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Multifamily Air Leakage Evaluation: A Modular Case Study

August 2022

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Acknowledgments

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List of Abbreviations and Acronyms

ACH	air change rate
ACH50	air change rate at 50 Pa
ANSI	American National Standards Institute
cfm	cubic feet per minute
DOE	U.S. Department of Energy
HSPF	heating seasonal performance factor
HVAC	heating, ventilating, and air conditioning
ICC	International Code Council
IECC	International Energy Conservation Code
NREL	National Renewable Energy Laboratory
RESNET	Residential Energy Systems Network
SEER	seasonal energy efficiency ratio
SHGC	solar heat gain coefficient
sfue	square foot of unit envelope
U	thermal transmittance
UEF	uniform energy factor

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Executive Summary

The purpose of this case study is to compare the air leakage rates of modular and site-built multifamily dwelling units. The methods, materials, and equipment were observed to be very similar in the modular and site-constructed units in this case study. The installation quality of building envelope measures such as insulation and air barrier appeared to be better for modular construction, because they were installed in a controlled, factory setting. Through field observations, we identified cosmetic damage to the envelope of modular units following transport to the building site, but with no resulting significant air leakage pathways. However, we did see air leakage pathways resulting from field modifications to the envelope of modular units to accommodate structural and mechanical connections. We found that the extensive use of through-wall HVAC systems, combined with the transport, placement, and rework of modular units may compromise the high-quality envelope installation and airtightness observed in the factory without careful planning and/or design. Opportunities for improvement identified from the tested modular dwelling units include minimizing and optimally locating penetrations, pre-cutting and detailing penetrations at the factory where possible, properly sealing field modifications, and using split HVAC systems in place of through-wall packaged systems.

To compare the air leakage rates of modular multifamily dwelling units with the air leakage rates of site-built dwelling units, we conducted on-site blower door tests on 7 modular and 19 site-built multifamily units using ANSI/RESNET/ICC 380-2019 Standard for Testing Airtightness of Dwelling Unit Enclosures. All modular and site-built units tested were Type III construction (protected wood-frame over podium or slab-on-grade). All units tested were located in Philadelphia, PA (Climate Zone 4a), and permitted under the IECC 2015 energy code. University of Nebraska-Lincoln and MaGrann Associates performed the envelope leakage testing for all modular and site-built units following certificate of occupancy but prior to tenant occupancy. For all tests, we observed the unit air leakage rate (cfm) and unit air change rate per hour (ACH) at a pressure of 50 Pa. For modular unit tests, we also observed air leakage rates at multipoint pressures between 20 and 60 Pa.

The modular units are smaller than the site-built units, so the envelope area of modular units is greater relative to unit floor area and interior volume. Without accounting for the size difference, results indicate that modular units had a higher air change rate (6.0) on average than both site-built project units (3.7 and 4.7, respectively). However, when normalized for this difference, the air leakage rate of modular unit envelope area (0.22 cfm/sf) is comparable to the air leakage rate of site-built unit envelope area (0.21–0.23 cfm/sf).

1 Background

Stagnant productivity and continued workforce shortages are driving a renewed interest in prefabricated construction. Building components manufactured in a controlled factory setting can reduce project cost, time, site logistics, and waste while also improving quality, labor productivity, and safety (Grosskopf et al. 2020). Off-site construction is the fabrication and assembly of building elements at a location other than the construction site and may consist of single and multi-trade assemblies such as pipe racks, headwalls, and bathroom pods to complete volumetric building modules (Figure 1).

Figure 1. Prefabricated multifamily building modules

All photos in report by Kevin Grosskopf, UNL

For schedule- or occupancy-driven projects with standardized, repetitive building units such as apartments and hotels, off-site prefabrication of building modules can proceed simultaneously alongside site work or on-site construction, reducing project time, overhead, and the impact of weather (Dodge 2020). The Modular Building Institute (MBI) found that modular multifamily projects were completed 6–8 months faster on average than comparable site-built projects, reducing costs and improving affordability (MBI 2019). Modular projects not only reduce the number of workers on-site but can also reduce many of the safety risks common on site-built projects. In contrast to a transient workforce under the control of multiple trade contractors, off-site construction relies on a stable, permanent workforce under a central point of control free of disruptions from other trades and unpredictable site conditions.

Although modular construction accounts for only 5% of the current commercial construction market in the United States (MBI 2019), significant growth is being realized in California and in the Northeast where energy costs and high housing costs are causing many residents to transition from single to multifamily housing. According to the U.S. Department of Housing and Urban Development, 24.6% of the U.S. population lives in multifamily residences. Accordingly, the use of prefabricated construction is expected to increase from 16% of multifamily projects in 2017 to over 50% of projects by 2025 (Dodge 2020).

Preliminary results of a U.S. Department of Energy study, *Modular Multifamily Construction: A Field Study of Energy Code Compliance and Performance*, suggest that greater quality controls associated with off-site prefabrication may also improve the energy performance of modular multifamily buildings when compared to traditional site-built buildings (DOE 2022). To date, results indicate that the efficiency of key energy measures in 16 modular multifamily buildings surveyed during construction met or exceeded the energy efficiency of key energy measures in 24 site-built multifamily buildings surveyed (Table 1).

Table 1. Average Efficiency of Key Energy Measures

Data from DOE (2022)

	Climate Zone 3				Climate Zone 4			
	Modular	***n***	**Site-built**	***n***	**Modular**	***n***	**Site-built**	***n***
Roof (U)	0.027	6	0.030	13	0.027	5	0.026	3
Wall (U)	0.050	6	0.051	16	0.046	5	0.049	4
Window (U)	0.29	5	0.29	15	0.28	7	0.29	8
Window (SHGC)	0.22	6	0.23	15	0.29	6	0.29	8
Window-Wall Ratio	0.16	6	0.24	7	0.25	5	0.24	2
HVAC (SEER)	16.2	9	14.9	7	13.8	6	14.2	5
HVAC (HSPF)	9.7	8	9.1	7	10.7	6	11.7	2
Domestic Hot Water (UEF)	0.95	8	0.89	6	0.94	4	0.92	2
Lighting (W/sf)	0.28	6	0.23	6	0.32	5	0.47	1

** Key energy measures identified by Pacific Northwest National Laboratory lost savings potential method.*

In that same study, ENERGY STAR® benchmarking scores for 14 post-occupancy modular multifamily buildings were higher on average (87) when compared to benchmarking scores of 129 site-built buildings (81) of the same age, size, and location. Although the average energy use intensity of modular multifamily buildings surveyed (36.4 kBtu/sf/yr) was slightly greater than the energy use intensity of site-built buildings (35.0 kBtu/sf/yr), occupant density was 30% higher in modular multifamily buildings compared to site-built buildings. Multifamily buildings used in that study were on average 6 stories in height and consisted of approximately 120 dwelling units and 150,000 sf of gross floor area (DOE 2022).

