.

How We Got Here

- ▶ Housing Development Consortium (HDC)
 - About
- ▶ Exemplary Buildings Program
- ▶ Charette & Design Guidelines
 - Wall Assemblies Guide

Wall Assemblies Guidelines

- ▶ Guidelines Developed to Target Effective R-22
- ▶ Multiple Wall Types
- ▶ Cavity-Only Wood-Framed Wall:
 - ▶ Example wall used 2x8 advanced framing (24" o.c.)
 - ▶ A maximum Framing Factor of 20% recommended
 - ▶ Douglas fir framing
 - ▶ R-31 Blown-In



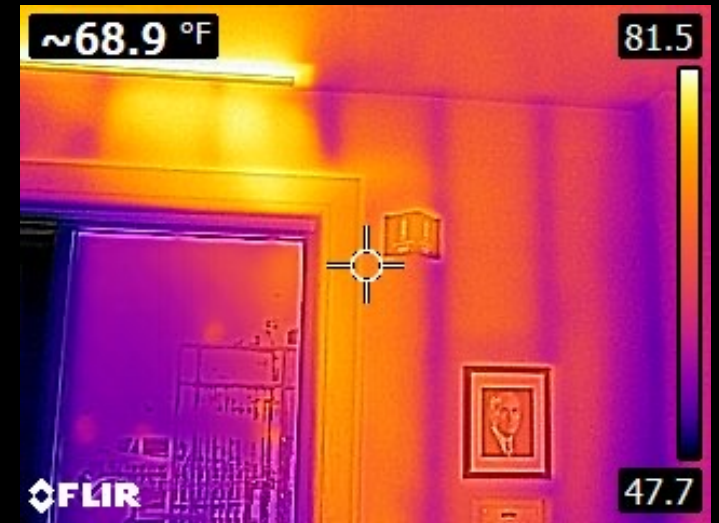
Wall Assemblies Guidelines

Cavity Only Insulation – Is it the way to go?



What is a Framing Factor?

- ▶ Simply put: The ratio of wood framing to cavity in an exterior wall.
- ▶ For example : A wall with a 25% framing factor will have walls with 25% framing and 75% insulation.
- ▶ Framing factor is used to establish the effective insulation value of a wall.



Past Research

- ▶ The ASHRAE TC 4.4 Research Project (RP-904) 2001
 - 120 low-rise residential dwellings – included multifamily < 3 stories
 - Northeast, Midwest, South, and West
 - Excluded Pacific Northwest and California Seismic Regions
- Recommended 25% Framing Factors

Table 4.8: Recommended Table of Framing Factors (all values in %)¹

Component	Detached	Attached	Multi-Family	All Dwellings
Window Area to Gross Wall Area	11.5 ± 3.7	12.7 ± 5.2	10.1 ± 4.8	11.5 ± 4.7
Door Area to Gross Wall Area	5.6 ± 2.4	7.1 ± 4.2	3.1 ± 3.2	5.2 ± 3.7
Rim Joist Area to Gross Wall Area	4.7 ± 2.6	5.3 ± 3.0	3.7 ± 3.9	4.3 ± 3.3
Framing Factors	Net	Net	Net	Net
Ceiling	7.1 ± 1.8	6.7 ± 1.9	6.2 ± 1.6	6.9 ± 2.1
Wall	24.2 ± 3.4	26.8 ± 4.8	24.4 ± 4.4	25.4 ± 4.5
Floor	11.3 ± 5.7	12.3 ± 6.7	10.9 ± 3.8	11.9 ± 5.1
Overall	14.9 ± 3.2	15.4 ± 3.1	16.3 ± 4.4	15.5 ± 3.8

¹ - ± values indicate one standard deviation

Past Research

- ▶ The California Energy Commission Project 2001
 - 60 single-family and low-rise multi-family dwellings
 - Recommended 27% Framing Factor
 - Multifamily up to 3-Stories

Recommended Table of Framing Factors (all values in %)

Component	ASHRAE (National) Results	California Results
Window Area to Gross Wall Area	12	12
Door Area to Gross Wall Area	5	7
Rim Joist Area to Gross Wall Area	4	Not Available - See Note
Framing Factors	Net	Net
Ceiling	7	7
Wall	25	27
Floor	12	Not Available - See Note
Overall	16	15

Note: Since the vast majority of dwellings in the State of California are constructed on slab-on-grade foundations, there is not sufficient framed floor data to calculate framing factors related to the floor. Rim Joist Area is included in the Gross and Net Wall Areas. See also Framing Factor Definitions in Section 3.6 of this report.

Energy Code Assumptions

Standard framing weighting factors:

Studs and plates	0.19
Insulated cavity	0.77
Headers	0.04

16" oc, 3 stud corners, uninsulated headers, partitions intersect exterior wall.

Intermediate framing weighting factors:

Studs and plates	0.18
Insulated cavity	0.78
Headers	0.04

16" oc, 2 stud corners, insulated headers, partitions don't intersect exterior wall.

Advanced framing weighting factors:

Studs and plates	0.13
Insulated cavity	0.83
Headers	0.04

24" oc, 2 stud corners, one jack stud per jamb, insulated headers, partitions don't intersect exterior wall.

Energy Code Assumptions

WSEC A103.2.1

ASHRAE 90.1-2022

Standard framing weighting factors:

Studs and plates	0.19
Insulated cavity	0.77
Headers	0.04

23%

25%

Intermediate framing weighting factors:

Studs and plates	0.18
Insulated cavity	0.78
Headers	0.04

22%

25%

(insulated headers)

(insulated headers)

Advanced framing weighting factors:

Studs and plates	0.13
Insulated cavity	0.83
Headers	0.04

17%

22%

Energy Code Assumptions

	2021 WSEC and SEC	ASHRAE 90.1-2022	Percent Difference
2x6 Standard R-21	R-17.5	R-15.9	10.1%
2x6 Intermediate R-21	R-18.5	R-16.9	9.4%
2x6 Advanced R-21	R-19.6	R-17.5	12.0%
2x8 Standard R-25	R-19.6	R-19.3	1.5%
2x8 Intermediate R-25	R-21.2	R-19.9	6.5%
2x8 Advanced R-25	R-22.2	R-20.6	7.8%

State of the Art

- ▶ Past studies have focused exclusively on buildings < 3 stories
- ▶ National model energy codes use non-seismic framing factors
- ▶ California studies show seismic framing factors slightly higher
- ▶ WSEC and SEC use lower factors than national codes
- ▶ Baseline differences range from 1%-12% in assumptions
- ▶ Framing lumber in Seattle is often Douglas Fir, which is 20% more conductive than the Spruce/Pine/Fir lumber assumed by codes.

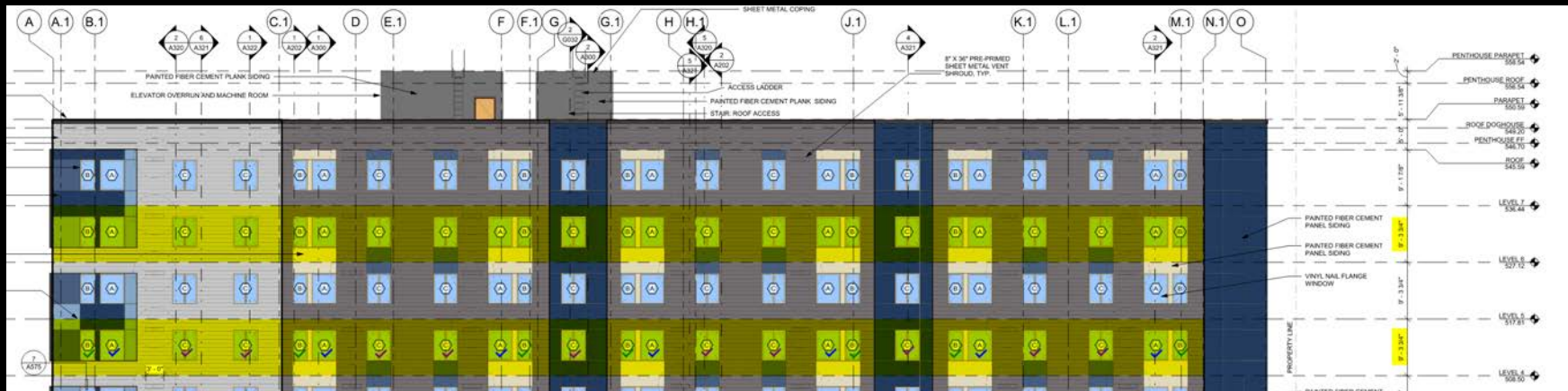
Methodology

- ▶ Field studies
 - Module definition
 - Count “extra” studs
- ▶ Calculations
 - Baseline module FFs
 - As-Built FFs
 - U-values

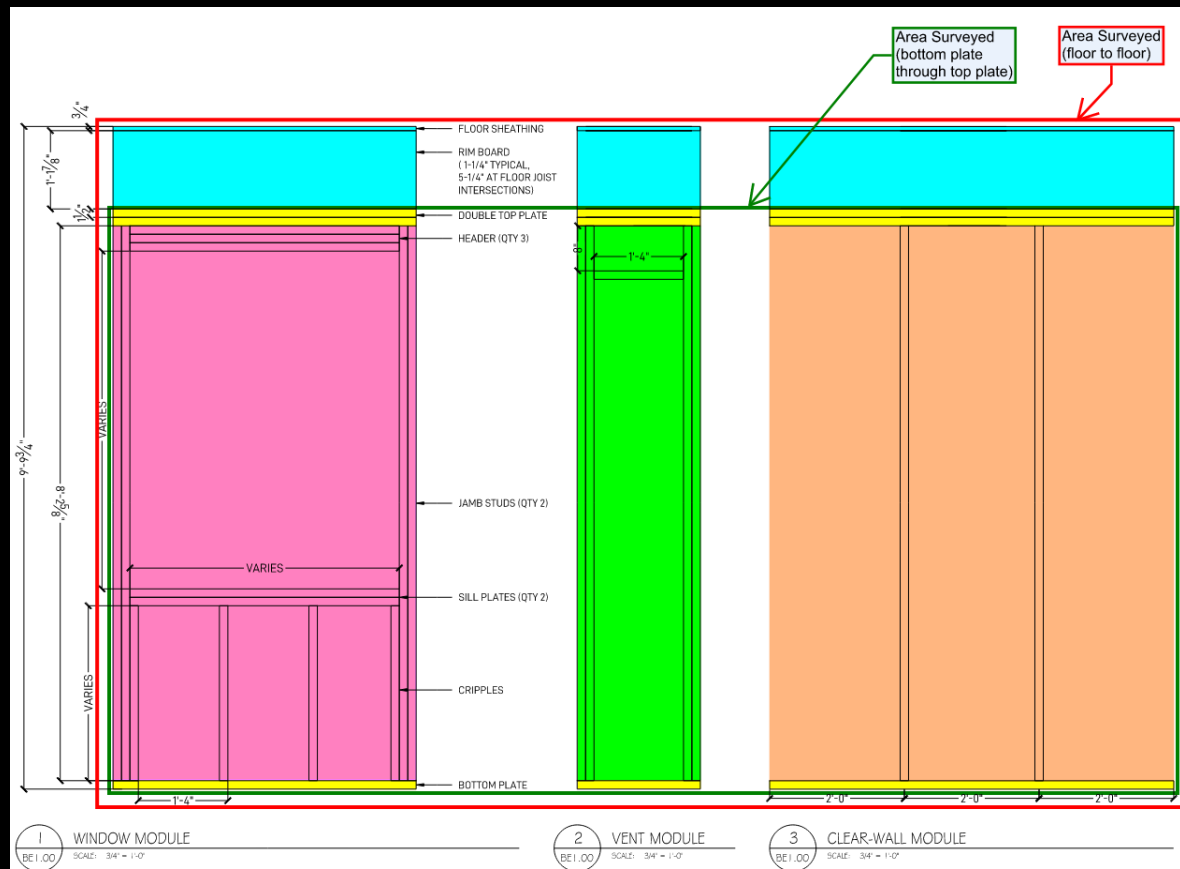


Area Surveyed

- ▶ 2-3 levels per building
 - ▶ Lower, middle, upper
- ▶ 2 elevations per building
- ▶ Average of 3,500 LF per building



Module Definition



Extra Studs: Field of the Wall



Extra Studs: Outside Corners



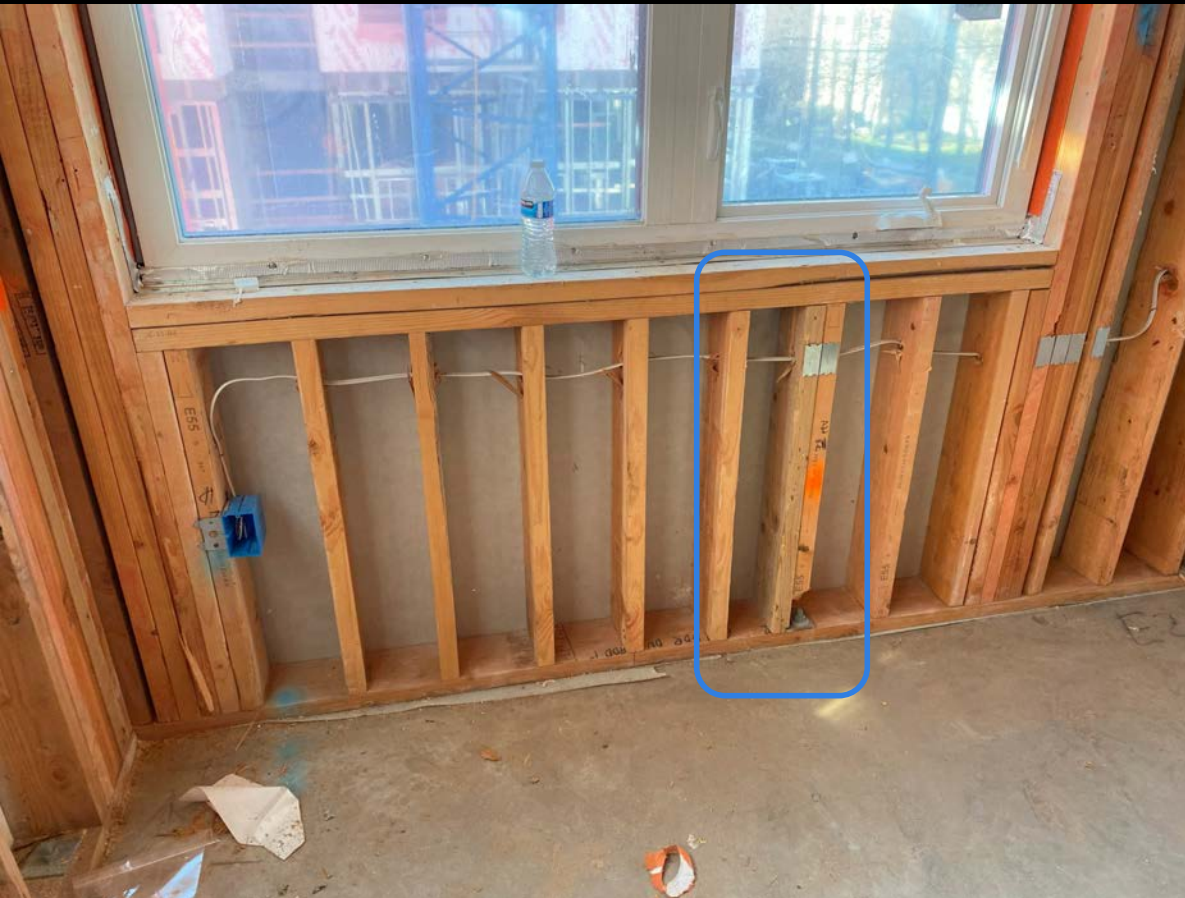
Extra Studs: Inside Corners



Extra Studs: Temporary Openings



Extra Studs: Cripples



Summary of Buildings Surveyed

5 Buildings Total

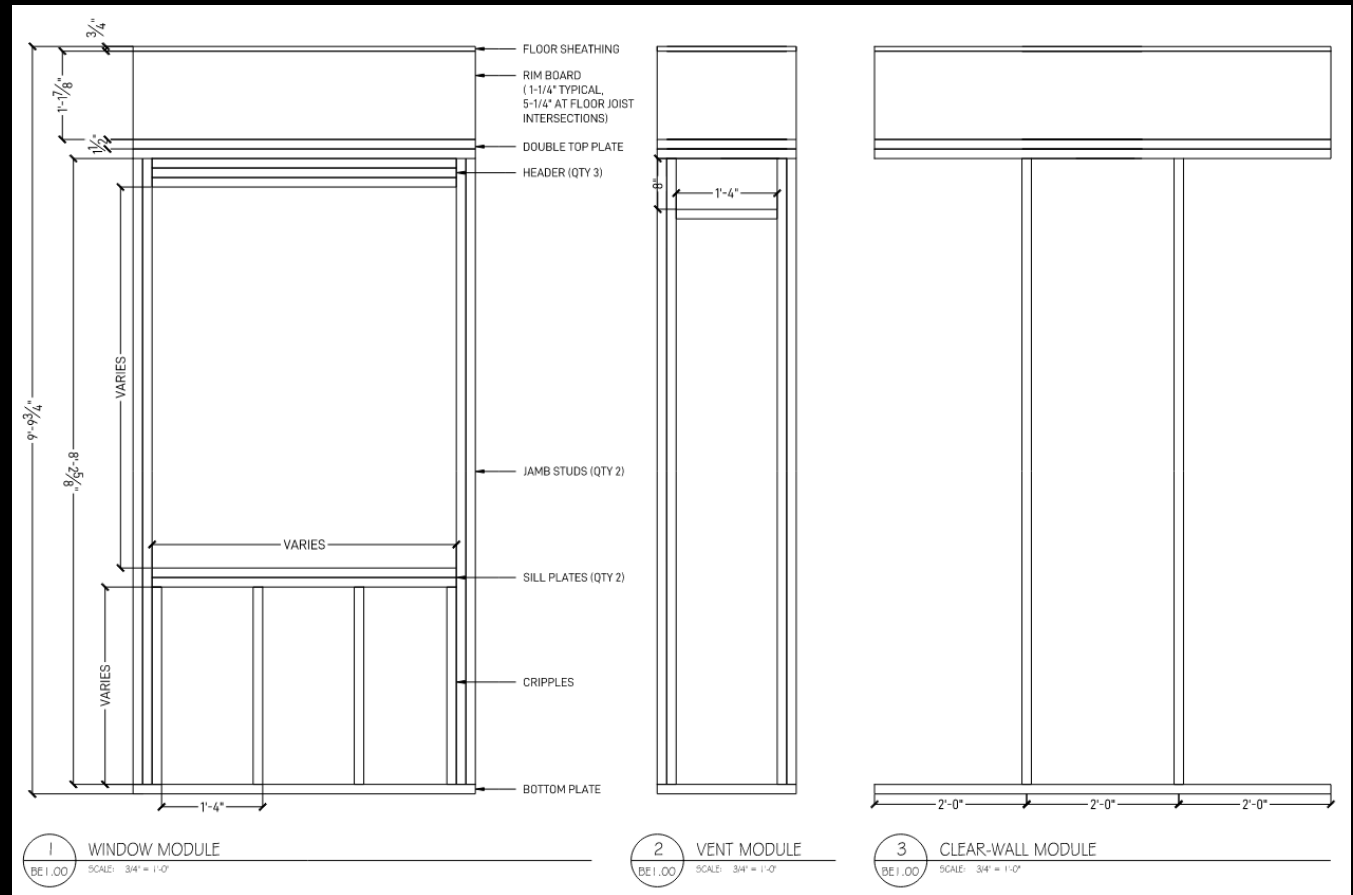
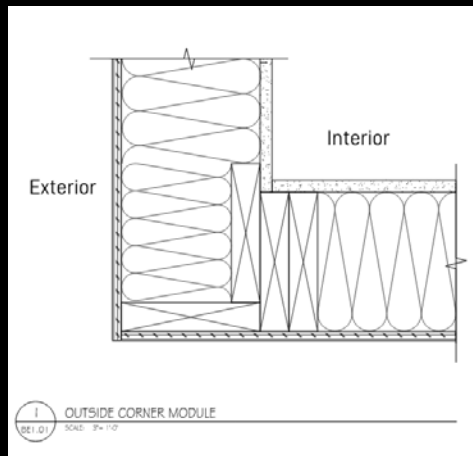
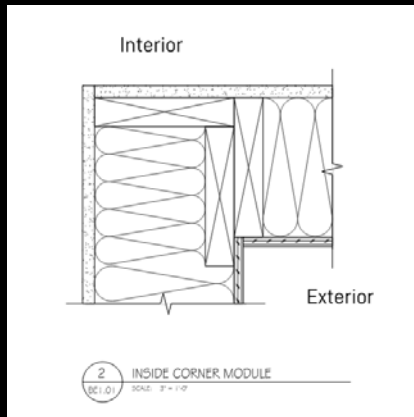
- ▶ Use:
 - 4 affordable housing mid-rise apartment buildings
 - 1 market rate mid-rise apartment building
- ▶ Exemplary Buildings Program - 3 part of the program
- ▶ Framing Type:
 - ▶ 2 Advanced framed buildings
 - ▶ 3 Intermediate framed buildings,
- ▶ 1 building pursuing Phius certification
- ▶ Energy Code years 2015, 2018



