Individual unit and guard-zone air tightness tests of apartment buildings

Angela Rohr DipArch BArch(Hons)[1], Dipl.-Phys. Andreas Kaschuba-Holtgrave[2],
Dipl. Ing. Stefanie Rolfsmeier[3], Dipl. Ing. (FH) Oliver Solcher[4]

1 JADE Hochschule Oldenburg,
Institute for Sustainable Architecture and Environmental Planning INAU,
Ofener Straße 16/19,
D-26121 Oldenburg, Germany
angela.rohr@jade-hs.de
Presenting and corresponding author

2 Energieberatung Holtgrave,
Senator-Wagner-Weg 4,
D-49088 Osnabrück, Germany

3 Ingenieurgemeinschaft Bau + Energie + Umwelt GmbH,
Zum Energie- und Umweltzentrum 1,
D-31832 Springe-Eldagsen, Germany

4 Fachverband Luftdichtheit im Bauwesen e. V. – FLiB,
Storkower Straße 158,
D-10407 Berlin, Germany

ABSTRACT

The air tightness of eight apartment buildings containing six to eleven units each on three or four floors has been tested with and without guard-zone pressure, i.e. with and without consideration of internal leakages. The layouts of these buildings varied: two of them had no central stairwell, in two other buildings, only some of the apartments were connected to the central stairwell, and the third type had all apartments connected to a central stairwell. During these tests, two to eight BlowerDoor systems were used simultaneously to create guard-zone pressure conditions.
In this report, the authors evaluate the test results of three buildings of different layout types.

Furthermore, a reference model for the specific air permeability of all construction materials used in the interior and exterior envelopes of each apartment was created for two buildings in accordance with the German Industrial Standards (DIN). We present the results of this assessment and put them in context with the results of the airtightness tests with and without guard-zone pressure.

The results indicate that the air leakage contribution of internal partitions is significant, namely **32%** and **27%** respectively. As this affects sound transmission, fire protection, odor transfer and the quality of ventilation, it is essential not only to assess the airtightness of the exterior, but also of the interior envelope of each apartment.

KEYWORDS

Air tightness
Guard-zone testing
Apartment buildings
Internal leakages

1 INTRODUCTION

The ventilation of a building occurs through windows and other intended penetrations of the building envelope providing fresh air to the users of the building. In contrast to intended ventilation, the air tightness of a building defines the infiltration and exfiltration rate of a building, i.e. the exchange of inside and outside air through leakages in the building envelope.

Air leakage of the assembly (subsystem) such as wall, window or interface between wall and window or penetrations is of course unintended and should be minimized for energy efficiency, draught exclusion and to avoid convective moisture in construction components. Furthermore, air will permeate through many of the materials used in exterior or interior partitions as a specific characteristic of the materials on a much smaller scale than leakage air flows.

Since 1995, the airtightness of buildings can be checked in practice against the limit values of the Thermal Insulation Regulation (WSVO, 1994) in the Federal Republic of Germany. During the past 20 years, many mostly smaller buildings (single-family houses) were tested. The limits of the 95 WSVO and stricter requirements, for example as established in Switzerland or for certified passive houses in Europe, are feasible. They can even be undercut significantly. A design for airtightness, determining the location of the air barrier and considering the materials and connections, facilitates practical implementation on site.

So far, the measuring principle and the assessment of leakages in large apartment buildings and in single-family houses is much alike. Operating time, equipment, and organization is more intensive for large buildings, while the testing period is frequently more constricted due to tighter deadlines. Many leakages in large buildings are of the same type as in single-family houses. However, new types of leakages occur in apartment buildings, such as elevator ventilation, internal leakages between individual units, installation ducts, individual penetrations for electrical lines, and centralized or compartmentalized ventilation ducts. Internal leakages connect one heated area to another or to unheated areas like stairwells, basements, or unheated attics.

Due to greater propelling forces or buoyancy in (multi-story) apartment blocks, leakages can potentially cause greater damage. Larger residential buildings are usually used more intensively and their humidity load is consequently higher. A larger share of leakages tends to accumulate in the roof area. When this occurs in apartments with a larger share of the building envelope or is even combined with increased risks on several accounts, good indoor-air hygiene and health conditions, the protection of occupants and the building from damages caused by excess humidity, and the performance of ventilation systems are at stake.