Although few differences between methods, materials, and equipment were observed in the DOE study, the installation quality of building envelope measures such as insulation and air barrier appeared to be better for modular construction because it was installed in a controlled, factory setting. Through field observations, we identified several instances of damage to the envelope of modular units following transport to the building site. Also observed were several field modifications to the envelope of modular units to accommodate structural and mechanical connections. Together with extensive use of through-wall HVAC systems, the transport, placement, and rework of modular units may compromise the higher quality of envelope installation and airtightness observed in the factory without careful planning and/or design.

To determine the extent of degradation in envelope airtightness associated with the transport of modular multifamily dwelling units, an NREL study, *Energy Efficiency in Permanent Modular Construction,* was commissioned in 2021 to compare factory airtightness to post-transport airtightness of 7 modular dwelling units (Pless et al. 2022). Beginning in May 2021, two rounds of testing were performed in the factory including ANSI/RESNET/ICC 380-2019 envelope leakage tests on units in a (1) pre-sealed and (2) sealed condition. Pre-sealed testing was first performed following the installation of windows, doors, and interior finishes. Sealed testing was then performed following the sealing of ductwork; HVAC cabinets; and mechanical, electrical, and plumbing penetrations. Sealed testing also included the use of a self-sealing aerosol designed to seal fine air leaks in the unit envelope. Results (Table 2) show none of the pre-sealed units would have met the 2015 IECC air change rate (≤ 3.0 ACH) requirement for residential and *low-rise* multifamily buildings. Once sealed, however, 6 of 7 units would have exceeded the 2015 IECC air change rate requirement.

Table 2. Pre-Set Modular Air Leakage Test Results

Unit	Unit Type	Unit Volume (cf)	Factory ACH50 (Pre-sealed)	Factory ACH50 (Sealed)	Site Staging Area ACH50*
1	1-Bedroom	4,333	9.0	1.8	6.0
2	Studio	3,193	5.9	1.0	7.7
3	1-Bedroom	4,333	10.8	3.1	3.7
4	Studio	3,193	6.9	1.8	6.0
5	1-Bedroom	4,400	5.7	1.7	6.2
6	1-Bedroom	4,400	7.4	2.4	-
7	1-Bedroom	4,400	6.4	1.1	6.3
	Average		7.4	1.8	6.0

** Site staging area tests lacked key components and did not represent final installed conditions.*

In December 2021, following transport approximately 500 miles from the factory to the project site, the same 7 units were again tested in a staging area prior to placement. These units, however, were tested with transportation wrap still installed. In addition, HVAC cabinets were unsealed, bath fans and lighting fixtures were not installed, and in one case, a window was missing. Also observed was cracking of drywall interiors. As a result, air leakage following transport was comparable to the pre-sealed condition observed in the factory (Table 2).

To determine if any further degradation in envelope airtightness occurred during crane placement and post-set rework, the same 7 units were tested a fourth time in May 2022 under a second NREL contract—this report details that work. Specifically, our team compared the air leakage rates of installed modular units to factory and post-transport (e.g., staging area) air leakage rates. In addition, we compared the air leakage rates of installed modular units to a baseline of 19 site-built multifamily dwelling units of similar Type III construction, located in the same area and permitted under the same energy code. All modular and site-built dwelling units were tested within 30 days of certificate of occupancy. The methods, results, and conclusions from these tests are provided in Sections 2–4.

2 Test Plan

2.1 Overview

The test plan includes the protocols and procedures that were used to evaluate the air leakage rate of 7 completed modular multifamily dwelling units and 19 comparable site-built dwelling units. Air leakage is defined as the number of unit air changes per hour (ACH) or cubic feet per minute of unit envelope area (cfm/sfue) under 50 Pa negative pressure. We compared modular unit air leakage rates to air leakage rates observed for the same modular units tested in the factory to determine the degradation in envelope airtightness (if any) associated with transportation, crane placement, and field modifications. Modular unit air leakage rates were also compared to baseline air leakage rates observed for site-built units.

2.2 Test Units

Post-set modular dwelling units tested in the field were the same 7 units tested in the factory as the other NREL (2022) study. Verification was accomplished by matching module identification labels in the factory to those observed in the field (Figure 2). Modular units consisted of 5 one-bedroom dwellings units and 2 studio dwelling units (Figures 3 and 4) as part of a 400-unit (260,000 sf) 7-story mixed-use multifamily project located in Philadelphia, PA. An additional 19 site-built dwelling units from two additional projects were also tested. Eleven of these dwelling units were comparable in size and layout to the modular units, consisting mainly of 1- and 2-bedroom dwelling units. Eight additional site-built units tested were significantly larger, multi-level dwelling units. All modular and site-built units tested were Type III construction (protected wood-frame over podium or slab-on-grade). All units tested were located in Philadelphia (Climate Zone 4a) and permitted under the IECC 2015 energy code. Testing for all modular and site-built units was done following certificate of occupancy but prior to tenant occupancy.

2.3 Test Protocols and Procedures

To compare the air leakage rates of modular multifamily dwelling units to the air leakage rates of site-built multifamily dwelling units, our on-site teams conducted blower door tests (Figure 5) using ANSI/RESNET/ICC 380-2019 Standard for Testing Airtightness of Dwelling Unit Enclosures. For all tests, the unit air leakage rate (cfm) unit air change rate per hour (ACH) and unit enclosure area air leakage rate (cfm/sfue) was observed at a pressure differential of 50 Pa. For modular unit tests, air leakage rates were also observed at multipoint pressures between 20 and 60 Pa. The interior volume and enclosure area of all test units was calculated using participant provided construction documents and On-Screen Takeoff software (Appendix A). Consistent with factory pre-sealed testing and site staging area testing, ductwork and HVAC cabinets were not sealed prior to testing of post-set modular units. Visually apparent air leakage pathways in the unit envelope (e.g., drywall cracking, field modifications, electrical openings) were documented. For site-built units, HVAC systems were fully installed and cabinets sealed.