Building 1 : “Adv. No Headers” - Characteristics

- ▶ **Building Type:** Affordable housing
- ▶ **Shape:** Some undulations of exterior wall, generally straight and split into sections
- ▶ **Windows:** ~2/room
- ▶ **Framing Type:** Advanced, 24” O.C. spacing
- ▶ **Primary Structure:** Shear walls on perimeter within survey
- ▶ **Floor Configuration:** Rim boards/joists

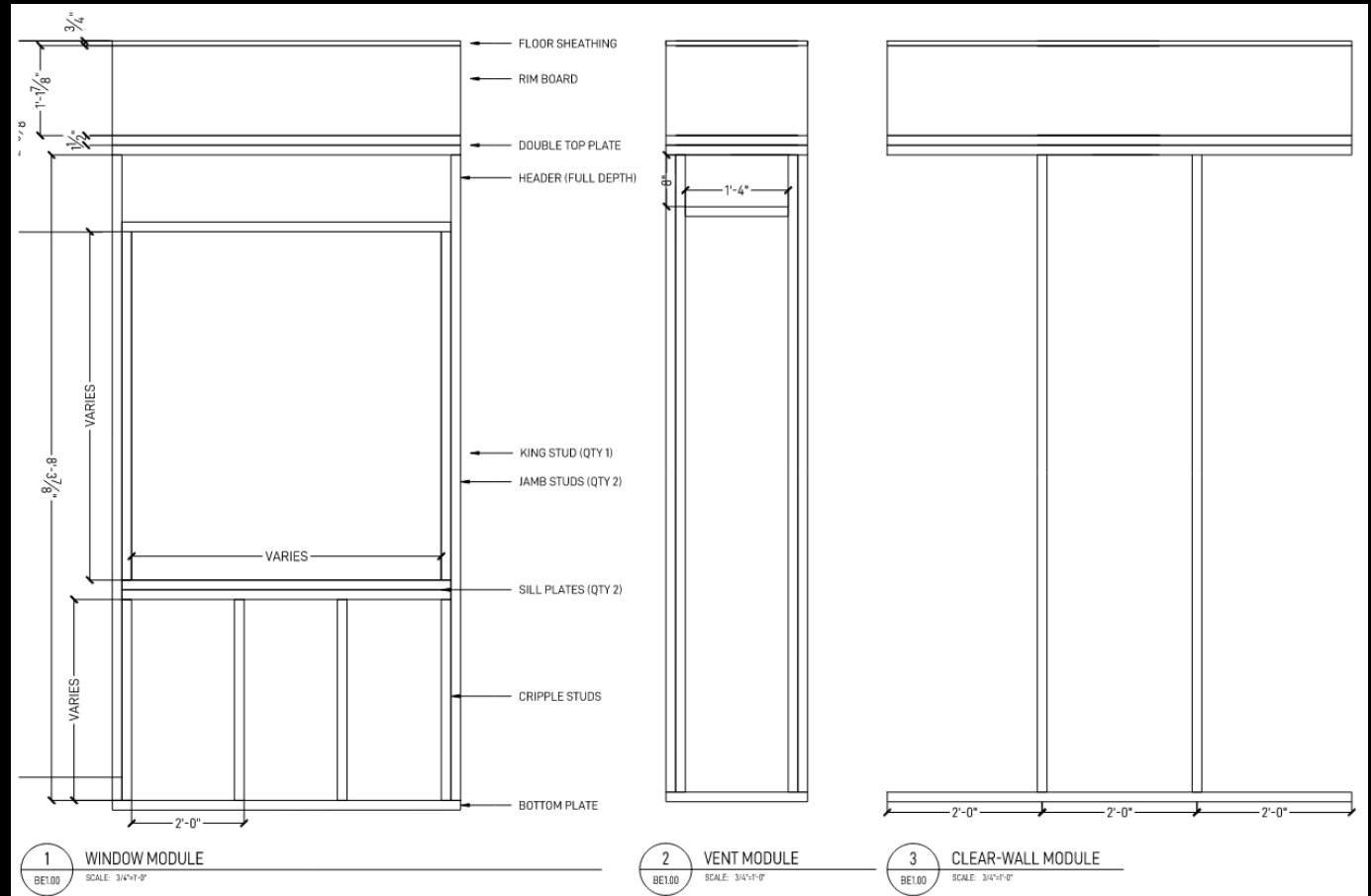
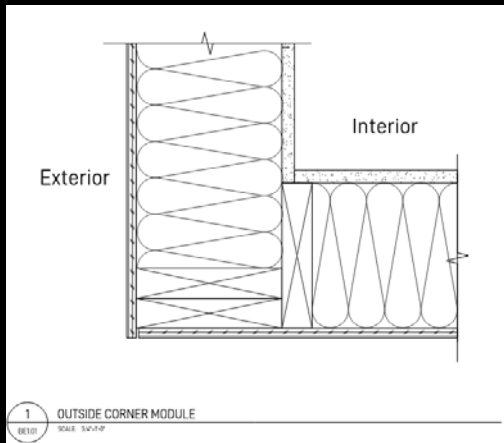
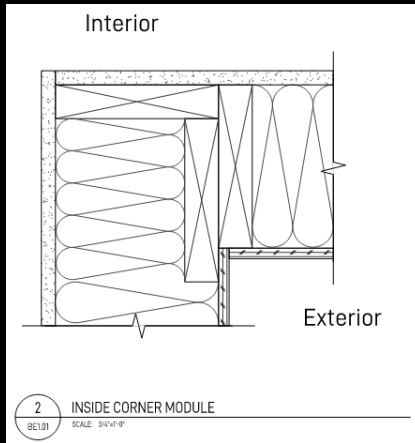
Building 1 : “Adv. No Headers” - Modules



Building 2: “Adv. w/ Headers” – Characteristics

- ▶ **Building Type:** Affordable housing
- ▶ **Shape:** Some undulations of exterior wall, generally U-shaped
- ▶ **Windows:** ~1/room, larger windows as opposed to multiple
- ▶ **Framing Type:** Advanced
- ▶ **Primary Structure:** Shear walls/primary structure within building interior
- ▶ **Floor Configuration:** Rim boards/joists, insulated headers

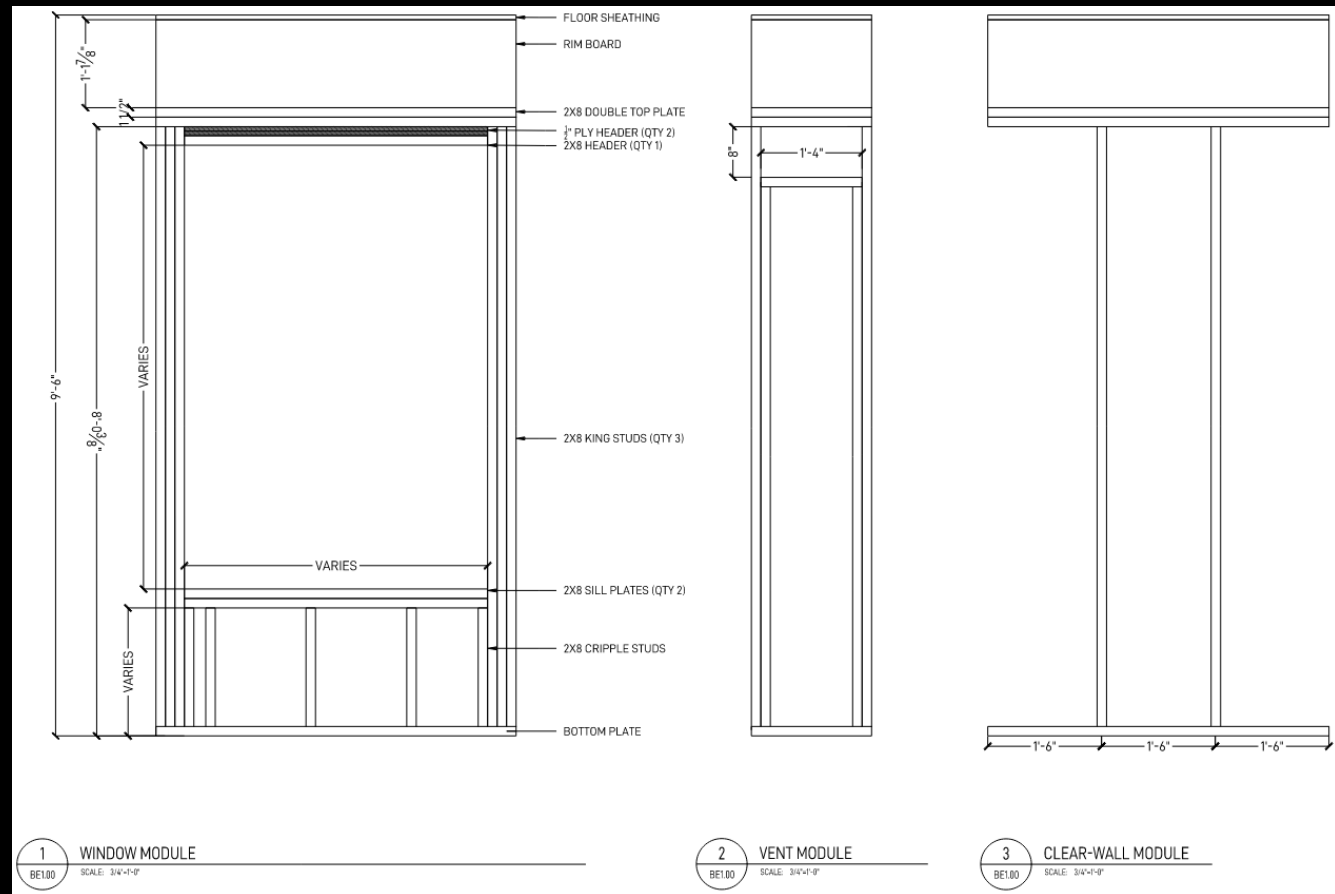
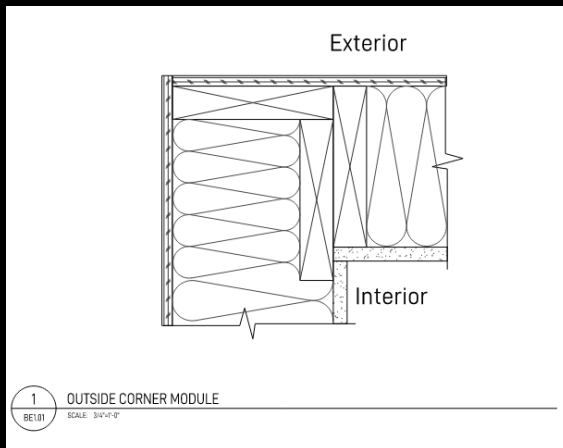
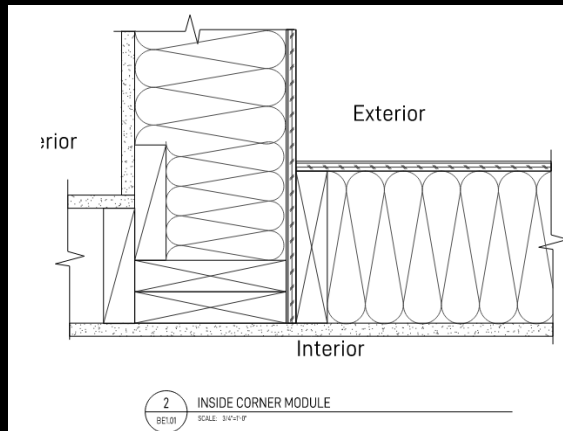
Building 2: "Adv. w/ Headers" – Modules



Building 3: “Int. Non-Bearing” – Characteristics

- ▶ **Building Type:** Affordable housing
- ▶ **Shape:** Generally straight, some undulations of the exterior wall
- ▶ **Windows:** ~2/room, medium sized windows
- ▶ **Framing Type:** Intermediate
- ▶ **Primary Structure:** Shear walls/primary structure within building interior
- ▶ **Floor Configuration:** Rim boards/joists

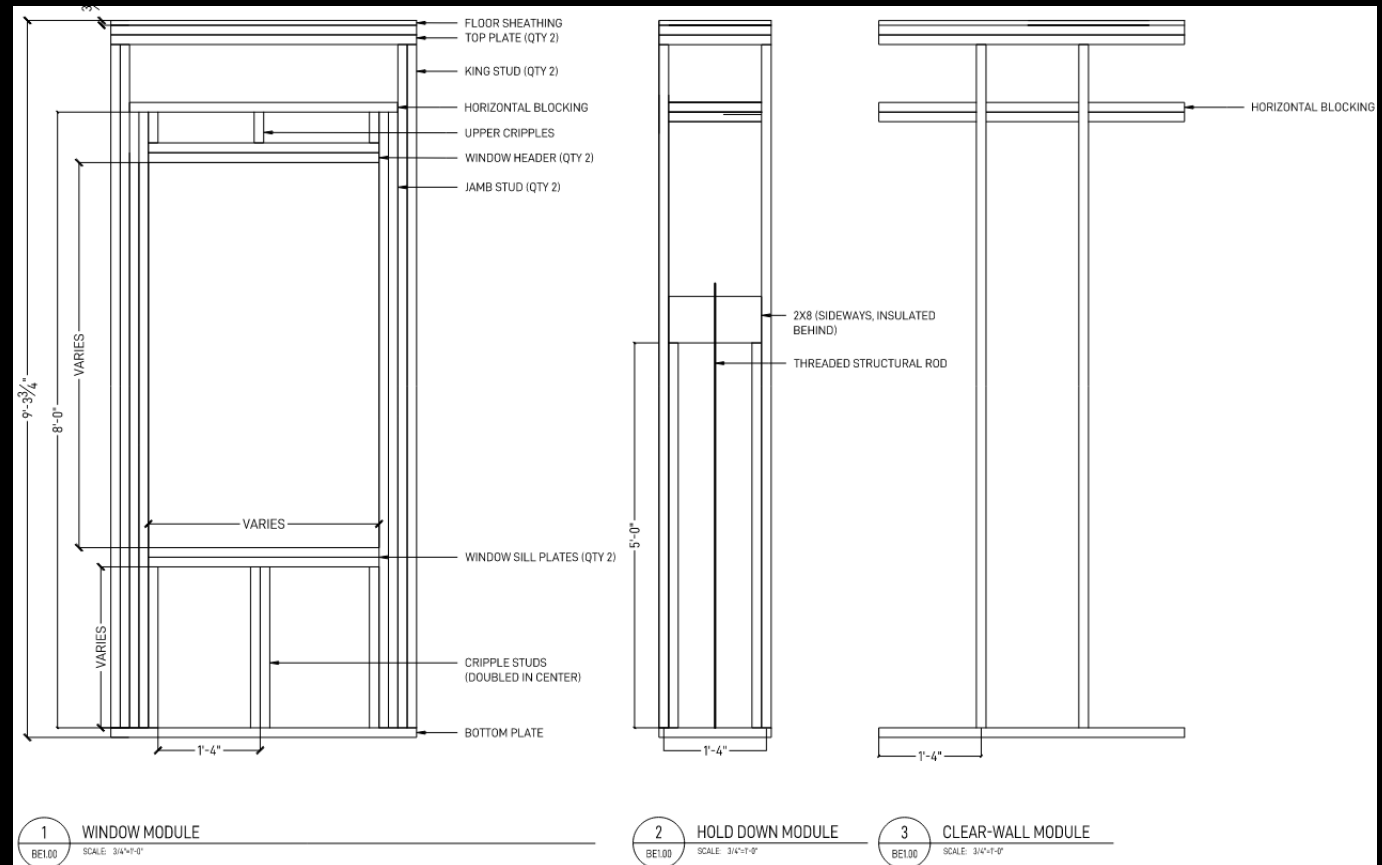
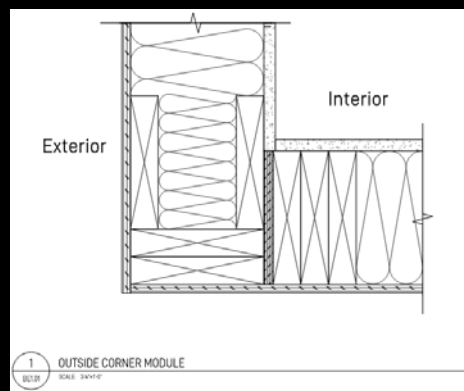
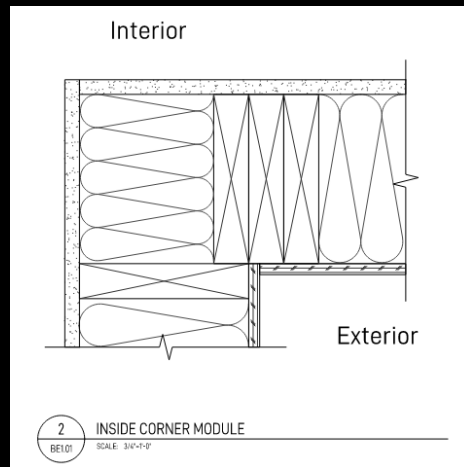
Building 3: “Int. Non-Bearing” – Modules



Building 4: “Int. Bearing” – Characteristics

- ▶ **Building Type:** Affordable housing
- ▶ **Shape:** Unique shape, lots of insets and undulations of exterior walls
- ▶ **Windows:** ~2-3 windows per room, lots of small windows
- ▶ **Framing Type:** Intermediate
- ▶ **Primary Structure:** Frequent tie-downs along exterior wall
- ▶ **Floor Configuration:** Platform framing

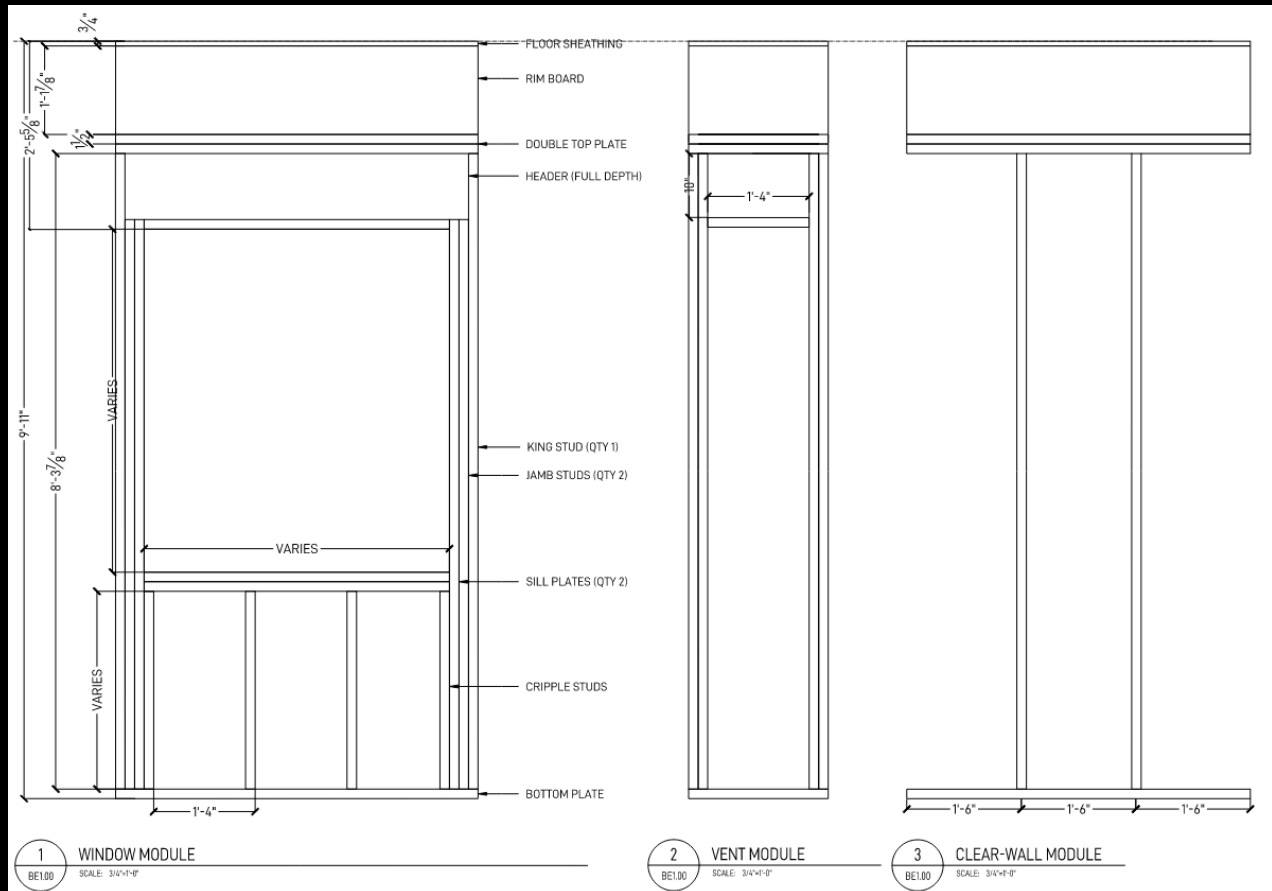
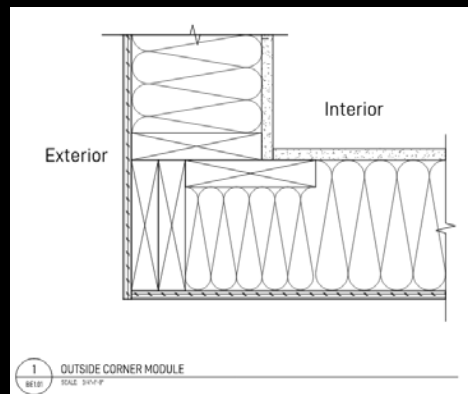
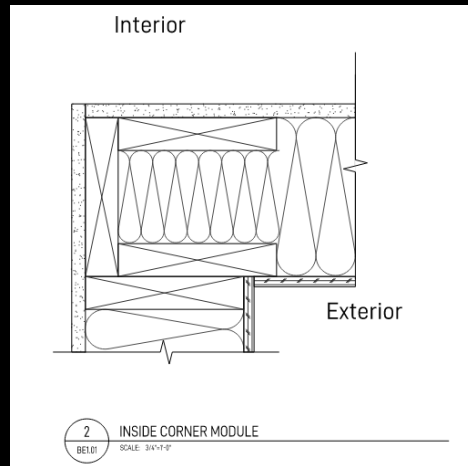
Building 4: "Int. Bearing" – Modules



