INTERNATIONAL ENERGY AGENCY
Energy conservation in buildings and
community systems programme

Technical Note AIVC 67

This publication was produced in close collaboration with TightVent Europe

Building airtightness: a critical review of testing, reporting and quality schemes in 10 countries

Air Infiltration and Ventilation Centre
Operating Agent and Management
INIVE EEIG
Lozenberg 7

INTERNATIONAL ENERGY AGENCY
Energy Conservation in Buildings and
Community Systems Programme

Technical Note AIVC 67

Building airtightness: a critical review of testing, reporting and quality schemes in 10 countries

François Rémi Carrié and Peter Wouters

September 2012

Disclaimer

The AIVC has compiled this publication with care. However, the AIVC does not warrant that the information in this publication is free of errors. No responsibility or liability can be accepted for any claims arising through the use of the information contained within this publication. The reader assumes the entire risk of the use of any information in this publication.

Author information

François Rémi Carrié and Peter Wouters

INIVE EEIG
Lozenberg 7
BE 1932 Sint-Stevens-Woluwe, Belgium

First published September 2012
AIVC document AIC-TN67
ISBN: 2-930471-35-2
EAN: 9782930471358

This publication is part of the work of the IEA's Energy Conservation in Buildings & Community Systems Programme (ECBCS), Annex 5: *'Air Infiltration and Ventilation Centre'* (AIVC).

International Energy Agency (IEA)

The IEA was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an International Energy Programme. A basic aim of the IEA is to foster co-operation among the twenty-four IEA Participating Countries to increase energy security through energy conservation, development of alternative energy sources and energy research development and demonstration (RD&D).

Energy Conservation in Buildings and Community Systems (ECBCS)

The IEA sponsors research and development in a number of areas related to energy. In one of these areas, energy conservation in buildings, the IEA is sponsoring various exercises to predict more accurately the energy use in buildings, including comparison of existing computer programs, building monitoring, comparison of calculation methods as well as air quality and studies of occupancy.

The Executive Committee

Overall control of the programme is maintained by an Executive Committee, which not only monitors existing projects but also identifies new areas where collaborative effort may be beneficial.

To date the following have been initiated by the Executive Committee (completed projects are identified by *):

1 Load Energy Determination of Buildings *
2 Ekistics and Advanced Community Energy Systems *
3 Energy Conservation in Residential Buildings *
4 Glasgow Commercial Building Monitoring *
5 Air Infiltration and Ventilation Centre
6 Energy Systems and Design of Communities *
7 Local Government Energy Planning *
8 Inhabitant Behaviour with Regard to Ventilation *
9 Minimum Ventilation Rates *
10 Building HVAC Systems Simulation *
11 Energy Auditing *
12 Windows and Fenestration *
13 Energy Management in Hospitals*
14 Condensation *
15 Energy Efficiency in Schools *
16 BEMS – 1: Energy Management Procedures *
17 BEMS – 2: Evaluation and Emulation Techniques *
18 Demand Controlled Ventilation Systems *
19 Low Slope Roof Systems *
20 Air Flow Patterns within Buildings *
21 Thermal Modelling *
22 Energy Efficient communities *
23 Multizone Air Flow Modelling (COMIS)*
24 Heat Air and Moisture Transfer in Envelopes *
25 Real Time HEVAC Simulation *

26 Energy Efficient Ventilation of Large Enclosures *
27 Evaluation and Demonstration of Residential Ventilation Systems *
28 Low Energy Cooling Systems *
29 Daylight in Buildings *
30 Bringing Simulation to Application *
31 Energy Related Environmental Impact of Buildings *
32 Integral Building Envelope Performance Assessment *
33 Advanced Local Energy Planning *
34 Computer-aided Evaluation of HVAC Systems Performance *
35 Design of Energy Hybrid Ventilation (HYBVENT) *
36 Retrofitting of Educational Buildings *
36 WG Annex 36 Working Group Extension 'The Energy Concept Adviser' *
37 Low Exergy Systems for Heating and Cooling of Buildings *
38 Solar Sustainable Housing *
39 High Performance Insulation systems (HiPTI) *
40 Commissioning Building HVAC Systems for Improved Energy Performance *
41 Whole Building Heat, Air and Moisture Response (MOIST-EN)
42 The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (COGEN-SIM)
43 Testing and Validation of Building Energy Simulation Tools
44 Integrating Environmentally Responsive Elements in Buildings
45 Energy-Efficient Future Electric Lighting for Buildings
46 Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo)
47 Cost Effective Commissioning of Existing and Low Energy Buildings
48 Heat Pumping and Reversible Air Conditioning
49 Low Exergy Systems for High Performance Buildings and Communities
50 Prefabricated Systems for Low Energy Renovation of Residential Buildings
51 Energy Efficient Communities
52 Towards Net Zero Energy Solar Buildings
53 Total Energy Use in Buildings: Analysis & Evaluation Methods
54 Analysis of Micro-Generation & Related Energy Technologies in Buildings

Annex 5: Air Infiltration and Ventilation Centre (AIVC)

The Air Infiltration and Ventilation Centre was established by the Executive Committee following unanimous agreement that more needed to be understood about the impact of air change on energy use and indoor air quality. The purpose of the Centre is to promote an understanding of the complex behaviour of air flow in buildings and to advance the effective application of associated energy saving measures in both the design of new buildings and the improvement of the existing building stock.

The Participants in this task are Belgium, Czech Republic, Denmark, France, Germany, Greece, Italy, Japan, Republic of Korea, Netherlands, New Zealand, Norway, Portugal, Sweden and United States of America.

ACKNOWLEDGEMENTS

The authors wish to thank AIVC and TightVent Europe for their support to produce this publication, as well as INIVE (whose members are BBRI, CETIAT, CIMNE, CSTB, eERG, ENTPE, Fraunhofer IBP, SINTEF, NKUA, TMT US, TNO) which facilitates both AIVC and TightVent Europe.

This publication was also made possible thanks to the financial support of the Belgian Construction Certification Association (BCCA) and the Flemish Energy Agency (VEA).

IEA ECBCS Annex 5: Air Infiltration and Ventilation Centre (AIVC)

The Air Infiltration and Ventilation Centre was established by the Executive Committee following unanimous agreement that more needed to be understood about the impact of air change on energy use and indoor air quality. The purpose of the Centre is to promote an understanding of the complex behaviour of airflow in buildings and to advance the effective application of associated energy saving measures in both the design of new buildings and the improvement of the existing building stock.

The Participants in this task are Belgium, Czech Republic, Denmark, France, Germany, Greece, Italy, Japan, Republic of Korea, Netherlands, New Zealand, Norway, Portugal, Sweden and United States of America.

The TightVent Europe "Building and Ductwork Airtightness Platform" was launched on January 1, 2011. It has been initiated by INIVE EEIG (International Network for Information on Ventilation and Energy Performance) with the financial and technical support of the following founding partners:

Building Performance Institute Europe, European Climate Foundation, Eurima, Lindab, Soudal, Tremco illbruck, and Wienerberger.

Since November 2011, BlowerDoor GmbH and Retrotec have joined TightVent and thereby bring air leakage measurement expertise to the consortium.

The platform aims at facilitating exchanges and progress on building and ductwork airtightness issues, namely through the production and dissemination of documents and the organization of events.

CONTENTS

ABSTRACT **3**

INTRODUCTION **3**

1 INTRODUCTION **3**

2 TOWARDS ENERGY PERFORMANCE CALCULATION CHECKS THROUGH MEASUREMENTS AT COMMISSIONING **4**

3 MOTIVATIONS FOR COMPETENT TESTER SCHEMES **5**

4 RELIABILITY ISSUES IN AIR LEAKAGE TESTING **7**

4.1 BACKGROUND ON TEST METHOD 7
4.2 SOURCES OF UNCERTAINTY IN DERIVED QUANTITIES 8
4.3 DEFINING ADDITIONAL SPECIFICATIONS TO PRESSURIZATION TEST PROTOCOLS 9
4.4 DEFINING SPECIFIC REQUIREMENTS FOR TESTING EQUIPMENT AND SOFTWARE 11
4.5 CHOOSING REFERENCE PRESSURE AND DATA COLLECTION AND ANALYSIS METHODS 12

5 TRAINING TESTERS **13**

6 RELIABLE REPORTING IN ENERGY CALCULATION METHODS **14**

7 AIRTIGHTNESS DATABASES TO MONITOR PROGRAMMES OR POLICIES **15**

8 KEY OPTIONS FOR A COMPLIANCE FRAMEWORK FOR AIRTIGHTNESS **16**

8.1 REGULATORY VERSUS VOLUNTARY APPROACH 16
8.2 WHAT TYPES OF REQUIREMENTS FOR WHICH BUILDINGS? 17
8.3 TYPE A REQUIREMENT - UPPER PERMEABILITY LEVEL 17
8.4 ALLOWANCES FOR NON-SYSTEMATIC TESTING 18
8.5 OPTIONS FOR COMPETENT TESTER SCHEMES 19
8.6 TYPE B REQUIREMENT - LOWER PERMEABILITY LEVEL - PROVISIONS FOR AIR RENEWAL (BEYOND STANDARD VENTILATION REQUIREMENTS) 20

9 QUALITY MANAGEMENT APPROACHES FOR AIRTIGHTNESS **21**

9.1 MOTIVATIONS FOR IMPLEMENTING QUALITY MANAGEMENT APPROACHES 21
9.1.1 Securing the expected performance – Making good airtightness predictable *21*
9.1.2 Comply with the energy performance regulation and get reward if applicable *22*
9.1.3 Contain costs and save on customer service *22*
9.1.4 Stay one step ahead of competitors *23*
9.2 THE ROLE OF AIRTIGHTNESS TESTS IN QUALITY MANAGEMENT APPROACHES 23
9.2.1 Intermediate voluntary site controls *23*
9.2.2 Towards quality management approaches *23*

10 SIGNIFICANT KNOWLEDGE GAP IN BUILDING AIRTIGHTNESS DURABILITY **24**

11 CONCLUSIONS **26**

12 REFERENCES **26**

13 ANNEX **29**

Abstract

This report gives a critical review of steps taken in 10 countries (Belgium, Denmark, Finland, France, Germany, Netherlands, Japan, Sweden, UK, USA) with regard to testing and reporting schemes as well as overall quality approaches to improve building airtightness. The analyses are mostly based on contributions and discussions with 20 speakers invited to the AIVC-TightVent airtightness international workshop held in Brussels, 28-29 March 2012; they also include information from earlier publications as well as from the authors' experience.

