



**KTH Architecture and  
the Built Environment**

## Advances in Thermal Insulation

- Vacuum Insulation Panels and Thermal Efficiency  
to Reduce Energy Usage in Buildings

Thomas Thorsell

Doctoral thesis  
Stockholm  
March 2012

KTH Royal Institute of Technology  
School of Architecture and the Built Environment  
Department of Civil and Architectural Engineering

Advances in Thermal Insulation - Vacuum Insulation Panels and Thermal Efficiency to Reduce  
Energy Usage in Buildings

Thomas Thorsell

© Thomas Thorsell, 2012

ISRN KTH-BYT/R-12/205-SE

ISSN 1651-5536

ISBN 978-91-7501-261-2

KTH Royal Institute of Technology  
School of Architecture and the Built Environment  
Department of Civil and Architectural Engineering  
Division of Building Technology  
Brinellvägen 23, SE-100 44 Stockholm

## Preface

After a long and winding road, this thesis is finally completed. The research that this thesis is based on has allowed me to work with an exceptionally broad spectrum of subjects through great many types of research ranging from microscopy and mathematical modeling to wall testing in chambers and in the field. In this text, I discuss such diverse matters as super insulation in the form of vacuum insulation panels, gas diffusion through multi-dimensional defect grids, thermal performance indicators for walls such as thermal efficiency and energy equivalent R-value.

I would like to thank my supervisors that have been involved, who have provided me with the opportunity to continue my work and to reach a doctoral degree. My Licentiate work was done at KTH on Vacuum Insulation Panels under the supervision of Prof. Gudni Jóhannesson after which I moved to Syracuse University to continue my work under the supervision of Prof. Mark Bomberg and Prof. Jianshun Zhang. Circumstances ended the USA endeavor after 3.5 years without the sought after doctoral degree which I have now finished at KTH under the supervision of Prof. Folke Björk and Prof. Mark Bomberg using pieces of research that I have collected from the work I have done through the years.

I would also like to express my appreciation to Professor emeriti Ove Söderström and Christer Sjöström who have not been directly supervising but been supportive and always interested.

I will not dedicate this text to anyone, in the end it was just another thing that had to be done, but I must recognize the wonderful family I have. I could not have done it without your support ©

Stockholm, 2012

A handwritten signature in black ink, appearing to read 'Thomas Thorsell', with a stylized, flowing script.

Thomas Thorsell

(Blank)

## Abstract

We are coming to realize that there is an urgent need to reduce energy usage in buildings and it has to be done in a sustainable way. This thesis focuses on the performance of the building envelope; more precisely thermal performance of walls and super insulation material in the form of vacuum insulation. However, the building envelope is just one part of the whole building system, and super insulators have one major flaw: they are easily adversely affected by other problems in the built environment.

Vacuum Insulation Panels are one fresh addition to the arsenal of insulation materials available to the building industry. They are composite material with a core and an enclosure which, as a composite, can reach thermal conductivities as low as  $0.004 \text{ W/(mK)}$ , or less. However, the exceptional performance relies on the barrier material preventing gas permeation, maintaining a near vacuum into the core and a minimized thermal bridge effect from the wrapping of barrier material round the edge of a panel.

A serpentine edge is proposed to decrease the heat loss at the edge. Modeling and testing shows a reduction of 60% if a reasonable serpentine edge is used. A diffusion model of permeation through multilayered barrier films with metallization coatings was developed to predict ultimate service life. The model combines numerical calculations with analytical field theory allowing for more precise determination than current models. The results using the proposed model indicate that it is possible to manufacture panels with lifetimes exceeding 50 years with existing manufacturing.

Switching from the component scale to the building scale, an approach of integrated testing and modeling is proposed. Four wall types have been tested in a large range of environments with the aim to assess the hygrothermal nature and significance of thermal bridges and air leakages. The test procedure was also examined as a means for a more representative performance indicator than R-value (in USA). The procedure incorporates specific steps exposing the wall to different climate conditions, ranging from cold and dry to hot and humid, with and without a pressure gradient. This study showed that air infiltration alone might decrease the thermal resistance of a residential wall by 15%, more for industrial walls.