Building 5: “Int. Market Rate” – Characteristics

- ▶ **Building Type:** Market rate mid-rise apartments
- ▶ **Shape:** Unique shape, lots of insets and undulations of exterior walls
- ▶ **Windows:** ~2-3 windows per room, lots of medium to large windows
- ▶ **Framing Type:** Intermediate
- ▶ **Primary Structure:** Minimal structure on exterior, mostly interior
- ▶ **Floor Configuration:** Rim board/joists

Building 5: "Int. Market Rate" – Modules



Framing Factor Results

	Actual FF	Code Target FF	% Increase Above Code Target
Building 1: "Adv. No Headers"	0.24	0.13	85%
Building 2: "Adv. w/ Headers"	0.21	0.13	62%
Building 3: "Int. Non-Bearing"	0.27	0.18	50%
Building 4: "Int. Bearing"	0.47	0.18	161%
Building 5: "Int. Market Rate"	0.42	0.18	133%

U-Value Results

	As-Built U-Value	WSEC U-Value	% Increase Above Code Target
Building 1: “Adv. No Headers”	0.053	0.045	16.7%
Building 2: “Adv. w/ Headers”	0.051	0.045	13.3%
Building 3: “Int. Non-Bearing”	0.055	0.047	16.0%
Building 4: “Int. Bearing”	0.082	0.049	66.6%
Building 5: “Int. Market Rate”	0.080	0.054	47.9%

R-Value Comparison

	2021 WSEC and SEC	As-Built R-Value
Building 1: “Adv. No Headers”	R-22.2	R-19.0
Building 2: “Adv. w/ Headers”	R-22.2	R-19.6
Building 3: “Int. Non-Bearing”	R-21.3	R-18.3
Building 4: “Int. Bearing”	R-20.4	R-12.3
Building 5: “Int. Market Rate”	R-18.5	R-12.5

Factoring Windows

	Window-To-Wall Ratio %	Whole Facade U-Value
Prescriptive Code	35%	0.12
Building 1: “Adv. No Headers”	17.5%	0.089
Building 2: “Adv. w/ Headers”	23.1%	0.099
Building 3: “Int. Non-Bearing”	10.4%	0.076
Building 4: “Int. Bearing”	20.9%	0.119
Building 5: “Int. Market Rate”	35.2%	0.143

Analysis - Categories

- ▶ Energy Use
- ▶ Annual Emissions
- ▶ Lumber Cost



ROM Expected Energy Use

- ▶ Higher framing factors may increase annual heating demand intensity by 0.14 kBtu/sf to 1.4 kBtu/sf.
- ▶ Expected annual energy cost increase for a 100k sf building ranges from \$400 to \$6,000 depending on HVAC system.
- ▶ Excess annual emissions for a 100k sf building is expected to be 3 to 100 tCO₂e depending on HVAC system.

Material Cost Comparison

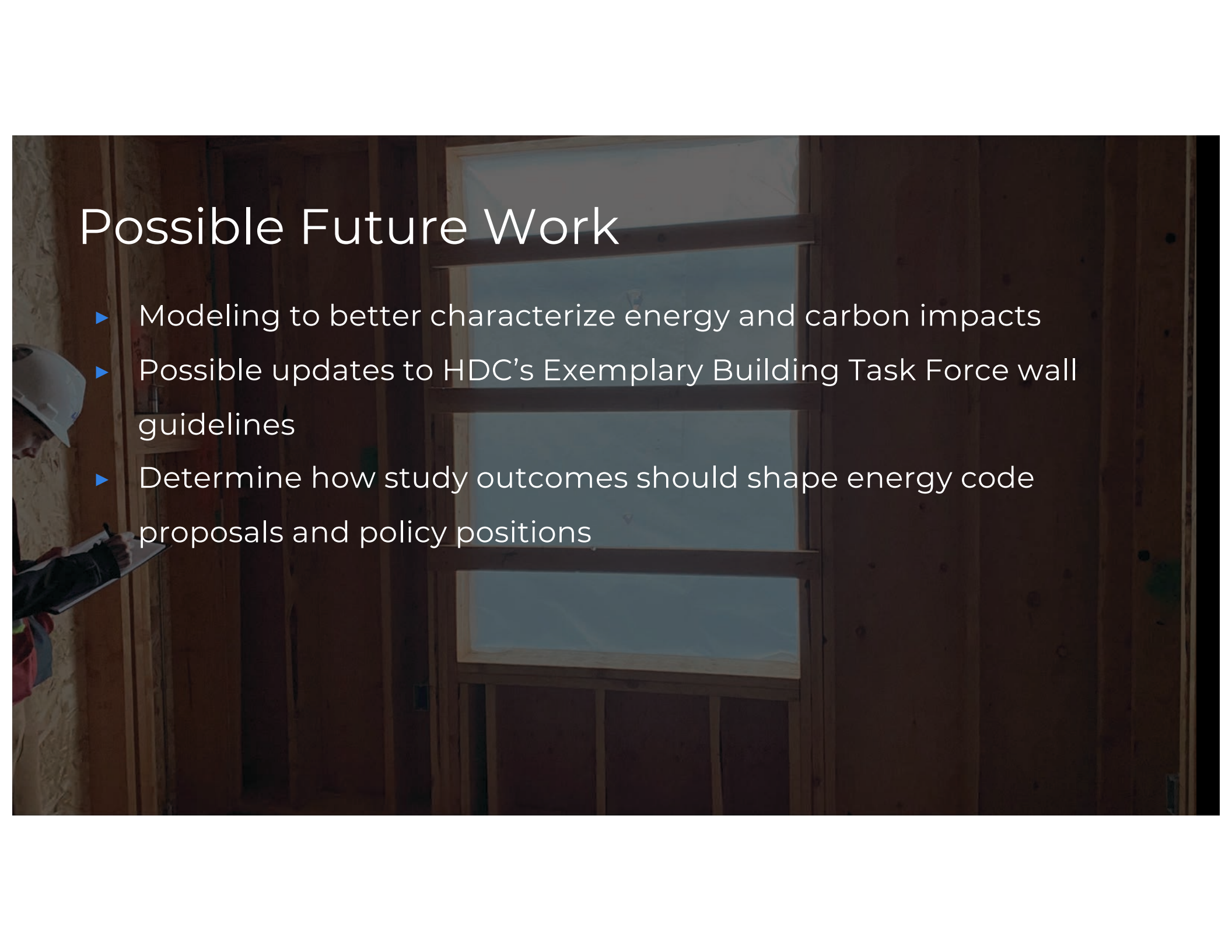
	Additional Material Cost/SF of Wall	Additional Material Cost per Unit
Building 1: "Adv. No Headers"	\$1.82	\$539
Building 2: "Adv. w/ Headers"	\$1.30	\$547
Building 3: "Int. Non-Bearing"	\$2.57	\$1,082
Building 4: "Int. Bearing"	\$2.82	\$579
Building 5: "Int. Market Rate"	\$0.77	\$185

High-Level Findings

- ▶ Cavity-only framing can be most cost-effective.
- ▶ Less wood is better for both energy and cost saving.
- ▶ Code assumed framing factors aren't always realistic.
- ▶ Washington State code assumptions are not conservative.
- ▶ Several known characteristics influence framing factors, may help control costs.
- Higher framing factors should be accounted for in code.

Lessons Learned

- ▶ Advanced framing measures have a significant impact
- ▶ If windows are consolidated into fewer windows, there can be significant impacts to the FF without changing window area
- ▶ Building massing and shape can have a significant impact on framing factors
- ▶ Code breaks out header FFs from wall FFs, but we rarely build with headers in PNW



Possible Future Work

- ▶ Modeling to better characterize energy and carbon impacts
- ▶ Possible updates to HDC's Exemplary Building Task Force wall guidelines
- ▶ Determine how study outcomes should shape energy code proposals and policy positions

Conclusion

Cavity-only wood frame structures are still a viable cost-effective wall assembly, with potential for further cost saving. As-built framing factors are higher than code assumptions, and characteristics that increase energy losses from higher framing factors should be accounted for in design.

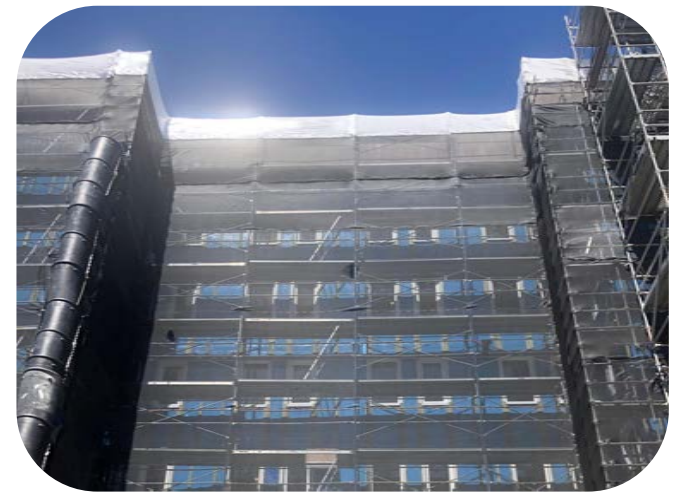
Airtightness Testing Methods

Building Form
Owner Goals
Performance Metrics
Risk Management
Insulation & Thermal Bridging
Airtightness Testing Methods
Ventilation Approaches

Airtightness Testing Methods

- WRB Materials
- Impacts of Test Prep on Air Leakage Results

WRB Materials



Impacts of Test Prep on Air Leakage Results

- ▶ Introduction
- ▶ Test Preparations
- ▶ Test Results
- ▶ Evaluation
- ▶ Unique Cases
- ▶ Conclusion



Measurement Uncertainty

- ▶ Any measurement of physical quantity has uncertainty.
- ▶ Measurement uncertainty should be evaluated and reported.
- ▶ Better understanding the scale of uncertainty can help our interpretation of results.



Airtightness Testing Challenges

- ▶ No two buildings are the same – inherent repeatability problem.
- ▶ Buildings are often large and complex. Many factors impact results.
- ▶ Wide variability in enclosure materials, installation, designs.
- ▶ Varying field conditions, different test operators.

Past Studies - Test Uncertainty Summary

Variable	Uncertainty Range	Impact on Airtightness	Source
Wind Speed	>15 mph	Error Doubled	(Brennan, Nelson and Olson, 2013; Walker et al., 2013)
Seasonal Variance	Cold Months	Up to 10% increased leakage rate	(Wahlgren, 2014)
Seasonal Variance	Warm Months	Up to 45% increased leakage rate	(Dickinson and Feustel, 1985)
Humidity	Fluctuating	Increased Variability	(Domhagen and Wahlgren, 2017)
Aging	50+ Years	Air leakage doubled	(Ylmén, Hansén and Romild, 2014)

Source

Benjamin Croyle, Dipendra Paneru, and Phalguni Mukhopadhyaya. 2025. Repeatability of whole-building airtightness testing in a residential wood-framed building under varying weather conditions. *Canadian Journal of Civil Engineering*.

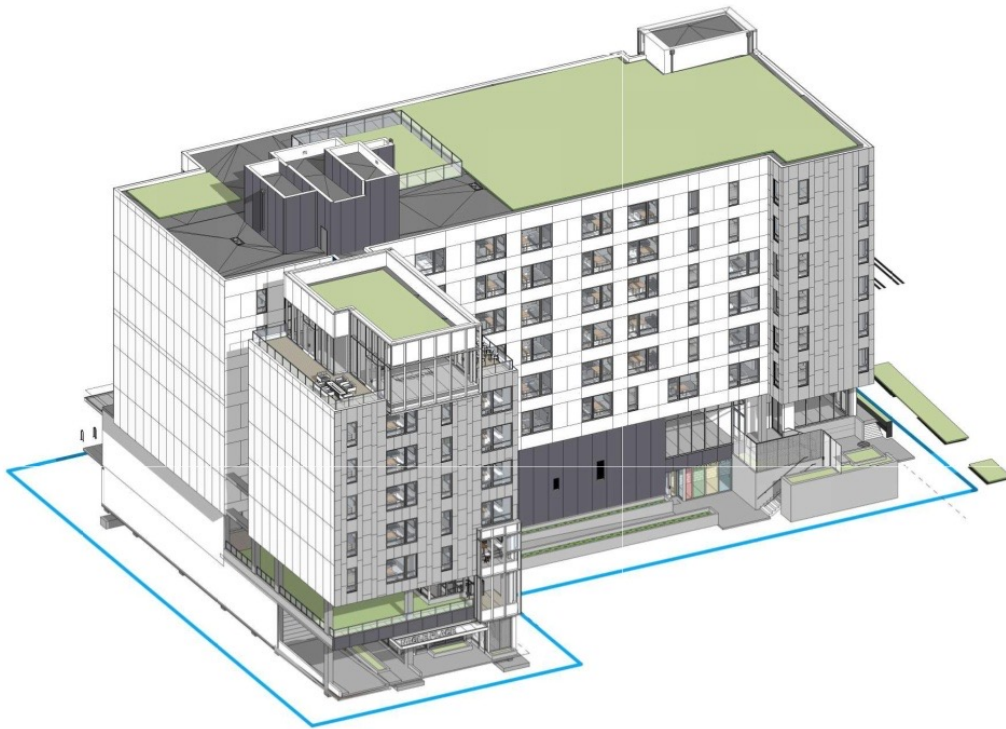
Past Studies - Croyle Study (2025)

- ▶ UVic Research examining the repeatability of airtightness testing.
- ▶ Tested the same 2-story building 18 times over 6 weeks.
- ▶ Assessed contribution of environmental factors to variation in test results but did not find strong correlation.
- ▶ Generally found good agreement in results, especially depressurization.

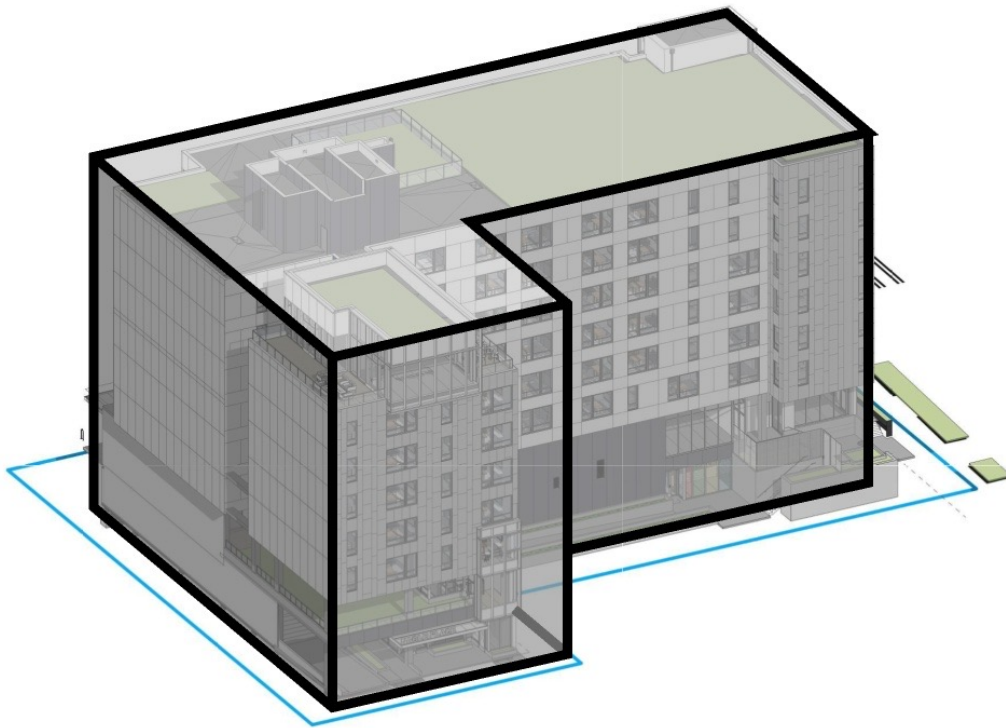
Source

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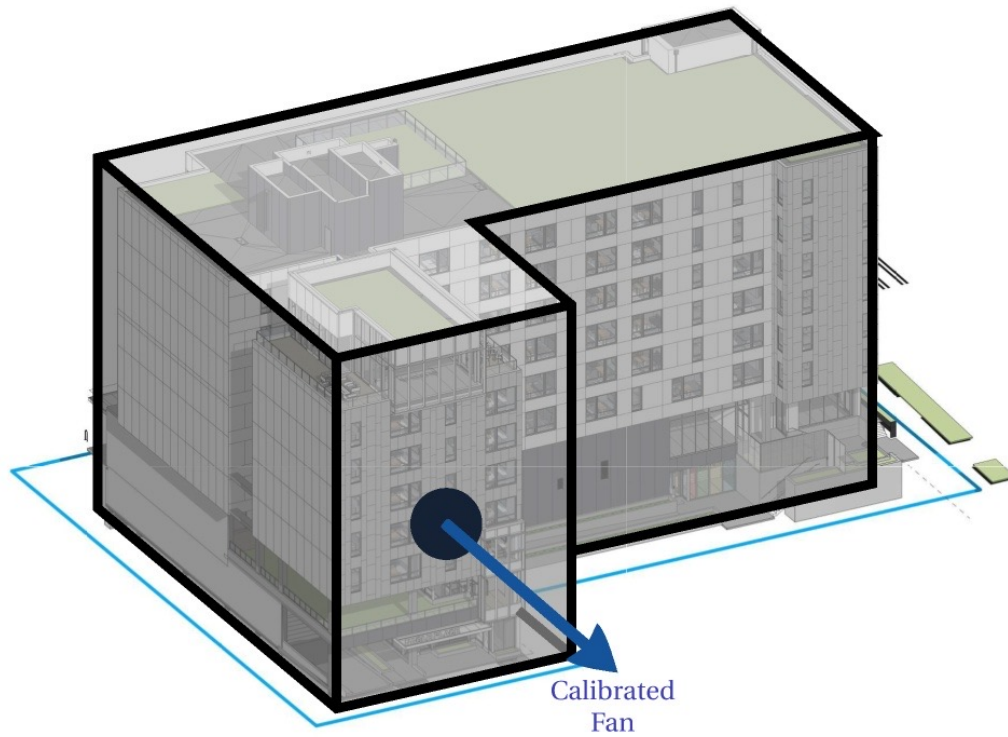
Test Overview



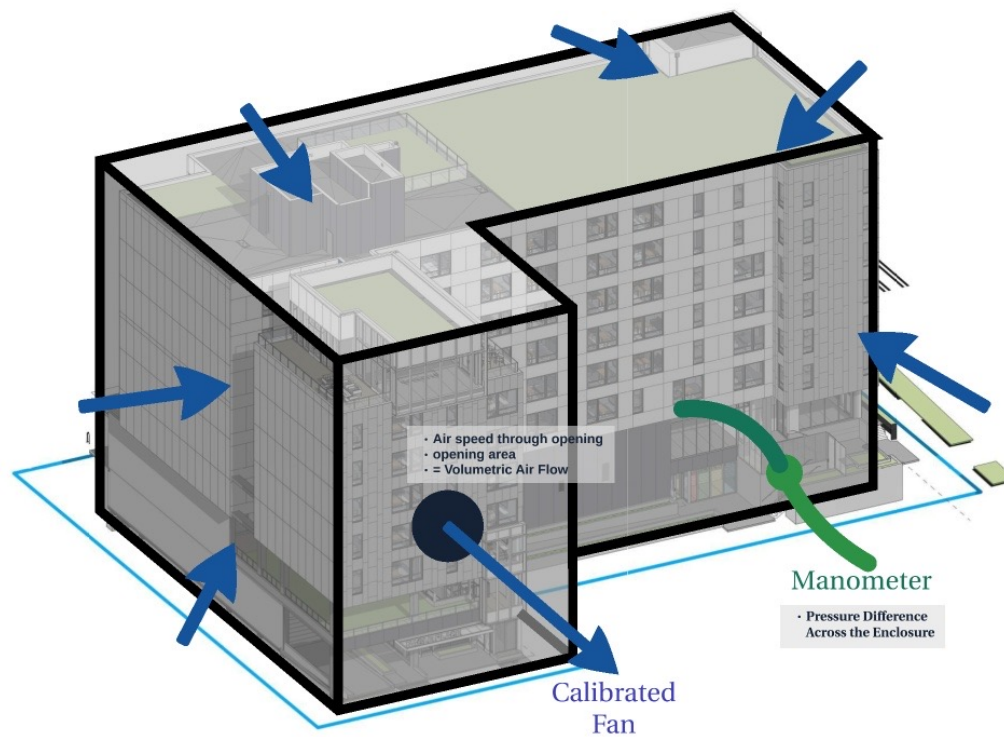
Test Overview



Test Overview



Test Overview



Leading Up To Test Day

- ▶ Pre-Test Coordination Meeting
- ▶ Pre-Test Punch Walk
- ▶ Complete Installation of Air Barrier
- ▶ Coordinate with Contractors



Memorandum

Super Generic Project Name

Building Air Barrier Test (2018 WSEC C402.5)

Pre-Test Meeting Agenda

Date of Pre-Test Meeting: 3/19/26

Date of Pre-Test Punch Walk: TBD

Date of Air Barrier Test: Currently scheduled for 4/28/26

Meeting Summary:

Attendees will go through the checklist below, including a general discussion of test dates, preparation, and timeline. A pre-test punch walk may also be scheduled separately. 4EA Building Science (4EA) understands that the GC will perform building test prep and coordinate with subcontractors, as outlined below.