We have examined the schemes derived to increase the reliability of air leakage tests because of the potentially large energy and economic impacts of erroneous results. This includes test specifications going beyond existing standards regarding building preparation, choice of reference values, data collection protocols and reference pressure, sampling rules for large or multi-family buildings, equipment calibration and analysis software validation. To enforce these specifications, some countries have derived competent tester schemes including trainings with an array of subsequent procedures—e.g., for training bodies, auditors trainings, centralized test data collection.

We have also analysed the various approaches to encourage tighter constructions. These range from purely voluntary schemes to systematic testing of minimum requirements, via requirements or incentives for subsidized projects, programmes or quality scheme implementation.

Overall, the main lessons learnt are that a) clear encouragements to systematic or non-systematic testing have led to market transformations while other options have failed to do so; and b) that carefully designed competent tester schemes are essential to give credit to incentives or requirements as well as to monitor airtightness policy measures.

Keywords

Airtightness, air infiltration, ventilation, quality, measurement

1 Introduction

Because envelope leakage is known to be very detrimental to the real performance of low-energy buildings in many climates (see Carrié et al., 2008a, 2008b), there is a growing number of initiatives that aim at improving building airtightness in practice. These range from mandatory airtightness testing for specific low-energy programmes to certification schemes for builders, via incentives for considerations for airtightness at early stages of design and intermediate pressurization tests during construction.

Some of these initiatives were presented during an international workshop held 28-29 March 2012 in Brussels (AIVC-TightVent, 2012; see also programme in annex § 13). 70 participants exchanged their views on the basis of presentations given by 20 experts representing 10 countries (Belgium, Denmark, Finland, France, Germany, Netherlands, Japan, Sweden, UK, USA) on requirements, quality and durability issues with regard to building airtightness.

This paper analyses and summarizes the contributions to this workshop with a specific focus on testing and reporting about building airtightness and on quality management issues for achieving a good airtightness. First, we discuss the underlying philosophy behind the increasing number of airtightness tests which implies greater attention to the confidence in the results and the way they are used e.g. for claiming benefits for subsidies or justifying for a minimum requirement. Second, we examine pros and cons of various options to encourage or require better airtightness. Finally, we analyse the potential of quality management approaches to foster progress with building airtightness as well as steps to improve confidence in its durability.

2 Towards energy performance calculation checks through measurements at commissioning

Over the past 40 years, calculation methods have become standard support tools for regulations or programmes to evaluate and set energy performance characteristics of buildings. This has led to the development of requirements and subsequent labels, certifications and technical approvals for products, systems and installers and even for designers to regulate the market and set examples.

Today, confidence in the actual energy performance of buildings before operation relies most of the time only on paper checks, at best on visual or on/off checks at commissioning.

Today, there exist widely used instruments to declare energy performance of buildings based on calculation methods as well as quality labels for products, systems and installers. Introducing testing schemes at commissioning implies greater attention at all steps in the construction process which reduces the risk of discrepancy between predicted and actual performance.

Airtightness testing can be a first step towards this approach.

This void in performance testing is suspected to be one major reason behind the discrepancies observed between predicted and real performance (Figure 1). For instance, it seems reasonable to assume that a testing method of the U-value of a building would bring greater confidence in insulation levels. Unfortunately, todays' methods for this are not robust enough to be used in a compliance framework.

While this may appear to be anecdotal, introducing testing schemes at commissioning implies in reality a fundamental change in the approach behind the building construction process. This change is about checking the building performance as built with measurements and not only on paper.

However, measurement checks before the building is in use are rarely required. In fact, envelope and ductwork airtightness are to our knowledge the unique building characteristic which is sometimes required to be measured on site when the building is finished either because the regulation imposes a minimum requirement or because credit for better airtightness (compared to a default value) can be claimed only if proven by measurement.

Unlike the U-value of a building or many other similar building characteristics that are used to predict the building energy performance, the experience of the Passivhaus Institute since the late 80s has proved that mandatory airtightness testing could be an effective means to increase building quality because it led professionals to pay more attention to construction details and follow-up on site.

Therefore, an airtightness testing scheme can be seen at two levels:

- it enables one to check that the predicted building energy performance will not be too affected by unwanted air infiltration;
- it is one step towards a performance check philosophy that urges professionals to evaluate and modify methods, similarly to what would entail a quality management approach.

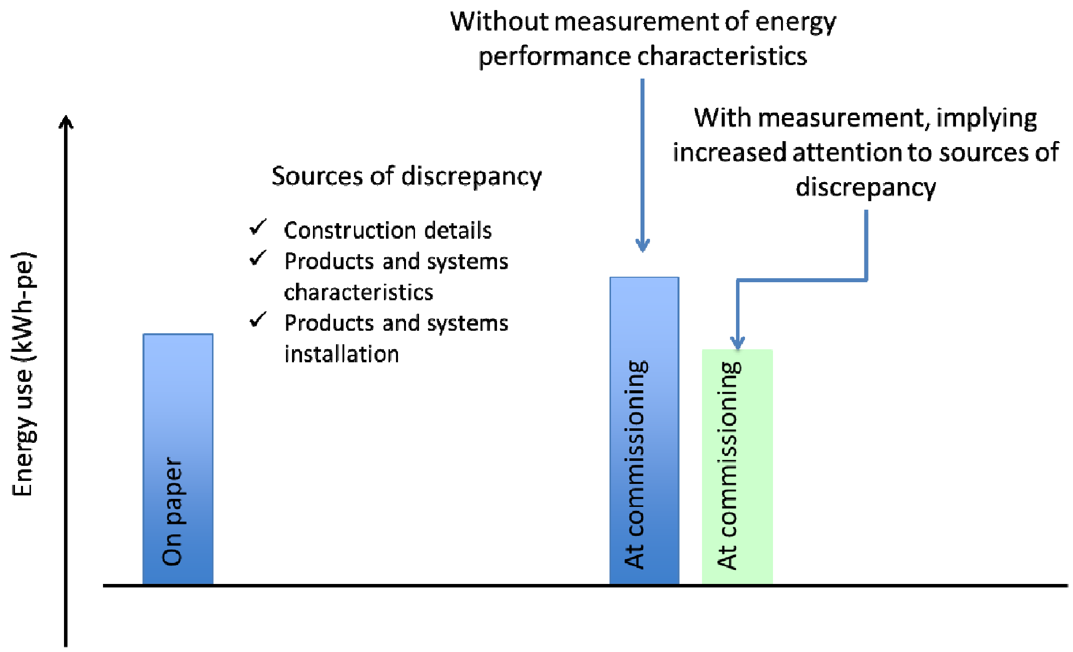

Figure 1: Expected impact of measurement of energy performance characteristics at commissioning. Performance checks at commissioning may reduce the discrepancy between predicted and real performance because professionals pay more attention to construction details and follow-up on site.

3 Motivations for competent tester schemes

The testing approach implies that the measurements are reliable and therefore, performed by competent testers. A few operational frameworks exist for competent testers. These schemes represent a great opportunity to increase confidence in the test results and their usage as well as to monitor policies or programmes.

If building airtightness testing is encouraged or enforced, the reliability of the test and use of the measurement results are key problems to address since it would otherwise discredit the approach. These problems are in fact similar to those that have led to the development of quality labels for designers, products and systems, and installers. Anyone who has performed a leakage test will confirm that finding out which openings should be sealed or closed during the test or how to interpret measurement data is not a trivial task. Performing such measurements require some background on the energy performance calculation method and HVAC systems, as well as experience with data analyses and field constraints.

This is probably one key reason behind the development in the past few years of competent schemes for testers (see Table 1). To our knowledge, such schemes are operational in Germany (www.flib.eu/certifications.html), in Denmark (www.klimaskaerm.dk), in Finland (www.rateko.fi), in France (www.qualibat.fr), in Japan, in the UK (www.bindt.org) and in the USA (http://www.resnet.us/professional/energy-rater). Note that Japan has developed a successful certification framework since the early 1990s: in 2011, about 3 800 testers were registered.

The development of such schemes represents an opportunity for improving the reliability of the tests and their usage, including for monitoring the application of policies.

Country	Competent scheme operator	Approximate number of competent testers as of mid 2012	Comments
DE	FliB www.flib.eu/certifications.html	170	*« Certified checker of air-tightness of buildings in the sense of energy saving regulation »* (FliB)
DK	DS certification	1 company (10 in the pipeline) representing altogether 15-20 testers	The Building Envelope Society (Klimaskaerm, www.klimaskaerm.dk) is a platform and society for airtightness and IR measurements in buildings. In collaboration with DS certification, it has established certification schemes for airtightness testers and IRtesters.
FI	VTT Technical Research Centre in Finland www.vtt.fi	Less than 100	RATEKO (www.rateko.fi) organizes courses and examinations.
FR	Qualibat www.qualibat.fr	350	Qualification was initially required for BBC-Effinergie voluntary label. It is now required for measurements in all new buildings in the framework of the RT 2012 energy performance of buildings regulation. Several « competent » training bodies organize courses and examinations.
JP	Institute for Building Environment and Energy Conservation	About 3800	Since 1998, engineers who measure the airtightness of houses must be registered. They must attend a training course including theory and practice and pass and examination.
UK	BINDT www.bindt.org	Several hundreds	*« An approved inspector is authorised to accept, as evidence that the requirements…have been satisfied, a certificate to that effect by a person who is registered by The British Institute of Non-Destructive Testing in respect of pressure testing for the air tightness of buildings. »* (Building Regulation 20B). The testers must attend an approved training course or be testing staff employed by a UKAS air tightness testing laboratory.
USA	RESNET http://www.resnet.us/professional/energy-rater	Several hundreds	For the Energy Star and the Guaranteed Performance programmes, certified experts (HERS raters) check the building characteristics with specific RESNET requirements for data analysis and collection. The rater must pass competency tests.

Table 1: Overview of operational competent tester schemes (partly using information from Afshari (2012), Kauppinen (2012a), Juricic (2012), Yohino (2012), Liddament (2012), Coulter (2012)).

4 Reliability issues in air leakage testing

4.1 Background on test method

The standard method used for quantifying the airtightness of a building is described in ISO 9972 (2006). It consists in measuring the airflow rate passing through a device at the indoor/outdoor interface when the building is artificially pressurized with a fan included in that device. All intentional building openings (doors, windows, ventilation air inlets and outlets, chimney, etc.) are closed or sealed during the test. Therefore the airflow passing through the device is due to the presence of leaks in the building envelope. Because the device includes a fan and is often positioned in the opening of a door, it is commonly called a *blowerdoor*.