2 DEFINITIONS

2.1 “guard-zone pressure” and “compartmental testing”

Air tightness testing can be conducted in the whole building, in each single compartment/unit separately or with guard-zone pressure between one or several units of a building.

The whole building can be tested as a single zone, when all units within the building are interconnected, for example by a shared stairwell. Where this is not the case, all units can be tested simultaneously, using the same pressure.

In a **single unit compartmentalization test**, each single unit is tested separately with a blower door, whilst adjacent spaces are not under pressure.

Very large buildings can be divided in sections, with several fans installed in adjacent sections of the building to create identical air pressure conditions. All airflows are adjusted to diminish pressure differences between sections. In consequence, no airflow will pass between adjacent sections, so that only leakages on the external envelope are recorded. This technique, the so-called **guard-zone test**, is useful to measure only one part of a building that is retrofitted or when one wants to establish interior air leakages. However, a guard-zone test may not work, if internal leakages are too large.

The airflow rates of the guard-zone tests are deducted from those of the single unit compartmentalization tests to determine the proportion of internal leakages.

2.2 Definition of “large buildings” and their permeability limits

According to German Industrial Standard DIN 4108-7 (DIN 4108-7, 2011) and the Energy Savings Regulation 2014 (EnEV, 2013), “large buildings” have an internal volume of 1,500 m^3 or more. For large buildings, the enclosure air leakage or permeability q_{50} is specified additionally to the air change rate n_{50}. The legal limits for enclosure air permeability q_{50} for buildings without mechanical ventilation are $q_{50} \leq 4.5$ m^3/m^2h and $q_{50} \leq 2.5$ m^3/m^2h for buildings with ventilation systems. This applies when the building envelope is tested, following testing procedure B (according to DIN EN 13829 (DIN EN 13829, 2001) and in accordance with ENEV 2014).

When procedure A (according to DIN EN 13829 and in accordance with DIN 4108-7 (DIN 4108-7, 2011)) is employed, a building is tested under normal conditions of use. Then, the limit is $q_{50} \leq 3.0$ m^3/m^2h as a general requirement!

3 OBJECT AND TEST CONFIGURATION

3.1 The testing procedure

After compliance with legal standards was verified, the leakage flow and the distribution of leakages within the building and on the building envelope was analyzed in more detail. We wanted to confirm an accumulation of leakages in ground floor or top floor apartments, or units with a large share of the building envelope. To this end, the following tests were conducted:

- Air tightness test of the entire building as a single zone
- unguarded air tightness tests of all individual apartments
- “compartmentalization” test
- guard-zone tests of all individual apartments with analog pressure in all apartments / building zones

We aim to identify the proportion of internal leakages in overall leakages of the entire envelope of an apartment. How large is the impact of internal leakages?

3.2 Tested buildings to date

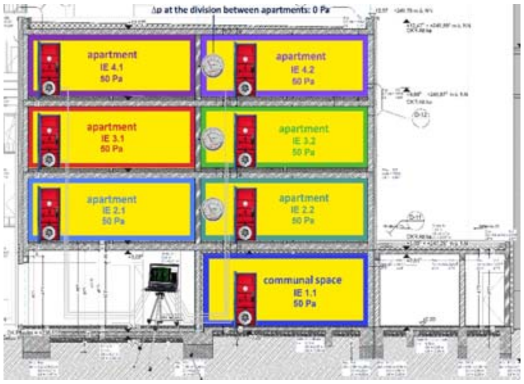
A total of eight apartment buildings have been tested unguarded and with guard-zone pressure.

4 apartment buildings with eleven units each in Osnabruck

In Osnabruck, four apartment blocks (**OA, OB, OC, OD**) with 11 apartments each and an internal volume of 2,360 to approx. 2,500 m^3 were tested. The buildings have central stairwells. Compartmentalization tests and guard-zone tests were performed in most of the units. In addition, the air tightness of the entire building as a single zone was tested.

Figure 1: Sectional view of apartment building OA in Osnabruck with a schematic view of a guard-zone test of a third floor apartment.