Test Requirements:

4EA understands that the air barrier test requirements for this project are based on compliance with 2018 Washington State Energy Code, Section C402.5, which includes a maximum allowable leakage rate of 0.25 CFM/sq.ft. of air barrier surface area at an induced pressure difference of 75 Pa. Testing will be conducted in general conformance with ASTM E-779.

Should the building not meet this target during the air barrier test, 4EA will document where air leakage was observed

during the test. Furthermore, section C402.5.1.2 of the 2018 Washington State Energy Code requires that the GC submits a report to the building owner and Code Official identifying the corrective actions taken to seal identified air leaks "to the extent practicable". However, if the test result exceeds 0.40 CFM/sq.ft., then the building must be retested until it is below this limit.

Pre-Test Checklist:

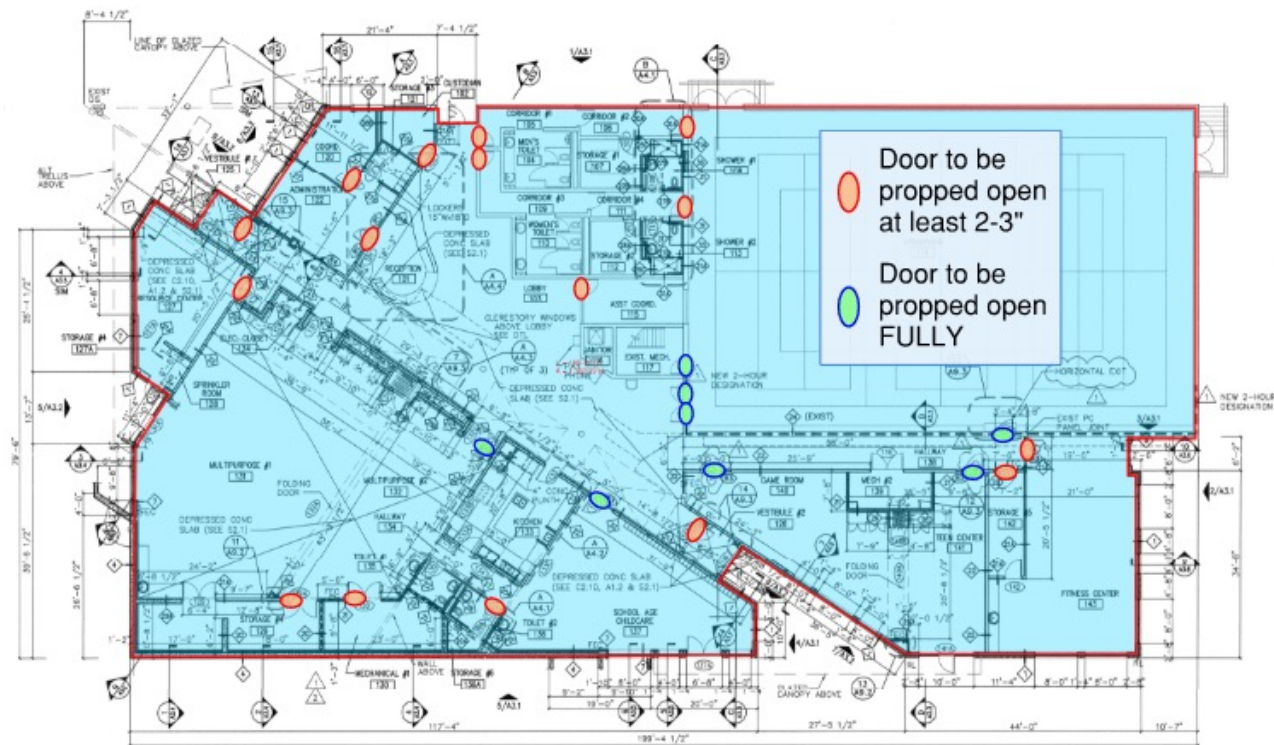
The following lists identify work to be completed prior to time of the test. Unless noted otherwise, all items are to be completed or coordinated by the GC.

Completion of Building's Air Barrier:

- Installation should be completed as final for ALL components of the building's continuous air barrier system (including WRB, fenestration systems, primary sealant joints, penetration detailing, and transitions between components). Typical end-of-construction items to review include:
 - Caulk/seal airtight drywall at seams, penetrations, and transitions at partitions between interior and exterior spaces (such as at elevator vestibules in the garage).

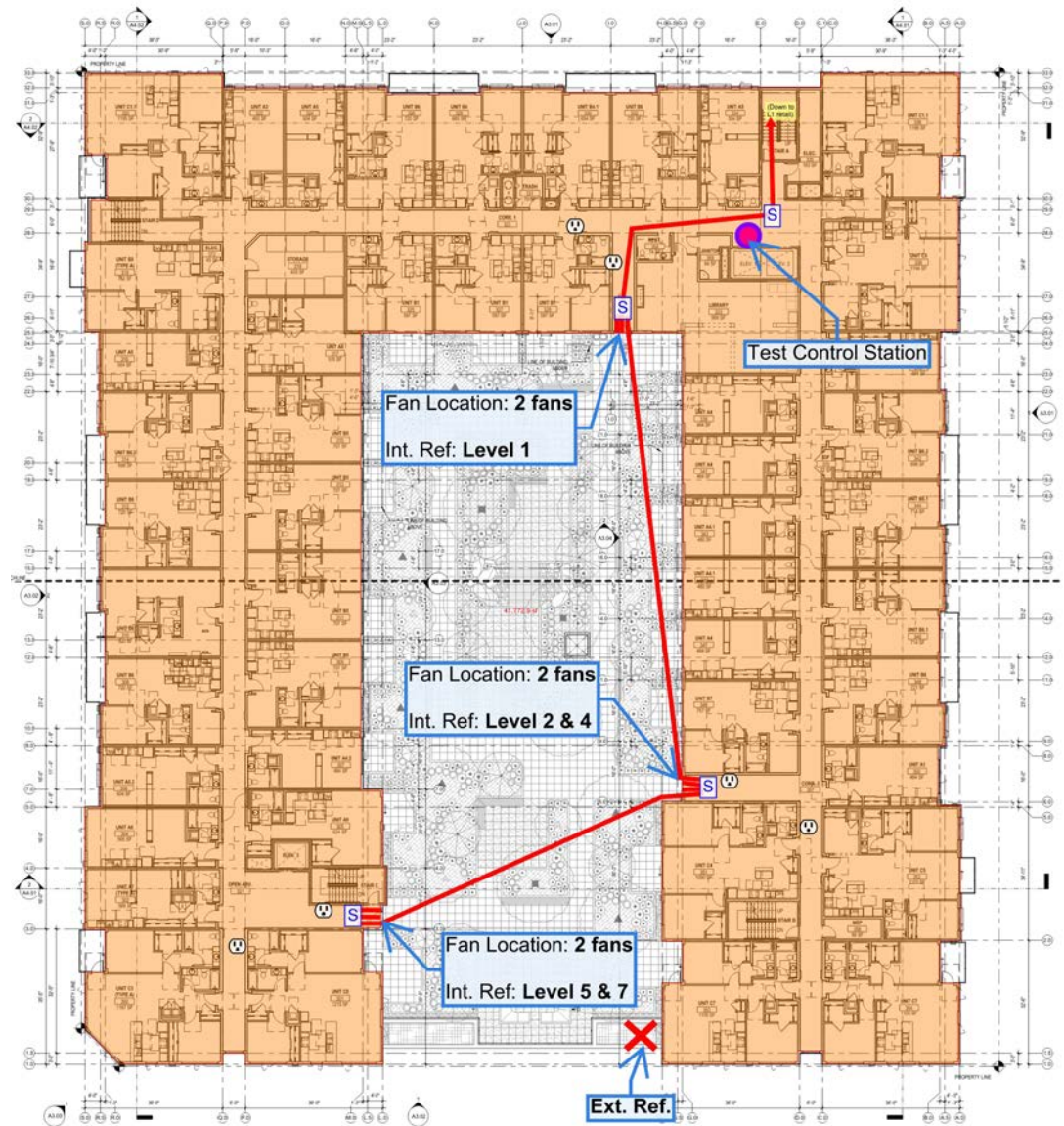
On Test Day – Preparations (+ Day(s) Before, As Needed)

- ▶ Building Preparations
 - ▶ Close exterior doors, windows
 - ▶ Prop open interior doors
 - ▶ Fill plumbing P-traps
 - ▶ Turn off HVAC systems
 - ▶ **Mask/seal HVAC systems***
 - ▶ Disable fire alarm
- ▶ Clear building of trades
- ▶ Don't forget to feed test team!



On Test Day – Testing

- ▶ Set Up Test Equipment
 - ▶ Install blower door fans
 - ▶ Connect fans to central control station
 - ▶ Run pressure reference tubes to exterior and interior
- ▶ Run Test
 - ▶ Representatives from electrical, mechanical & masking team on site
 - ▶ Troubleshooting/calibration
 - ▶ Pressurization (and depressurization)
 - ▶ Conduct diagnostics, as needed



HVAC Isolations – What is the Intent?

- ▶ Purpose of the test:
 - ▶ To satisfy a code requirement?
 - ▶ To evaluate the building envelope/enclosure construction?
 - ▶ To assess anticipated infiltration rates for operation?
- ▶ The answer to the above helps answer the following:
 - ▶ Should leakage through intentional openings (e.g., mechanical louvers, air ducts, etc.) be considered as unintentional/uncontrolled air leakage?



HVAC Isolations – What are the Standards?

- ▶ ASTM E779 – *Standard Test Method for Determining Air Leakage Rate by Fan Pressurization*
- ▶ ASTM E1827 – *Standard Test Methods for Determining Airtightness of Buildings Using an Orifice Blower Door*
- ▶ ANSI/RESNET/ICC 380 – *Standard for Testing Airtightness of Building, Dwelling Unit, and Sleeping Unit Enclosures; Airtightness of Heating and Cooling Air Distribution Systems; and Airflow of Mechanical Ventilation Systems*
- ▶ USACE – *Air Leakage Test Protocol for Building Envelopes*
- ▶ ASTM E3158 – *Standard Test Method for Measuring the Air Leakage Rate of a Large or Multizone Building*



HVAC Isolations – What do the Standards Say?

Standard	Preparation of Intentional Openings
ASTM E779	Limited guidance – dampers to be closed
ASTM E1827	2 Methods: • Closed test (BE Quality): Mask openings when assessing BE quality • Occupied test (Infiltration): No masking of intentional openings
ANSI/RESNET/ICC 380	No masking of intermittently operating vents and registers
USACE Procedure	Masking of intentional openings permitted
ASTM E3158	2 Methods: • Building Envelope: Masking of intentional openings permitted • Operational Envelope: No masking of intentional openings



Interior Masking

(The 'scrambled eggs' of HVAC isolations)

- ▶ Pros:
 - ▶ Faster, less specialized work (i.e., cheaper)
 - ▶ Easy access
 - ▶ Not impacted by weather
- ▶ Cons:
 - ▶ Potential for leaks to bypass masking
 - ▶ Isolations are not at the enclosure
 - ▶ Can be removed by other trades before test



Exterior Masking

(The 'omelet' of HVAC Isolations)

- ▶ Pros:
 - ▶ Effective at isolating HVAC systems
 - ▶ Efficiency increases with taller buildings (more items per drop)
- ▶ Cons:
 - ▶ Specialized work (bosun chair drops)
 - ▶ Access limitations/restrictions
 - ▶ Adhesion of masking can be impacted by cold, rain, wind
 - ▶ Sun exposure can "bake on" masking



Mechanical Dampers

(The 'sous vide eggs' of HVAC Isolations)

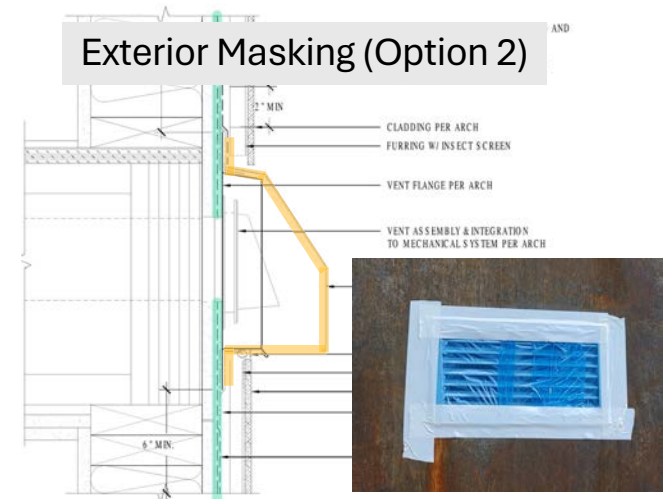
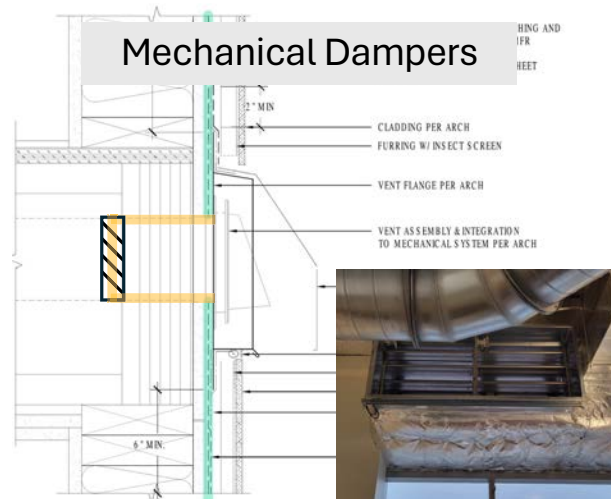
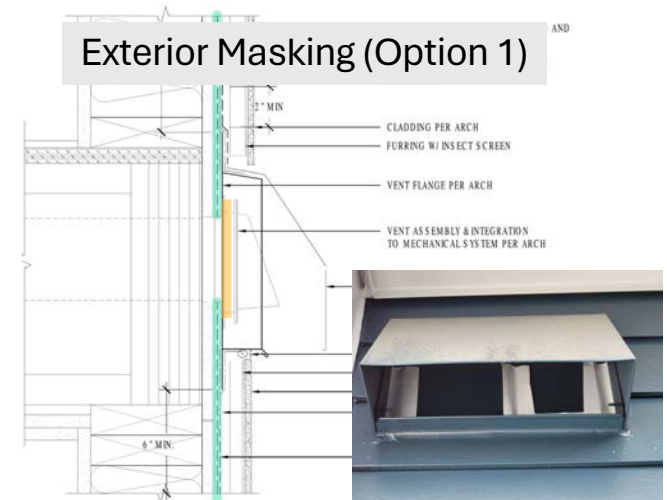
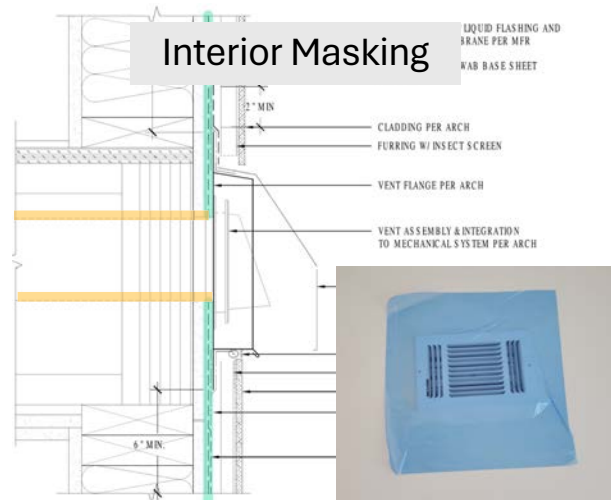
- ▶ Pros:
 - ▶ Avoids significant labor requirements of other HVAC isolation methods
 - ▶ Similar effectiveness to exterior isolations
- ▶ Cons:
 - ▶ Limited applicability – Requires rated dampers
 - ▶ Coordination between HVAC and electrical



HVAC Isolation Approaches

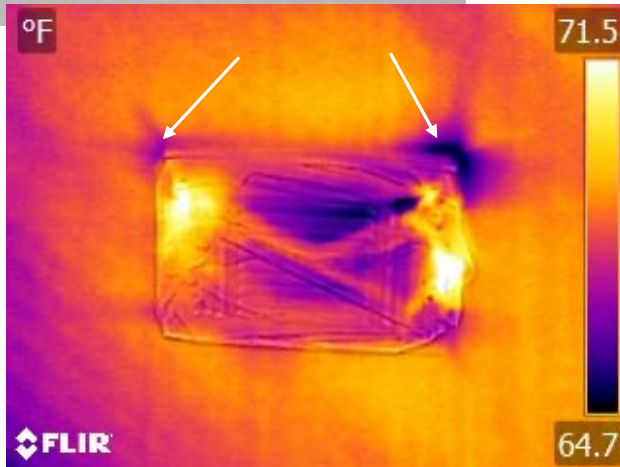
Building's Air
Barrier Path

Air Tightness
Boundary Added
by Isolations



HVAC Isolations – Quality

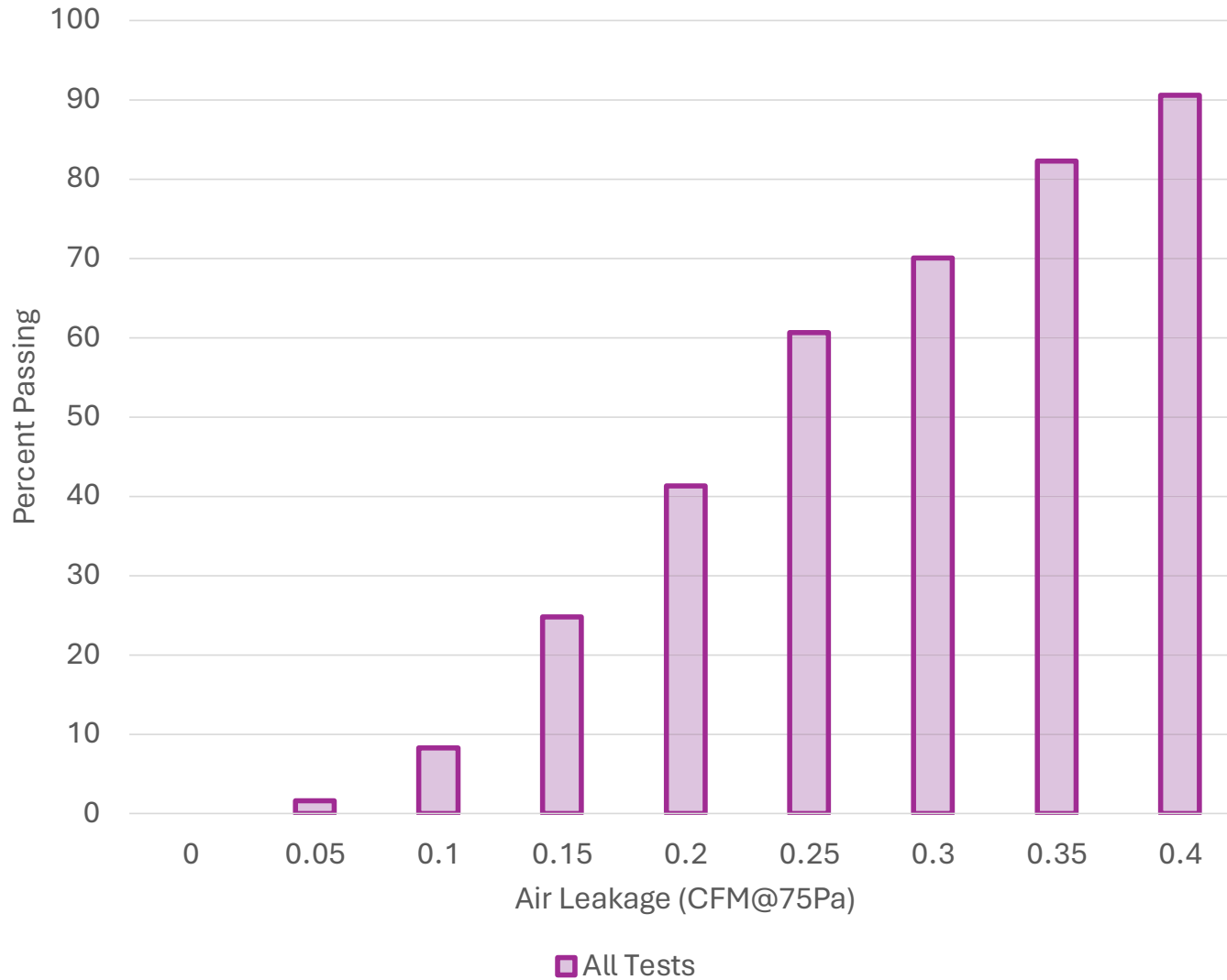
(Examples of some “bad eggs”)



