LEAKAGE REDUCTIONS FOR LARGE BUILDING AIR SEALING AND HVAC SYSTEM PRESSURE EFFECTS

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ABSTRACT

Building air leakage tests were conducted on six commercial and institutional buildings before and after air sealing work. The test protocol generally followed the requirements of ASTM E779, with additions to address the complexities of testing larger buildings. The buildings were one to three stories and were constructed between 1936 and 2007, with floor areas that ranged from 27,000 to 246,000 ft^2 (2,500 to 22,900 m^2). Before air sealing, the buildings were relatively tight with normalized air leakages that ranged from 0.15 to 0.31 cfm@75Pa/ft^2 (2.6 to 5.7 $m^3/h\cdot m^2$) using above grade envelope area and 0.09 to 0.19 cfm@75Pa/ft^2 including below grade walls and slab.

The air sealing focused on cost effective spray foam sealing of the wall/roof joints, with upgrades of exterior door weatherstripping a second priority. The sealing reduced air leakage from 6 to 18% with a median of 11%. For three of the buildings, the air sealing contractor generated the work scope and estimated the physical leakage area to be sealed. The contractor estimated air sealing was significantly greater than the measured values. The ratio of measured change in the EqLA to estimated sealed area ranged from 0.05 to 0.31.

There was a consistent and significant bias for higher leakage under pressurization than depressurization. The ratio of pressurization to depressurization tightness for the pre and post sealing measurements varied from 1.12 to 1.31 with a mean value of 1.22. Individual door tests indicated that doors with loose latches being pushed open during pressurization may have been responsible for about 17% of the increased leakage for pressurization at one of the schools.

The air tightness tests were conducted with exhaust fans, outdoor air inlets, and exhaust air outlets temporarily sealed. Single point tests were conducted after the seals were removed to compute mechanical system leakage. The normalized leakage ranged from 0.019 to 0.137 cfm@75Pa/ft^2 and increased the envelope leakage by 15% to 119%. This suggests that mechanical system air leakage can have a significant effect on building air leakage when the systems are off.

Air sealing contractors often estimate energy savings from monthly average wind pressure or wind and stack pressure models that do not include heating, ventilation, and air conditioning (HVAC) effects. Long-term building pressure monitoring indicated that HVAC operation positively pressurized many of the buildings. For one of the buildings the pressure at roof level was typically above +40Pa when the outside temperature was lower than 40F. In those situations ignoring the HVAC pressure effect results in high estimates of air infiltration and air sealing energy savings. However, there were also times when the HVAC system caused depressurization and in those situations infiltration and air sealing savings would be underestimated.

KEYWORDS
Airtightness, infiltration, commercial buildings, mechanical system leakage, HVAC pressure effect.

1. INTRODUCTION

Building architects, engineers, contractors, and facility managers tend to think of large buildings as fairly airtight and assume that envelope air leakage does not typically have a significant impact on energy use in commercial and institutional (C&I) buildings (Persily, 1988). Emmerich (2005) conducted modelling that contradicts that conventional wisdom, estimating that infiltration accounts for 33% of total heating energy use in U.S. office buildings.

Several states, including Minnesota, have recently incorporated air barrier requirements into their energy codes for new C&I buildings. In addition, the US Army Corps of Engineers (USACE) has established a performance airtightness requirement for new buildings and major retrofits of 0.25 cfm/ft^2 (1.25 $L/s \cdot m^2$) of total enclosure surface area at a pressure of 75 Pascals (USACE, 2010); and other codes or organizations have adopted a standard of 0.4 cfm/ft^2 (2.0 $L/s \cdot m^2$). However, the building stock that existed prior to this increased emphasis on envelope tightness contributes much more to overall energy use than do buildings built since these changes, and will continue to for many years, as the C&I building stock turns over slowly. Reducing air leakage energy use in existing buildings requires effective screening tools to identify buildings with a higher probability of having treatable leaks; investigation methods to identify key envelope air leakage deficiencies and/or mechanical system pressure issues; and reliable procedures to estimate cost and savings.