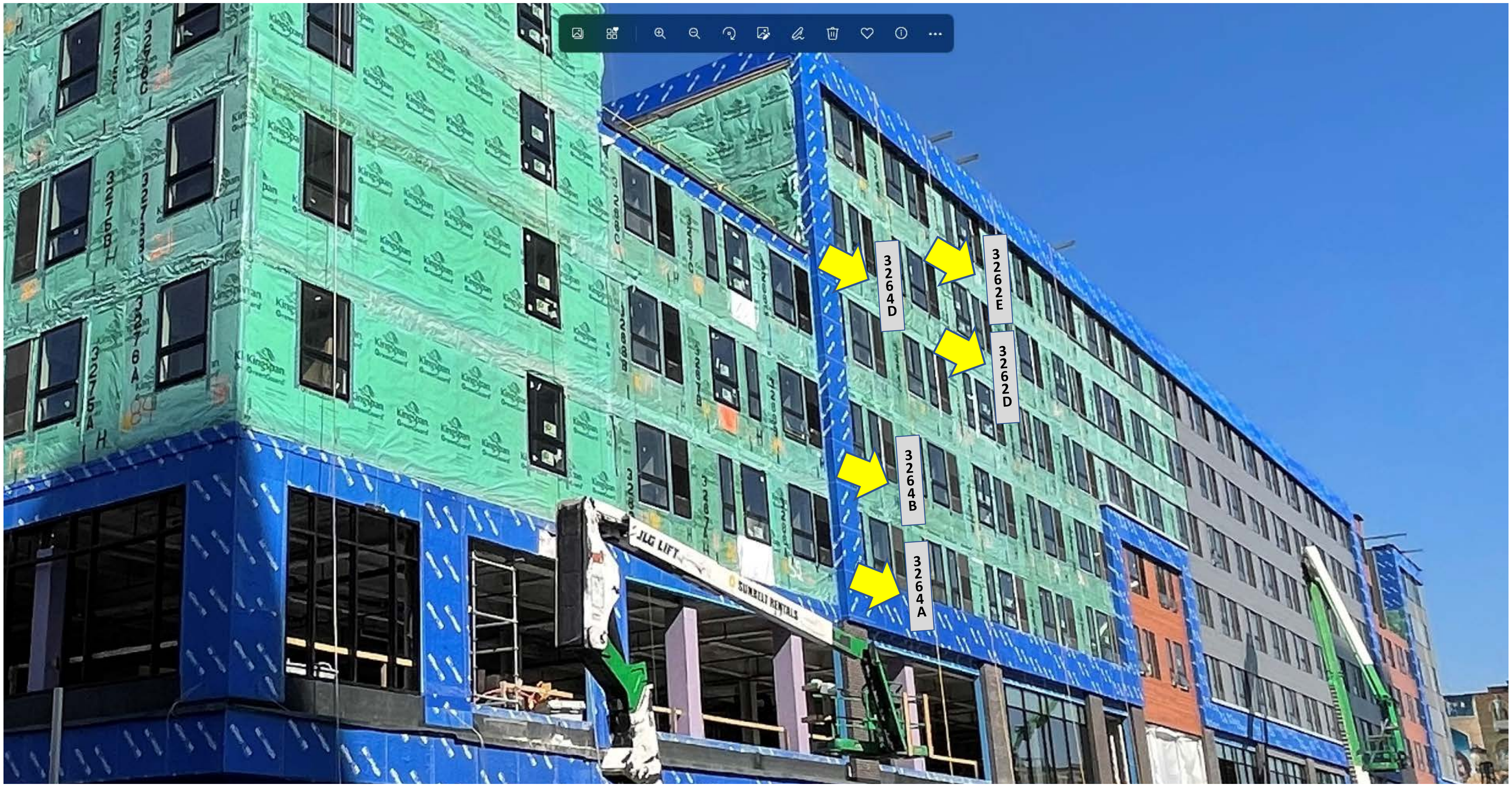

Figure 2. Location of 5 one-bedroom modular test units as part of a 400-unit multifamily project located in Philadelphia, PA. Two additional studio tests units not shown.

Figure 3. Studio modular test unit

Figure 4. One-bedroom modular test unit

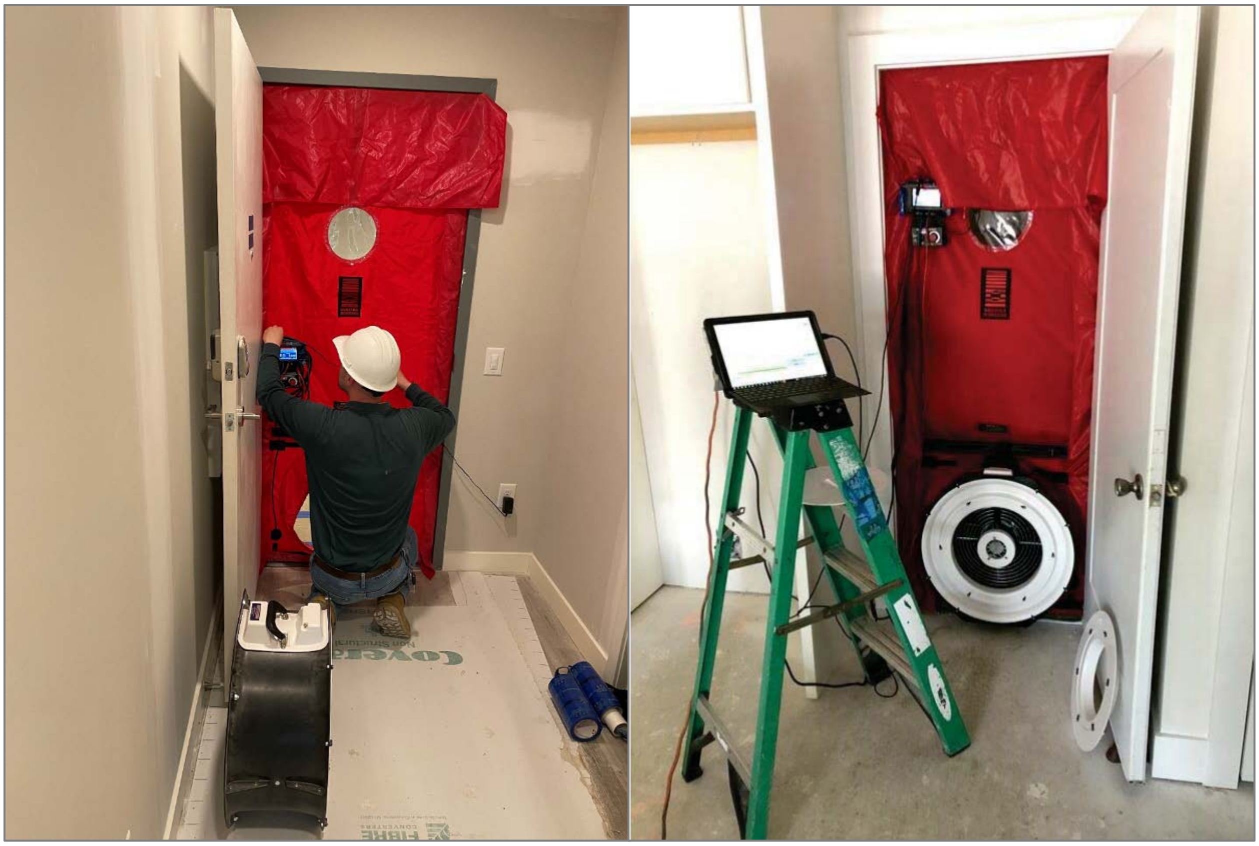

Figure 5. ANSI/RESNET/ICC 380-2019 envelope leakage test setup

3 Results

3.1 Overview

In this section, the air leakage rates of installed modular dwelling units are compared to factory and post-transport air leakage rates. In addition, the air leakage rates of installed modular dwelling units are compared to a baseline of 19 site-built dwelling units of similar age, construction, location, and energy code.

3.2 Modular and Site-Built Air Leakage Test Results

Post-set air leakage test results for modular units ("project 1") are presented in Table 3. Dwelling unit air leakage rates range from 5.0–7.9 ACH at 50Pa. The average air change rate for the 7 modular units tested is 6.0 ACH. Similarly, enclosure air leakage rates range from 0.21–0.30 cubic feet per minute per square foot of dwelling unit enclosure area (cfm/sfue). The average enclosure air leakage rate for the 7 modular units tested is 0.22 cfm/sf.