Sample Set – Overview

	Multifamily (Group R)	Non-Residential
Interior Masked	119	2
Exterior Masked	43	12
Closed Dampers	1	25
Mixed Method	34	14
Sample Total by Type	195	53
Sample Total	248 Conducted 2012-2026	

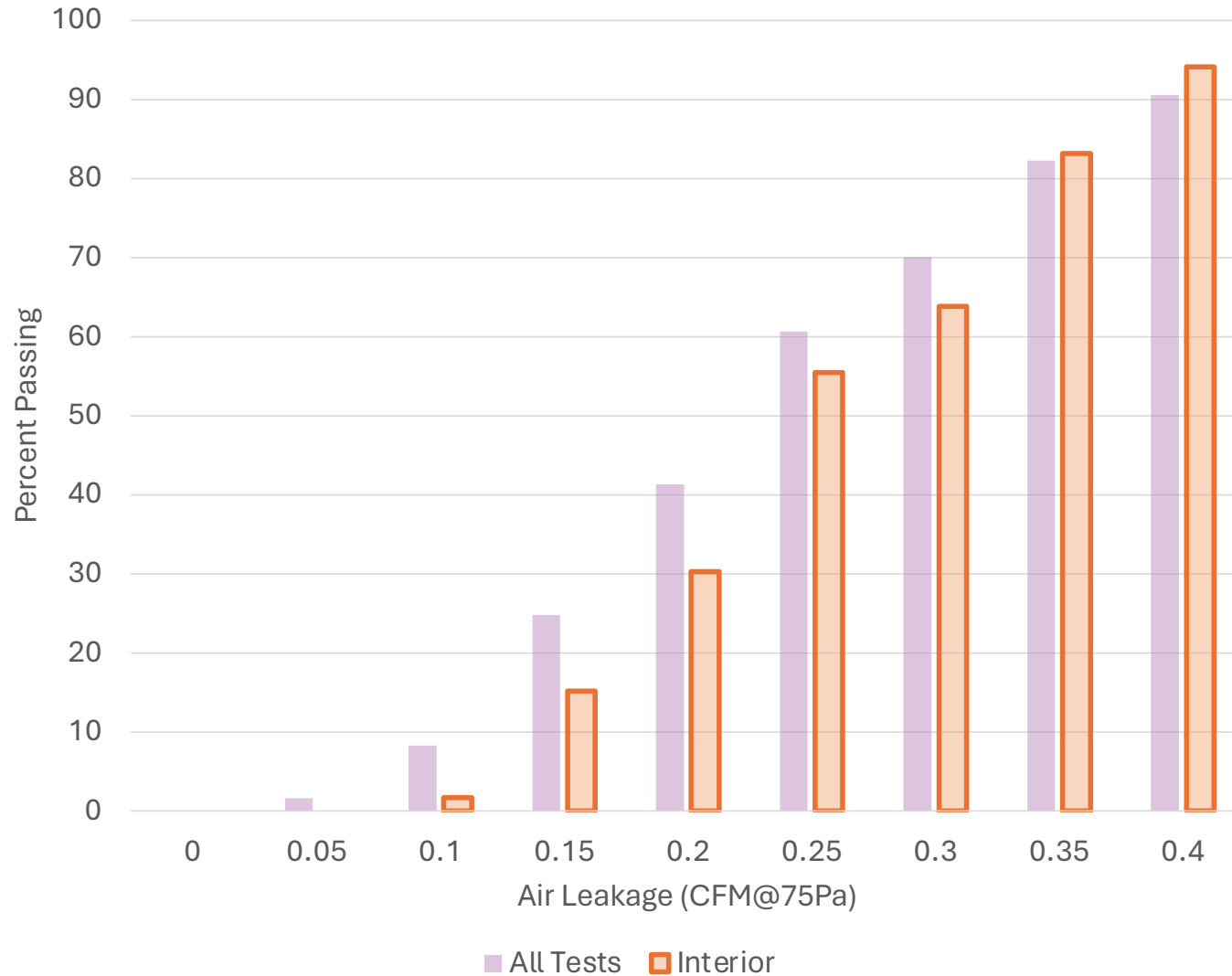
Air Barrier Test Leakage Results



Key Takeaway(s)

- Full sample set plotted as cumulative histogram

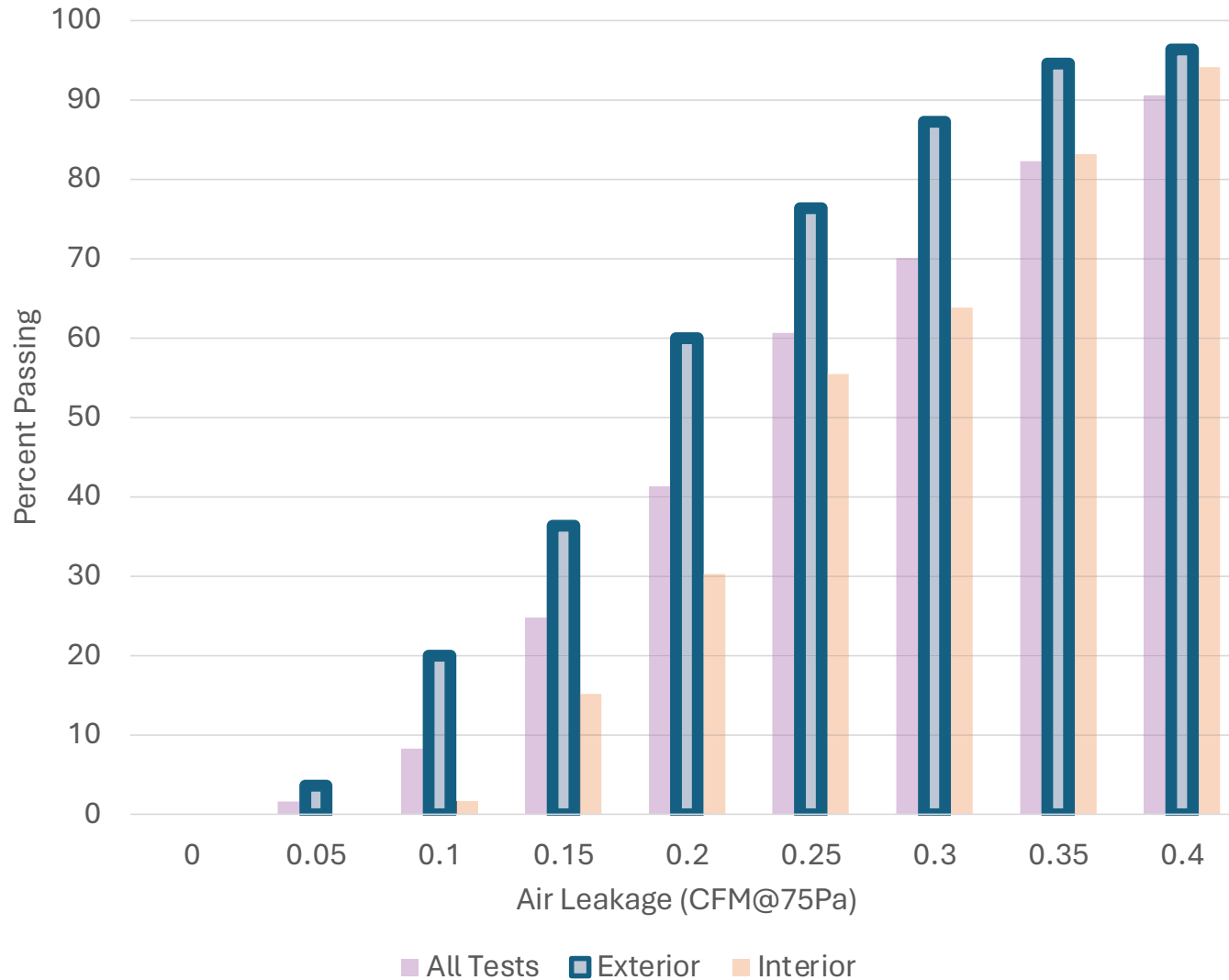
Air Barrier Test Leakage Results – Interior Masking



Key Takeaway(s)

- Reasonable approach for 0.4 CFM75 target
- Below 0.4 CFM75, this approach begins to struggle

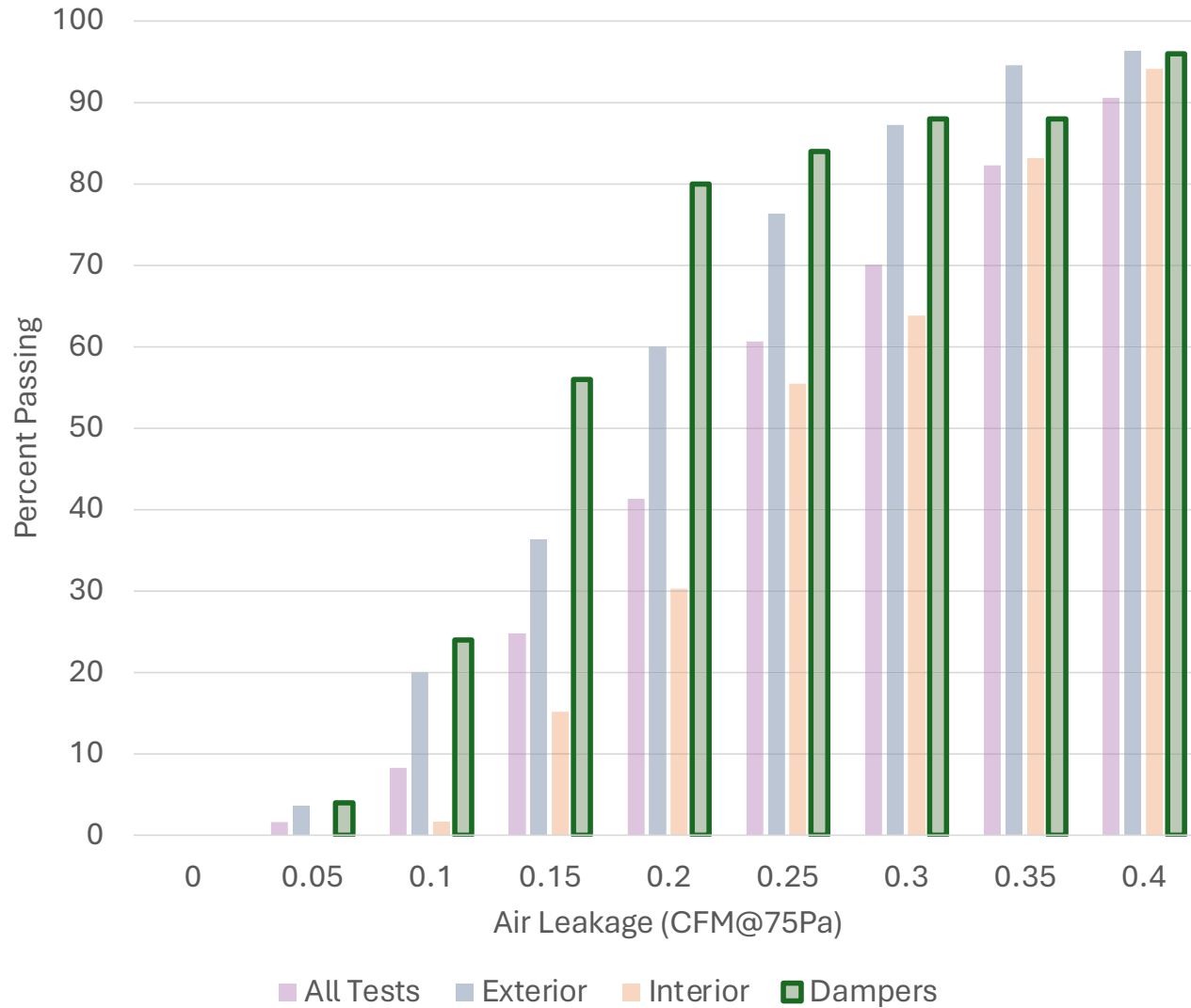
Air Barrier Test Leakage Results – Exterior Masking



Key Takeaway(s)

- Consistently exceeds the average (across all isolation methods) results
- Approaches 80% passing at 0.25 CFM75 target (when including all historical testing)

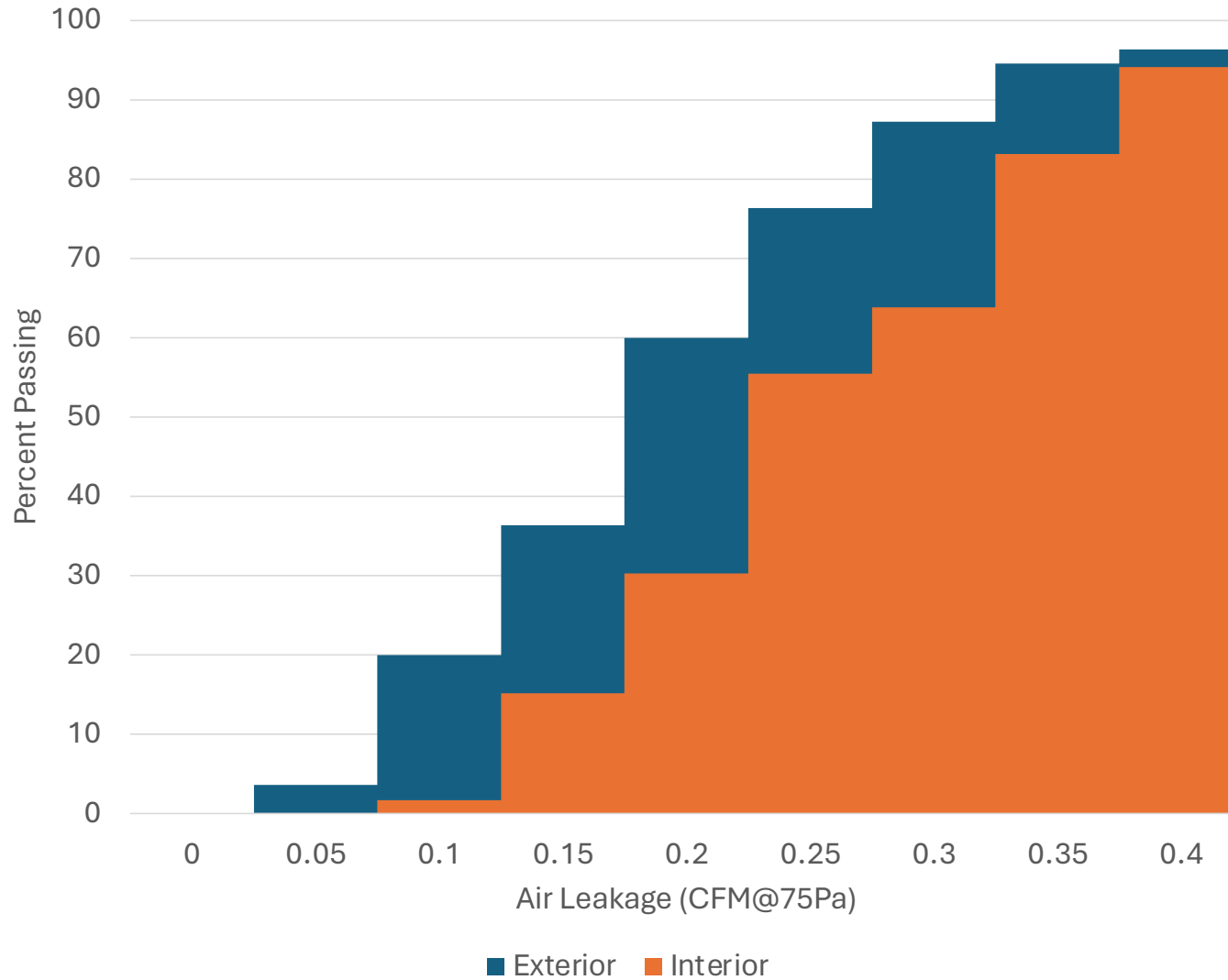
Air Barrier Test Leakage Results – Mechanical Dampers



Key Takeaway(s)

- Similar, if not slightly better, passing rates than exterior masking

Air Barrier Test Leakage Results



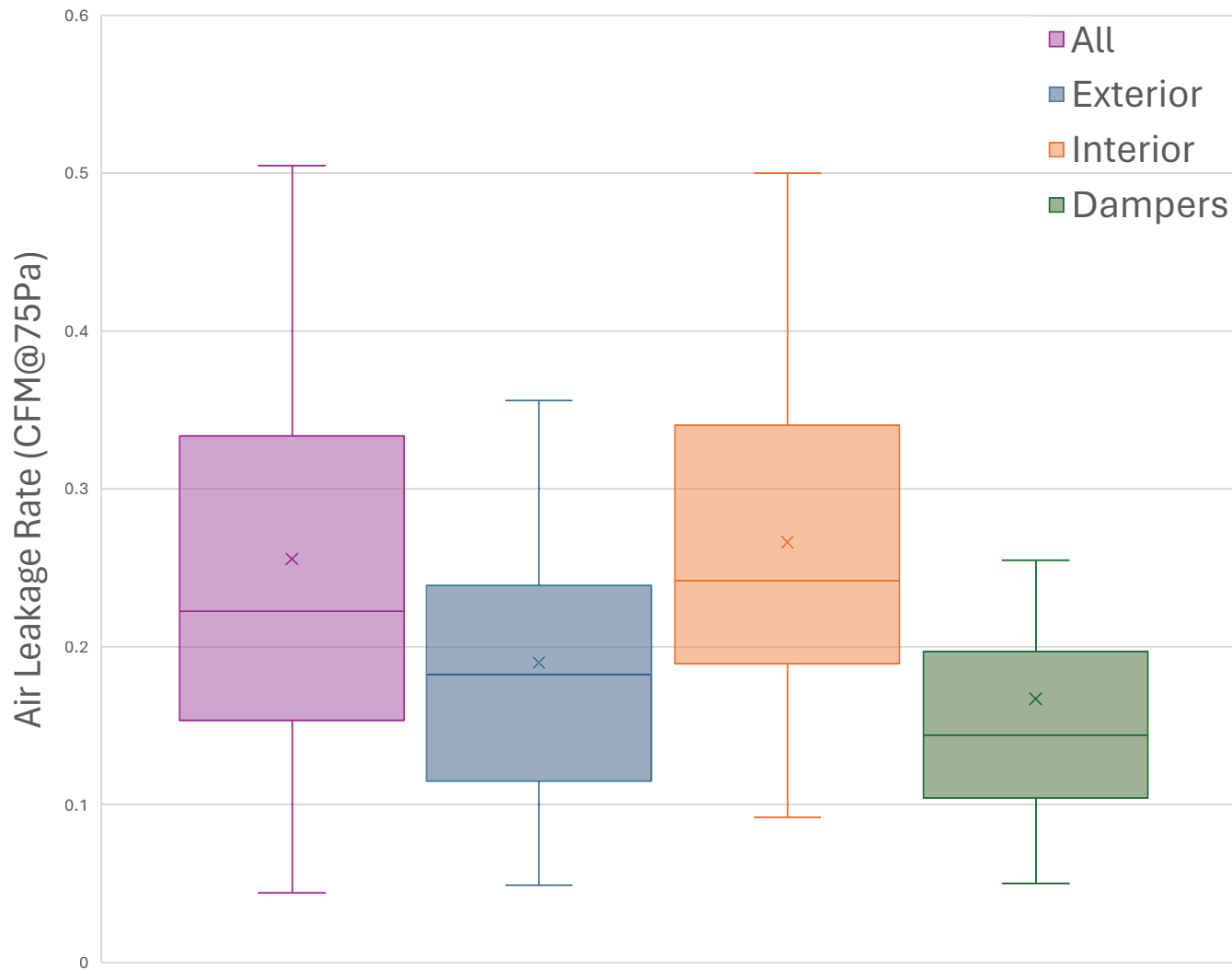
Key Takeaway(s)

- Exterior masking consistently outperforms interior masking

Statistical Summary – All Groups

	Exterior	Interior	Damper
Median Air Leakage (cfm/sf@75Pa)	0.18	0.24	0.14
Mean Air Leakage (cfm/sf@75Pa)	0.19	0.27	0.17
Standard Deviation	0.11	0.11	0.10
Margin of Error (95% Confidence)	0.03	0.02	0.04
Lower 95% Confidence Interval	0.16	0.25	0.13
Upper 95% Confidence Interval	0.22	0.29	0.21

Test Results by Prep Method



Key Takeaways

- Exterior masking and dampers only have fewer “very high” tests.
- Median interior masked test is in the upper quartile of exterior masked tests.