2 apartment buildings with six units each plus a communal space in Iserlohn



In Iserlohn, A free standing building (**IE**) and an annex to an existing music school building (**IF**) with internal volumes of 1,420 m³ / 1,175 m^3 were tested. Compartmentalization tests and guard-zone tests were performed in all units. In building **IE**, we also tested the communal space. The buildings have no internal stairwell. The apartments are accessed via galleries and a common outside staircase. In building **IF** (not shown in Fig. 6), all apartments except one are multistory.

Figure 2: Sectional view of apartment building **IE** with six apartments and a communal space in Iserlohn showing the test setup.

2 apartment buildings in Iserlohn with eleven units each

Furthermore, we tested the airtightness of apartment buildings **IG** and **IH** with eleven units and an internal volume of 2,880 m³ each. Both buildings have an internal stairwell, but only five, respectively four apartments have access to it. The ground floor apartments can be entered directly from outside, the second floor apartments are accessed via galleries. Compartmentalization tests and guard-zone tests were performed in all units.

Figure 3: Sectional view of apartment building **IH** with 11 apartments in Iserlohn showing the test setup.

Since only seven, respectively eight Blower Door Systems were available, four / five apartments with access to the stairwell were treated as one single section during guard-zone testing. The remaining six / seven apartments were each equipped with a Blower Door System. The guard-zone tests were repeated five / six times, so that a guard-zone test was performed in each apartment, including those with direct access to the stairwell.

Compliance with legal requirements

All buildings are equipped with central exhaust air systems and according to German Energy Savings Regulation (EnEV, 2013) consequently must meet the requirements: An air change rate n_{50} of 1.5 h^{-1} and an air permeability of the envelope area q_{50} of 2.5 m³/m²h. In all guarded tests of the complete buildings, all eight objects comply with requirements for the n_{50} air change rate and the q_{50} envelope-based air flow (air permeability at 50 Pa). In seven of the eight buildings, the weighted mean of all single unit compartmentalization tests also complies with the requirements. With **2.64 m³/m²h,** only the result for the q_{50} averaged from the external envelope of building **IE** exceeds the limit. The test results of individual unit compartmentalization tests in three out of four top-floor apartments at Borsigstraße in Osnabrück also exceed the limits. Their shed roofs have a timber construction.

4 RESULTS

4.1 Key results for the examined objects

Table 1: air volume, airflow, envelope area and airflow rates based on volume / envelope area with and without guard zone pressure in all tested buildings. The colored highlighting of the air change rates shows a qualitative assessment of the results.

Buildings	V	Envelope	V_{50} with guard-zone*	n_{50} with guard-zone	n_{50} compartmentalized	q_{50} with guard-zone	q_{50} compartmentalized
	[m³]	[m²]	[m³/h]	[h⁻¹]	[h⁻¹]	[m³/m²h]	[m³/m²h]
OA	2 400	960	1 514	n/a	0.63	n/a	1.58
OB	2 365	1 010	1 244	n/a	0.53	n/a	1.23
OC	2 385	1 060	1 205	n/a	0.51	n/a	1.14
OD	2 150	925	1 050	n/a	0.49	n/a	1.14
IE	1 420	750	1 299	0.92	1.40	1.73	2.64
IF	1 175	725	1 156	0.95	1.27	1.54	2.06
IG	2 880	1 440	2 168	0.75	1.10	1.50	2.19
IH	2 855	1 480	2 427	0.85	1.10	1.64	2.13

Color Coding	Appraisal of Result
0.41-0,5	Very good
0,51-0,6	Good
0,61-0,7	
0,71-0,8	
0,81-0,9	
0,91-1,0	
1,01-1,1	
1,11-1,2	
1,21-1,3	
1,31-1,4	
1,41-1,5	
1,51-x	Exceeding legal requirement for buildings with mechanical ventilation

The n_{50}-values shown under "with guard-zone" are the test results of the guard-zone tests, respectively referring to each entire building.

The n_{50}-values shown under "compartmentalized" are the weighted medium of all single unit compartmentalization tests conducted in all units of the building, including stairwells where they exist. The airflow rates of the guard-zone tests are deducted from those of the single unit compartmentalization tests to determine the proportion of internal leakages.

Proportion of interior leakage in the air leakage of the apartment / in the average enclosure air leakage

In buildings **IE, IF, IG** and **IH**, the **proportion of internal leakages** within the entire building comes to **22%** to **36%** respectively.