Table 3. Post-Set Modular Air Leakage Test Results (Project 1)

Unit	Unit floor Area (sf)	Unit Volume (cf)	Enclosure Area (sf)	Unit Air Leakage (cfm)	Unit Air Leakage (ACH)	Enclosure Air Leakage (cfm/sfue)
1	490	4,333	1,700	369	5.1	0.21
2	375	3,193	1,390	406	7.6	0.29
3	490	4,333	1,760	362	5.0	0.21
4	375	3,193	1,390	422	7.9	0.30
5	500	4,400	1,780	367	5.0	0.21
6	500	4,400	1,780	418	5.7	0.23
7	500	4,400	1,780	436	5.9	0.24
				Average	6.0	0.22

Average post-set modular air leakage rates (6.0 ACH) were comparable to average factory pre-sealed (7.4 ACH) and post-transport air leakages rates (6.0 ACH). Variability in air leakage among the 7 modular dwelling units tested was noticeably higher for factory and post-transport tests (Figure 6). The benefits of efforts to seal modular units in the factory did not appear to significantly improve airtightness following unit transport and placement. The average modular air leakage rate following factory sealing (1.8 ACH) was likely accomplished by temporary sealing of ductwork, HVAC cabinets, and electrical openings. The use of a self-sealing aerosol and manual sealing of mechanical, electrical, and plumbing penetrations likely had lesser effect on modular unit airtightness and likely explains the modest improvement between average factory pre-sealed air leakage rates (7.4 ACH) and average post-transport and post-set air leakage rates (6.0).

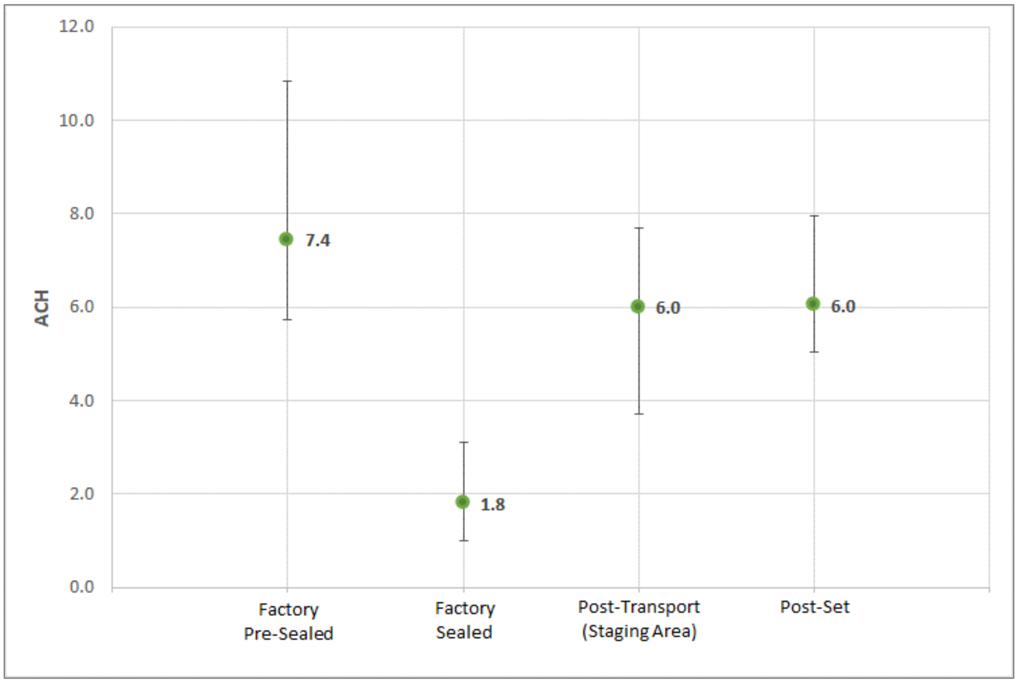

Figure 6. Pre-set and post-set modular air leakage test results

Air leakage test results for the first 11 of 19 total site-built units ("project 2") are presented in Table 4. Dwelling unit air leakage rates range from 3.7–5.5 ACH at 50 Pa. The average air change rate for the 11 site-built units tested is 4.7 ACH. Similarly, enclosure air leakage rates range from 0.18–0.27 cfm/sf of dwelling unit enclosure. The average enclosure air leakage rate for the 11 site-built units tested is 0.23 cfm/sf.

Table 4. Site-Built Air Leakage Test Results (Project 2)

Unit	Unit floor Area (sf)	Unit Volume (cf)	Enclosure Area (sf)	Unit Air Leakage (cfm)	Unit Air Leakage (ACH)	Enclosure Air Leakage (cfm/sfue)
1	750	7,875	2,717	610	4.6	0.22
2	950	9,975	3,207	670	4.0	0.21
3	723	7,592	2,596	463	3.7	0.18
4	723	7,592	2,596	596	4.7	0.23
5	823	8,642	2,924	797	5.5	0.27
6	750	7,875	2,717	638	4.9	0.23
7	950	9,975	3,207	774	4.7	0.24
8	723	7,592	2,596	676	5.3	0.26
9	823	8,642	2,924	599	4.2	0.20
10	750	7,875	2,717	630	4.8	0.23
11	950	9,975	3,207	875	5.3	0.27
				Average	4.7	0.23

Air leakage test results for an additional 8 site-built units ("project 3") are presented in Table 5. Dwelling unit air leakage rates range from 1.6–7.2 ACH at 50 Pa. The average air change rate for the 8 site-built units tested is 3.7 ACH. Similarly, enclosure air leakage rates range from 0.10–0.37 cfm/sf of dwelling unit enclosure. The average enclosure air leakage rate for the 8 additional site-built units tested is 0.21 cfm/sf. Of note, unit 1 had not been fully completed prior to testing. Excluding unit 1, the average air leakage rate for the remaining 7 units in project 3 are 3.2 ACH and 0.18cfm/sf, respectively.

Table 5. Site-Built Air Leakage Test Results (Project 3)

Unit	Unit floor Area (sf)	Unit Volume (cf)	Enclosure Area (sf)	Unit Air Leakage (cfm)	Unit Air Leakage (ACH)	Enclosure Air Leakage (cfm/sfue)
1	1,500	13,500	4,380	1,630	7.2*	0.37*
2	2,450	22,050	5,966	1,288	3.5	0.22
3	1,500	13,500	4,380	977	4.3	0.22
4	2,450	22,050	5,966	1,082	2.9	0.18
5	1,500	13,500	4,380	470	2.1	0.11
6	2,450	22,050	5,966	1,366	3.7	0.23
7	1,500	13,500	4,380	993	4.4	0.23
8	2,450	22,050	5,966	578	1.6	0.10
				Average	3.7	0.21

** Unfinished unit.*

The modular units were smaller than the site-built units, so the envelope area of modular units was greater relative to unit floor area and interior volume. Without accounting for the size difference, results (Table 6) indicate that modular units had a higher air change rate (6.0) on average than both site-built project units (3.7 and 4.7 respectively). However, when normalized for this difference, the air leakage rate of modular unit envelope area (0.22 cfm/sf) was comparable to the air leakage rate of site-built unit envelope area (0.21–0.23 cfm/sf).