Analysis of Variance (ANOVA)

DESCRIPTION		Group Mean	0.232532338		
Groups	Count	Sum	Mean	Variance	SS
Exterior	55	10.44	0.19	0.0128	0.69
Interior	120	31.95	0.27	0.0130	1.55
Damper	26	4.34	0.17	0.0093	0.23

			Alpha	0.05		
Sources	SS	df	MS	F	P value	F crit
Between Groups	0.348	2	0.1739	11.50	1.88751E-05	<3.09
Within Groups	2.475	198	0.0125			
Total	2.823	200	0.0141			

Key Takeaways

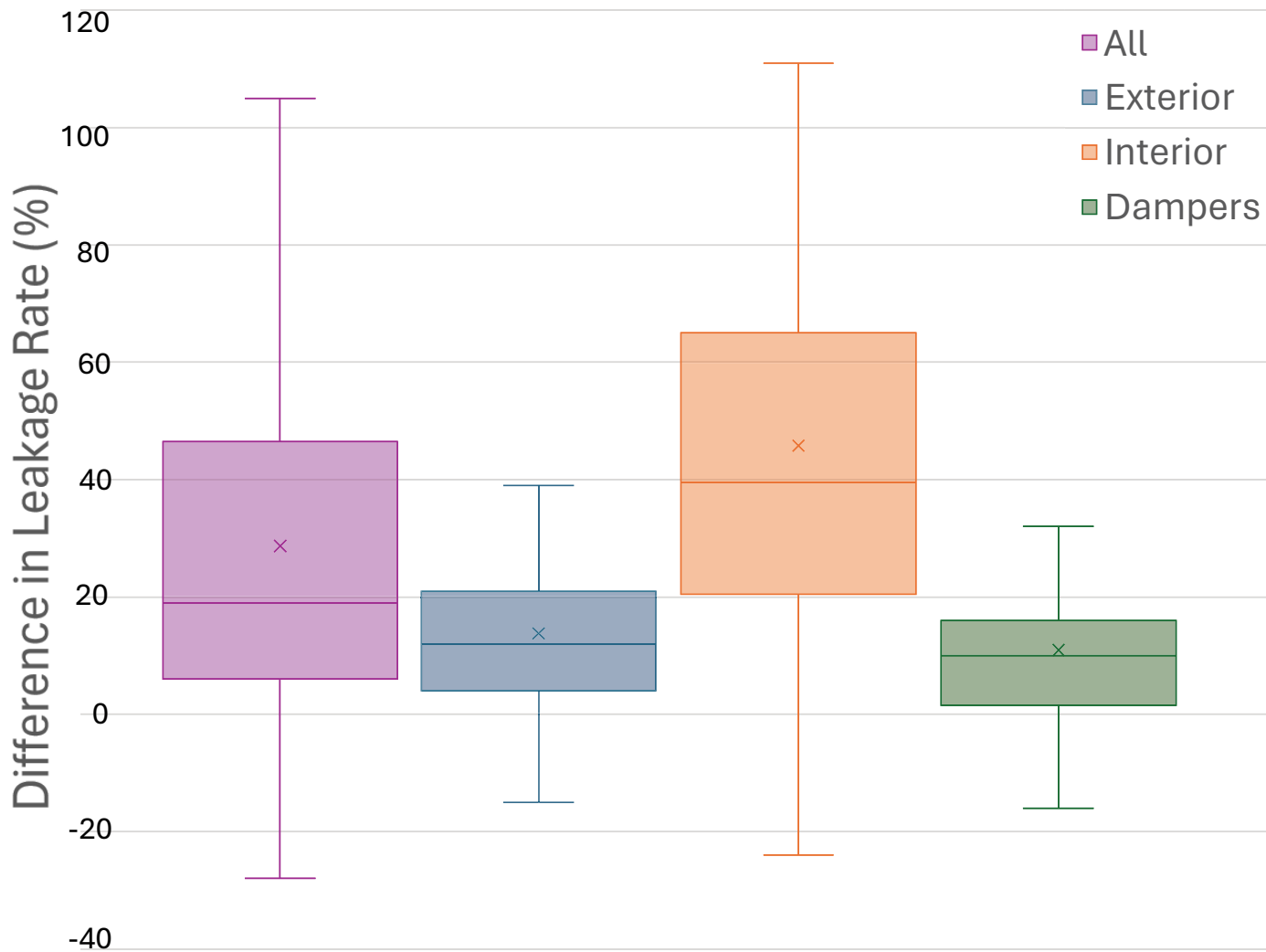
- There is significantly more variance between groups than within the groups.
- Null hypothesis – that all groups are equivalent – is rejected.
- Difference is significant.

Depressurization-Pressurization Spread

Air Leakage Difference Depressurization to Pressurization	All	Exterior	Interior	Damper
Median % Increase (cfm/sf@75pa)	19.0%	12.0%	39.5%	10.0%
Mean % Increase (cfm/sf@75pa)	28.8%	13.8%	45.7%	11.0%
Standard Deviation (cfm/sf@75pa)	32.3%	16.7%	35.4%	15.0%

- ▶ In general, lower air leakage rates in depressurization is known and expected.
- ▶ Expected spread is roughly 2.7x higher with interior masking.
- ▶ Interior masking is more than a standard deviation higher than exterior.
- ▶ Standard deviation is more than double for interior masking (more variability).

Difference in Depressurization and Pressurization



Key Takeaways

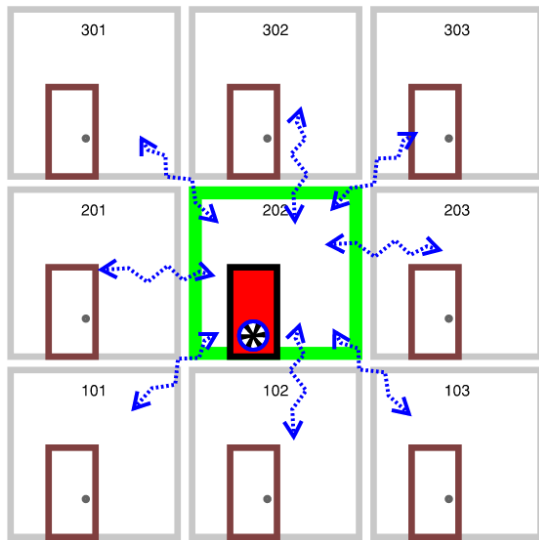
- Far greater differences between depressurization and pressurization with interior masked buildings.
- Exterior masked and closed damper buildings have similar results.

Possible Explanations

- ▶ Duct leakage
- ▶ Connections between ducts and registers/louvers/equipment
- ▶ Difficult to seal appliances & equipment and connections

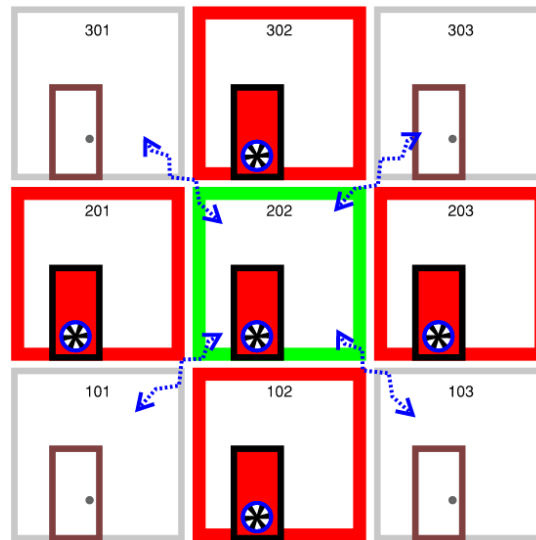


Guarded / Unguarded Tests – Overview

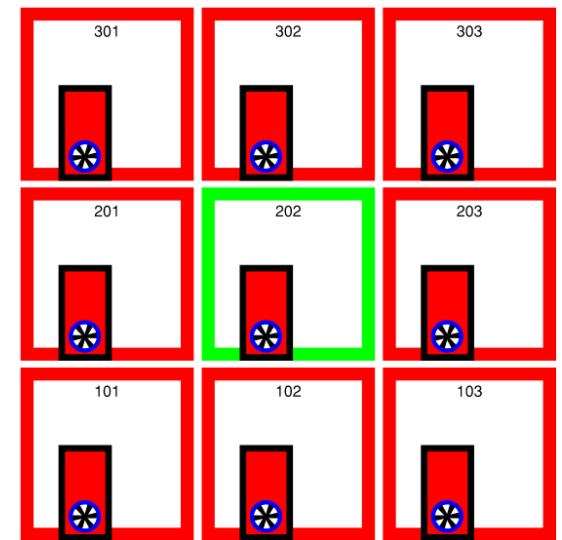


Unguarded

(i.e., Compartmentalization Testing)

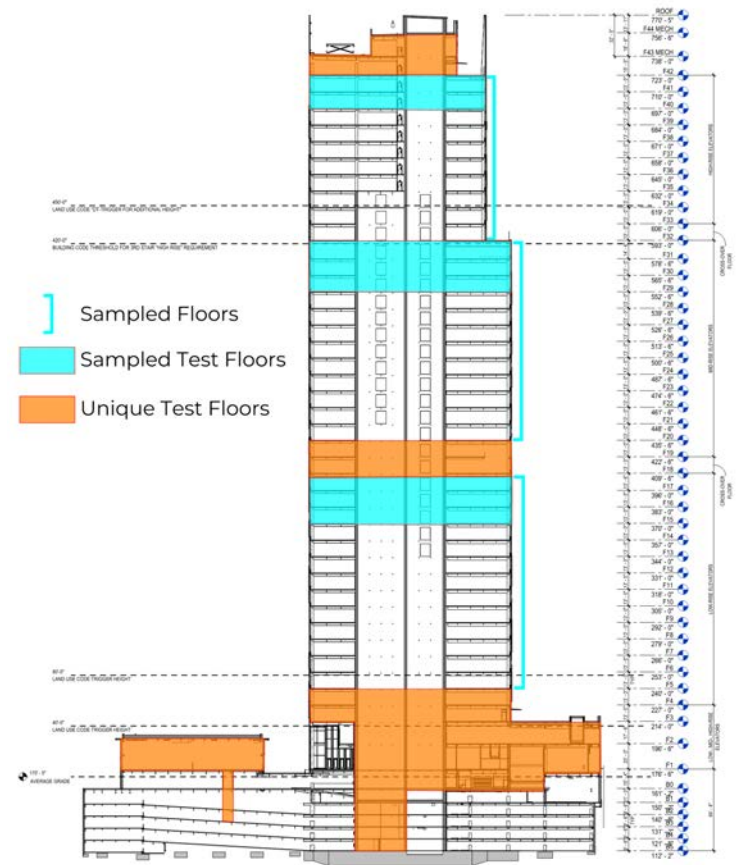
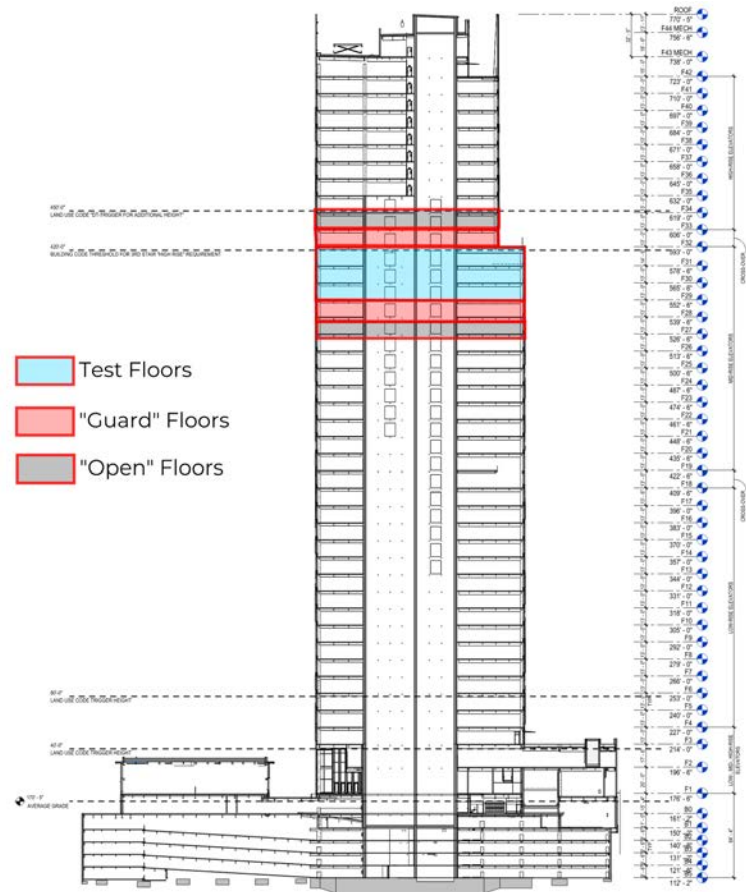


Guarded



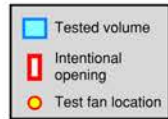
“Fully” Guarded

Multi-Section – Tower Sampling (Guarded)



Preliminary Test Set-Up

Preliminary Air Barrier Test Set-Up:
(Air distribution via HVAC ducts/openings,
elevator shaft & intentional openings)
Fans Required: 1



4 ENERGY CODE AIR BARRIER/THERMAL ENVELOPE
PLAN LEVELS 5-7
SCALE: 1/16" = 1'-0"



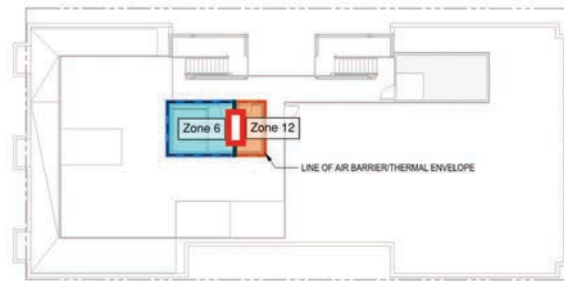
3 ENERGY CODE AIR BARRIER/THERMAL ENVELOPE
PLAN - LEVELS 3-4
SCALE: 1/16" = 1'-0"



2 ENERGY CODE AIR BARRIER/THERMAL ENVELOPE
PLAN - LEVEL 2
SCALE: 1/16" = 1'-0"



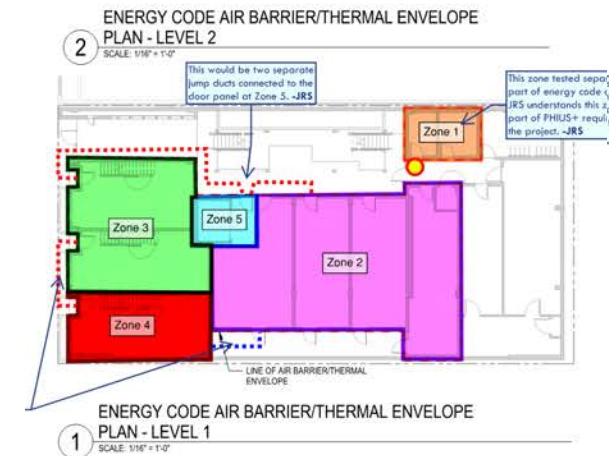
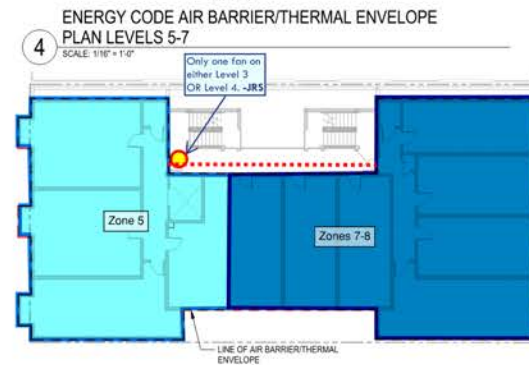
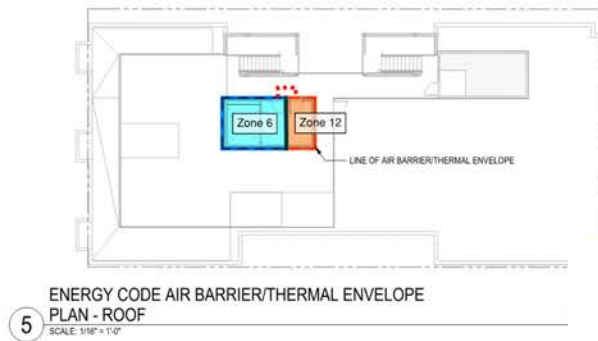
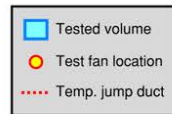
1 ENERGY CODE AIR BARRIER/THERMAL ENVELOPE
PLAN - LEVEL 1
SCALE: 1/16" = 1'-0"



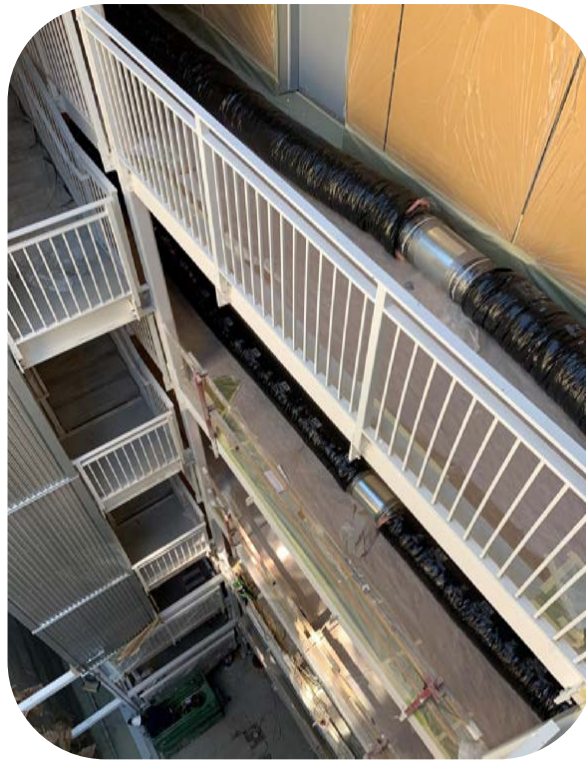
5 ENERGY CODE AIR BARRIER/THERMAL ENVELOPE
PLAN - ROOF
SCALE: 1/16" = 1'-0"