Results from the research underpin a discussion concerning the importance of a holistic approach to building design if we are to meet the challenge of energy savings and sustainability. Thermal insulation efficiency is a main concept used throughout, and since it measures utilization, it is a partial measure of sustainability. It is therefore proposed as a necessary design parameter in addition to a performance indicator when designing building envelopes. The thermal insulation efficiency ranges from below 50% for a wood stud wall poorly designed with incorporated VIP, while an optimized design with VIP placed in an uninterrupted external layer shows an efficiency of 99%, almost perfect. Thermal insulation efficiency reflects the measured wall performance full scale test, thus indicating efficiency under varied environmental loads: heat, moisture and pressure.

The building design must be as a system, integrating all the subsystems together to function in concert. New design methodologies must be created along with new, more reliable and comprehensive measuring, testing and integrating procedures. New super insulators are capable of reducing energy usage below zero energy in buildings. It would be a shame to waste them by not taking care of the rest of the system. This thesis details the steps that went into this study and shows how this can be done.

Key words: Vacuum insulation panels, VIP, serpentine edge, thermal bridge, composite film, gas diffusion, defect dominated, holistic approach, building enclosure, integrated testing and modeling, energy equivalent, field performance, air flow, thermal insulation efficiency

## Sammanfattning

Allt fler människor börjar så smått inse att vi faktiskt påverkar klimatet genom våra utsläpp, som kan relateras till den ökande energianvändningen och den pågående industrialiseringen i världen. Många länder har också satt upp mål för framtida energibesparingar. Eftersom en stor del av den energi vi förbrukar används i byggnader är byggsektorn ett naturligt mål för besparingar. För att nå uppsatta mål för energibesparing, inom byggandet, måste förbättringar ske i varje del av byggnaderna, från det lilla till det stora. Vidare måste perspektiven breddas från material och komponentfokus till en helhetssyn på hela byggnaden som ett system, där alla delar måste samverka för att minska energiförbrukningen.

I det lilla, på materialnivå, tas en ny typ av isolering upp, nämligen vakuumisoleringspaneler (VIP), vars isolerande förmåga är 6-8 gånger bättre än traditionell fiberisolering. VIP:ar består av ett kärnmaterial som innesluts av en gastätt skal. Den höga isoleringsförmågan uppnås genom att gasen i kärnmaterialiet extraheras så att ett lätt vakuum skapas, därav namnet vakuumisoleringspanel. Inkapslingen består oftast av kompositfilmer med flera lager plastfilm, vissa metalliserade med ett tunt ytskikt i t ex aluminium. Eftersom den låga värmekonduktiviteten hos en panel är beroende av det låga trycket i kärnan, avgör gasinträngningens hastighet också panelens livslängd. Vanligtvis anses en panel ha fallerat om värmekonduktiviteten i dess mitt överstiger ett visst gränsvärde, ofta  $8 \text{ mW}/(\text{m}^2\text{K})$ . Optimalt för livslängden vore att använda en inkapsling av solid metall som anses vara helt gastät. Men eftersom skalet även måste omsluta kanterna på panelen skulle ett skal av solid metall skapa stora extra värmeförluster vid panelens kanter, alltså lokala köldbryggor. Om inte panelerna är väldigt stora skulle en sådan metallkant i de flesta fall neutralisera hela den termiska vinsten av vakuumpaneler.

De fyra första artiklarna, som ligger till grund för denna avhandling, behandlar olika aspekter av VIP. De två första, artikel I och II, behandlar en alternativ kantlösning designad för att minska effekten av värmeförlusten vid panelkanten. Den föreslagna kanten har formen av en serpentin. Här visas genom numeriska simuleringar och genom laborietester att en serpentinkant kan minska värmeförlusten med mer än 50 % jämfört med en traditionellt rak kant av samma material och tjocklek. Vidare visas genom numeriska simuleringar att en serpentinkant i 0.1 mm rostfritt stål närmar sig värden jämförbara med de mest använda barriärfilmerna, men det krävs fler än tjugo serpentin. Svårigheten med serpentinkanterna är tillverkningen, främst i panelens hörn.