This project was initiated to develop and test envelope air leakage screening protocols, investigation protocols, measure the change in building leakage due to air sealing, model the effect of leakage reduction on space conditioning loads, and generate cost and savings estimation procedures. Project staff conducted air leakage investigations on 25 existing C&I buildings, including whole building air leakage tests before and after air sealing on six of those buildings. They also recorded continuous building indoor to outdoor pressure and merged it with automation system trend data to evaluate the effect of the heating, ventilation, and air conditioning (HVAC) system on building pressure. Those results are being used to develop CONTAM models (Walton, 2013) that include HVAC pressure effects. This paper presents the results of the air leakage tests and continuous pressure monitoring.

2. METHODOLOGY

The building air tightness tests generally followed the requirements of ASTM E779-10 (2010), with additions to address the complexities of testing larger buildings. The key additions to or clarifications of the test protocol are outlined below:

- **In/outdoor pressure sensors**. The average of four ground level in/outdoor pressure measurements placed on different sides of the building was used to indicate the building indoor with respect to outdoor pressure difference.
- **Baseline pressures**. Building baseline pressures were measured for at least five minutes before and after both the pressurization and depressurization tests.
- **Test pressures**. Multiple, calibrated fans were used to vary the baseline adjusted building in/outdoor pressure at 5Pa increments from approximately 15 to 75Pa. Measurements were conducted at 13 to 16 pressure levels for 60 seconds at each level.
- **Mechanical systems**. All mechanical dampers were closed and the dampers or terminations of the outside air ducts, exhaust air ducts, and exhaust fans were temporarily sealed. After the depressurization test was completed, the temporary seals were removed sequentially from the mechanical equipment while the test fans were

used to depressurize the building to a baseline adjusted pressure of approximately -75Pa. One minute of measurements were recorded at each stage of the unsealing. The measured fan flow rate and building pressure were used with the depressurization test baseline and flow exponent to compute a total building leakage for a reference pressure of 75Pa. The “envelope only” building leakage was subtracted from that value to determine the additional leakage due to the mechanical systems.

Project staff used commercially available software to record building pressure differences, record fan flow rates, control test fan speeds, graphically display the measurements, and compute air leakage values. They improved data quality by using distributed gauges to minimize tube lengths and real-time regression analysis to identify erroneous measurements.

Experienced staff or consultants conducted the building air leakage investigations with a combination of an exterior infrared (IR) survey and interior leak investigation with smoke visualization. They used the building’s HVAC system or temporary fans to pressurize the buildings for the exterior surveys (ASTM E1186-03, 2009); and conducted the investigations with a minimum inside to outside temperature difference of 18F, with no direct solar radiation on the surfaces for four to six hours prior to the survey. The results of the IR survey and experience of typical leakage sites helped guide a visual envelope leakage investigation. From the building interior a smoke puffer was used to release chemical smoke near suspected leakage sites. The velocity and volume of smoke movement indicated the relative magnitude of air leakage. The investigations typically focused on wall/roof intersections, roof elevation changes, exterior doors, mechanical system penetrations, and windows. The final step in the process was to determine code compliant methods for sealing the major envelope air leaks. Staff consulted building wall and roof air barrier details when available; and only considered sealing that required limited or no removal of building materials.

Air sealing contractors often estimate energy savings from monthly average wind pressure or wind and stack pressure models. The models do not typically include the effects of mechanical system operation on the building pressure. Pressure monitors were installed at the buildings to record one minute averages of building inside with respect to outside pressure differences at one to three interior locations. The tubes for the outdoor pressure reference exited the buildings at either the roof or ground level depending on accessibility. The monitoring periods lasted 50 to 200 days. The pressure data was converted to 15 minute averages and merged with local weather station outdoor temperature, wind speed, and wind direction data. Building automation system trend data was used to identify occupied and unoccupied operation modes. The data has been analyzed to evaluate the effect of HVAC operation on the variation in building pressure with outside temperature.

The next phase of the project is developing CONTAM models (Walton, 2013) using the building air leakage test data to establish the sum of the envelope and mechanical system leakage. The unoccupied mode data will determine the building’s neutral level to assist with assigning the vertical distribution of CONTAM envelope air leakage. Finally, analysis of the occupied mode pressure and HVAC trend data will establish the variation with outside temperature in building pressure induced by the HVAC supply and exhaust system flow rates.