For buildings **OA, OB, OC** and **OD**, the **proportion of internal leakages** in all apartments totals between **26%** and **31%**. The stairwells were not tested individually.

4.2 Proof of internal leakages between apartments in building IH

Due to internal leakages, the test results for individual apartments mutually affect each other. This is particularly evident at building **IH**. The airflow rates measured in apartments atop each other are interdependent. Figure 4 depicts a pressure profile with the mutual reaction of apartments **IH 1.3** and **IH 3.3** during a depressurization test. We turned off Fan **IH 1.3** in a ground floor maisonette apartment just before 9 pm resulting in a much higher airflow rate in second floor apartment **IH 3.3** during depressurization. The shutdown of fan **IH 1.3** has no impact on the airflow rates in other apartments. Two minutes later, fan **IH 1.3** is started again, resulting in an inverse reaction of the airflow rate of fan **IH 3.3**, which settles eventually at approx. -8 Pa. The only other fan reacting to this change of pressure is Fan **IH 1.1** with a visible, but small amplitude (a deviation of up to 3 Pa). With less than 48 m² net floor area, apartment **IH 1.1** on the ground floor is the smallest unit in the building. Changes in the airflow rate have a much higher impact in this apartment than in others with a net floor area of more than 100 m².

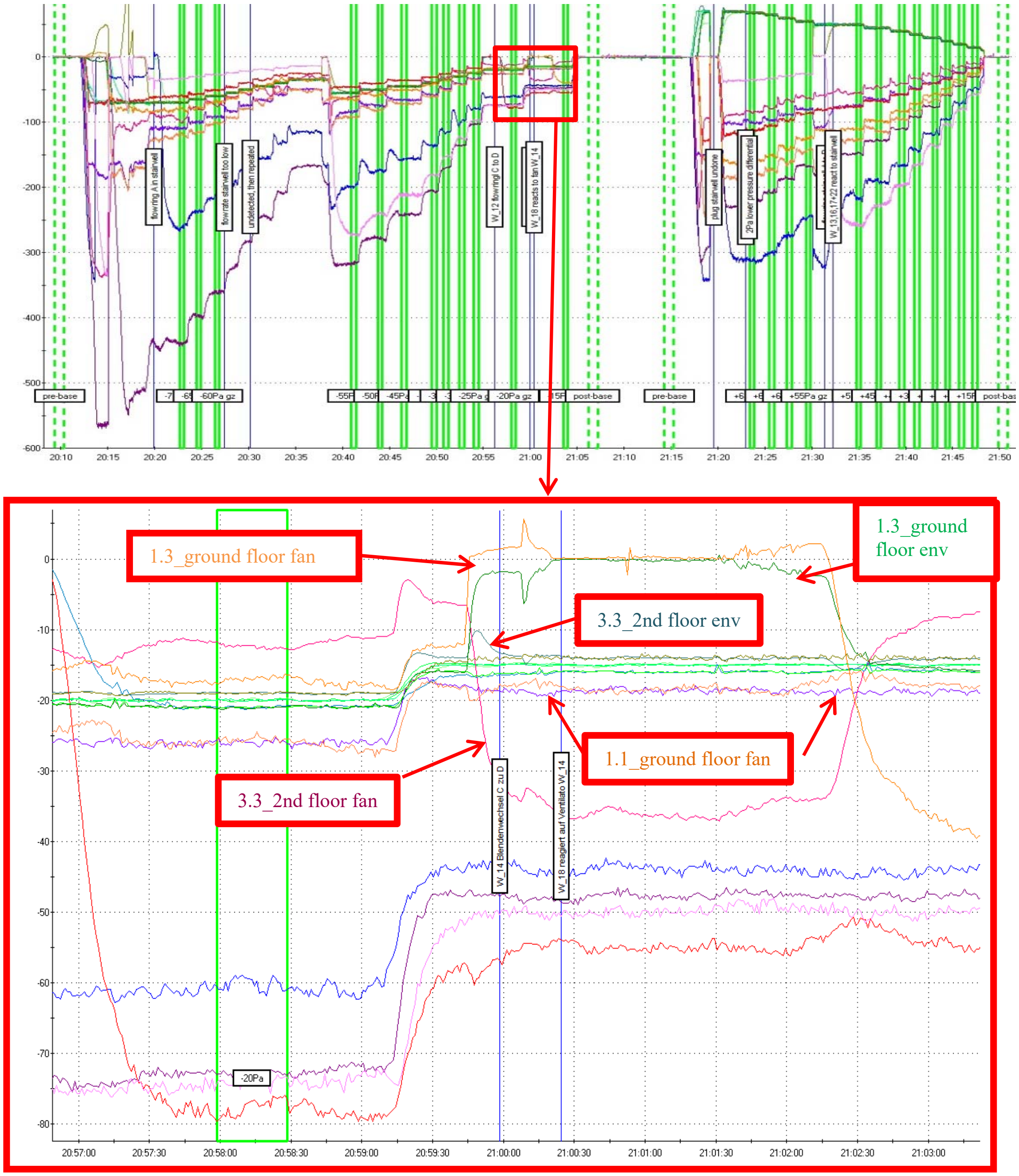


Figure 4: building **IH**: Airflow rates in apartment 1.3 and 3.3 at depressurization react to each other (see text above)

4.3 Location of internal leakages

At this point, we need to find a better way to determine, whether a leakage is internal or external. A duct running through the whole building may create significant leakage flow in all adjacent apartments but may not be covered by guard-zone pressure. This may adulterate the airflow of individual apartments, but will not show in the airflow rate of the whole building.

In the buildings we assessed, in general, top floor apartments tend to hold a higher proportion of air leakages than apartments on other floors, regardless of the construction. The difference to the other apartments becomes more apparent under guard-zone pressure. In some buildings, other apartments also held a high proportion of the leakage flow, sometimes with no apparent reason. In other cases, such as the communal space on the ground floor of building **IE**, high leakage flows were due to a large glass door element and the location adjacent to the plant room and some ventilation ducts servicing the entire building.

Figure 5: building **IH**: internal leakages were found in power distribution units, central water distribution units, pre-wall sanitary installation and internal partitions

Elevators in some buildings contribute significantly to the air leakage, depending on the construction of the elevator ventilation. The roof membrane in buildings **IG** and **IH** was laid out loosely over the opening, but was not sealed at the borders. Under pressurization, the roof membrane was lifted and a significantly higher amount of air escaped than under depressurization.