Final Air Barrier Test Set-Up

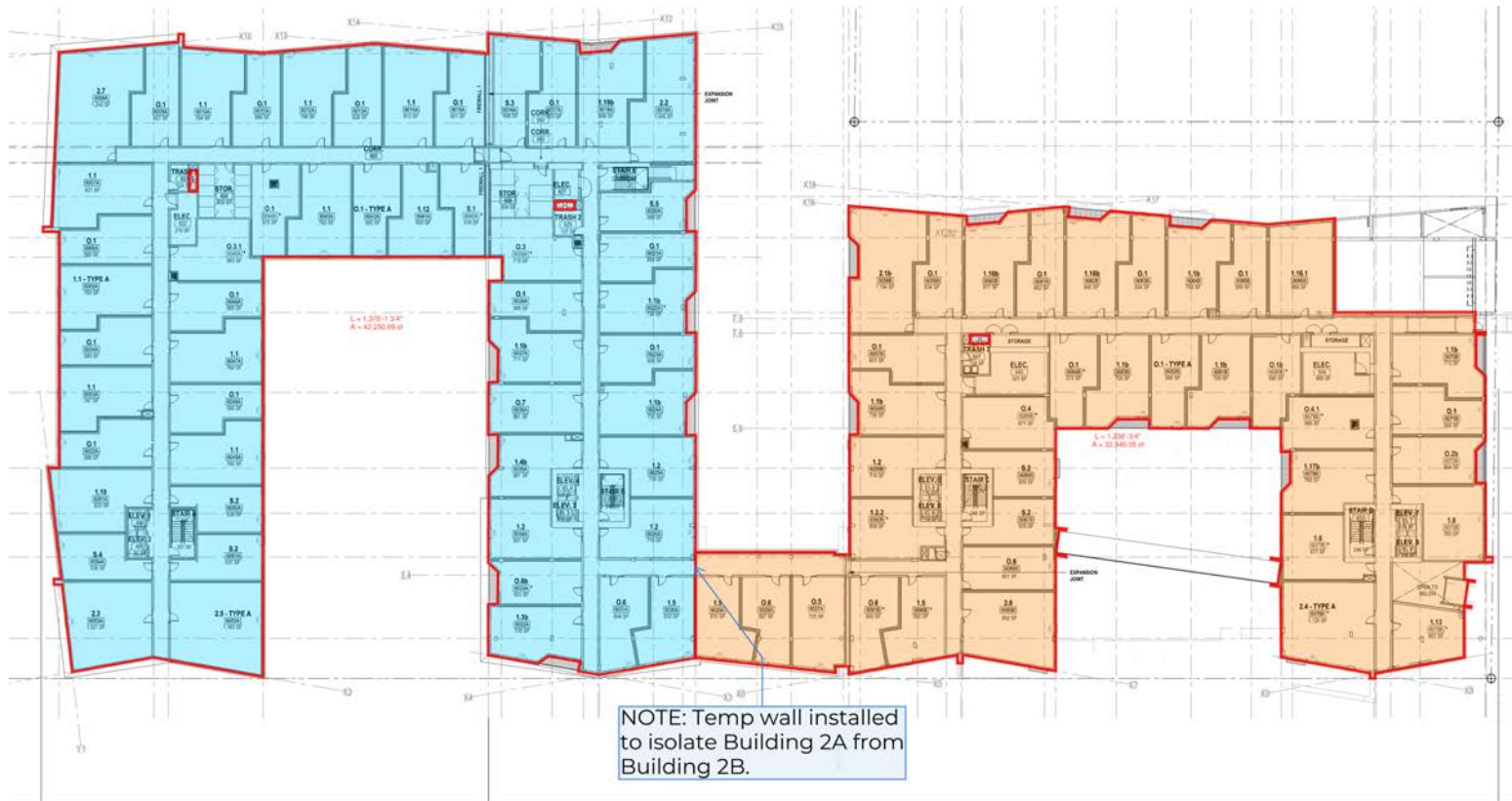
Final Air Barrier Test Set-Up:
(Air distribution via HVAC ducts,
elevator shaft & "jump ducts")
Fans Required: 1



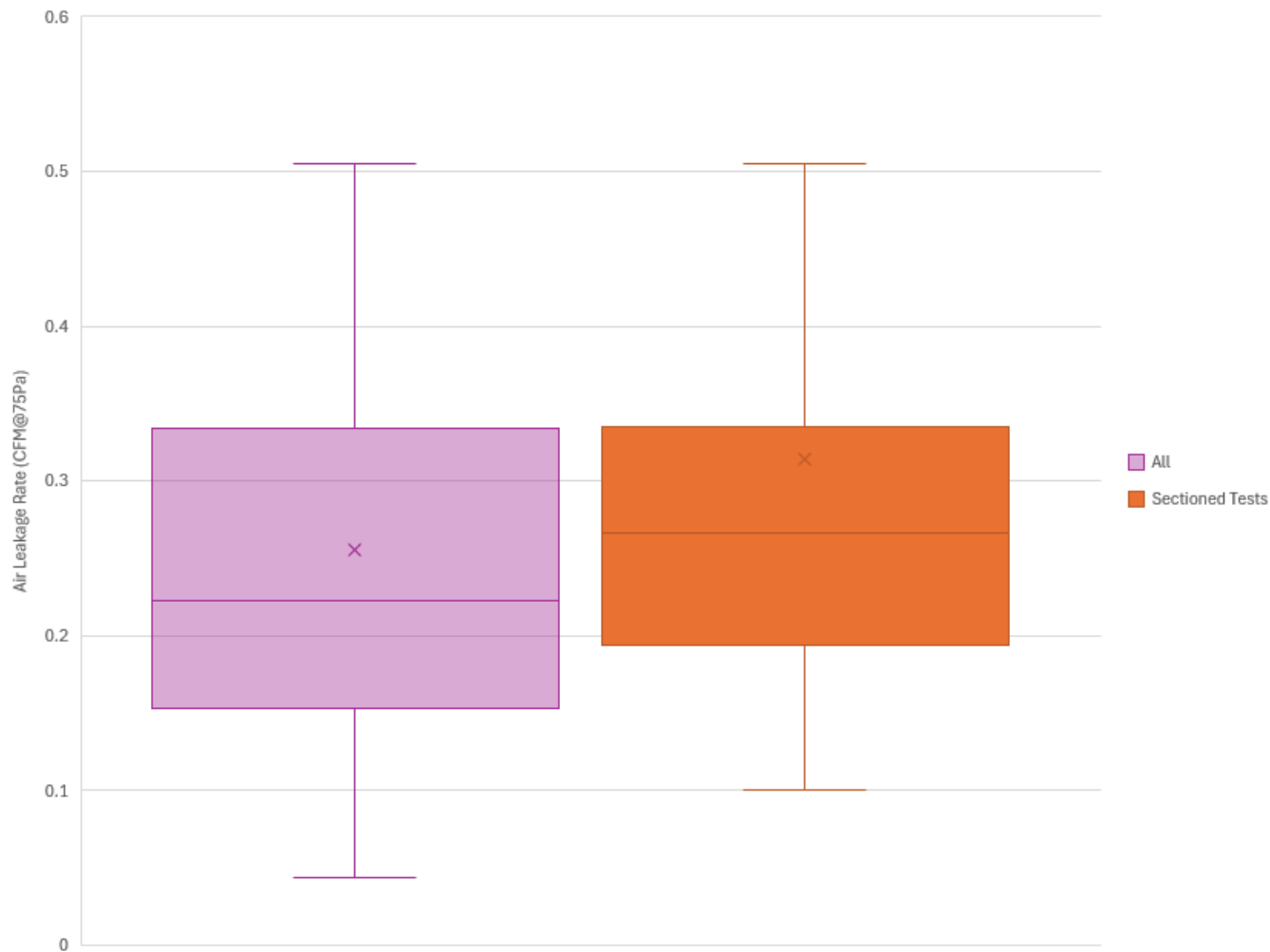
Jump Ducts



Multi-Section – Phased Construction/ Occupancy (Unguarded)



Sectioned Tests vs All Tests



Key Takeaways

- “Sectioned” testing generally performs worse than average

Error Summary

- ▶ Testing of buildings prepared with interior masking consistently show higher air leakage rates, and higher differences between depressurization and pressurization.
- ▶ We believe this may be an over-reporting of air leakage rates through measurement error associated with building preparation.
- ▶ We attribute much of this additional air leakage to operational air leakage rather than envelope air leakage.

Overall Implications

- ▶ The good news – buildings are likely more airtight than air leakage testing shows.
- ▶ High cost of exterior prep is a barrier to getting more accurate results, sometimes its not practical.
- ▶ Interior masking can have substantial benefits to assessing and controlling operational air leakage, which is more associated with energy use but is neglected by exterior masking.

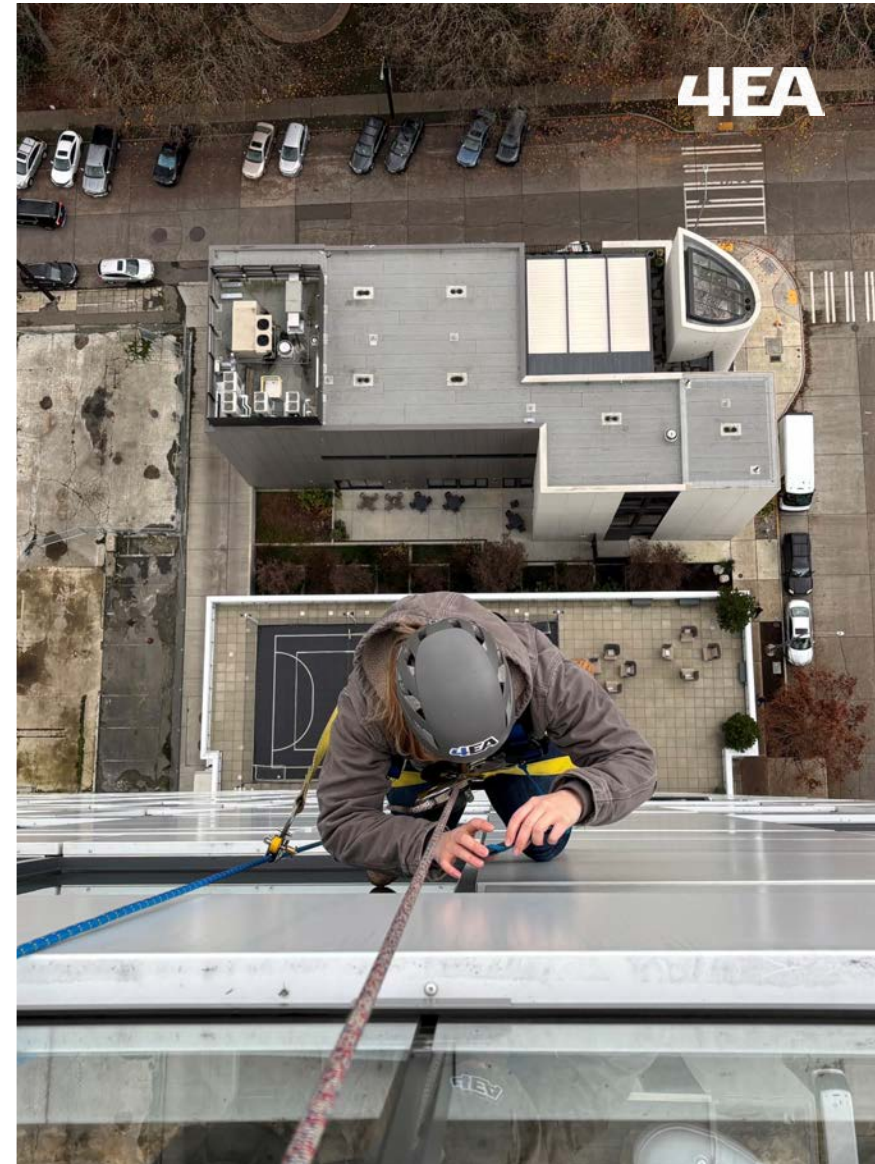
Future Work Needed

- ▶ There is still non-zero measurement error with exterior masking, this would be better to understand.
- ▶ More data is needed. A public or shared database for air leakage test reporting would help further industry knowledge and code development.



Policy Considerations

- ▶ More accurate tests don't necessarily mean more airtight buildings.
- ▶ Standards may benefit from harmonizing procedures for sealing intentional openings and, when permitted, account for measurement error.
- ▶ The more stringent airtightness targets get – the more important measurement error becomes. Interior masking may become less viable in the future.



Building Form
Owner Goals
Performance Metrics
Risk Management
Insulation & Thermal Bridging
Airtightness Testing Methods

Ventilation Approaches

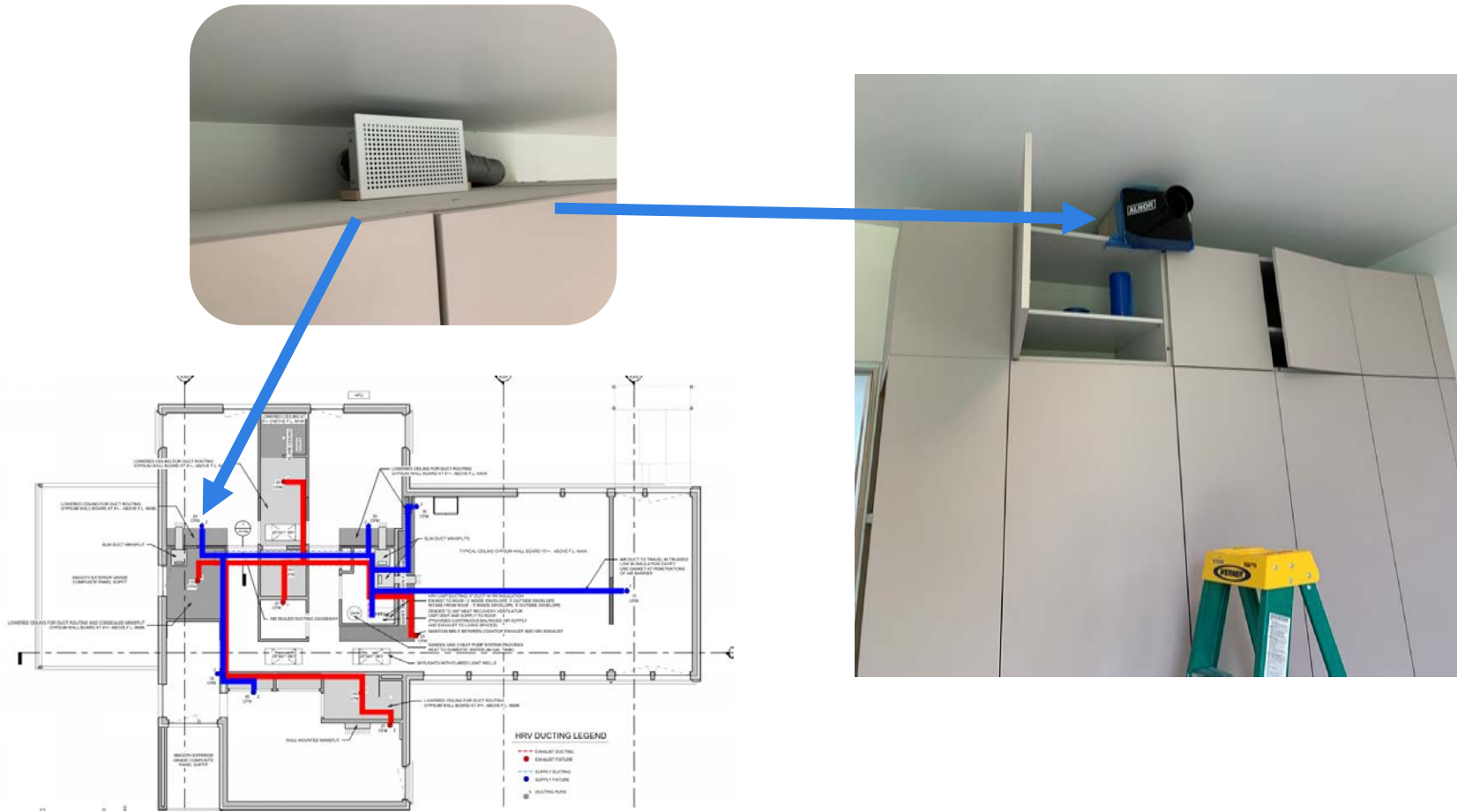
Ventilation Approaches

- **System Configuration**
- **System Optimization for Performance & Longevity**
- **Balancing & Commissioning**

Balanced Ventilation with Heat Recovery



Single-Family Balanced Ventilation



Hobson Place South

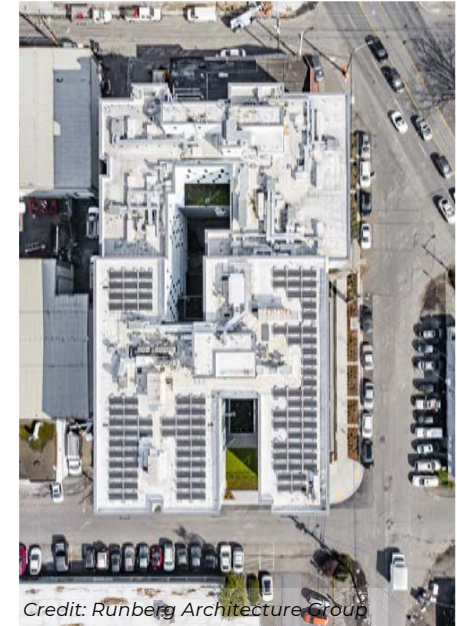
Owner/Developer: DESC

Owners Rep: Lotus Development Group

Architect: Runberg Architecture Group

Mechanical Engineer: Rushing Company

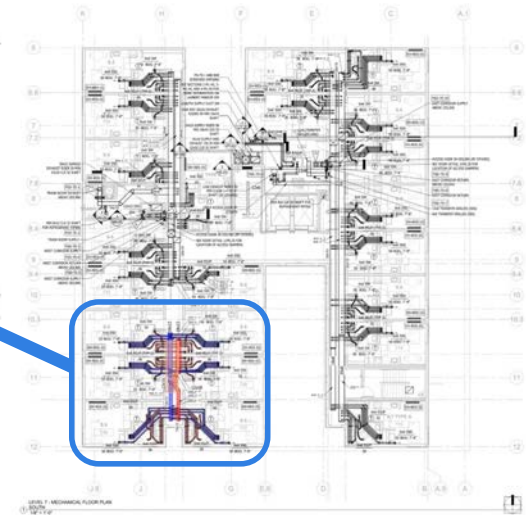
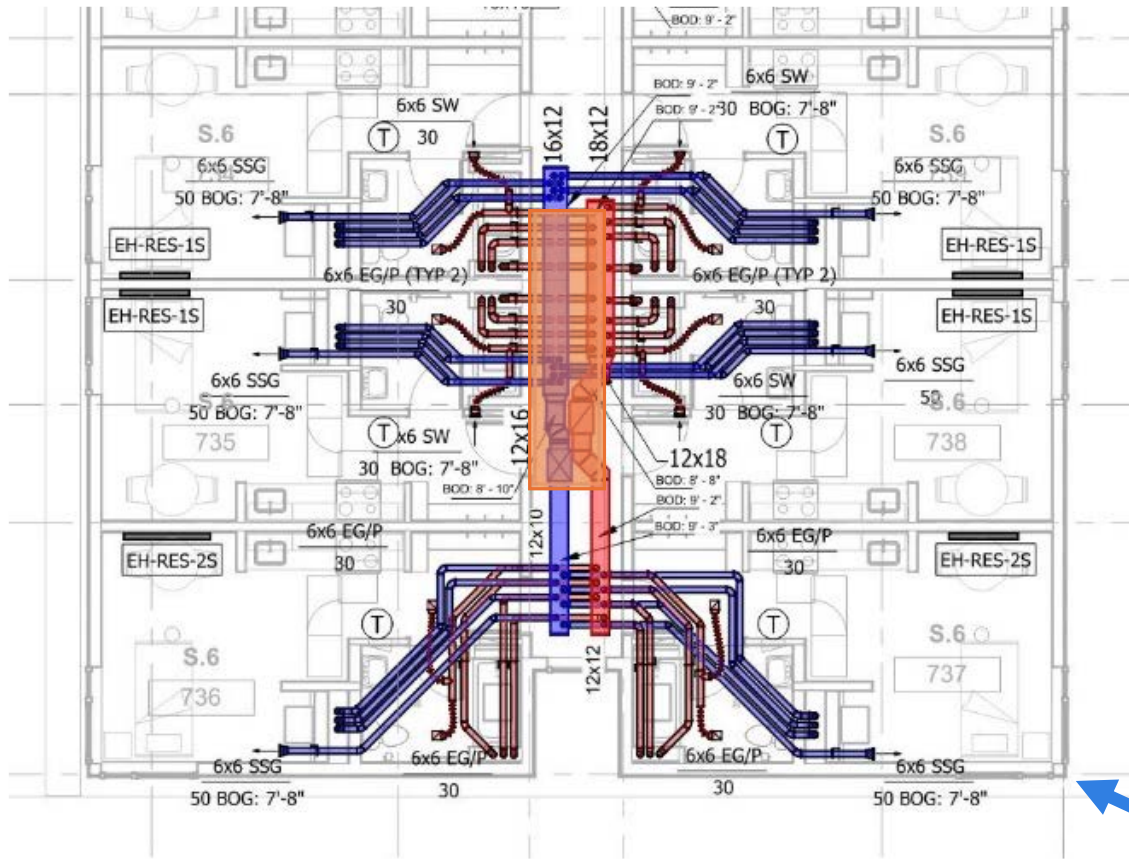
General Contractor: Walsh Construction Co.





Systems & Efficiencies

- Three Swegon rooftop ERVs serving four residential floors
 - Two Gold RX25s
 - One Gold RX11
- Minimum calculated heat recovery efficiency of 80%



Hobson Place South

Balancing & Commissioning

- ▶ Involved TAB/mechanical contractor early on in process
- ▶ Equipment needed to verify Phius air flow targets

Centralized Building Wings

PROS

- Keeps most of the ductwork within building enclosure.
- Maintenance – fewer units and less invasive to residents.

CONS

- Need additional height in top floor to accommodate ductwork (trunk).
- Requires code exception/alternate at jurisdiction's and Fire Marshal's discretion.