3. RESULTS AND DISCUSSION

3.1. Pre-Sealing Building Tightness

The project conducted air sealing and leakage tests on two elementary schools, a middle school, a university library, a combination community library/office, and a small office building. The building IDs shown in Table 1 indicate the building type. The buildings were one to three stories tall built from 1936 to 2007, with floor areas ranging from 26,927 to 246,365 ft^2 (about 2,500 to 22,900 m^2). The pre-sealing building air tightness normalized by the above grade envelope area (i.e. five sides) ranged from 0.15 to 0.31 cfm/ft^2 (2.6 to 5.7 m^3/h·m^2) and 0.09 to 0.19 cfm/ft^2 when normalized by the six sides area that includes below grade walls and slab (see Table 1). Both sets of values use a reference pressure of 75Pa.

Table 1: Building characteristics and pre-sealing air tightness

	Floor	Envelope Area (ft^2)		Air Leakage at 75Pa				#	Constr	
					5 Sides		6 Sides			
Building ID	Area (sf)	5 Sides[1]	6 Sides[2]	(cfm)	(cfm/ft^2)	(m^3/h·m^2)	(cfm/ft^2)	Stories	Year	Wall Type
Elem School TF	59,558	87,419	146,977	27,425	0.31	5.7	0.19	1	1951	Masonry & corrugated metal panel
Middle School	138,887	130,318	208,733	32,818	0.25	4.6	0.16	3	1936	Cast concrete w/CMU infill
Small Office	26,927	38,340	65,267	9,177	0.24	4.4	0.14	1	1998	EFIS tip up (3 walls) and CMU block
Univ Library	246,365	98,240	171,712	23,356	0.24	4.3	0.14	3	1967	Cast concrete w/CMU infill & brick ext
Elem School PS	60,968	84,798	145,766	17,602	0.21	3.8	0.12	1	1965	CMU w/brick exterior
Library/Office	55,407	84,558	139,965	12,321	0.15	2.6	0.09	1	2007	Steel studs & brick or stone cladding
Minimum	26,927	38,340	65,267	9,177	0.15	2.6	0.09			
Mean	98,019	87,279	146,403	20,450	0.23	4.2	0.14			
Median	60,263	86,108	146,371	20,479	0.24	4.3	0.14			
Maximum	246,365	130,318	208,733	32,818	0.31	5.7	0.19			

1 – above grade surface area
2 – includes below grade exterior walls and slab

The buildings were much tighter than expected, even though many of the buildings were older and none were required to meet a tightness standard at the time of construction. The average normalized tightness of 0.23 cfm/ft^2 (4.2 m^3/h·m^2) was 83% less than the average value of 1.38 cfm/ft^2 reported by Emmerich (2011) for a convenience sample of 227 U.S. C&I buildings. The tightness of the leakiest of the six buildings was less than the 25th percentile of Emmerich's database and was 25% tighter than the USACE standard. It is possible that buildings in cold climates are tighter due to greater concern for cold drafts, frozen pipes, and higher space heating costs. A previous analysis by Emmerich (2005) suggested that buildings in colder climates are generally tighter than the U.S. average. The results for these six buildings are consistent with that trend, but a larger sample is necessary to properly determine the distribution of normalized leakage and the fraction of new buildings that would be impacted by a leakage standard or existing buildings that are likely to have cost effective air sealing opportunities.

3.2. Air Sealing Leakage Reduction

The air sealing focused on cost effective spray foam sealing of the wall/roof joints, with upgrades of exterior door weatherstripping a second priority, and mechanical system penetration sealing was completed at some of the buildings. An air sealing contractor conducted the initial investigations of the three school buildings. Project staff conducted follow-up investigations and the contractor adjusted the work scope based on staff feedback. The contractor's proposals included estimates of leakage area to be sealed and energy savings. For the three elementary and middle schools the contractor estimated that 81% of the sealing would be produced from wall/roof joint foam sealing and 15% from exterior door weatherstripping. Sealing estimates were not established for the other three buildings. For two of the buildings (*Univ. Library* and *Library/Office*) the work only included wall/roof sealing. The rooftop unit penetrations and CMU beam wall pockets near the roof were sealed for about a quarter of the *Small Office* building.