Table 6. Summary of Modular and Site-Built Air Leakage Test Results

	Number of Units	Average Unit Floor Area (sf)	Average Unit ACH	Average Unit cfm/sfue*
Modular units (project 1)	7	460	6.0	0.22
Site-built units (project 2)	11	810	4.7	0.23
Site-built units (project 3)	8	1,975	3.7	0.21

** Cubic feet per minute of air leakage per square foot of unit envelope area (cfm/sfue)*

3.3 Modular Air Leakage Analysis

Visual inspection of post-set modular units identified several instances of damage to the envelope of the units following transport to the building site. Damage consisted of cracks in the drywall, which had mostly been repaired prior to testing. Also observed were several field modifications to the envelope of modular units to accommodate mechanical connections. In several units, field rework was noted in ceilings to relocate fire protection or other mechanical, electrical, and plumbing systems (Figure 7). In addition, access panels were cut beneath the HVAC system in every test unit to relocate or connect condensate piping (Figure 8). In other cases, supply duct chases from the HVAC system appeared to be unsealed (Figure 9). Together with the use of through-wall vertical terminal heat pump systems, which are inherently less airtight than comparable spilt HVAC systems used in the site-built units, considerable air leakage was traced to the mechanical closet.

To determine the air leakage through the HVAC closet, a louvered return air panel in modular unit 4 was removed and sealed (Figure 10) and the blower door test repeated. The unit 4 air leakage rate was reduced roughly 20% from 422 CFM50 to 337 CFM50 (7.9 ACH50 to 6.3 ACH50). Results of multipoint airtightness tests further suggest that modular air leakage was likely caused by a smaller number of larger openings in the modular unit enclosure. On average, the slope of the trend line showing unit air leakage (cfm) in relation to unit air pressure (Pa) for modular dwelling units is 0.52 (Figure 11). A slope approaching 0.50 suggests air leakage caused by a smaller number of larger openings in the unit enclosure. A slope approaching 1.0 suggests air leakage caused by a larger number of smaller openings in the unit enclosure. This phenomena is explained by the Bernoulli's power law, $Q = C(\Delta P)^n$ where:

Q = flow
C = flow coefficient
P = pressure
n = flow exponent

The slope of the multipoint test line is defined by the flow exponent (n), a dimensionless variable. When flow resistance is proportional to airflow velocity, as is the case for a small opening in the building envelope, the slope approaches 1.0, a laminar condition. When flow resistance varies with airflow velocity, as is the case for a large opening in the building envelope, the slope approaches 0.5, a turbulent condition.

Figure 7. Unsealed ceiling access

Figure 8. Unsealed condensate access (note relocated drain hole filled with batt insulation)

Figure 9. Unsealed penetration into above-ceiling supply and exhaust duct chase

Figure 10. Supplemental test in modular unit 4 to determine air leakage through HVAC cabinet

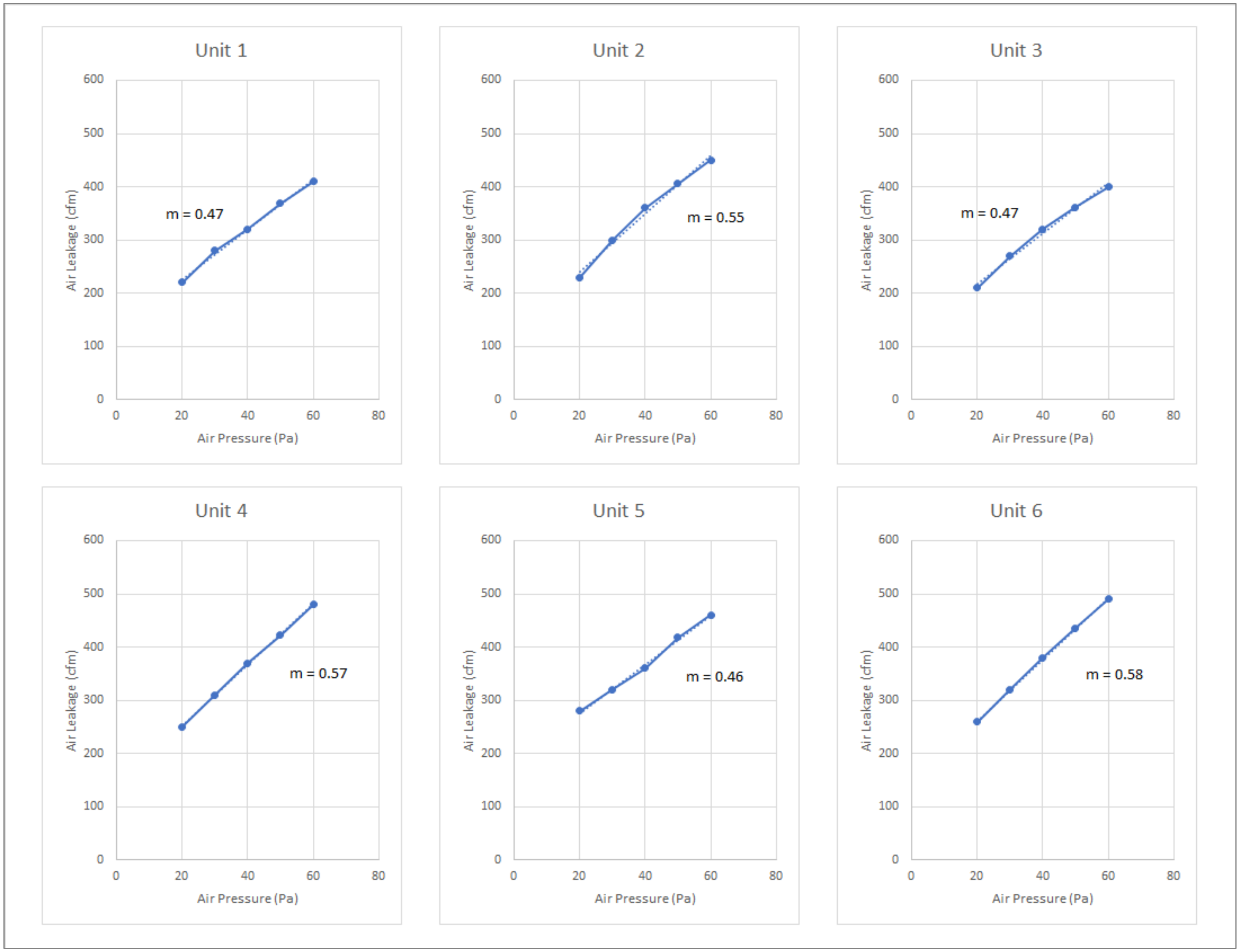

Figure 11. Multipoint blower door tests, modular units 1–6

4 Conclusions

The transport, placement, and rework of modular units create the potential to compromise airtightness achieved in a quality-controlled setting. Damage to the modular envelope following transport to the building site was observed for several test units, consisting mostly of cracks in the drywall, but did not appear to be a significant pathway for air leakage in the tested modular dwelling units. Results of multipoint airtightness tests instead suggest that the air leakage was likely caused by larger openings such as through-wall HVAC systems and field modifications to the envelope to accommodate mechanical connections. In fact, 20% or more of the air leakage in the tested modular units may be attributed to the HVAC closet.