De bästa filmer som användes då studien, presenterad i artikel III, gjordes (2005) innehöll dubbla metalliseringslager, vilket ansågs vara optimalt för låg värmeförlust runt kanten och acceptabel livslängd. Livslängden för en, inte alltför liten panel bedömdes till 20-30 år i IEA Annex 39 projektet (IEA, 2005a). Som tidigare nämnts är det gasens diffusionshastighet genom skalet in i kärnan som avgör livslängden hos en panel, varför modeller för diffusion genom barriärer med flera metallbeläggningar studerades i artikel III. Litteraturstudien visade att det är korrekt att anta att gas diffusionen sker i första hand genom defekter i metalliseringslagren. I en film med flera separata metallbeläggningar sker alltså diffusionen först genom defekterna i ett första metalliseringslager, för att sedan fördelas i substratfilmen och åter koncentreras för att passera genom defekterna i det andra metalliseringslagret och så vidare genom hela filmen. Det visade sig att de få modeller som fanns för defektkontrollerat flöde genom kompositfilmer med mer än en metallisering utgick från kraftiga förenklingar avseende både defekternas form, storlek och inbördes avstånd. I artikel III presenteras en modell som tar hänsyn till både defektstorlekarna och inbördes avstånd dem emellan. Modellen baseras på ett antagande att gaskoncentrationen är konstant genom hela substratet på ett avstånd av en substrattjocklek från mitten av defekten, en konstant koncentrationscylinder. Detta antagande förankrades i resultat från numerisk modellering,

som antydde att ett sådant antagande inte skulle introducera alltför stora fel. Modellen kombinerar numerisk modellering av flödesmotstånd mellan defekten och denna cylinder av konstant koncentration och den analytiska lösningen för dipoler i fält. Modellen visade lovande resultat när dessa jämfördes med uppmätta resultat, den visade även rimliga skillnader jämfört med tidigare förenklade modeller. Under arbetet karakteriserades även metalliseringar från en vakuumpanel för att skapa en bild av kvalitén i metallbeläggningen. Det visade sig att det var stora kvalitetsskillnader hos de olika metallbeläggningarna i den film med dubbla lager som utvärderades. Den förbättrade modellen som utvecklats under detta arbete indikerar att om kvalitet hos den bästa beläggningen kunde uppnås hos båda metalliseringslagren så kan gastransporten halveras och som följd vakuumpanelens livslängd väsentligt förlängas.

I den sista artikeln som behandlar vakuumpaneler, artikel IV, ersätts den enskilda vakuumpanelen av en hel byggnad. Här tas ett helhetsgrepp på hur vakuumpaneler kan integreras i byggnader och vilka krav som då ställs på panelerna. Speciellt två olika motstridiga krav diskuteras: motsättningen mellan att minimera värmeförlusten vid kanten och livslängden som redan diskuterats ovan. En liknande motsättning finns mellan isoleringsförmåga och hållfasthet. Vill man använda en vakuumisolering i ett sandwichelement måste antingen ytterelementen fästas mot vakuumpanelen med lim eller liknande, vilket medför att panelen måste kunna ta upp de laster sandwichelementet utsätts för. Alternativt kan de två ytterelementen sammanfogas i den yttre randen av en kassett, vilket gör att laster kan tas upp utan att vakuumpanelen däremellan belastas. I detta fall kommer sammanfogningen runt randen skapa ytterligare värmeförluster förutom de som redan finns inbyggda i vakuumpanelen, alltså ytterligare en köldbrygga.

Då ett superisolerande material används i en konstruktion kommer effekten av en eventuell köldbrygga att förstärkas på grund av den stora temperaturgradienten som uppkommer över ett tunt material med låg värmekonduktivitet (høgt värmemotstånd). Vakuumpanelen med dess egenskaper som gasbarriär kommer dessutom, om den placeras i ett lager i en vägg, att till stor del förhindra luft- eller fuktkflöden. Det flöde som sker kommer att koncentreras till de glipor som bildas mellan panelerna. Effekter på grund av luftflöden genom väggkonstruktioner är av stor vikt i det arbete som presenteras i de tre sista artiklarna V-VII.

Många av de metoder som idag används för att termiskt karakterisera material och konstruktioner bygger på metoder som endast ger medelvärden, såsom calibrated eller guarded hot box eller motsvarande för material. De flesta standardtesterna utförs dessutom under konstant temperaturförhållanden utan tryck- eller fuktlast. Många gånger resulterar testerna i ett värde för värmemotstånd (R-value i USA), eller i Europa, ett U-värde (värmetransmissionskoefficient) för en vägg eller en värmekonduktivitet för ett material. Uppmätt under stationära förhållanden kan ett sådant värde möjligen användas för att i teorin jämföra prestanda, men värdena reflekterar sällan verkligheten i fält. Detta har även visat sig genom att forskare funnit avvikelser mellan förutsagd (beräknad) och uppmätt prestanda (Brown et al., 1993, Said et al., 1997). Trots begränsningen i använda testmetoder används resultaten ofta för beräkningar av termisk prestanda hos material, byggdelar och hela byggnader.