The air sealing of the three schools was completed at the bid price by the commercial contractor who specified the work. A different commercial contractor conducted the air sealing at the *Univ. Library* and *Small Office* sites on a time and materials basis. Project staff completed the limited sealing at the *Library/Office* building and costs were estimated based on the second contractors' time and materials rates. Post sealing IR scans and smoke puffer/visual investigations were completed to confirm that specified air leakage was sealed. All of the work was determined to be successful except some of the wall/roof sealing at the *Univ. Library* building which required additional exterior sealing that could not be completed prior to the post test scheduled date.

The measured change in building tightness was smaller than expected. The reduction in leakage at 75Pa (CFM75) ranged from 6% to 17% with a mean of 10% (see Table 2). The building with the highest normalized leakage had the greatest relative reduction in leakage and there was somewhat of a trend of greater reductions for the leakier buildings. In addition, the air sealing cost per CFM75 reduction increased for tighter buildings except for the *Library/Office* building where there was an isolated, significant wall/roof leak that was inexpensive to seal. The results suggest that it is possible to reduce the leakage of even tight buildings. However, the sealing potential is better for leakier buildings unless concentrated leaks can be identified that are inexpensive to seal. Since few U.S. air sealing contractors conduct air leakage tests, they must rely on smoke puffer/visual leakage investigations to identify cost effective air sealing opportunities.

Table 2: Envelope air sealing results

	Air Leakage at 75Pa				Leakage Area							Sealed Area (sf)		
	(cfm)		Reduction		EqLA (ft^2)		Reduction		Air Sealing Cost			Contractor Estimated		
Building ID	Pre	Post	(cfm)	(%)	Pre	Post	(ft^2)	(%)	Total	($/CFM75)	($/$ft^2$)	Roof/Wall	Total	Meas/Est
Elem School TF	27,425	22,699	4,726	17%	15.2	12.5	2.7	18%	$ 18,550	$ 3.92	$ 6,822	8.84	11.49	0.31
Middle School	32,818	28,872	3,947	12%	16.6	13.8	2.8	17%	$ 23,700	$ 6.00	$ 8,434	11.73	14.98	0.24
Small Office	9,177	8,470	708	8%	4.6	4.1	0.5	10%	$ 4,768	$ 6.73	$ 10,058			
Univ Library	23,356	21,963	1,392	6%	13.1	12.8	0.2	2%	$ 15,918	$ 11.43	$ 65,159			
Elem School PS	17,602	15,837	1,765	10%	9.6	8.9	0.7	7%	$ 26,700	$ 15.13	$ 38,132	14.45	16.94	0.05
Library/Office	12,321	11,369	953	8%	6.9	6.0	0.9	13%	$ 1,152	$ 1.21	$ 1,297			
Minimum	9,177	8,470	708	6%	4.6	4.1	0.2	2%	$ 1,152	$ 1.21	$ 1,297			
Mean	20,450	18,201	2,249	10%	11.0	9.7	1.3	11%	$ 15,131	$ 7.41	$ 21,650			
Median	20,479	18,900	1,579	9%	11.3	10.7	0.8	12%	$ 17,234	$ 6.37	$ 9,246			
Maximum	32,818	28,872	4,726	17%	16.6	13.8	2.8	18%	$ 26,700	$ 15.13	$ 65,159			

1 – at 10 Pa reference pressure for orifice with a discharge coefficient of 0.61
All leakage values are average of pressurization and depressurization tests