Air change rate is important because it is used to evaluate compliance for code and above-code thresholds, which is typically reported volumetrically in the form of air changes per hour at a pressure of 50 pascals. The tested modular units had a higher air change rate (6.0) on average than both tested site-built project units (3.7 and 4.7, respectively). However, when normalized to the unit envelope area for each modular and site-built dwelling unit, the air leakage rate of modular envelopes (0.22 cfm/sfue), was comparable to the air leakage rate of site-built envelopes (0.21–0.23 cfm/sfue).

Opportunities exist for air leakage improvement in modular dwelling units, including minimizing and optimally locating penetrations, pre-cutting and detailing penetrations at the factory where possible, proper sealing of field modifications, and use of split systems in place of through-wall packaged systems. In addition to improved airtightness, minisplit/multisplit systems typically have higher efficiency (20+ SEER) compared to packaged systems (14 SEER), especially those with variable refrigerant flow, and wall or ceiling mounted split systems can maximize available dwelling unit floor space.

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Appendix A. Test Unit Floor Plans

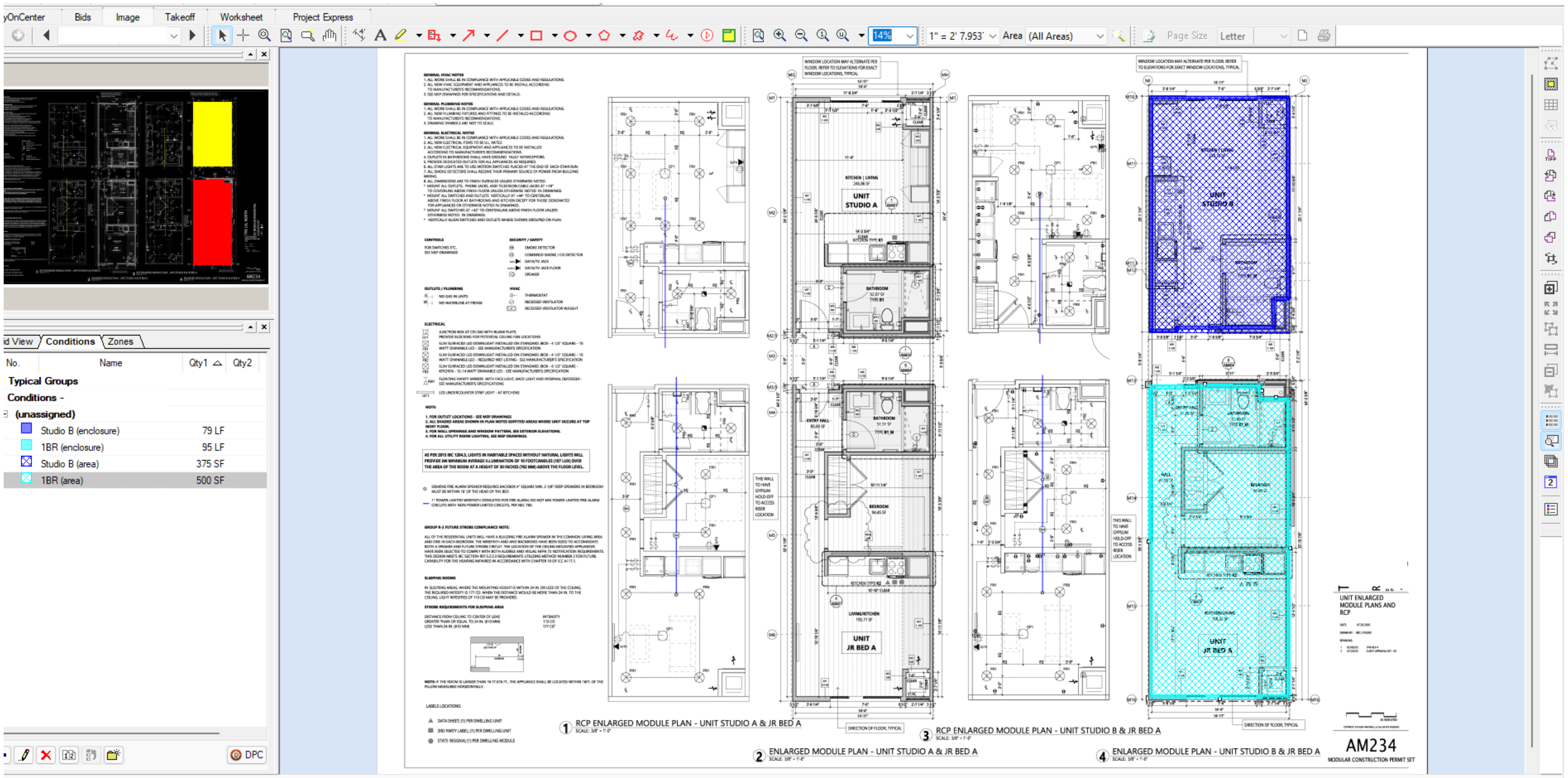

Figure 12. Modular test unit studio and one-bedroom floor plans (project 1)