Buildings **OA, OB** and **OC** and **OD** are of the same type of construction. The flow rates improved in order of the test dates from **n_{50} = 0.63 h^{-1}** in building **OA** to **n_{50} = 0.51 h^{-1}** in building **OD.** The test results document the learning curve of the construction team.
In all four buildings in Osnabruck, the test results in the top floor apartments were significantly worse than on the other floors. The roofs are of timber construction.

Internal leakages in buildings **IG** and **IH** were caused especially by electric and air ducts and were more pronounced, although not exclusively between units situated atop each other than next to each other (stack or buoyancy effect). They also occurred in sanitary installations in pre-wall systems and in electric installations (even in internal walls within units). Services ducts contribute significantly to internal air leakages and can be connected to outside air via unheated basements or attics. Leaking air may be drawn from ducts into internal walls, electric fittings and below the floor screed. In buildings **IE** and **IF**, we found significant leakages in electric fuse boxes and in services connections to the plant room.

From the data gathered in buildings **IG** and **IH**, we could not deduce an obvious difference in internal leakages between units connected or not connected to the staircase.

5 AIR PERMEABILITY OF THE BUILDING ENVELOPE

A model to establish the air permeability of the building envelope was created for buildings **OD** and **IG**. As a working title, we refer to it as *Null Model*. The specific air permeability of all the components of the airtight layer, all window connection joints and the window gaskets was laid down based on legal threshold values for building components. The expected airflow rate disregarding leakages was calculated from those threshold values and the area or length of the respective building parts and connections.

The envelope areas of the apartments were divided up into exterior and interior surfaces. At 50 Pa, we determined an air permeability of **0.3** m³/m²h for the entire exterior envelope area of building **OD**, leaving aside the effect of leakages.
The window and front door connection joints and the window gaskets are responsible for the vast majority of the calculated airflow. Only about **9 %** of the airflow of building **OD** and **6 %** of building **IG**, are attributed to the air permeability of component surfaces. According to the requirements of German Industrial and European Standard DIN EN 12207 (DIN EN 12207, 2017), window class 4, a limit of **0.29** m³/mh was set for the air permeability of the opening joint of windows.
The interior boundary surfaces between apartments and the front doors were considered in the same way.
We intend to verify the air permeability values of the envelope areas via component measurements as the project progresses further.