Although there are standardized methods for airtightness testing, many sources of discrepancy on the derived quantities used for calculation and/or compliance purposes remain.

In a compliance framework, it is necessary to:

- *define additional specifications to the protocols with regard to building preparation, reference values, sampling rules;*
- *check the test equipment accuracy with appropriate calibration procedures;*
- *further specify data collection and analyses procedures consistent with the reference pressure chosen.*

The standard assumes that the following power law between the airflow rate and the pressure difference across the building envelope applies:

$$q_L = C_L \, \Delta p^n \qquad \text{(Equation 1)}$$

where:

q_L is the volumetric leakage airflow rate ($m^3\, h^{-1}$);

C_L is the air leakage coefficient ($m^3\, h^{-1}\, Pa^{-n}$);

Δp is the pressure difference across the building envelope (Pa); and

n is the airflow exponent (-).

This law enables the tester to assess the airflow rate at any pressure difference although the measurement may not have been done precisely at that pressure. For instance, the airflow rate may be interpolated at a reference pressure of 50 Pa, although the envelope has been subjected to a pressures of 11, 23, 32, 43, 51, 62 Pa. It may also be extrapolated to a reference pressure outside the range of pressure tested, e.g., at 4 Pa. ISO 9972 gives a regression method to achieve this interpolation or extrapolation at the reference pressure chosen.

For compliance checks, the tester has to derive quantities based on leakage airflow rate at the reference pressure normalized by the volume of the building, the building envelope area, or the floor area. It may also be necessary to provide a conventional leakage area at a given pressure.

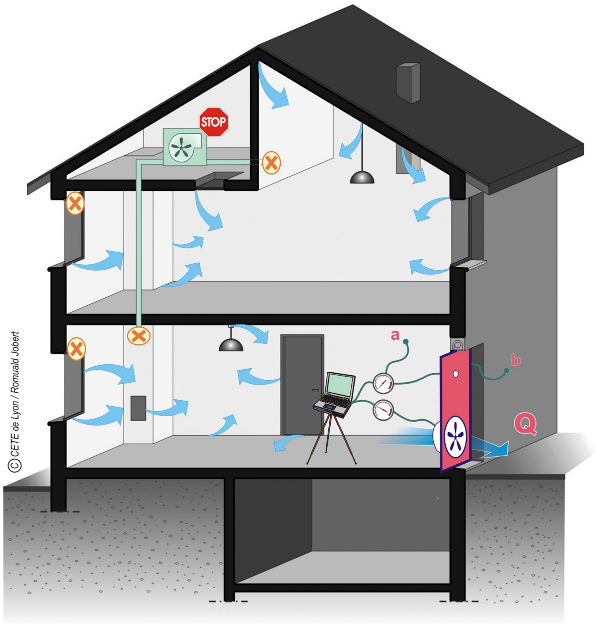

Figure 2: Schematic representation of an airtightness test, with pressurization equipment installed, intentional building openings closed. In this case, the building is depressurized and the airflow rate (Q) measured at the device matches the sum of the leakage airflow rates represented with blue arrows. Source CETE de Lyon.

4.2 Sources of uncertainty in derived quantities

While the test principle is simple and can give reproducible results with standard protocols (Delmotte, 2011), experience shows that there can also be wide differences in the derived quantities according to the test and to the tester. The sources of these differences include:

1. The building preparation, in other words, the way the openings are sealed or closed. In fact, depending on the calculation method that uses the measurement result, some openings may be sealed or closed or left open. For instance, if there is an intentional opening which is accounted for in an energy performance calculation method—i.e., the airflow rate through this opening is calculated with the hole characteristics—the opening must be closed; otherwise, it must not be closed. Discrepancies can also occur because the sealing/closing of the openings artificially increases or decreases the intrinsic building airtightness level;
2. Reference values—e.g. volume, envelope area or floor area. The biggest concern lies with the volume whose definition remains subject to interpretations whereas the floor or the envelope areas are well-defined at national levels. Besides, for energy performance calculations, the volume is not used. Therefore, there are no possible cross-checks;
3. Sampling assumptions for large or multi-family buildings or developments of single-family/semi-detached houses. With large or multi-family buildings, it is often impractical or not economically feasible to conduct airtightness tests on the whole building. Therefore, the test is conducted on parts of the building, e.g. on several apartments or on a fire partition of a large building. Obviously, the way individual tests will be conducted and consolidated has a great influence on the derived quantity obtained to be used in the energy calculation. The same concerns apply to a housing development where only a few houses are tested;
4. The equipment uncertainty and software errors. Current calibration requirements for the pressure and flow measurement devices are likely insufficient to guarantee little deviation between test results, especially when the tester measures low airflow rates.

Besides, software errors calculating the airtightness or the derived quantities can of course seriously impact the derived quantities obtained;

5. Wind and stack effects, reference pressure, data collection protocol and analysis method. These issues are interconnected. Although the ISO protocol eliminates tests in windy conditions, significant discrepancy can be observed in such cases, especially when the reference pressure for the derived quantity is low. Also, data collection and analysis methods different from ISO 9972 may yield better measurement accuracy.

In a compliance framework which may have serious impacts for building professionals and building owners (for instance, financial penalties or legal disputes), it is important to minimize these sources of discrepancy. Our recommendation would be to take the steps listed below.

4.3 Defining additional specifications to pressurization test protocols

Several documents exist to address points 1, 2 and 3 above in specific contexts (see for instance AFNOR GA P 50-784, 2010; Association Minergie, 2007; Delmotte, 2007; DIN4108-7, 2011). These documents apply to a specific calculation method either used in the context of an energy regulation (e.g., the Belgian or French regulations) or a programme (e.g., Minergie).

Such guidelines are absolutely necessary because ISO or national standards cannot deal with the specificities of each calculation method for which the test may be performed. Subsequently, the room left for interpretation in the standards can easily change the end result by factor of 2.

Regarding the building preparation, the documents usually list a number of typical openings and the way they should be dealt with when testing (Table 2). While the list of openings could be standardized at international level, their preparation before the test cannot since it depends on the assumptions of the calculation model used.

Clarify and cross-check the input values that are used for the quantities derived from the measurements.

It is helpful to clarify the reference value in these documents. Our recommendation would be to use a reference value unambiguously defined, e.g.:

- the floor area or the envelope area which are usually defined in a local context;
- the “standard volume”, as expressed in the recommendations of the Minergie association (2007), which is based on a standard envelope area to volume ratio of 0.8 m^{-1}.

The original motivation for the “standard volume” approach — which is equivalent to using the leakage flow at 50 Pa divided by the envelope area (q_{50}) as indicator — is that the volume-based indicator[1], n_{50}, is not representative of the quality of the envelope. In addition, we have reservations about the use of the volume as a reference value as it is ambiguously defined in the ISO 9972 or EN 13829 standards and a better definition would lead to additional work for the tester with no added-value. In practice, one may assume a 20% deviation between the volumes calculated by different testers. Besides, interested parties can be tempted to increase

[1] The volume-based indicator, n_{50}, is defined as the leakage airflow rate at 50 Pa divided by the building volume.

this value since it will result in a better n_{50} value with no penalty on energy calculations. On the other hand, artificially increasing the floor and envelope areas are detrimental either for taxes or for energy calculations, which means that the cheating risk is limited if there is a cross-check between these values.

Ventilation system		Type of outdoor air aperture	Preparation of outdoor air aperture and exhaust air grilles	Maximum air change rate at 50 Pa, $n_{50, max}$ (h^{-1})
Natural ventilation	Via windows only		Not applicable	3.0
	Cross ventilation via outdoor air apertures	Not closable	No measures	3.0
		Closable, without self-regulation	Closure of outdoor air aperture	3.0
		With self-regulation	Sealing of outdoor air aperture	1.5
	Shaft ventilation	Not closable or no outdoor air aperture	No measures at outdoor air aperture, sealing of exhaust air grilles	1.5
		Closable, without self-regulation	Closure of outdoor air aperture, sealing of exhaust air grilles	1.5
		With self-regulation	Sealing of outdoor air aperture and exhaust air grilles	1.5
Mechanical ventilation	Exhaust system	Closable, without self-regulation	Sealing of outdoor air aperture	1.0
		With self-regulation	Sealing of outdoor air aperture	1.0
	Supply and exhaust system	-	Sealing of exhaust, exit, supply and outdoor air ducts	1.0

Table 2: Recommended building preparation and recommended maximum air change rates for the airtightness measurement at 50 Pa pressure difference according to DIN 4108-7:2011-01 (2011). Table extracted from Erhorn-Kluttig and Erhorn (2012).

This approach is used in the French context where the tester is required to take the same value for the envelope area as the one used in the building energy performance calculation.

Sampling rules for multi-family or large buildings or for housing developments have been defined in France, Germany and the UK.

Regarding large and multi-family buildings, there are often practical limitations to measure the air permeability of the whole building. The main reasons are: the building is too large to be pressurized unless many blower-doors are combined and/or specific equipment is used; the floors are not connected with an internal airflow path; or the stairway is very leaky, e.g. due to a lift shaft or a fire access door. For these buildings, it is common to measure the airtightness of individual zones separately. Some documents propose specific rules a) to choose the units/parts that must be tested; and b) to extract the criteria that will be used. Walther and Rosenthal (2009) give an overview of different sampling methods in use in Europe. In Germany, at least 20% of the total number of apartments should be tested, with at least one tested apartment at the top floor, one at an in-between floor and one at the ground floor. In UK, zone testing should cover at least 20% of the building's envelope area. In France, 3 apartments have to be measured if the building has

30 units or less, and 6 apartments otherwise. The apartments must have the largest ratio of floors and windows length per floor area and must be located at the top, intermediate and ground floors (see AFNOR GA P 50-784, 2010). Conventionally, the input value for the building energy performance calculation is the weighted-average of the tests results, the applicable weights being the envelope area of each apartment.

Rules should be set also if it is possible to avoid systematic testing on all houses of a development. In the UK, "in a large housing development the test should be made on at least three units of each dwelling type. Testing should be undertaken within the construction of the first 25% of each dwelling type so that any faults in design can be corrected before the remaining buildings are constructed" (see Liddament, 2012a, pp. 22). In France, 3 houses with the largest ratio of floors and windows length per floor area have to be measured. Conventionally, the input value for the energy performance calculation for the houses that have not been tested is the maximum between the highest permeability obtained on the 3 houses tested and a threshold value. The threshold value was introduced so that quality management approaches presented later in this paper (see § 9) keep an advantage compared to mere sampling.

4.4 Defining specific requirements for testing equipment and software

In the UK, accredited laboratories offer calibration services for testing equipment.