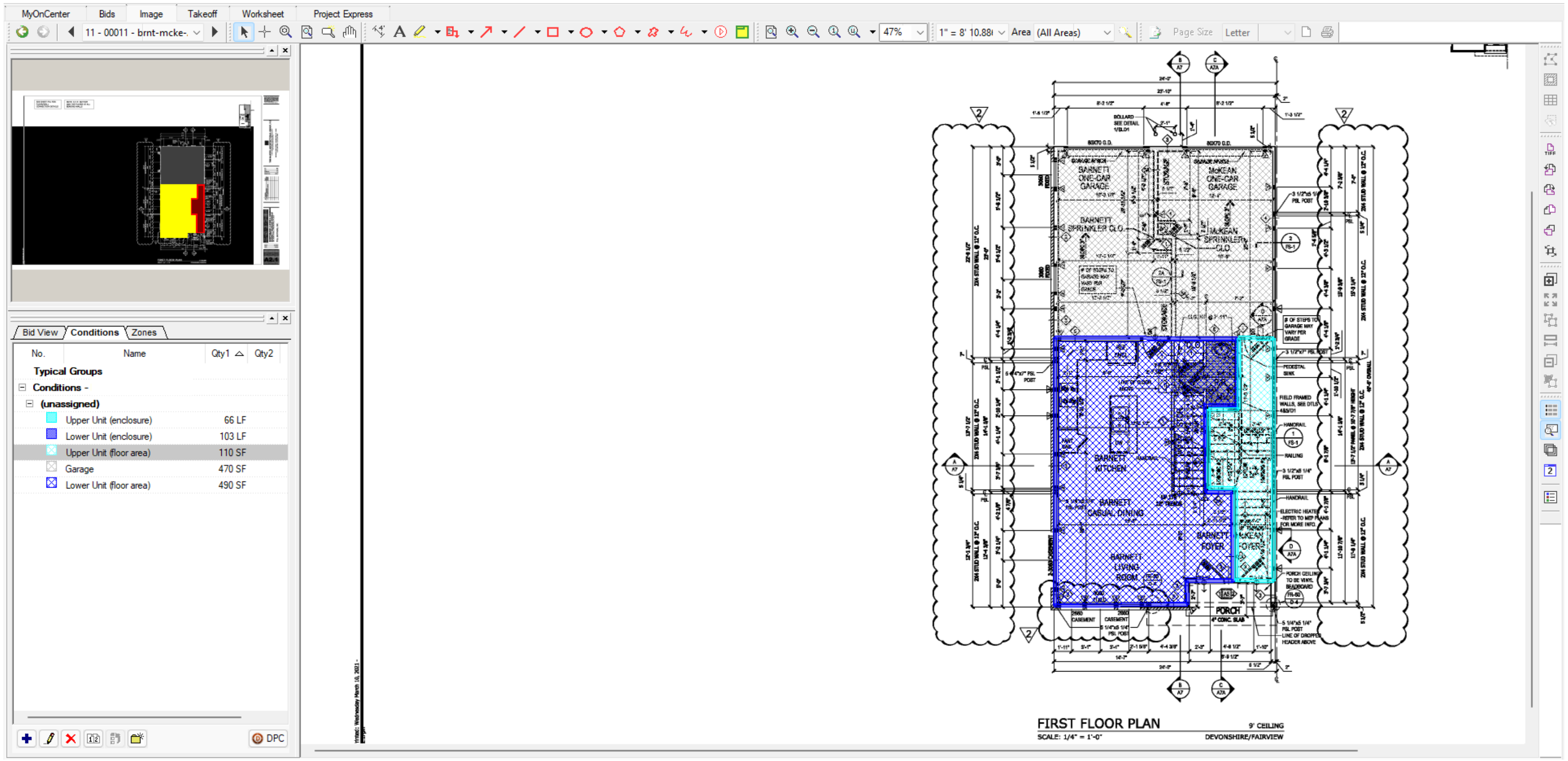

Figure 13. Site-built test unit floor plans, level 1 (project 3)

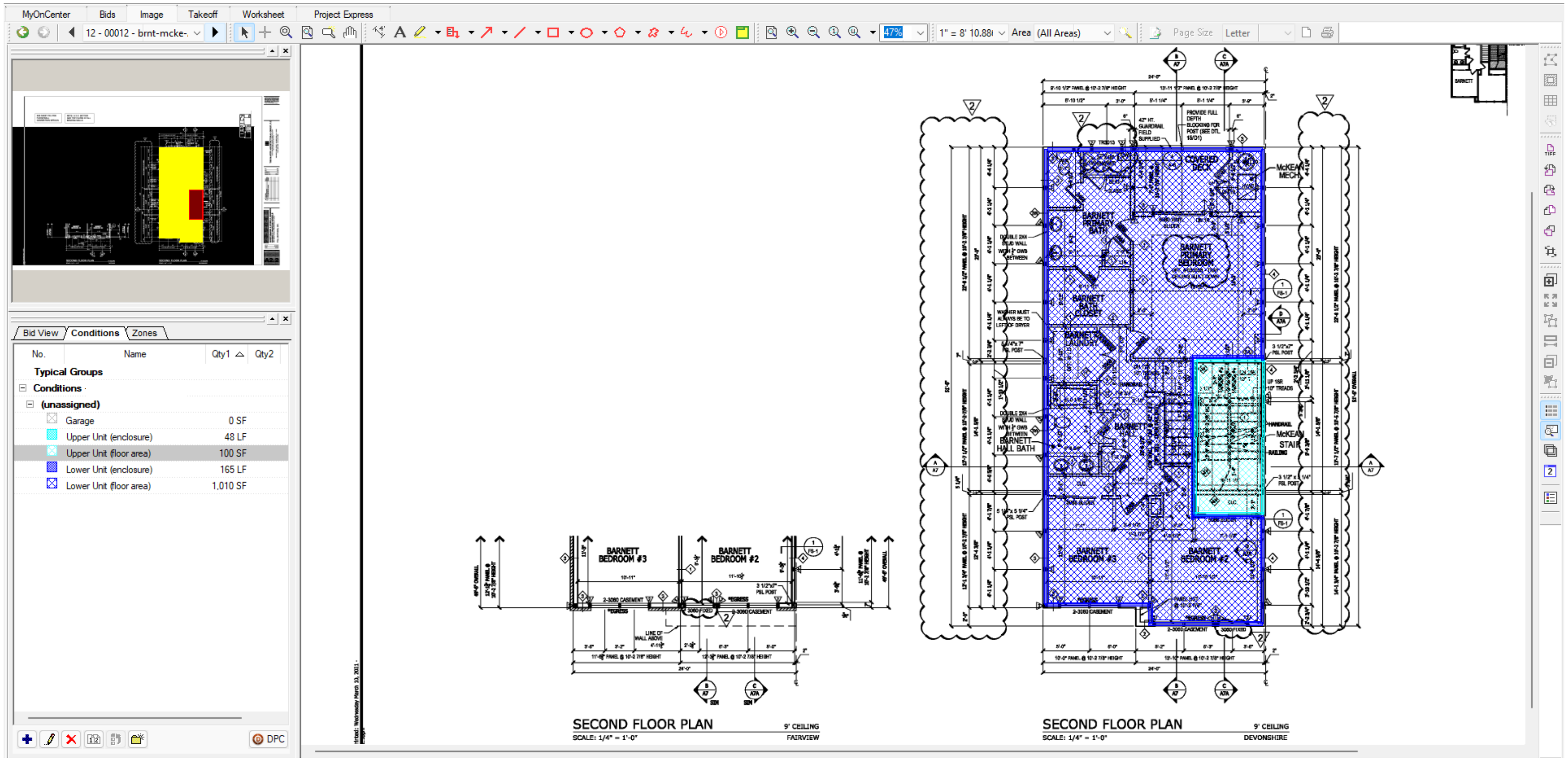

Figure 14. Site-built test unit floor plans, level 2 (project 3)