5.1 *Null model* for building OD

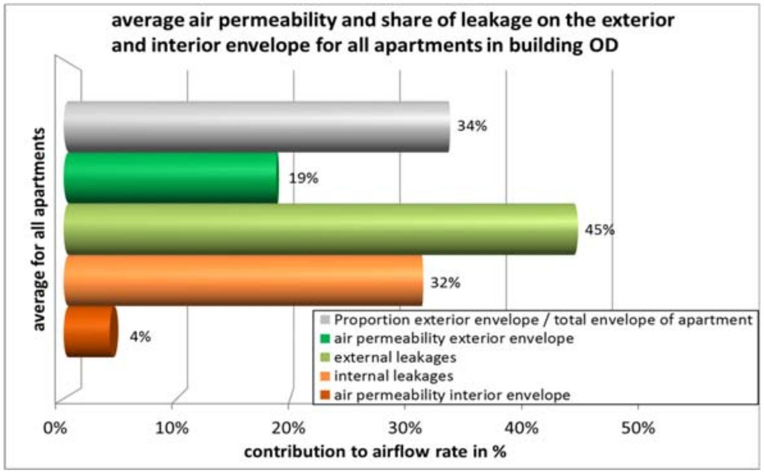


Figure 6: Contribution to the air permeability measured at building **OD**, weighted mean in relation to the envelope area of all apartments.

The air permeability of the envelope area was divided at the ratio of interior and exterior envelope proportions and was subtracted from the measured airflow rate. The share of the calculated air permeability of the interior and exterior envelope areas including window and door joints at building **OD** totals **19%** and at building **IG 17%**. The difference is conclusive due to the more complex building layout of building **IG**: there are less internal and some more external door connections due to the gallery access to some apartments.
In each apartment, a guard-zone test and a compartmentalized test were conducted. The airflow of the compartmentalization test minus the calculated air permeability of the total envelope area equals the leakage flow of the envelope area. The airflow rate of the guard-zone test equals the leakage flow of the exterior envelope area. It was deducted from the total leakage flow to arrive at the leakage flow of the interior envelope area.

In building **OD**, an average of **32% internal** and **45% external leakages** was determined. In building **IG**, the identified averages were **27% internal** and **54% external leakages**.
This shows that internal leakages contribute a significant proportion of the leakage flow. The area-based weighted mean share of window and door connections in the calculated air permeability of the envelope area of each apartment in building **OD** is **84%** and in building **IG 89%**. In proportion, the permeability of the envelope area has very little impact.

6 CONCLUSIONS

The aim of this research is to show the share of internal and external leakage flows in apartment buildings. Internal leakages occur between adjacent apartments or building parts of the same temperature. External leakage flows are airflows through leakages in the exterior envelope.

To better understand the distribution of internal and external leakages, to verify the air permeability specifications for the surfaces of building components and windows, and to facilitate further analysis of existing data, it is necessary to conduct component air permeability measurements. The issue of internal leakages must be analyzed further, because an envelope-based q_{50} as proposed in German Industrial and European Standard DIN EN 12831 (EN 12831, 2017) is not yet feasible. This analysis is to be evaluated in the context of the results of the FLiB research report *Evaluation of leakages in airtight layers* (Vogel, K., 2016).

The tests show that a large percentage share of the leakage flow, **26%** and **27%** respectively, stems from internal leakages. The leakage flow in the top-floor units was, on the whole, significantly higher than in the other apartments. We have also found that a large share of exterior envelope, e.g. in a ground floor apartment, does not necessarily result in an increased leakage flow.

Anybody conducting guard-zone tests, must take into account possible connections to ducts running through the entire building that may not be covered by guard-zone pressure, but also cause leakages, such as a services duct connecting an underground car park to all floors.

The air permeability of individual building components and joints is determined and discussed based on limit values from relevant standards. Different reference values are compared to get conclusive and comparable parameters for the evaluation of the airtightness of building components.