Sherman and Palmiter (1995) give an interesting discourse on the sources of uncertainty and the assessment of their impact. Although Delmotte (2011) has shown that current standards can give reproducible tests in favourable climatic conditions, they include choices which may be questioned, including the number of pressure stations, the min and max pressures, the regression method, or the equipment's characteristics and calibration.

In the UK, testers must use properly calibrated equipment. For this, several companies offer calibration services and deliver a certificate issued in accordance with the laboratory accreditation requirements of the United Kingdom Accreditation Service. (UKAS is one of the signatories to the International Laboratory Accreditation Co-operation (ILAC) Arrangement for the mutual recognition of calibration certificates issued by accredited laboratories.)

UKAS requires airflow rate calibration at different flow regimes. This includes the various configurations that can actually be used by the tester (e.g., the various rings that may be placed to increase the pressure drop reading for the airflow rate).

To our knowledge, the UK is the only country where this issue has been addressed in detail. France is considering using a similar approach to justify for the calibration requirements in a revised version of the application guide AFNOR GA P 50-784 to EN 13829. In particular, today the guide allows airflow calibration by the device manufacturer as well as by an accredited organization, but there are no specifications for issuing the certificate.

Provide test cases for software validation.

Finally, the issue of software errors is important, but fortunately, easy to resolve with examples of measurement datasets and analysis. This was successfully implemented in the French context with freely-available reference spreadsheets developed by CETE de Lyon and available at http://www.rt-batiment.fr.

4.5 Choosing reference pressure and data collection and analysis methods

There are two ways to deal with the uncertainties generated by wind and stack effects:

- choosing a high reference pressure making these effects negligible compared to the pressure generated during the test, in which case the relevance of the uncertainty estimate is not crucial;
- using advanced methods to allow good uncertainty estimates in parallel to guidance for result interpretation.

The first approach is probably the easiest to implement in a compliance framework where building air leakage is verified. It increases the precision, repeatability and reproducibility of the test results under varying meteorological conditions. The downside of this approach is that it increases the risk of deviation in the infiltration airflow estimates at low pressures, which may be used in certain energy calculation methods. This is the case for instance in calculation tools using network models or using the flow at 4 Pa in the direct method as described in EN 15242 (2007). In fact, significant errors can be induced at low pressures because the exponent of the mathematical law between airflow rate and pressure is usually set to a default value of 0.667 although it typically ranges between 0.55 and 0.75 (Figure 3).

It is not entirely clear to the authors at this time whether the best solution is to use a low or a high pressure in a compliance framework. However, since energy performance regulations calculate conventional energy use, we are more and more inclined towards a reference pressure of 50 Pa (which is adopted in most EU countries) to overcome uncertainties generated by wind and stack effect, and thereby reduce the risks of disputes arising from the uncertainties in the airtightness indicator.

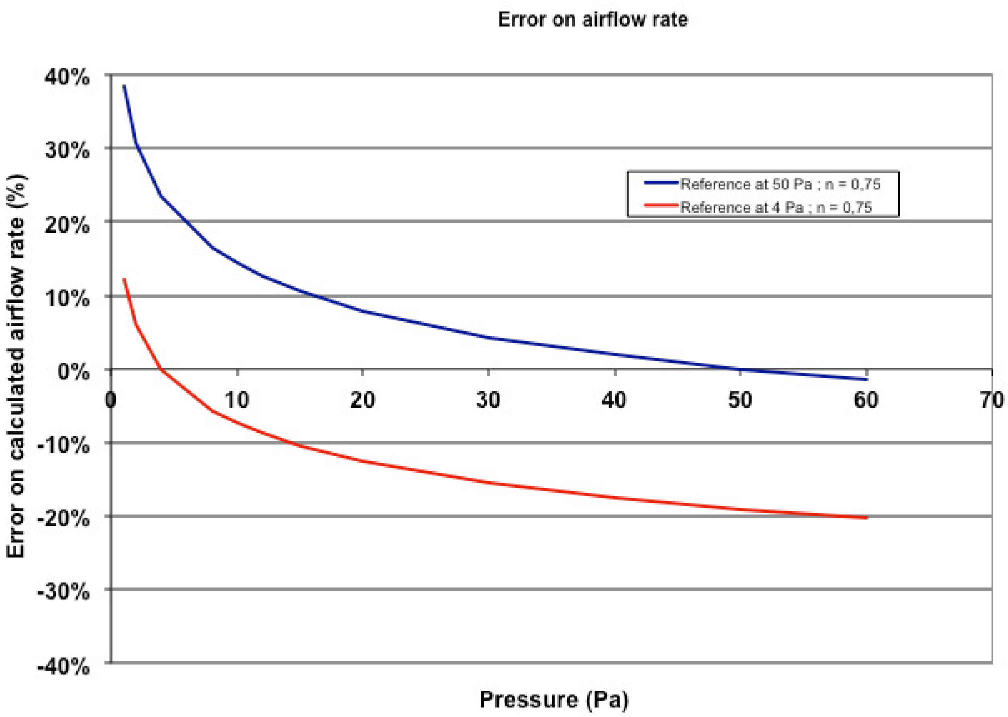

Figure 3: Error on calculated airflow as a function of pressure inside the building for an actual flow exponent of 0.75, assuming a flow exponent of 2/3 in the calculation.

Regarding data collection and analysis methods, the choice is limited with ISO 9972. It is likely that the data collection proposed inherited from devices with analogue displays only can be considerably improved with:

- increased number of points and longer sampling periods for the measurements of the zero-flow pressure as well as for the other pressure stations;
- weighted regression analysis instead of the unweighted option proposed in ISO 9972.

However, solid argumentation to come up with a robust proposal for data collection and analysis is still lacking.

5 Training testers

Competent tester schemes involve trainings that include theory and practice as well as a validation procedure.

In a compliance framework, it is key that the testers understand the rules to overcome the sources of errors. For this, training appears to be a mandatory step, but the fundamental issue is to define precisely the knowledge and know-how the testers must acquire. Being able to perform a test according to the rules implies:

- knowing and understanding the purpose and steps of the tests, including preliminary information to obtain as well as analysis of test results;
- knowing and understanding the rules, including building preparation, calculation of derived quantity, calibration, etc.;
- knowing how to use the equipment on site;
- knowing how to identify leakage sites;
- knowing how to write a report;
- staying up-to-date with rule changes.

Additionally trained testers may be required to file reports or report data to a central body for example if they are certified or if this is required by regulation. Therefore, they must be aware of the reporting procedures.

To our knowledge, specifications for training bodies include part or all of the points listed in Table 3.

Training programme	Training validation
▪ Fundamentals of ventilation and infiltration ▪ Regulatory context for airtightness ▪ Fundamentals of airtightness measurement ▪ Report contents ▪ Practice measurement	▪ Theoretical examination ▪ Measurement on site supervised by experienced tester ▪ Evaluation of report(s) submitted to the training body

Table 3: Specifications identified for training bodies for air leakage testing. Depending on the context, the specifications may include part or all of points listed.

This can lead to rather standardized training programmes; however, in the French context, this approach was found very useful to guarantee the quality of the information provided to the trainees. Note that in this context, the specifications have evolved considerably:

- starting with one-day trainings performed with experienced testers only to initiate the process between June 2008 and March 2009;
- followed by two-day trainings with minimum score to be obtained on a multiple-choice questionnaire and positive evaluation of a report performed autonomously by the training body; and

- since January 2012, with the full scope listed in Table 3 leading most of the time to 4-day trainings.

Additionally applicants to be "authorized testers" in the French context must include in their application administrative information as well as proof of successful training evaluations and 5 test reports to be evaluated in a commission by independent experts.

A reasonable trade-off must be found between the training cost implied by the training requirements and the benefits in terms of reduced risk of faulty tests. Note also that the competence of the tester can be re-checked "on the fly", e.g., if the tester is recognized competent in a given context. For example, in the Danish context, there is no prior practical examination or validation of test reports, but this is checked when the tester sends his yearly report to the certification body to prolong his certification.

6 Reliable reporting in energy calculation methods

Reliable testing is of course a key step, but the correct use of the test results is equally important. In the UK for instance, the test results must:

- be handed to the building owner;
- be consistent with the inputs in the calculation method;
- comply with minimum requirement, if applicable.

Evidence shows that the correct information is not always transferred to the bodies concerned with these points. Therefore, specific procedures are necessary to secure reporting.

To increase confidence in compliance statements, it is important to secure data transfer between the interested parties.

In particular, airtightness related data must be consistent in the test report, the calculation method, and the information given to control bodies.

Competent tester schemes can help reach this goal.

There are a number of ways this could be done, but one keyword is *consistency check* between building authorities, independent inspectors that issue energy performance certificates, and airtightness testers.

One way to resolve this is:

1. To include requirements for collecting and checking consistency of the airtightness tests in qualification or accreditation schemes for independent inspectors; and
2. To secure transmission of certificates between independent inspectors and building authorities and subsequent use for compliance checks and sanctions.

The first aspect is partly covered by the new scheme of the French energy performance of buildings regulation RT 2012 that requires a certificate stating the consistency between the calculation and various key points (energy generation, renewables, airtightness, insulation) through paper or visual checks. Concerning airtightness, the reference document is the airtightness test report which implies communication between the tester and the person that issues the certificate of consistency. This individual may be the architect, the inspector who issues the energy performance certificate, the accredited auditor if applicable (this is specific to the French context), the building certification body if the building applies for an energy performance label.

The second aspect is well-covered in the context of energy performance of buildings declarations in the Flemish region of Belgium with mandatory upload to a central server for computerised processing and archiving (Tilmans and Van Orshoven, 2009). Similar systems could be envisioned for airtightness testing, potentially with cross-checks between building characteristics used to issue the energy performance certificate.

The approach summarized in Figure 4 whereby building characteristics are centralized and checked to issue the EP certificate which becomes the central information for building control and project owners could be an efficient way to guarantee consistency of inputs.