The contractor estimated air sealing was significantly greater than the measured values. The actual leakage sealed was estimated from the difference in the pre to post equivalent leakage area (EqLA). The ratio of measured change in the EqLA to estimated sealed area was 0.24 and 0.31 for the two leakier buildings, but only 0.05 for the second to tightest building. For that building the contractor estimated area to be sealed was <u>greater than the total leakage</u>. Since the post sealing inspections showed little or no leakage at the areas sealed, it appears that the reason for the high sealed area estimates was an inability to properly estimate physical leakage areas and not poor air sealing techniques. While judging the velocity of smoke movement into a gap and the size of the gap used to estimate the size of leaks, that method is only qualitative. The width of a visible gap at a joint will overestimate the equivalent width of the air leakage path when there are greater restrictions downstream in the path. For example, the visible leak area for the gaps sealed at the *Library/Office* building was 3.3 ft^2 but the measured change in the EqLA was 0.9 ft^2 when the area was sealed. Finally, while it is possible to use this method to estimate the flow rate of air moving into a leak, the pressure across the leak would need to be known to accurately quantify the equivalent leakage area. This limited sample suggests that further work is required to develop methods to more accurately determine physical leakage area.

3.3. Pressurization and Depressurization Comparison

There was a consistent and significant bias for higher leakage under pressurization than depressurization. The ratio of pressurization to depressurization tightness for the pre and post sealing measurements for the six buildings varied from 1.12 to 1.31 with a mean value of 1.22 (see top row of Figure 1). This indicates that there are portions of the building envelope that are significantly leakier under pressurization than depressurization. This could be due to membranes that are pulled tight to a surface under depressurization or other “flapper” situations. Project staff noticed that the school buildings had a number of loose door latches that allowed the doors to push open during higher pressures of the pressurization test (typically above 25Pa). Pressurization and depressurization tests were conducted on 17 doors at three of the school buildings. Figure 2 displays the results for one of the doors with “loose latch” movement. For 65% of the 17 doors, the pressurization CFM75 was over 40% greater than that for depressurization, and the average leakage difference was 18 CFM75. If that average difference is applied to the 26 exterior doors for *Elem School TF*, the leakage difference of 458 CFM75 would equal 17% of the 2,667 CFM75 higher leakage under pressurization for the entire building. The door movement due to loose latches provides one example of additional pressurization leakage. It is expected that there are several additional situations that are not as easy to observe or quantify. This raises the issue of whether a single test or an average best represents the building leakage under typical operation, and which should be used for building tightness compliance standards.