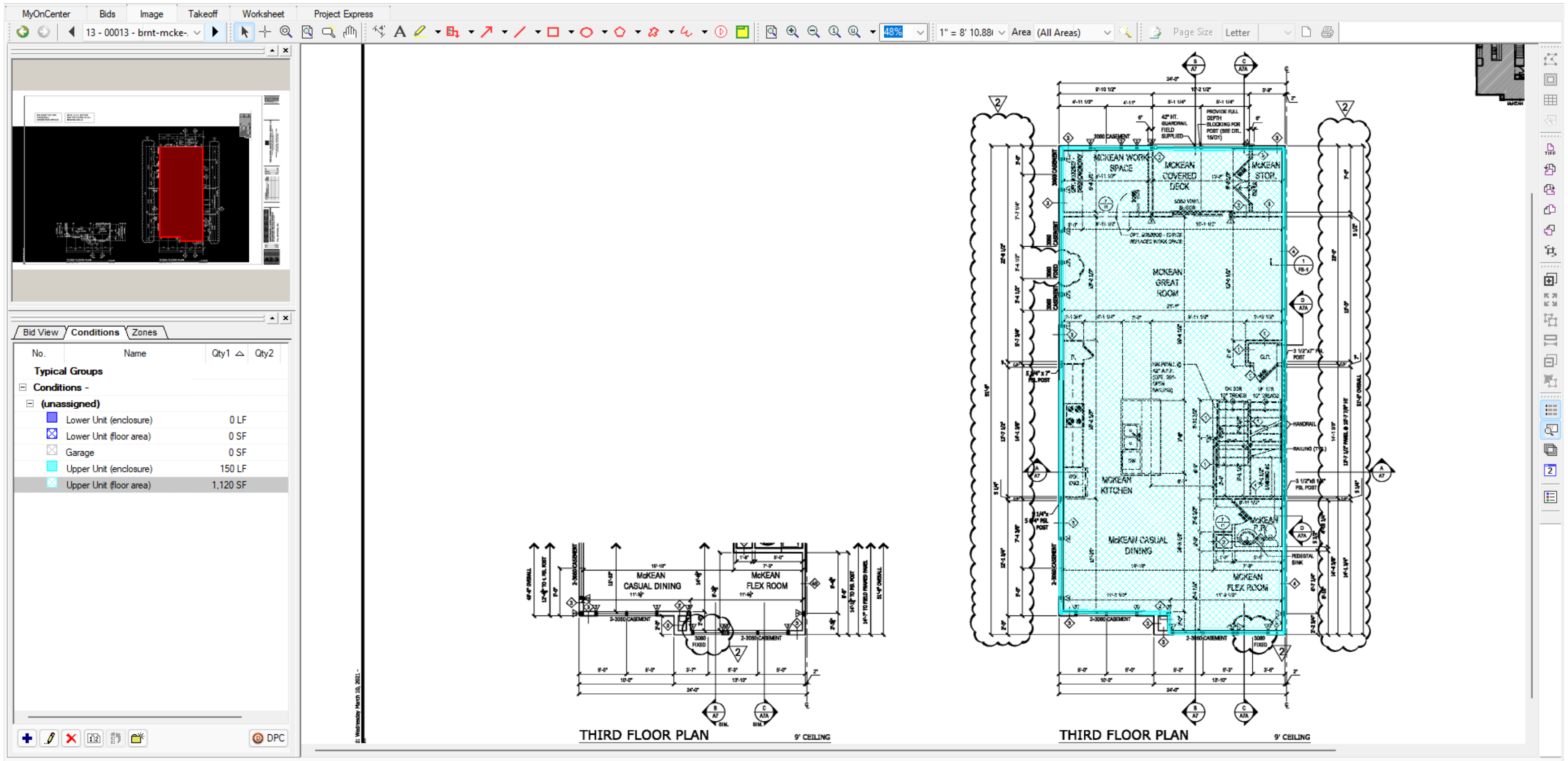

Figure 15. Site-built test unit floor plans, level 3 (project 3)

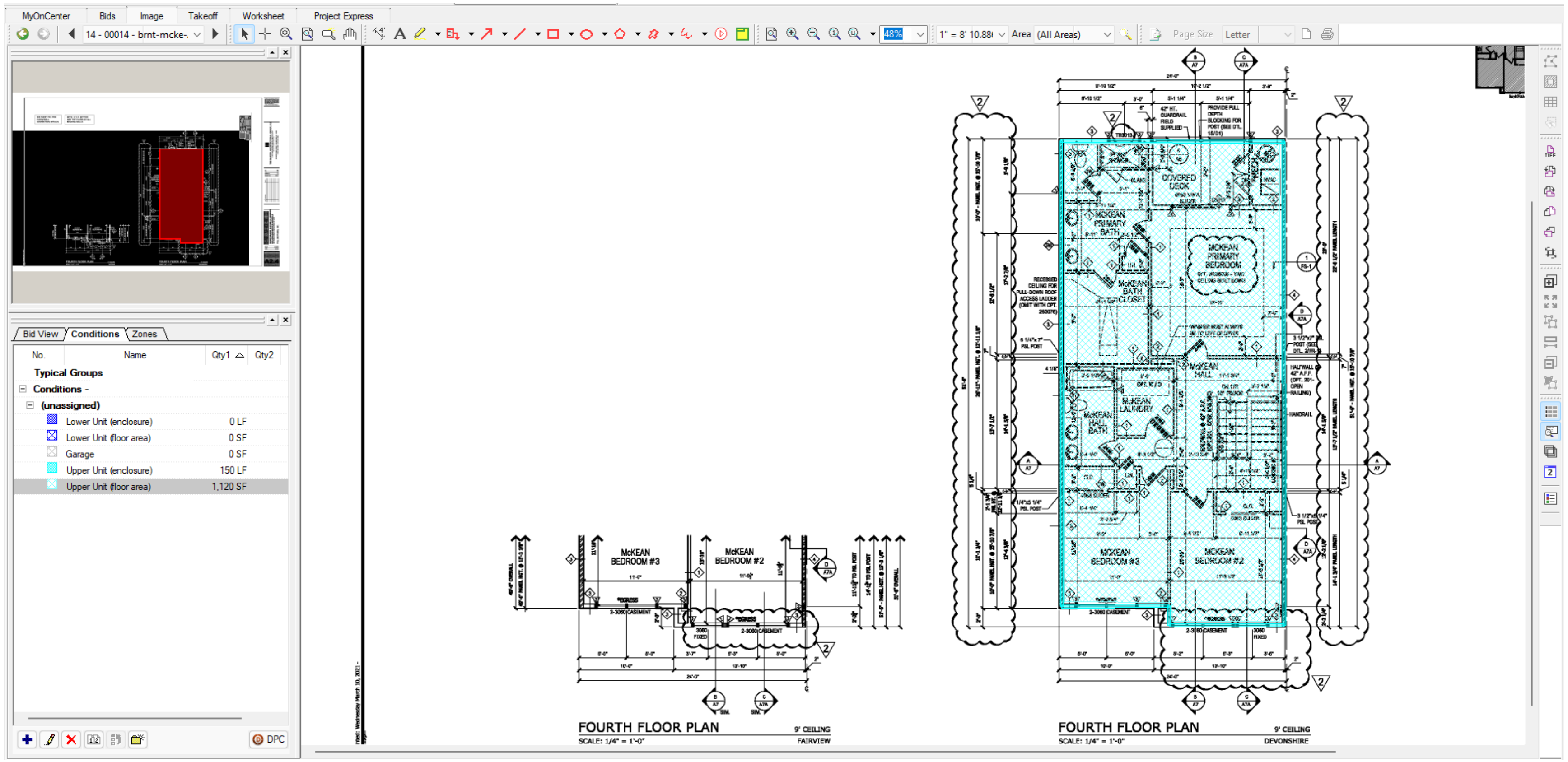

Figure 16. Site-built test unit floor plans, level 4 (project 3)

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