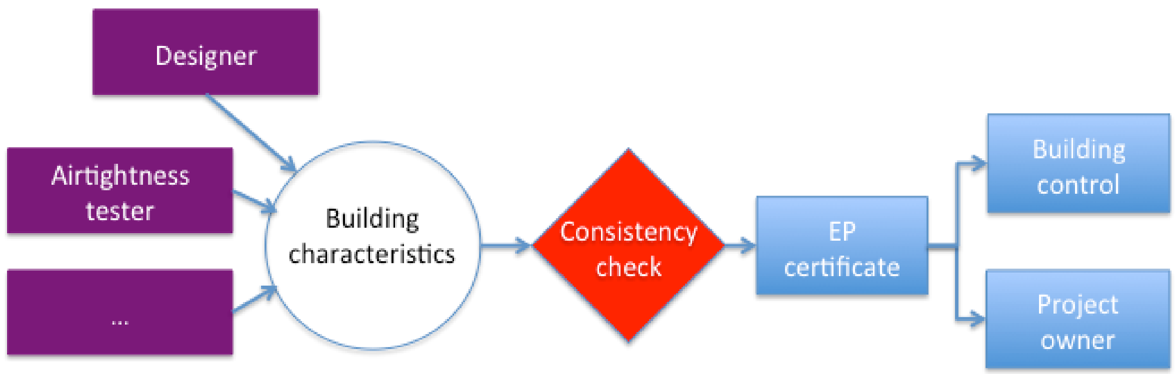

Figure 4: Possible scheme for improving the reliability when using building characteristics

7 Airtightness databases to monitor programmes or policies

In a concern for efficiency, airtightness databases may be developed around competent tester schemes.

Appropriate databases allow:
- *Consistency checks;*
- *Building characteristics monitoring;*
- *Quality checks of the testers, e.g., via periodic evaluation of their test reports.*

The scheme represented in Figure 4 can be a solid basis for the development of airtightness databases. Leakage data could be either:
- collected and extracted at the building characteristics level; or
- extracted through the energy performance certificate.

The first option is obviously more difficult to implement but it has two key advantages:

1. Databases of building characteristics are extremely useful to monitor policies and programmes. One interesting example is the French "observatoire BBC", www.observatoirebbc.org, whose goal is to share experience on low-energy buildings solutions. Databases organized as suggested in Figure 5 would avoid duplicating efforts for control and monitoring, e.g., it could serve for a purpose similar to the "observatoire BBC" as well as to perform consistency checks prior to issuing the certificate;
2. It could also serve to monitor the testers through their test reports. With an appropriate framework, these may be checked periodically for quality assurance purposes and the prolongation of their qualification may be subjected to positive evaluation of a few reports. Statistical tests can also performed to screen suspicious testers.

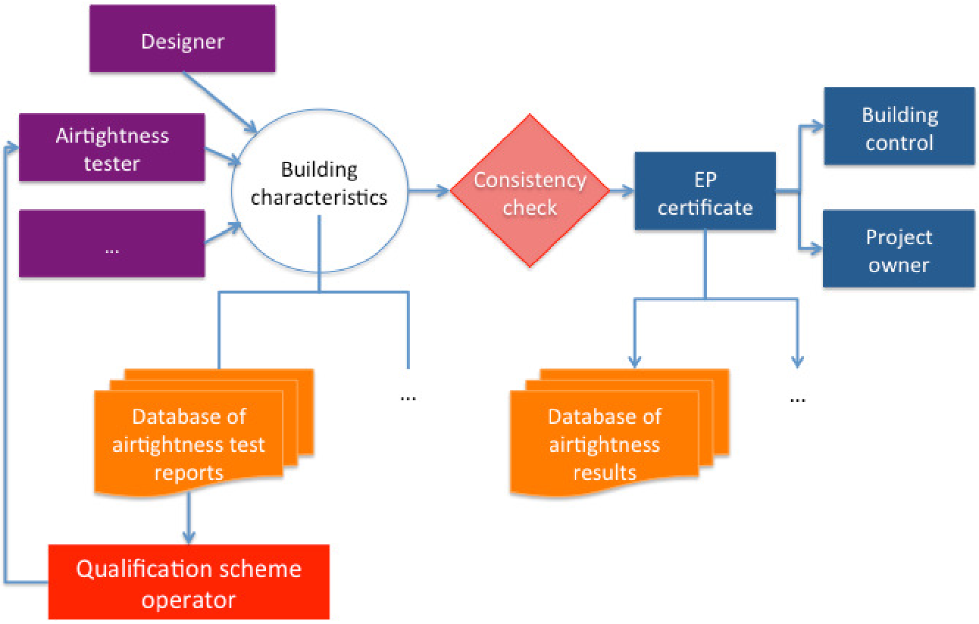

Figure 5: Possible scheme for improving the reliability when using building characteristics

8 Key options for a compliance framework for airtightness

8.1 Regulatory versus voluntary approach

Regulatory and voluntary approaches may converge, e.g., with the introduction of airtightness requirements for subsidized buildings or specific programmes gradually shifting to a regulatory requirement.

There are a number of bodies that can include encouragements or requirements on permeability levels. Regulations imply that the rules apply to all buildings defined within the scope, whereas standards or guidelines or voluntary labels apply on a voluntary basis unless referred to in a regulation. For instance, the Effinergie, Minergie-P or Passivhaus labels include minimum airtightness requirements for the buildings applying for these labels. The US Army Corps of Engineers has minimum airtightness requirements for all new and renovated US army buildings. On the other hand, the regulations in the UK (since 2002) and France (since 2012) include minimum requirements for selected buildings.

Testing scheme	Frequency	Examples
Strict	Systematic testing and strict control of reporting procedure	Mostly voluntary schemes: Passivhaus, Minergie-P, Guaranteed Performance Homes, US Army Corps of Engineers, etc.
Intermediate	Airtightness levels must be justified. It always involves some testing but not systematically.	Regulatory schemes in e.g. France and the UK. Effinergie label.
Loose	Tests rarely performed	Most countries

Table 4: Options with testing schemes

The origin of the approach is important because it has implications on social acceptance as well as on the number of buildings concerned by airtightness tests (Table 4). However, regulatory and voluntary approaches can be complementary. In fact, experience shows that requirements are well-accepted in voluntary programmes. Many public authorities have introduced specific airtightness requirements in successful calls for proposals and subsidies for low-energy buildings. This can be viewed as a first step to a regulatory requirement to prepare the market. This approach has been successful in France (with the BBC-Effinergie requirements later integrated in the 2012 regulation).

8.2 What types of requirements for which buildings?

Building regulations or other technical specifications (standards, guidelines, etc.) may take into account airtightness to answer two major concerns:

A. A limitation of envelope leakage is desirable because of the energy impacts. This position is often further backed up with indoor air quality and building damage issues (in particular, to ensure proper operation of the ventilation system and reduce moisture risk) that can be due to poor airtightness. Implicitly, this approach calls for ensuring proper ventilation airflow rates. The underlying philosophy may be condensed by the mantra "*build tight, ventilate right*".

B. The benefits for *very low* leakage levels may be small or even counter-productive in terms of indoor air quality and cost. This position mostly stems from problems when dealing with renovated building with no ventilation system (whether natural, hybrid or mechanical) or from insufficient air supplied to unvented combustion appliances inside the conditioned space (de Gids and Borsboom, 2012, Sherman and Walker, 2012). This concern may be summarized by "*how tight is too tight*".

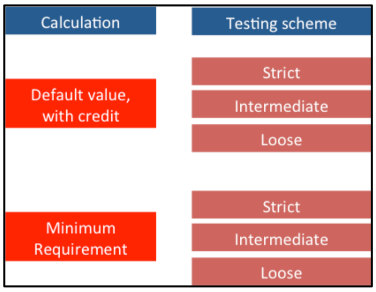

Figure 6: Approaches for calculation methods and testing schemes.

Several approaches may be used in the same framework depending e.g., if it is a new building or not, on building location, usage, etc.

While this may seem obvious, a pre-requisite is to identify the need for type A or type B requirements, which may differ depending on building characteristics, usage and location.

8.3 Type A requirement - Upper permeability level

In this case, the objective is to encourage building professionals to build airtight. For this, we can identify two main approaches (Figure 6):

- Approach 1: Define a default airtightness value (i.e., which can be used in the energy performance calculation without testing) but give a credit to better airtightness if proven;
- Approach 2: Impose a minimum requirement, i.e., a maximum level of acceptable leakage for the building envelope. This approach may or may *not* include mandatory testing.

In the same regulation or programme, one may find a mix between the two approaches depending on the climate zone or the building usage or whether the building is new or renovated. The reasons behind such distinctions include the variability of the energy benefits of tight envelopes depending on their types and location, or in the case of renovation, the risk for poor design potentially increasing building damage. Note that in the specific case of existing buildings, if mandatory envelope airtightness improvements are envisioned, we strongly recommend to include them in a framework that addresses IAQ and building damage issues—e.g., to take provisions for adequate ventilation together with envelope tightening.

The relevance of one approach versus another can be discussed at length based on intuition and concrete examples; however, it is useful to recall some facts for decision-making:

It is a fact that market transformations are underway where clear signals to encourage testing have been implemented.

1. It is a fact that the airtightness market has drastically changed in the UK since mandatory testing has been introduced gradually starting in 2002.
2. The market is also clearly changing in France since the introduction of mandatory requirements for residences in the popular BBC-Effinergie label (as of mid-2012, over 22 000 dwellings certified, requests for over 250 000 dwellings in process, see www.observatoirebbc.org). Note that there was already a significant bonus for better airtightness in the 2000 and 2005 energy performance regulations, but alone, it had not been sufficient to induce a major change in the market.

8.4 Allowances for non-systematic testing

Allowances for non-systematic testing were found necessary in large-scale schemes for practical and economic reasons as well as for social acceptance.

There are several limitations to implementing a strict scheme on large scale:

- The extra cost for systematic testing;
- The number of competent testers. 100 is a rough estimate of the average number of tests performed per year per tester, i.e., 1 000 trained testers would be necessary to perform 100 000 tests per year;
- Practical issues with large or multi-family buildings, which call for testing building parts in many cases;
- The bonus for professionals engaged in quality processes is indirect, i.e. they cannot avoid systematic testing, but they may have other motivations (see § 9);
- Social acceptance among building professionals.

To overcome these problems, several options can be explored, including giving rules for:

1. Buildings that are impractical to be tested as a whole. This aspect has been discussed earlier based on experience from France, Germany and the UK (see § 4.3), that calls for clear rules to avoid competition distortion and disputes that may arise following the choice of the test zones;
2. Tests to be performed on samples in housing developments as explained in the explanation of additional specifications in France and the UK (see § 4.3);
3. Credits for state-approved quality management schemes as enforced in France or for builders certification in Japan. In the context of the French energy performance regulation, this allows without systematic testing either justification for the minimum requirement or the use of a better value than the default value (Leprince et al., 2011). Typically, the applicant is a builder, but in fact, there are no restrictions regarding the applicant's business. The basic requirements for the quality management approach to be state-approved in France are:
   a. to identify "who-does-what" and when;
   b. to trace each step of the approach;
   c. to prove that the approach is effective based on measurements on a sample;

d. to propose a scheme to ensure that the approach will remain effective with time, based on measurements on a sample.