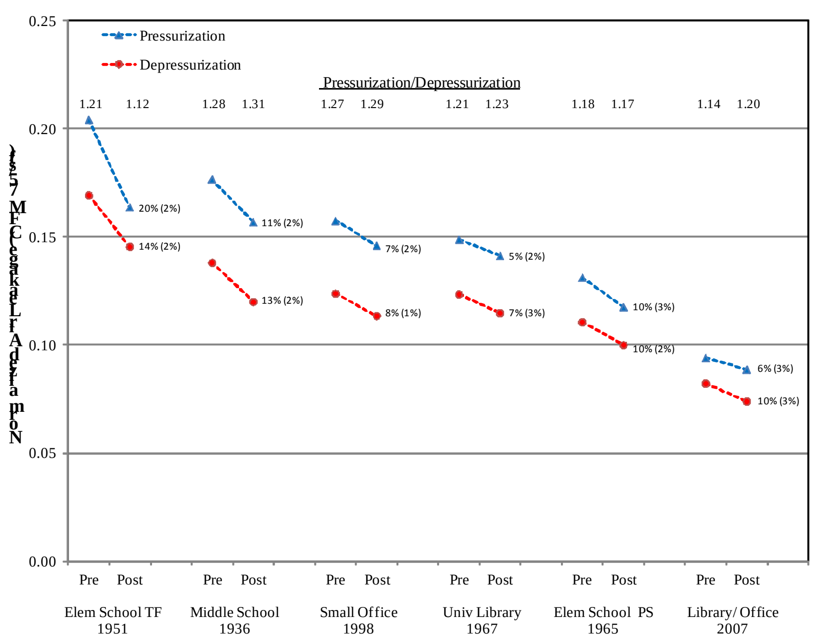

Figure 1: Building normalized envelope leakage pre and post air sealing

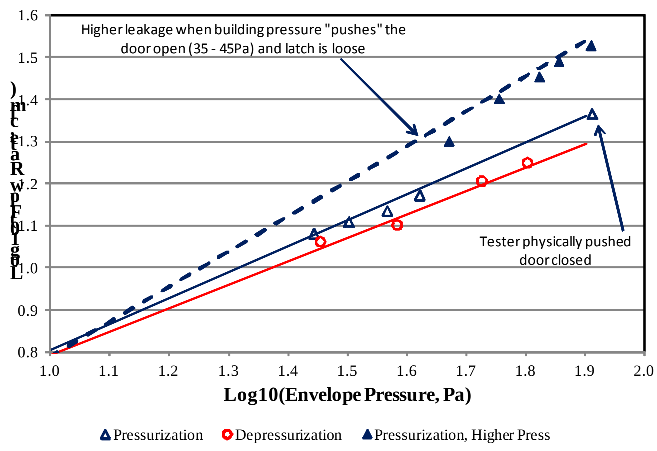

Figure 2: Pressurization and depressurization leakage tests on a door with a loose latch

The difference in the pressurization and depressurization tightness also presents a concern for evaluating the effect of air sealing. Figure 1 displays the pre and post pressurization and depressurization normalized leakage. The percent change is shown to the right of the post measurement and the 95th confidence interval uncertainty is included in parenthesis. For five of the six buildings, the difference between percent change in tightness computed from the pressurization and depressurization tests is less than the sum of the uncertainties. This indicates that each test method provides similar relative changes in tightness, so either could be used to evaluate the effect of air sealing.

There was often a significant difference in the pressurization and depressurization power law equation exponent. Figure 3 displays the exponents from the pre and post tests with the error bars representing the 95th percentile confidence intervals. The pressurization exponent was greater than that for depressurization for 10 of the 12 tests, and for 7 of those the difference was greater than the sum of the uncertainties.

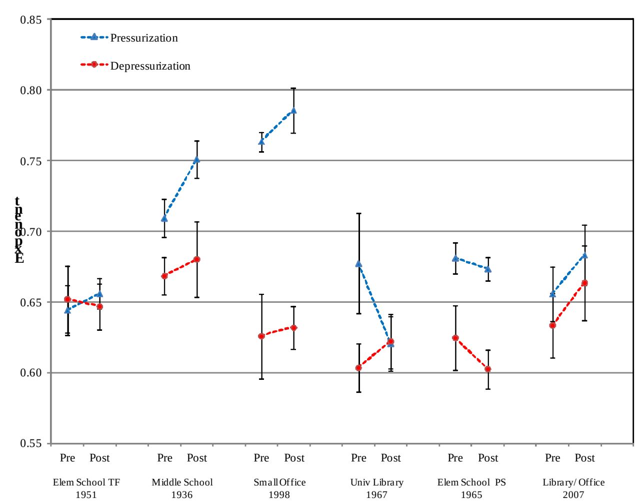

Figure 3: Power law flow equation exponent pre and post air sealing

3.4. Mechanical System Leakage

When the mechanical systems are operating and the outside/exhaust air dampers are opened to regulate air flow, the damper leakage is typically not a concern. However, when the systems are off, the dampers become part of the building's air barrier and damper leakage causes additional building air infiltration or exfiltration. Damper leakage poses a greater concern for buildings with a higher fraction of time when the mechanical systems are off.

The mechanical system leakage varied from 1,618 to 23,516 CFM75 and the six sides normalized leakage varied from 0.019 to 0.137 cfm/ft^2 with a mean of 0.047 cfm/ft^2 (see Figure 4). For three of the buildings, the mechanical system leakage increased the total building leakage by over 50%. These three buildings were constructed in 1967 or earlier, while two buildings built more recently (1998 and 2007) had relatively low mechanical system leakage. This suggests that improving damper tightness offers a significant energy efficiency opportunity to existing buildings and should be a consideration for new construction. Further work is required to assess the methods, cost, and tightness improvements of damper retrofits.