För att komma förbi dessa begränsningar föreslås ett integrerat tillvägagångssätt, i artikel V, som kombinerar testning och modellering. Målet med metoden är att i ett första steg skapa en prestandaindikator för värmeisolerande förmåga hos ett material som visar mer än basprestanda uppmätt under optimala förhållanden. I steg 2 kan mätdata från den föreslagna proceduren användas till att verifiera en sk HAM-modell, som sedan kan användas för dynamiska beräkningar av termisk prestanda under dynamisk last.

I den föreslagna metodiken ersätts de medelvärdesmätande metoderna med lokala mätningar med sensorer, strategiskt placerade för att fånga det termiska beteendet hos den testade komponenten. För att motsvara de större klimatologiska belastningarna en vägg utsätts för har en testprocedur som innehåller fyra steg föreslagits. Motivering till det valda testprogrammet är ämnet för artikel V där bakgrunden presenteras till varför en alternativ testmetod är nödvändig. Där finns också en utförlig motivering för varje individuellt steg. De fyra huvudstegen beskrivs endast i korthet nedan:

I det första steget bestäms värmemotståndet under stationära förhållanden. Den enda signifikanta lasten är en temperaturgradient från insidan till utsidan. Den relativa fuktigheten hålls nominellt på 50 % på insidan; avsikten är att mäta väggens basprestanda avseende värme, det vill säga samma värde som kan mätas med något av de tidigare nämnda standardtesterna. Det uppmätta värmemotståndet från steg 1 utgör även basen för den reducerade isoleringsförmågan i de följande teststegen. Alltså, den försämring som uppmäts i de följande stegen anges som procent av det värde som uppmäts i steg 1.

Temperaturskillnaden och fuktförhållanden bibehålls och kompletteras med ett övertryck av 50 Pa på utsidan, vilket skapar potential för luftflöde i motsatt riktning till värmeflödet. Målet med det andra steget är att mäta isoleringsprestanda då det finns en potential för luft att flöda igenom väggen.

I steg 3 vänds temperaturgradienten men tryckpotentialen bibehålls, det vill säga riktningarna hos luft- och värmeflödet sammanfaller. Det utvändiga klimatet representerar i steg 3 ett varmt och fuktigt klimat och används som en fuktkälla. I och med steg 3 blir förändringarna dynamiska. Därför behövs ett mellansteg då förhållandena i komponenten tillåts stabiliseras innan belastning och mätning i steg 3 påbörjas.

I steg 4 återställs förhållandena till desamma som i steg 2 för att mäta hur väl komponenten återhämtar sig efter uppfuktning.

Tester enligt det ovan beskrivna programmet utfördes på fyra olika typer av väggar som används i USA, två som är vanliga i bostadshus och två som används i industriella byggnader. Uppmätta försämringsgraden under steg 2 spände mellan 3% till 14% för de två väggarna avsedda för bostadshus. Motsvarande värden för industriväggarna var mellan 8% och 14%. Ytterligare resultat på väggtyperna avsedda för bostadshus presenteras och diskuteras i artikel VI och resultat från testerna på de industriella väggarna presenteras i artikel VII, där även ett antal felkällor som kan uppstå vid väggtester i klimatkammare diskuteras.

I de avslutande kapitlen av denna avhandling diskuteras, med avstamp i resultat från utförda tester både på vakuumpaneler och på väggsektioner, hur viktigt det är med en helhetssyn på byggnader för att kunna skapa ett hållbart byggande, som bl a innefattar att spara energi och material. Som ett mått på hur effektivt isoleringen i en konstruktion används, föreslås att begreppet isoleringseffektivitet används som komplement till det redan använda U-värdet. Isoleringseffektivitet kan definieras som det verkliga, numeriskt beräknat eller uppmätt värmemotstånd, delat på det nominella värmemotståndet utan inverkan av degraderande effekter. Genom numeriska beräkningar påvisas att ett lager med vakuumpaneler genombrutet av träreglar, som i en uppreglad vägg, har en isoleringseffektivitet lägre än 50 % medan ett isoleringslager som placeras obrutet på utsidan av reglarna närmar sig 99 % – det kan alltså inte bli så mycket bättre. Indirekt ger isoleringseffektivitetsvärdet även ett mått på en aspekt av hållbart byggande, eftersom det krävs en jämförelsevis mindre mängd isolering för att uppnå ett givet U-värde om isoleringen appliceras med en hög effektivitet. Isoleringseffektivitet kan användas för att på ett alternativt sätt se på resultaten från de presenterade fullskaletesterna, vilket då ger effektiviteten under olika typer av klimatlast: värme, fukt och tryck.