The French EP regulation gives little detail regarding the actual content of the approach besides those basic requirements, so there is a great flexibility for the applicant to adapt to his constraints. Several pioneers have engaged in the scheme since 2007 with promising results as explained by Leprince et al. (2011). The benefits of such approaches are discussed below (see § 9.1).

8.5 Options for competent tester schemes

Requirements or credits that imply testing should be underpinned by a competent tester scheme.

The competence should be attached to both the company and the tester.

Training, examination, checks should be performed under the authority of the government either directly or through an accredited organization.

Based on our experience in air leakage testing and the feedback from stakeholders, it is clear to us that requirements or credits in the EP calculation that imply testing have to be underpinned by a competent tester scheme. However, there are several paths for this as illustrated in Table 5:

- One option is to have the test performed by a qualified and *independent* inspector. Independence means that there is no legal connection between the tester and the client for which he performs the test, hoping this will reduce the risks of false declaration (but this may happen anyways). The major problem with this solution lies in the extra cost involved with external testing;
- Another option is to have the test performed by a qualified inspector, with no specific independence requirement. This option would allow for internal testing, for instance a builder could use his own test results to justify compliance to the energy performance requirements. It is much lighter but one could fear conflicts of interests leading to falsified test results. On the other hand, the Swedish experience with ductwork air leakage testing shows that it is manageable. It is not entirely clear how this would be done in the case of envelope airtightness tests, but one specific point of attention should of course be the dissuasion of the checks and sanctions.

Independent tester required	Checks to avoid falsification of results	Training, examination and checks to continuously evaluate testers competence	Competence attached both to the tester and his company
Pros for YES: Reduces the risks of false declaration, but involves higher costs Pros for NO: Lower costs and wider acceptance of airtightness testing among practitioners	YES, in all cases: Training, examination, checks should be performed under the authority of the government either directly or through an accredited organization ▪ Falsification of results is easy and therefore appropriate instruments should be developed to fight this risk. This includes checks which could be partly screened with the database of test results. ▪ Training programmes are a first screen but testers acquire their expertise mostly by doing many tests in real conditions. Besides, protocols may change with revisions of regulations. Continuous evaluation is therefore necessary.		YES, in all cases: Because the tests involve equipment and procedures that are under the control of the company, and skills that are specific to a person, the competence of the testers should be specific to both the tester and the company.

Table 5: Overview of recommendations for options for competent tester schemes

In both cases, this implies that training and examination is specified by the government either directly or through an accredited organization that also performs checks on the qualified individuals and if necessary gives sanctions such as loss of qualification for the tester and/or its company.

We recommend that the competence be attached to both the tester and its company because tests involve equipment and procedures under the control of the company and specific skills for the tester. Therefore, both are responsible for the good achievement of the measurement.

8.6 Type B requirement - Lower permeability level - Provisions for air renewal (beyond standard ventilation requirements)

Minimum air leakage requirements do not appear to be a satisfactory solution to overcome poor air renewal.

The objective is to avoid indoor air quality problems due to a combination of airtightness and inadequate air renewal provisions. The specifications or recommendations are generally expressed in terms of a minimum air leakage level for specific systems. For instance, in the Netherlands, NEN 2687 requires $n_{50} \geq 2\ h^{-1}$ for buildings with mechanical ventilation systems with natural supply. A similar concept has been developed in the USA with the Building Tightness Limit (BTL), which is a tightness limit that determines when a mechanical ventilation system is necessary.

Typical examples of concerns that have led to setting lower permeability levels include:

- tightening of existing buildings that relied on leakage for air renewal prior to retrofitting or without prior treatment of liquid water penetrations (e.g., by capillarity);
- provisions for air supply for unvented combustion appliances inside the conditioned space;
- provisions for air renewal in case of ventilation system fault.

While these concerns are obviously legitimate, it is not clear to the authors that recommending a lower airtightness limit addresses correctly the issues raised. Of course, besides the energy penalty, one question remains whether infiltration can provide the necessary airflows both in terms of quantity and quality. Several shortcomings can be mentioned:

1. It is very difficult (if not impossible) to target a minimum leakage level. This is often caricatured with the expression "*make it just bad enough*", which is challenging to implement in reality both in terms of technology and management;
2. Although the overall renewal may be sufficient, rooms may be short-circuited, yielding IAQ problems locally.

With regard to the unvented combustion appliances, an alternative has been developed in France with a minimum opening size to provide air to the appliance. The reader may argue that it is the same as requiring a minimum leakage level, but the fact that it is an identified opening makes a fundamental difference. Namely, it overcomes the two shortcomings mentioned in the previous paragraph. Still, one major drawback of this method remains that users may be tempted to seal the opening. Maybe the only satisfactory solution is to gradually phase out these types of appliances if their combustion airflow rate is significant compared to the ventilation airflow rate.

In summary, taking provisions for air renewal through air infiltration is questionable although there may be legitimate concerns; therefore, it does not seem appropriate at this time to further investigate how such requirements could be enforced.

9 Quality management approaches for airtightness

9.1 Motivations for implementing quality management approaches

Several professional builders have implemented specific quality guidelines to deal with airtightness in the construction process, although this may have implied profound changes in their prior technical measures and organisational scheme (Bodem, 2012; Coulter et al., 2012; Sikander, 2012; Kauppinen et al., 2012b; Zhivov et al., 2012; Juricic et al., 2012; Yoshino, 2012). We have identified four major motivations behind their initiative, which are detailed below.

9.1.1 Securing the expected performance – Making good airtightness predictable

Project owners or builders aiming at improving building or ductwork airtightness often get frustrated in their first attempts. In fact, 90% of the envelope or the ductwork can be remarkably well designed and realized for excellent airtightness, but if the remaining 10% is poorly treated, the result can be very far from expectations.

Quality management is one key to overcome this problem. In France, based on third-party testing results, this scheme gives good results. Figure 7 compares results obtained on French buildings where an approved quality management approach has been implemented (8 applicants, 94 measurements) with 1792 measurements extracted from “authorized testers” database. Although the building is heavily biased towards low-energy buildings (Leprince et al., 2011), Figure 7 shows the quality management benefits as the airtightness is both better (lower average value, curve is more to the left), and more predictable (smaller standard deviation, curve step is steeper). To gain better confidence in this statement, an evaluation (with controls performed by state technicians on houses that benefit from this measure) is underway (see Juricic et al., 2012).

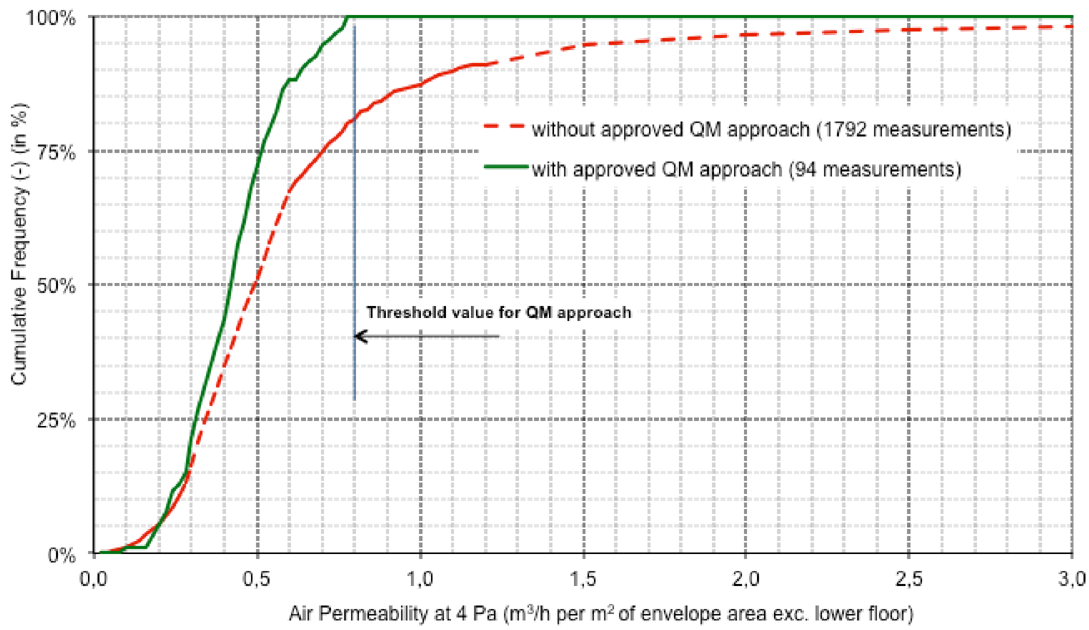

Figure 7: Distribution of measured airtightness of houses with and without implementation of an approved quality management approach (France). Green step is steeper, i.e. the range of airtightness values obtained is narrower. Source Leprince et al. (2011)

9.1.2 Comply with the energy performance regulation and get reward if applicable

Of course, securing the expected airtightness becomes more critical with minimum airtightness requirements included:

- in the regulation (e.g., the UK or the French regulation, since 2002 and 2012 respectively); or
- in building specifications (e.g., linked to a label such as Passivhaus, Minergie-P, Effinergie).

Since 2006, the French regulations rewards quality management approaches. In the French case, successful applicants for approval of their quality management system can use a better value than the default value in the energy performance calculation without systematic testing. (In practice, they test about 10% of their yearly production.) With the 2012 energy performance regulation, this will also be one path to prove compliance to the minimum airtightness requirements without systematic testing. A similar concept is also operational in Japan.

9.1.3 Contain costs and save on customer service

Table 6 gives a summary of cost estimates for reaching about n_{50} = 2.5 h^{-1} in the French context, including the quality management option. It does not integrate the cost for the development and implementation of the quality management approach; however, it points out the significant savings on energy and customer service[2], which alone can make the case to a builder to integrate quality principles in the construction process.

Cost estimates (in Euros exc. VAT)	
Cost for airtightness material and workmanship	500 to 1,000 €
Cost for airtightness testing	500 € (50 to 100 € on average on the yearly production with a quality management procedure, i.e., about 10% of the production is tested)
Estimated energy savings	30 to 150 € per year
Savings on customer service with a QM procedure	1,500 €

Table 6: Cost estimates for reaching 0.6 $m^3/h/m^2$ (about n_{50} = 2.5 h^{-1}) in new individual dwellings in France. The savings on the customer service are based on feed-back from builders who have implemented such approaches.