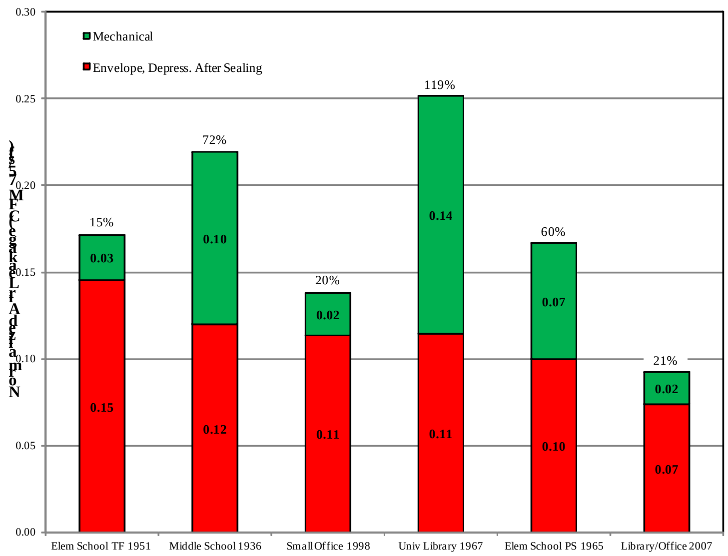

Figure 4: Building normalized envelope and mechanical system leakage

3.5. Mechanical System Building Pressure Effect

This project sorted the 15 minute building pressure and weather data into occupied/unoccupied or day/night modes of operation. Figure 5 scatter and box & whisker plots display the relationship of building pressure with outside temperature for three of the buildings. The *Elem School TF* building has three air handling units, six rooftop units, and six fan coil units for the original portion of the building and the four additions. Some units have outside air and some use an economizer operation. None of the units or exhaust fans operates at night and there is no active building pressure control. The system relies on a pre-determined balance of outside and exhaust air to maintain the building design pressure. Except for one hour morning and evening transition periods, the HVAC operation produced a positive building pressure at the roof monitoring position and the majority of the building exterior was under positive pressure during the occupied mode. The second row of plots for the *Univ. Library* shows a more extreme example of building pressurization. For milder weather the pressure at the roof typically varies from +10 to +30Pa during daytime operation, but when the outside temperature is lower than 40F the building pressure is consistently above 40Pa. None of the four air handlers has active building pressure control. I insufficient or malfunctioning exhaust capacity that produces high positive building pressures and often causes entry doors to blow open. For both buildings, ignoring the effect of HVAC operation on building pressure would produce overestimates of air infiltration loads and of energy savings due to envelope air sealing.