(Blank)

## List of Included Papers

This thesis is based on the following included papers;

---

- Paper I. **Edge Loss Minimization in Vacuum Insulation Panels.**  
*Thomas Thorsell and Ingemar Källebrink.*  
*Published in Proceedings of the 7th Nordic Building Physics Symposium, IBRI / KTH, Reykjavik, Iceland, June 13-15, 2005, pp. 945-952.*  
Ingemar did his master thesis on the subject under co-supervision by me and he thereby collected some of the literature and served as a discussion partner when this article was written.
- Paper II. **Edge Loss Minimization in Vacuum Insulation Panels**  
– Model Verification.  
*Thomas Thorsell.*  
*Published in Proceedings of the Third International Building Physics Conference, Concordia University, Canada, August 27-31, 2006, pp. 251-256.*
- Paper III. **A Hybrid Model for Diffusion Through Barrier Films with Multiple Coatings**  
*Thomas Thorsell.*  
*Published in Journal of Building Physics Volume 34 Issue 1, April 2011*  
*First published online November 18, 2010*
- Paper IV. **Integrating vacuum Insulation Panels in Building Constructions:**  
– An Integral Perspective  
*Martin J. Tenpierik, Johannes J.M. Cauberg, Thomas I. Thorsell.*  
*Published in Construction Innovation, 2007; vol. 7: pp. 38 – 53.*  
This article was written in collaboration with colleagues from the IEA annex 39 on vacuum insulation. My portion of writing was focused on the technical, primarily thermal, aspects of VIPs.
- Paper V. **Integrated Methodology for Evaluation of Energy Performance of the Building Enclosures – Part I: Test Program Development**  
*Mark Bomberg and Thomas Thorsell*  
*Published in Journal of Building Physics, July 2008; vol. 32, 1: pp. 33-48.*  
This article gives background and motivation to the test protocol and the measurement setup that was used. I am the second author for this article because others did much exploratory work leading up to the test procedure before I got involved but I am responsible for the final procedure.
- Paper VI. **Integrated Methodology for Evaluation of Energy Performance of Building Enclosures – Part II: Examples of Application to Residential Walls**  
*Thomas Thorsell and Mark Bomberg.*  
*Published in Journal of Building Physics, July 2008; vol. 32, 1: pp. 49-65.*  
All the testing, modeling and writing of the draft paper was done by me under the supervision of Prof. Bomberg, who also laid his hand upon the final wording of the document.
- Paper VII. **Integrated Methodology for Evaluation of Energy Performance of the Building Enclosures: Part 3 – Uncertainty in Thermal Measurements**  
*Thomas Thorsell and Mark Bomberg.*  
*Published in Journal of Building Physics, July 2011; vol. 35, 1: pp. 83-96.*  
I did all the testing, modeling and writing the draft paper under the supervision of Prof. Bomberg, who laid his hand upon the final wording of the document.

## Other related publications by the author

### 1.1.1 Licentiate Thesis

---

#### **Advances in Thermal Insulation in Buildings - Means to Prolong Service Life.**

**Thomas Thorsell**

*School of Architecture and the Built Environment, Div. of Building Technology. Stockholm, KTH – The Royal Institute of Technology. October 2006.*

### 1.1.2 Peer reviewed international conference papers

---

#### **OSB Sheeting with Integral Water Resistive Barrier.**

**Thorsell, Thomas and Mark Bomberg.**

*BEST 2: A New Design Paradigm for Energy Efficient Buildings. Portland, Building Enclosure Council-BEC Portland, April 12-14, 2010*

#### **The Need for Evaluation of Energy Performance of Building Enclosures**

**Thomas Thorsell and Mark Bomberg.**

*Healthy Buildings 2009, 9th International Conference & Exhibition. Sept 2009*

#### **Energy Performance R-Value: Part 1 - Development of Integrated Evaluation Methodology for Building Enclosures.**

**Mark Bomberg and Thomas Thorsell.**

*BEST 1: Building for Energy Efficiency and Durability at the Crossroads. Minneapolis, Building Enclosure Council BEC-Minnesota. June 10-12, 2008*