Ellie Passivhaus

Owner/Developer: Sound West Group

Architect: NK Architects

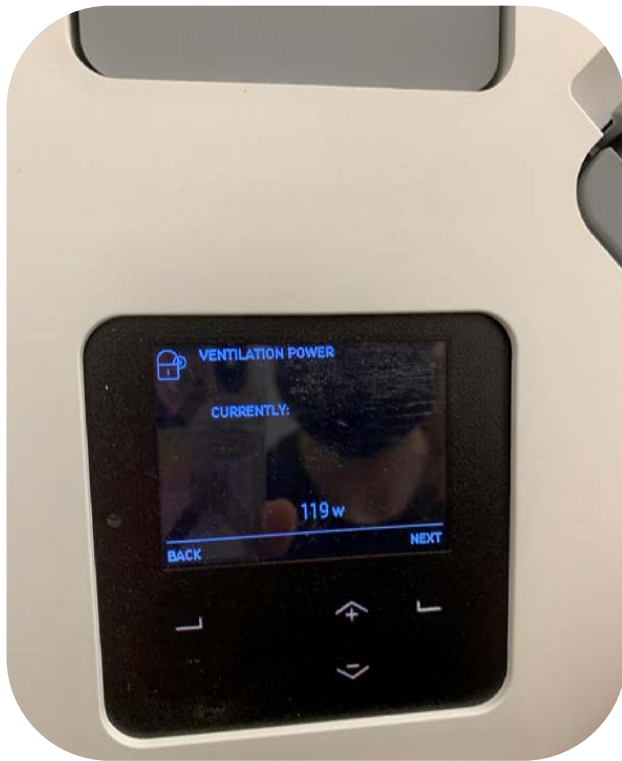
Mechanical Engineer: Staengl Engineering

General Contractor: Cascade Built

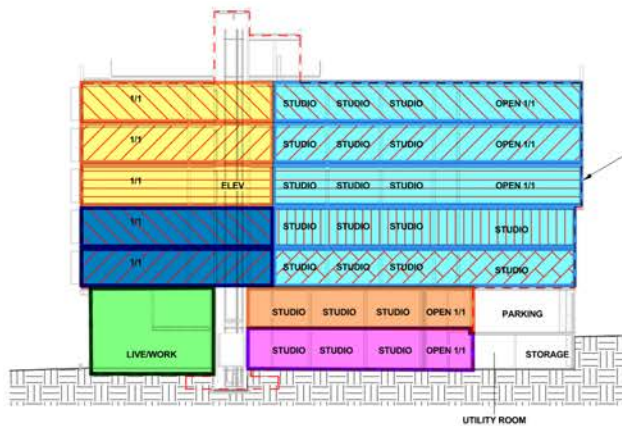
Ellie Passivhaus



Systems & Efficiencies



- Fifteen HRVs
 - Twelve Zehnder Q600s (heat recovery efficiency up to 87%)
 - Three Zehnder CA160s (heat recovery efficiency up to 95%)



7 THERMAL ENVELOPE DIAGRAM SECTION - EAST-WEST 1
SCALE: 1/16" = 1'-0"



4 ENERGY CODE AIR BARRIER/THERMAL ENVELOPE
PLAN LEVELS 5-7
SCALE: 1/16" = 1'-0"



3 ENERGY CODE AIR BARRIER/THERMAL ENVELOPE
PLAN - LEVELS 3-4
SCALE: 1/16" = 1'-0"

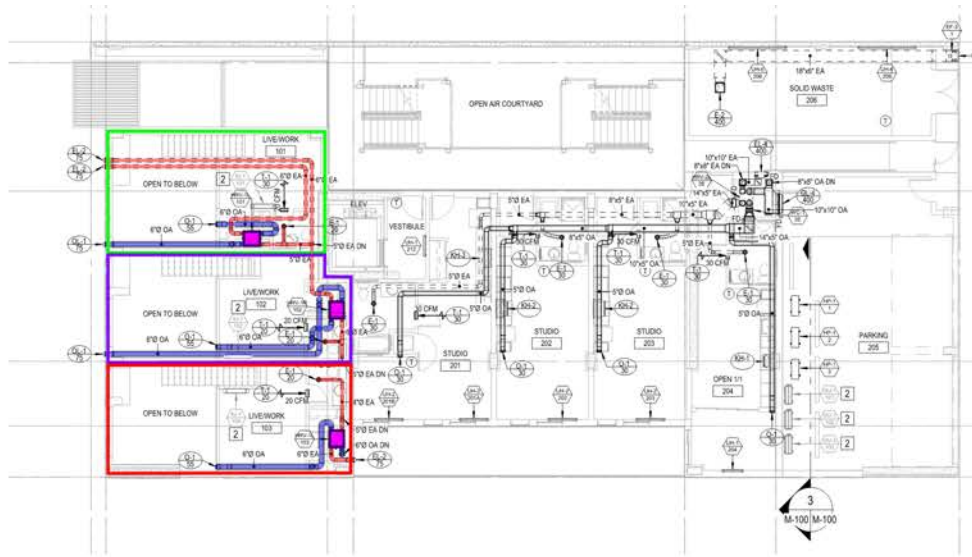


2 ENERGY CODE AIR BARRIER/THERMAL ENVELOPE
PLAN - LEVEL 2
SCALE: 1/16" = 1'-0"

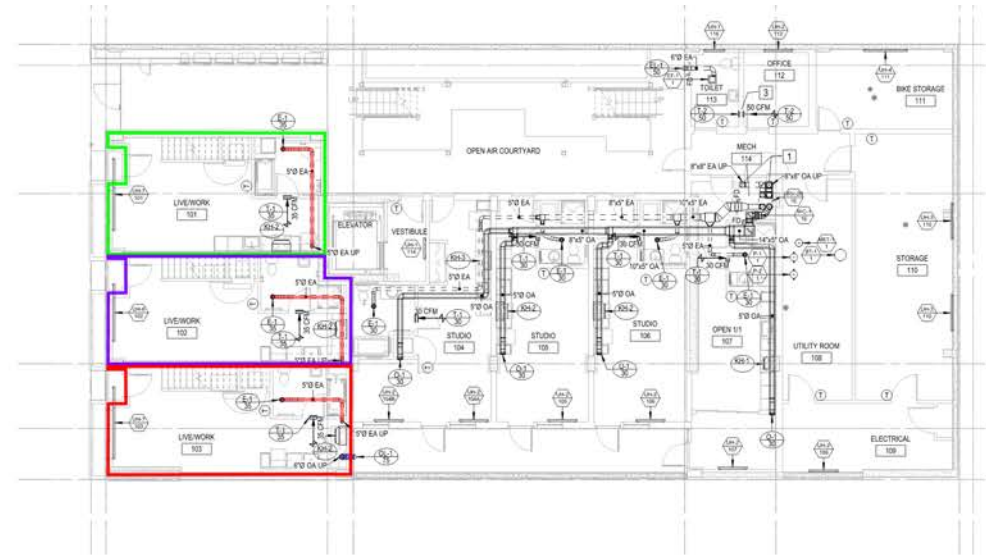


1 ENERGY CODE AIR BARRIER/THERMAL ENVELOPE
PLAN - LEVEL 1
SCALE: 1/16" = 1'-0"

Unitized Systems

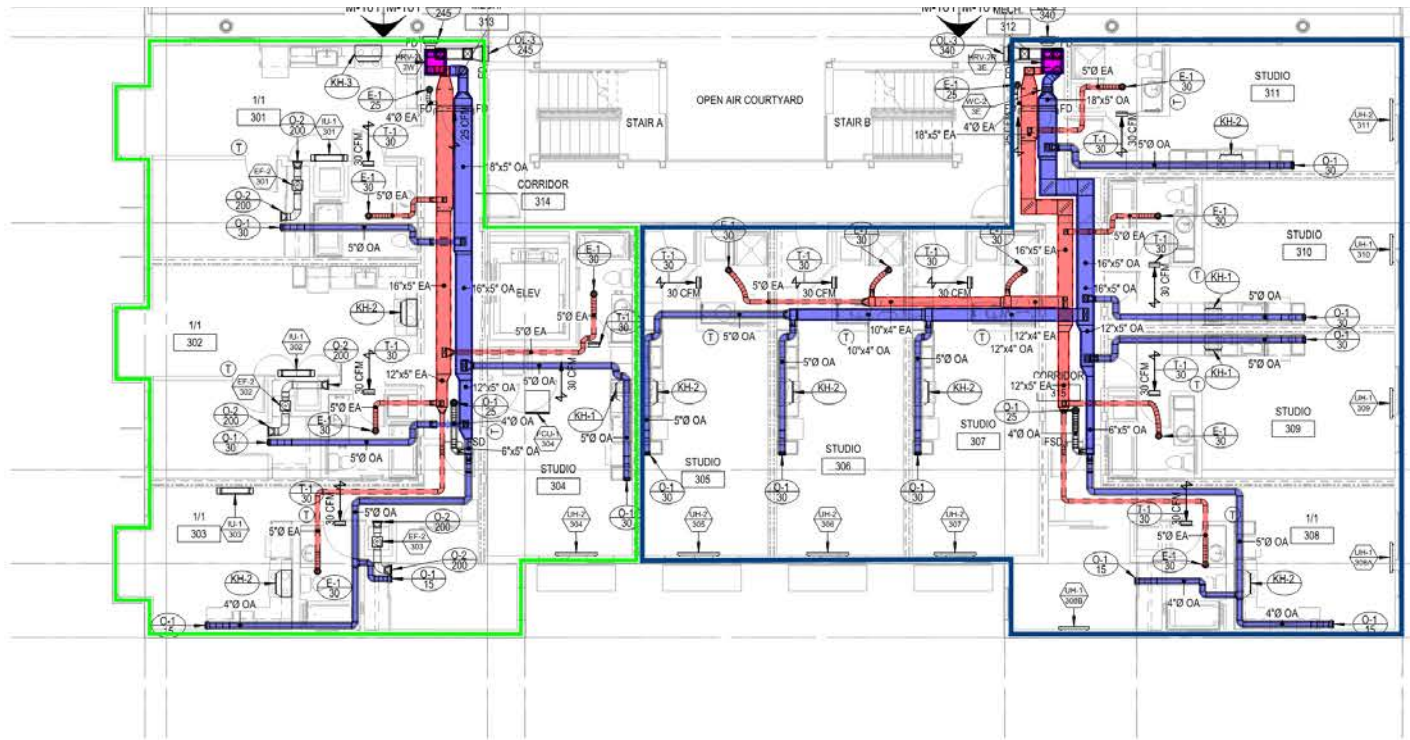


② LEVEL 2 - MECHANICAL DUCTWORK PLAN
1/8" = 1'-0"



① LEVEL 1 - MECHANICAL DUCTWORK PLAN
1/8" = 1'-0"

Centralized Horizontal, Floor-by-Floor



① LEVEL 3 - MECHANICAL DUCTWORK PLAN
1/8" = 1'-0"

Mechanical Spaces



Balancing & Commissioning



Hybrid: Centralized, Horizontal (Floor-by-Floor) & Unitized Systems

- Pros:
 - No area required on roof
 - No vertical shafts running through each floor
 - Equipment is within building enclosure
- Cons
 - Room(s) or closet(s) on each floor
 - Locating intake and exhaust through side of building
 - More floor height to accommodate corridor soffit for horizontal trunks

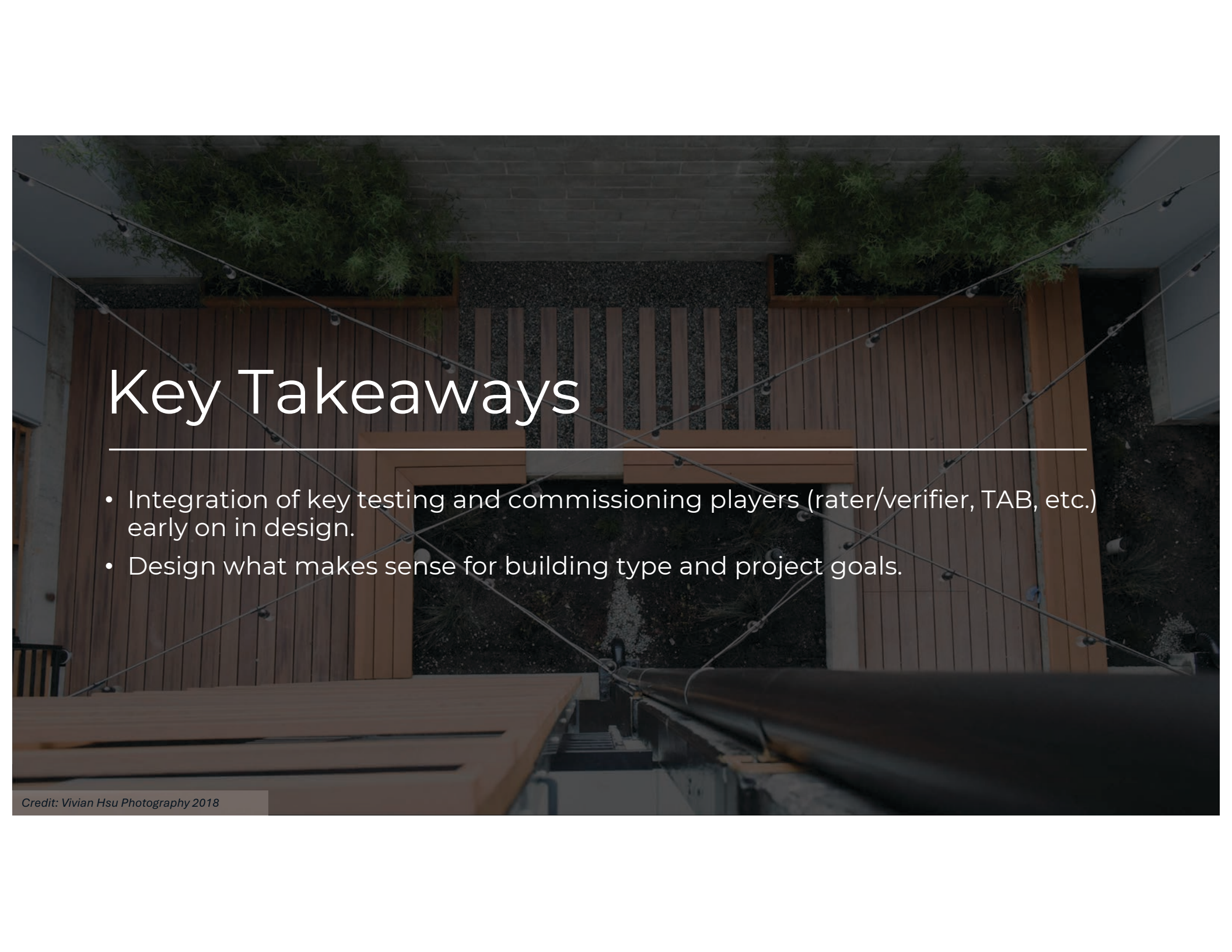




Advantages of Optimized Balanced Ventilation Configurations

- Additional solar panels
- More marketable amenity space





Key Takeaways

- Integration of key testing and commissioning players (rater/verifier, TAB, etc.) early on in design.
- Design what makes sense for building type and project goals.

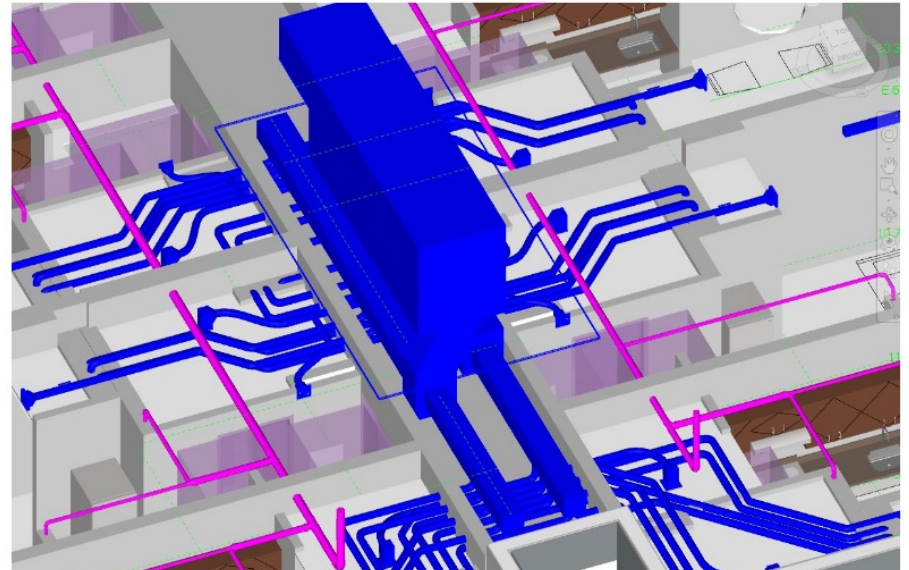
The Housing Development Consortium of Seattle-King County

Acknowledgement

- Exemplary Building Program by Housing Development Consortium (HDC) of Seattle-King County

GUIDELINES FOR **BALANCED VENTILATION WITH HEAT RECOVERY**

Part of a series highlighting techniques for designing & building better affordable housing



AGENDA

Building Form

Owner Goals

Performance Metrics

Risk Management

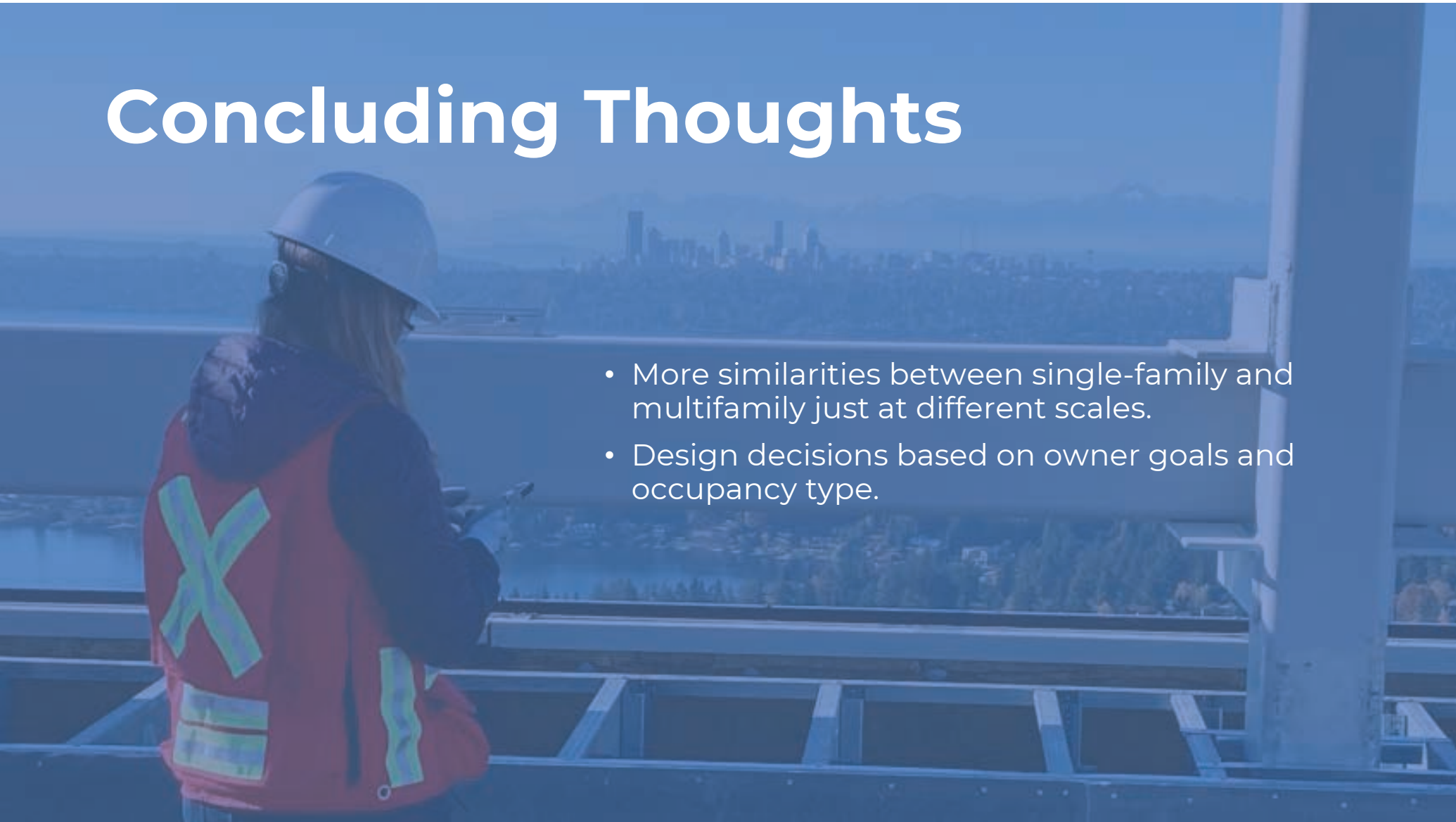
Insulation & Thermal Bridging

Airtightness Testing Methods

Ventilation Approaches

Concluding Thoughts

- More similarities between single-family and multifamily just at different scales.
- Design decisions based on owner goals and occupancy type.



Questions?



Thank you!

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