In fact, pioneering consultants in quality management approaches in the French regulatory context[3] have put forward savings on customer service on the order of 1,500 € with a proper implementation of quality principles for airtightness. This results from the extra care given to the design and execution of building details. Of course, airtightness represents only one piece

[2] Customer service covers all works that are performed under guarantee upon customer request—e.g., door and window adjustments, sealing of water leaks, touch-up of paint scratches, etc.

[3] Since 2006, the French regulation has introduced a scheme for approved QM approaches for airtightness that allows the applicant to claim a given airtightness level without systematic testing. The QM approach is developed by the applicant and must be approved by the ministry in charge of construction. See Carrié et al. (2010) or Leprince et al. (2011) for an overview of this scheme.

of the puzzle to improve the overall building quality. However, according to the parties involved, when dealt with properly in the building process, this piece has a significant positive influence on the other building concerns, including window and insulation installation, treatment of thermal bridges, ventilation airflow rates, etc.

Finally, although there is no scientific evidence of this, it seems reasonable to assume that quality approaches implying a well-designed and implemented airtightness strategy are more likely to remain effective in time than last- minute remedial actions. This may also have a significant impact on customer service costs.

9.1.4 Stay one step ahead of competitors

With secured airtightness levels, possible benefits in energy performance regulations, and cost containment, airtightness quality management can clearly help professional project owners being competitive. One or several of these reasons mostly explain why several builders have engaged in these approaches despite the workload and changes induced with their development.

In general, these builders also use this to promote their companies, and thereby win on several sides to stay ahead of their competitors.

9.2 The role of airtightness tests in quality management approaches

9.2.1 Intermediate voluntary site controls

It is well-known that it is very risky to wait until the end of the construction to find out if airtightness has been correctly dealt with (Bodem, 2012). In fact, once finished, it is usually much more difficult to correct defects than during the construction phase. For this reason, it is advised to perform envelope pressurisation tests during the construction and to seal the leaks that have to and can be sealed. This practice becomes fairly common for envelope airtightness for building professionals aiming at low-energy targets. Also, experience shows that such tests are very instructional for designers and workers as they better realize the weak points and ways for improvements in their contribution. Such tests can be encouraged for instance through pilot projects supported at national or regional level.

9.2.2 Towards quality management approaches

Intermediate and final testing make a first step into quality management: Checking and Acting (corrections applied) will in turn lead professionals to better Plan and Do (Figure 8).

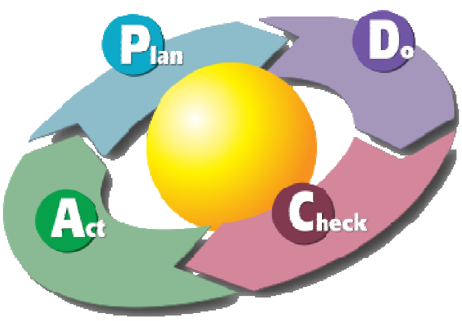

Figure 8: Schematic representation of the PDCA cycle (source: Wikipedia)

To deepen this concept, schemes are operational in Japan (since about 1992) and in France (since 2006 and both for envelope and ductwork in that country starting in 2011) to give credit to approved quality management approaches by introducing the possibility to claim for a better value than the default airtightness value in the EP-calculation, without performing systematically a test.

Symbol	Term	Task
P	Plan	Establish objectives and processes in accordance with expected results, detail specifications, plan work foreseen
D	Do	Do work according to plan
C	Check	Check actual results against expected results
A	Act	Take corrective actions in case of discrepancy between actual and planned results

Table 7: Steps of the PDCA cycle.

10 Significant knowledge gap in building airtightness durability

Ideally, envelope airtightness should not degrade significantly over the years. This means that the durability should be taken into account when drawing details, choosing and assembling products, and operating the building. Work is obviously needed is this area but short-term actions could improve significantly the situation.

To our knowledge, the information regarding building airtightness durability is very limited. There are a few studies where airtightness measurements have been performed within a time interval of several months or years. These may show reasonably stable air leakage levels (Erhorn-Kluttig et al., 2009); or on the contrary, significant deviations from original value with the building age (Hansén, 2012), or season (Borsboom and de Gids, 2012; Yoshino, 2012). However, there are no detailed analyses regarding the key parameters influencing airtightness durability.

In fact, such analyses entail a number of difficulties to correctly determine influencing factors, including:

- Design options
- Product choice
- Product assembly
- Building operation and maintenance
- Building environment and climate

Of course, these factors are usually highly correlated—e.g., design options will have a great influence on product choice or the accessibility of the airtight layer.

Therefore, envelope airtightness durability is obviously a very complex field of study (Ackermann, 2012; Hansén, 2012; Michaux et al., 2012), but the good news is that there are ways to make progress with the steps listed below:

1. Documenting appropriate design options. The construction details developed in the MININFIL project (additional information at http://www.cete-lyon.developpement-durable.gouv.fr) is one example of such initiative. While imperfect at this stage since such approach can only rely on experts statements that have little long-term feedback, it gives a collection of examples which are expected to lead to a good airtightness but

which can evolve as users' feedback is organized and analysed. A complementary initiative could be to document common design mistakes;

2. Developing adequate test methods for seals. A method and device has been developed in Germany to test the fatigue of adhesives due to wind stress with artificially aged samples at 65°C and 80 relative humidity, which should be used as the basis for justifying the durability requirement in the German regulation (Ackermann, 2012). This is to our knowledge the only test method that addresses this issue. In other words, as of today, a designer or contractor cannot select product based on their quality in terms of durability since there is no standardized method to test those products. In addition, he does not even know if the product will remain effective 1 or 50 years;
3. Documenting and demonstrating good assemblies, and controlling them on site. Experience shows that workers' training is fundamental because airtightness requirements often calls into question their traditional methods. For this, videos or site demonstration are highly appreciated. Documenting the implementation of the products according to their specifications and construction details also proves to be useful;
4. Including recommendations in buildings' users guide. It is well-known that the occupants can seriously affect envelope leakage. The impact varies considerably with the design of the airtightness layer—e.g., whether or not it can be punctured when installing pieces of furniture. While users' guide are more and more considered necessary in low-energy buildings (for instance, it is required in the French Effinergie+ label), these could easily include some information to prevent inappropriate actions or minimize their impact on the air permeability.
5. Including checks when the energy certificate is re-issued. Sweden has an interesting periodic inspection scheme for ventilation systems (Andersson, 2012) which could inspire the development of periodic checks for the envelope leakage. Because building airtightness or ventilation system characteristics can affect significantly the building's energy use, it seems worth exploring whether such scheme can converge with energy performance certificates. Besides, since in Europe, these are valid for 10 years at most, there could be a great opportunity to use this framework to monitor changes in leakage levels.

Figure 9: Apparatus developed in Germany to test the durability of adhesives under alternating loads. Each tape is attached to weight that periodically puts the tape under stress (see Ackerman, 2012).

11 Conclusions

This review shows that market transformations on building airtightness are underway in various contexts. Although there may be allowances for non-systematic testing, the common ground behind these trends is that tests must be performed to justify for a given airtightness level. It also draws the attention to carefully design a competent tester scheme both to avoid discredit on the testing approach with unreliable tests and to monitor the application of the requirements or recommendations. Our analyses further underline the convergence between quality approaches for building airtightness and leakage tests.

The information gathered in this paper, the analyses of pros and cons of various approaches, as well as the suggested options for further or new developments stem from discussions with many stakeholders and experts, for which the AIVC-Tightvent airtightness international workshop held in March 2012 has been a cornerstone. Beyond the workshop participants, this has drawn interest from parties involved in airtightness compliance framework and competent tester schemes developments. Obviously, fostering exchanges remains key to allow benchmarking for revised or new schemes to improve building airtightness.

12 References

[1] Ackermann, T. 2012. “Alternating loads – a method for testing the durability of adhesives in air tightness layers”. Proceedings of the AIVC-TightVent international workshop, 28-29 March 2012, Brussels, Belgium. pp. 61-66.

[2] AFNOR GA P 50-784. 2010. *Performance thermique des bâtiments. Guide d’application de la norme NF EN 13829 : 2001*. Février 2010.

[3] Afshari, A., Bergsøe, N.C. 2012. “Philosophy and approaches for airtightness requirements in Denmark”. Proceedings of the AIVC-TightVent international workshop, 28-29 March 2012, Brussels, Belgium. pp. 39-44.

[4] AIVC-TightVent. 2012. “Achieving relevant and durable airtightness levels: status, options and progress needed”. Proceedings of the AIVC-TightVent workshop, 28-29 March 2012, Brussels, Belgium.

[5] Andersson, J. 2012. “Can we learn from the Swedish quality approach to ductwork airtightness and the regular inspection of ventilation systems?” Proceedings of the AIVC-TightVent international workshop, 28-29 March 2012, Brussels, Belgium. pp. 95-101.

[6] Association Minergie. 2007. *Directive pour les mesureages de la perméabilité à l’air dans les constructions Minergie-P et Minergie*. Janvier 2007. 20 pp., http://www.thech.ch/files/inhalte/Messanleitung_2007_f.pdf, also available in German.

[7] Bodem, M. 2012. “From the drawing table to the implementation of appropriate construction details on site”. Proceedings of the AIVC-TightVent international workshop, 28-29 March 2012, Brussels, Belgium. pp. 147-151.

[8] Borsboom, W. and de Gids, W. 2012. “Seasonal variation of facade airtightness: field observations and potential impact in NZEB”. Proceedings of the AIVC-TightVent international workshop, 28-29 March 2012, Brussels, Belgium. pp. 77-84.

[9] Carrié, F.R., Charrier, S. and Leprince, V. 2010. “Implementation of measurement and quality frameworks in the French regulation for achieving airtight envelopes”. Proceedings of the AIVC conference. Seoul, Korea. Paper n° 6A -3.

[10] Carrié, F.R., Rosenthal, B. 2008a. “An overview of national trends in envelope and ductwork airtightness”. *AIVC Information Paper VIP* . n°29, August 2008, 6 pp.,

http://www.aivc.org/medias/pdf/Free_VIPs/VIP29_Airtightness.pdf, http://www.asiepi.eu/wp-5-airtightness/information-papers.html.

[11] Carrié, F.R., Wouters, P., Heijmans, N., Rosenthal, B., Aurlien, T., Guyot, G., 2008b. *Ways to stimulate a market transformation of envelope airtightness. Analysis of on-going developments and success stories in 4 European countries*. Web event, 12th December 2008, http://www.asiepi.eu/wp-5-airtightness/web-events/web-event-1.html

[12] Coulter, J. et al. 2012. “New construction energy efficiency programs in the United States – lessons learned from two quality management programs”. Proceedings of the AIVC-TightVent international workshop, 28-29 March 2012, Brussels, Belgium. pp. 163-171.