#### **Integrated Methodology for Evaluation of Energy Performance of the Building Enclosures; Part 2: Examples of Application to Residential Walls.**

**Thomas Thorsell and Mark Bomberg.**

*BEST 1: Building for Energy Efficiency and Durability at the Crossroads. Minneapolis, Building Enclosure Council BEC-Minnesota. June 10-12, 2008*

## Table of Contents

<b>Preface .....</b>	<b>III</b>
<b>Abstract.....</b>	<b>V</b>
<b>Sammanfattning.....</b>	<b>VII</b>
<b>List of Included Papers.....</b>	<b>XI</b>
<b>Other related publications by the author .....</b>	<b>XII</b>
<b>Table of Contents .....</b>	<b>XIII</b>
<b>Chapter 1: Introduction.....</b>	<b>1</b>
1.1 General context.....	1
1.2 Comfort - durability – economy .....	4
1.3 Sustainable engineering.....	5
1.4 What is being done by society to reduce energy usage in buildings? .....	6
1.5 How do we go about making the necessary progress? .....	6
1.6 Aim of the research.....	9
1.7 Outline of the thesis.....	14
1.8 Nomenclature .....	15
1.9 Acronyms .....	17
<b>Chapter 2: Air as an insulator has reached its useful limit.....</b>	<b>19</b>
2.1 Introduction.....	19
2.2 Physics of thermal insulation, thermal transport.....	19
2.3 New insulation materials and other energy preserving approaches .....	21
2.4 Vacuum Insulation Panels .....	26
2.5 Service Life Time .....	27
2.6 Thermal Performance of VIP .....	32
2.7 Polymer and coated polymer film barriers.....	36
2.8 Modeling of gas transmission through barrier films with dual coatings .....	44
2.9 VIPs in buildings.....	47
<b>Chapter 3: Integrated Testing and Modeling .....</b>	<b>51</b>
3.1 Literature study.....	51
3.2 Enclosure component testing.....	76
<b>Chapter 4: Discussion.....</b>	<b>93</b>
4.1 An holistic Approach and Sustainable Engineering.....	93
4.2 Thermal Insulation Efficiency .....	96
4.3 Definition of Insulation Efficiency .....	96
4.4 Effects of Thermal bridges.....	99
4.5 Effects of Air leakages .....	101
<b>Chapter 5: Conclusions.....</b>	<b>103</b>
5.1 Material Scale .....	103
5.2 Component scale .....	104
5.3 Building Scale .....	104
<b>Chapter 6: Future work .....</b>	<b>107</b>
6.1 Vacuum insulation panels .....	107
6.2 Integrated testing and modeling .....	108
<b>Personal Reflection .....</b>	<b>111</b>

<b>References .....</b>	<b>113</b>
<b>Summary of included articles .....</b>	<b>121</b>
Vacuum Insulation Panel (VIP) .....	121
Wall Component Performance .....	124

## Appendices

Paper I	<b>Edge Loss Minimization in Vacuum Insulation Panels.</b>
Paper II	<b>Edge Loss Minimization in Vacuum Insulation Panels</b> – Model Verification.
Paper III	<b>A Hybrid Model for Diffusion Through Barrier Films with Multiple Coatings</b>
Paper IV	<b>Integrating vacuum Insulation Panels in Building Constructions:</b> - An Integral Perspective
Paper V	<b>Integrated Methodology for Evaluation of Energy Performance of the Building Enclosures – Part I:</b> Test Program Development
Paper VI	<b>Integrated Methodology for Evaluation of Energy Performance of Building Enclosures – Part II:</b> Examples of Application to Residential Walls
Paper VII	<b>Integrated Methodology for Evaluation of Energy Performance of the Building Enclosures - Part III:</b> Uncertainty in Thermal Measurements

# Chapter 1: Introduction

## 1.1 General context

As an outcome of the BEST<sup>1</sup> conference in 2008 a white paper was produced to clarify the current status of the building industry and what development needed to take place in order for us to meet the increasing demand for sustainability. The authors, (Bomberg and Onysko, 2008), wrote:

*“The building industry is at a crossroads and the question is where do we go from here? The “green” train has left the station but the tracks are still being built. At the far end there is an ALA<sup>1</sup> commitment to achieving a 2030 carbon neutral future (and improvement in the existing building stock). At the beginning, just outside the station, there is a lot of good will but also a realization that the majority of existing highly inefficient buildings will be with us well beyond 2030”.*