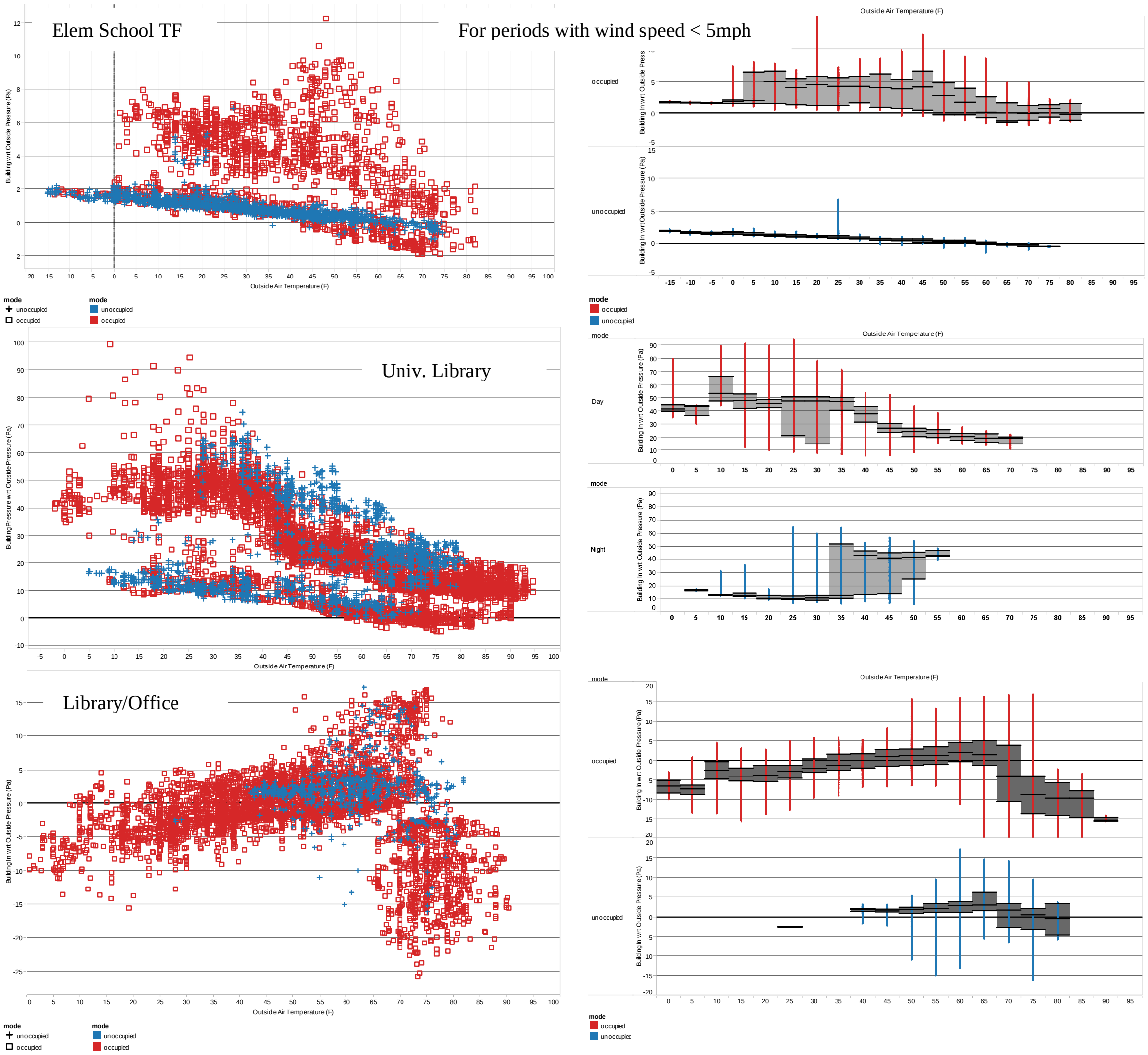

Figure 5: Occupied and unoccupied mode building pressure with outside temperature

The third building (Library/Office) has active building pressure control, but the pressure sensor for one of the air handlers was malfunctioning. The building did not often achieve its pressure set point of +10Pa and typically only maintained a positive building pressure at outside temperatures of 40F to 70F. The remainder of the time the building was depressurized, with significant depressurization in warmer weather. For this situation ignoring the HVAC pressure effect would result in underestimates of air infiltration and air sealing savings.

4. CONCLUSIONS

The buildings were much tighter than the U.S. average reported by previous studies, even though many of the buildings were built before 1970 and none was required to meet a tightness standard at its time of construction. Previous studies have suggested that buildings in colder climates are tighter, so these buildings follow that trend. Our air sealing results indicate that it is possible to reduce the leakage of already tight buildings. However, the sealing potential is better for leakier buildings, unless investigators can identify concentrated leaks that are inexpensive to seal. The contractor estimates of physical leakage area that would be sealed were less than a third of the measured reduction in leakage area. IR scans and smoke puffer investigations confirmed that the specified leaks were successfully sealed, which suggests that it is necessary to improve methods for estimating leakage area.

The type of test and mechanical system leakage has a significant effect on building tightness results that must be considered for tightness performance standards. The leakage for pressurization tests was an average of 22% greater than that for depressurization. It is unclear which test is a more valid indicator of leakage under typical conditions. HVAC systems are often designed to positively pressurize buildings, but one of the leakage paths (*i.e.* loose door latches) only occurred at pressures above 25 to 35Pa. For half of the buildings, including the mechanical system leakage increased the total building leakage by over 50%. Since the mechanical system is part of the envelope when it is not operating, that leakage can significantly impact air infiltration, and leakage reduction presents an opportunity for energy savings.

For many of the buildings, ignoring the effect of HVAC operation on building pressure would produce overestimates of air infiltration loads and high predictions of energy savings due to envelope air sealing. However, in some instances HVAC depressurization caused increased infiltration that would result in underestimates of infiltration and air sealing savings.

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