[13] De Gids, W. and Borsboom, W. 2012. “Philosophy and approaches for airtightness requirements in the Netherlands”. Proceedings of the AIVC-TightVent international workshop, 28-29 March 2012, Brussels, Belgium. pp. 3-8.

[14] Delmotte, C., and Laverge, J. 2011. “Interlaboratory tests for the determination of repeatability and reproducibility of building airtightness measurements”. Proceedings of the AIVC-TightVent conference. Brussels, Belgium. pp. 183-187.

[15] Delmotte, C. 2007. “Mesurer l’étanchéité à l’air des bâtiments selon la norme NBN EN 13829 : quelques precisions”. *Les dossiers du CSTC*, n° 1/2007, 4 pp. Janvier 2007.

[16] DIN 4108-7. 2011. *Thermal insulation and energy economy in buildings - Part 7: Air tightness of buildings - Requirements, recommendations and examples for planning and performance*. Beuth Verlag (2011).

[17] EN 13829. 2001. *Thermal performance of buildings. Determination of air permeability of buildings. Fan pressurization method*. CEN.

[18] EN 15242. 2007. *Ventilation for buildings — Calculation methods for the determination of airflow rates in buildings including infiltration*. CEN.

[19] EnEv. 2009. Energy saving ordinance (EnEV) *“Verordnung zur Änderung der Energieeinsparverordnung“* of 29 April 2009. Bundesgesetzblatt (BGBl.) Jahrgang 2009 Teil I, Nr. 23, S. 954-989.

[20] Erhorn-Kluttig H., Erhorn H., Lahmidi H. 2009. *Airtightness requirements for high performance buildings*, Information Paper n° P157, March 2009, 5 p., http://www.buildup.eu/publications/5656, http://www.asiepi.eu/wp-5-airtightness/information-papers.html

[21] Erhorn-Kluttig, H. Erhorn, H. 2012. “Philosophy and approaches for airtightness requirements in Germany”. Proceedings of the AIVC-TightVent international workshop, 28-29 March 2012, Brussels, Belgium. pp. 9-18.

[22] European Union. 2010. “Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast)”. *Official Journal of the European Union*. 18 June 2010. L 153/13-34.

[23] Hansén, M. 2012. “Changes in airtightness after 10-20 years”. Proceedings of the AIVC-TightVent international workshop, 28-29 March 2012, Brussels, Belgium. pp. 67-75.

[24] ISO 9972. 2006. *Thermal performance of buildings – Determination of air permeability of buildings -- Fan pressurization method.*

[25] Juricic, S., Boithias, F., and Biaunier, J. 2012. “Lessons learnt from the qualification of airtightness testers and regulatory QM scheme in France”. Proceedings of the AIVC-TightVent international workshop, 28-29 March 2012, Brussels, Belgium. pp. 111-119.

[26] Kauppinen, T., et al. 2012a. “Philosophy and approaches for airtightness requirements in Finland”. Proceedings of the AIVC-TightVent international workshop, 28-29 March 2012, Brussels, Belgium. pp. 45-57.

[27] Kauppinen, T., Nissinen, K, Möttönen, V. 2012b. "The development of quality guidelines in Finland". Proceedings of the AIVC-TightVent international workshop, 28-29 March 2012, Brussels, Belgium. pp. 153-162.

[28] Leprince, V. et al. 2011. "Quality Management Approach to Assess Buildings Air-tightness - Requirements and Checking". Proceedings of the AIVC-TightVent conference. Brussels, Belgium. pp. 104-106.

[29] Liddament, M. 2012a. "Philosophy and approaches for airtightness requirements in the UK". Proceedings of the AIVC-TightVent international workshop, 28-29 March 2012, Brussels, Belgium. pp. 19-27.

[30] Liddament, M. 2012b. "UK experience with quality approaches for airtight constructions". Proceedings of the AIVC-TightVent international workshop, 28-29 March 2012, Brussels, Belgium. pp. 103-110.

[31] Michaux, B., Loncour, X. Mees, C. "The DREAM project - Assessing the durability of envelope airtightnesss". Proceedings of the AIVC-TightVent international workshop, 28-29 March 2012, Brussels, Belgium. pp. 85-91.

[32] Sherman, M, and Palmiter, L. 1995. "Uncertainties in Fan Pressurisation Measurements". *Airflow Performance of Building Envelopes, Components and Systems*. ASTM STP 1255, M.P. Modera and A.K. Persily, Eds. American Society for Testing and Materials, Philadelphia. 1995. pp. 266-283.

[33] Sherman, M.H., Walker, I.S. 2012. "Philosophy and approaches for airtightness requirements in the USA". Proceedings of the AIVC-TightVent international workshop, 28-29 March 2012, Brussels, Belgium. pp. 29-37.

[34] Sikander, E. 2012. "A method to ensure airtightness of the building envelope". Proceedings of the AIVC-TightVent international workshop, 28-29 March 2012, Brussels, Belgium. pp. 175- 181.

[35] Tilmans, A., Van Orshoven, D. 2009. "Belgium: Impact, compliance and control of legislation". International Workshop on Impact, compliance and control of energy legislations. 8 pp. http://www.buildup.eu/system/files/content/P174_Belgium_Impact_compliance_control_ASIEPI_WP3.pdf.

[36] Walther, W, Rosenthal, B. 2009. *Airtightness testing of large multi-family buildings in an energy performance regulation context*. ASIEPI information paper#165.

[37] Yoshino, H. 2012. "System for ensuring reliable airtightness level in Japan". Proceedings of the AIVC-TightVent international workshop, 28-29 March 2012, Brussels, Belgium. pp. 121-128.

[38] Zhivov, et al. 2012. "Achieving good airtightness in new and retrofitted army buildings". Proceedings of the AIVC-TightVent international workshop, 28-29 March 2012, Brussels, Belgium. pp. 129-145.

13 Annex

First day, Wednesday March 28 2012

09:30-10:00 Introduction

- *Context, challenges and opportunities regarding airtightness*, Peter Wouters, INIVE EEIG, Belgium

10:00-11:15 Session 1: Philosophy and approaches regarding airtightness requirements: country views

- *Philosophy and approaches for airtightness requirements in the Netherlands*, Willem De Gids, VentGuide, Netherlands / Wouter Borsboom, TNO, Netherlands
- *Philosophy and approaches for airtightness requirements in Germany,* Heike, Erhorn-Kluttig, IBP, Germany
- *Philosophy and approaches for airtightness requirements in the UK*, Martin Liddament, VEETECH, UK

11:30-13:00 Session 2: Philosophy and approaches regarding airtightness requirements: country views

- *Philosophy and approaches for airtightness requirements in the USA*, Max Sherman, LBNL, USA
- *Philosophy and approaches for airtightness requirements in Denmark,* Alireza Afshari, Sbi, Denmark
- *Philosophy and approaches for airtightness requirements in Finland*, Timo Kauppinen, VTT, Finland
- *Airtightness requirements: a lawyer point of view*, Rik Honoré, Belgium

14:00-15:30 Session 3: Durable airtightness performance: what we know and where we need to go

- *Alternating loads – a method for testing the durability of adhesives in air tightness layers*, Thomas Ackermann, University of Applied Sciences, Minden, Germany
- *Changes in airtightness after 10-20 years*, Magnus Hansén, SP Technical Research Institute, Sweden
- *Seasonal variation of facade airtightness: field observations and potential impact in NZEB*, Willem De Gids, VentGuide, Netherlands / Wouter Borsboom, TNO, Netherlands
- *The DREAM project - Assessing the durability of envelope airtightness*, Benoit Michaux, BBRI, Belgium

14:45-16:45 Session 4: Structured discussion: Pros and cons of various approaches for airtightness requirements - Recommendations and pitfalls to avoid

- *Reasons behind the new approach to requirements in the energy performance regulation RT 2012*, Jean-Christophe Visier, CSTB, France

16:45-17:15 Inspiring experience

- *Can we learn from the Swedish quality approach to ductwork airtightness and the regular inspection of ventilation systems*?Johnny Andersson, Ramböll, Sweden

Second day, Thursday March 29 2012

09:00-10:40 Session 5: Dealing with airtightness in the construction process: reliable airtightness testing and reporting

- *UK experience with quality approaches for airtight constructions*, Martin Liddament, VEETECH, UK
- *Lessons learnt from the qualification of airtightness testers and regulatory QM scheme in France*, Florent Boithias / Sarah Juricic, CETE de Lyon, France
- *The Japanese airtightness certification framework for builders and testers*, Hiroshi Yoshino, Tohoku University, Japan
- *Achieving good airtightness in new and retrofitted army buildings*, Alexander Zhivov, USACE, USA
- *Initial ideas for achieving reliable airtightness assessment in the Belgian context*, Xavier Loncour / Peter Wouters, BBRI, Belgium

11:00-12:30 Session 6: Dealing with airtightness in the construction process: reliable airtightness testing and reporting

- *From the drawing table to the implementation of appropriate construction details on site*, Mario Bodem, Ing + Arch, Germany
- *The development of quality guidelines in Finland*, Timo Kauppinen, VTT, Finland
- *United States New Construction Program Comparison – Can a Quality Management Program Guarantee Heating and Cooling Costs of $1 Per Day*? Jonathan Coulter, Advanced Energy, USA
- *A method to ensure airtightness of the building envelope*, Eva Sikander, SP Technical Research Institute, Sweden
- *Initial ideas for achieving reliable airtightness assessment in the Belgian context*, Xavier Loncour / Peter Wouters, BBRI, Belgium

12:30-13-15 Workshop conclusions

- *Highlights of the workshop and next steps within AIVC and TightVent,* Peter Wouters / Rémi Carrié, INIVE, Int.

The Air Infiltration and Ventilation Centre was inaugurated through the International Energy Agency and is funded by the following countries:

Belgium, Czech Republic, Denmark, France, Germany, Greece, Italy, Japan, Republic of Korea, Netherlands, New Zealand, Norway, Portugal, Sweden and United States of America.

The Centre provides technical support in air infiltration and ventilation research and application. The aim is to provide an understanding of the complex behaviour of the air flow in buildings and to advance the effective application of associated energy saving measures in both the design of new buildings and the improvement of the existing building stock.

Air Infiltration and Ventilation Centre
Operating Agent and Management
INIVE EEIG
Lozenberg 7
B-1932 Sint-Stevens-Woluwe
Belgium

www.aivc.org
Tel: +32 2 655 77 11
Fax: +32 2 653 07 29
inive@bbri.be
www.inive.org