During the last few years, writers from different countries searching for mobilization of social and technological progress coined different terms, such as zero energy housing, zero emission, energy efficiency, or zero carbon balance etc. We will use the term "Sustainable Engineering<sup>2</sup>" (SE) as we are coming to the realization that for buildings, in addition to the need for limiting energy use, there is a need for better control of air pollution, air and water flow (including rain) and sustainable and healthy material use. Sustainable Engineering requires a new paradigm for design. We do not design assemblies anymore; we design buildings as systems with a focus on the contribution of materials and assemblies, while considering the use of the space and the impact upon the environment. Seldom have science and socio-economic considerations led us to the same conclusions. We must address challenges in many fields where the built environment is yet a small but important part.

These include:

- a) climate change
- b) renewable resources - sustainability
- c) energy efficiency - energy conservation
- d) comfort - durability - economy
- e) name it - there is a need for sustainable engineering.

### 1.1.1 Climate change

Current warming of the surface temperature on Earth is larger than what natural variations can explain; scientists can see that the changes currently taking place are very much larger than the natural changes that took place before the start of the industrial revolution. Furthermore, there is a clear correlation between, on the one hand, the level of industrialization of the world with increasing usage of fossil fuels and increasing amounts of greenhouse gases in the atmosphere, and on the other hand the increasingly warmer climate (Riebeek, 2010).

The global trend has been to use energy in steadily larger amounts: not only do most countries use more energy per capita, but also the global population is constantly increasing. We, humankind, just do what we have always done. Energy usage at the dawn of civilization is described by Cook (Cook, 1971). About 1 million years ago, before we knew how to control fire, we only consumed the energy embodied in the food we ate. As we evolved to become hunters we had more food

---

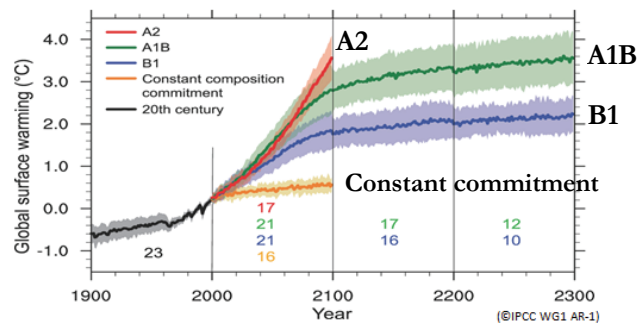
<sup>1</sup> American Institute of Architects

<sup>2</sup> Center for Sustainable Engineering is a partnership of Syracuse University, Carnegie Mellon University, University of Texas at Austin, Arizona State University, and Georgia Institute of Technology.

available to us, and we began to use fire for warmth. Thus, man consumed burning fuel in addition to increased amounts of food (Riebeek, 2010).

About 5000 B.C primitive agricultural man had learned to grow crops and keep animals for food and work. As long as man only used energy from the food he ate, he consumed about 2000 kcal per day, which was an increase of 18% per capita. Primitive man consumed about 2000 kcal per day, but by the end of the low-technology era, about 1870, the consumption in England was up to about 70 000 kcal daily per capita in total energy. In the 1970's the consumption per person per day in the US peaked at 230 000 kcal. The Energy statistics published by International Energy Agency (IEA) reported the primary energy usage in the world to be 6 115 million tons of oil equivalent (Mtoe) in 1973 and the population was then 3 937 million people, hence the global average per capita per day consumption was 42 550 kcal (1 toe = 107 kcal) to be compared with 230 000 kcal in the US. Today the global average is 50 250 kcal per person per day, which is an increase of 18% per capita; however, the global population has increased by 70% as well and the total increase in global energy consumption was well above 100% from 1973 to 2008 (IEA, 2010).

The noticeable climate change and the trend of increasing energy usage have raised concerns for the future. To evaluate the impact of our continually increasing energy usage, and emissions thereof, future consumption of fossil fuels and resulting greenhouse gas release was modeled under the Intergovernmental Panel on Climate Change (IPCC). Different development scenarios were used to predict global effects on the climate (IPCC, 2007). The modeled scenarios predict the global mean temperature to increase between some few degrees up to 6 °C until 2100. Graphs for the temperature increases for a few selected scenarios are shown in Figure 1. The most severe scenario shown, predicts roughly a fourfold increase in emission release and it describes a scenario of humanity continuing to burn more and more fossil fuels as the global population increases, and the world develops. The bottom graph shows a constant composition scenario, with a stabilization of greenhouse gas release into the atmosphere at the year 2000 levels, hence, no additional emission after 2000 and still there is an increase in temperature.