The results to date show that there is a considerable amount of internal leakages between apartments. The transfer of sound, fire, smoke, and odor does not only make further discussion of this topic useful, but imperative.

When conducting guard-zone tests unit by unit, the calculation of the envelope area of the respective unit according to European Industrial Standard DIN EN 13829 should be reconsidered. Outside air does not infiltrate through leakages in component surfaces adjacent to heated parts of a building. They are consequently of no importance for confirming compliance with legal requirements.

The research is as yet not completed. Meanwhile, an interim evaluation shows some distinctive aspects:

- The n_{50} characteristic airtightness values of apartments on the top floor / in the attic tend to be higher than in other apartments.
- q_{50}-values in apartments on the top floor are generally higher than in other apartments.
- Apartments with a large part of envelope area exposed to outside air do not necessarily show a higher air leakage flow.
- Besides the percentage of envelope area, the way building components are implemented also contributes to the leakage level.
- Leakage between units can be significant. In some cases, the difference between compartmentalized and guard-zone tests amounts to more than 100%.

A preliminary analysis of the collected data shows the following:

- The distribution of the leakage flows is not homogenous. Consequently, the airtightness of the building does not always match the airtightness of certain building sections.
- Elevators in some buildings contribute significantly to the air leakage, depending on their construction and especially on how the elevator ventilation is executed.
- Anybody conducting guard-zone tests, must take into account possible connections to ducts running through the entire building that may not be covered by guard-zone pressure, such as a services duct connecting an underground car park to all floors.

7 REFERENCES

(1994) Wärmeschutzverordnung (WärmeschutzVO). Verordnung über einen energiesparenden Wärmeschutz bei Gebäuden.
Thermal Protection Regulation. Regulation for Energy Saving Thermal Insulation for Buildings.

(2011) DIN 4108-7:2011-01 Wärmeschutz und Energie-Einsparung in Gebäuden – Teil 7: Luftdichtheit von Gebäuden – Anforderungen. Planungs- und Ausführungsempfehlungen sowie –beispiele.
German Industrial Standard DIN 4108-7:2011-01 Thermal insulation and energy economy in buildings – Part 7: Air tightness of buildings – Requirements, recommendations and examples for planning and performance.

(2013) Zweite Verordnung zur Änderung der Energieeinsparverordnung.
Second Regulation for the Alteration of the Energy Savings Regulation.

(2001) DIN EN 13829: 2001-02 Bestimmung der Luftdurchlässigkeit von Gebäuden – Differenzdruckverfahren.
European Industrial Testing Standard DIN EN 13829: 2001-02 Determination of air permeability of buildings – Fan pressurization method.

(2017) EN 12831-1:2017-07 Heizungsanlagen und wasserbasierte Kühlanlagen in Gebäuden - Verfahren zur Berechnung der Norm-Heizlast.
European Standard EN 12831-1:2017-07 Heating systems and water based cooling systems in buildings - Method for calculation of the design heat load.

(2017) DIN EN 12207:2017-03 Fenster und Türen – Luftdurchlässigkeit – Klassifizierung.
European Industrial Standard DIN EN 12207:2017-03 Windows and doors – Air Permeability – Classification.

(2013) FLiB Infoblatt „Messung im Bestand". *Fachverband Luftdichtheit im Bauwesen.*
FLiB information sheet „testing in existing buildings". *Professional association air tightness in the building trade.*

Vogel, K. Sous, S. Zöller, M. Grün, G. Norrefeldt, V. (2016) FLiB Forschungsbericht „Bewertung von Fehlstellen in Luftdichtheitsebenen". *Fachverband Luftdichtheit im Bauwesen.*
FLiB Research report „Evaluation of Flaws in Air Tightness Layers". *Professional association air tightness in the building trade.*

Kaschuba-Holtgrave, A. Rohr, A. Rolfsmeier, S. Solcher, O. (2015) Leckageströme im Mehrfamilienhaus – mit Schutzdruck detailliert messen, *BuildAir Symposium.*
Kaschuba-Holtgrave, A. Rohr, A. Rolfsmeier, S. Solcher, O. Air Leakage Flows in Multi-Story Family Buildings – Detailed Guard Zone Testing, *BuildAir Symposium.*