**Figure 1: Predictions of future global mean temperature increase as predicted by the IPCC.**

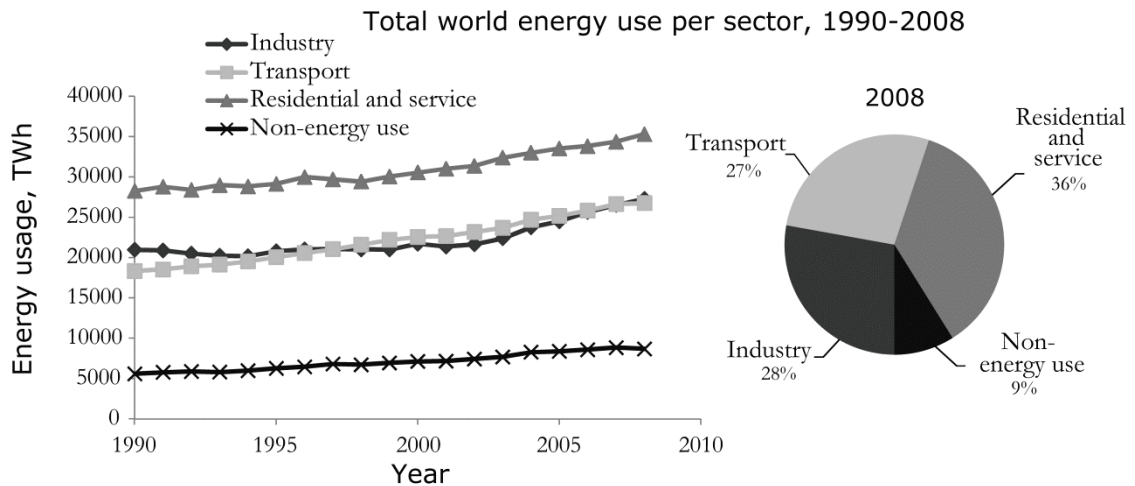
The IPCC modeling shows that it is not sustainable to continue along the current path, Figure 1, even if we stopped the release of greenhouse gases today, we will still see serious effects on the climate.

#### **1.1.1.1 Renewable resources – sustainability**

The function of a building remains the same as many years ago, while today the demands on the level of comfort has risen, the acceptance of poor indoor air quality is becoming extinct, the green trend calls for minimal usage of nonrenewable resources. Sustainability is the name of the game today.

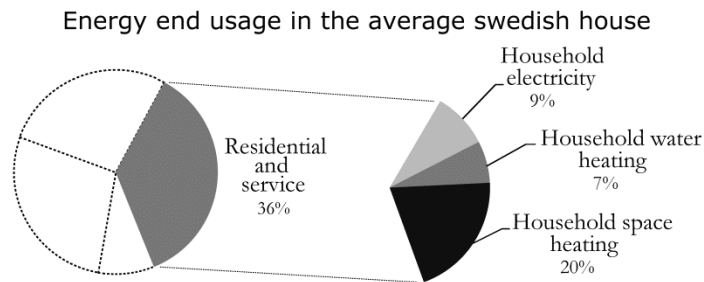
### 1.1.1.2 Energy efficiency - energy conservation

The building sector consumes more energy than what is used for transportation, as can be seen in Figure 2.



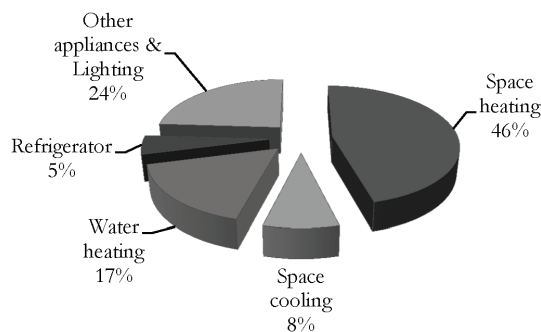
**Figure 2: The trends in energy usage separated into usage sectors.**

The amount of energy used in buildings in 2008 was about 35 000 terawatt-hour (TWh) globally. Locally, both the usage and the amount of energy vary; it is adapted to regional needs. In colder regions more energy is used for heating, while in warmer regions the amount of energy used for cooling is becoming more significant.



**Figure 3: Energy end usage in an average house in Sweden.**

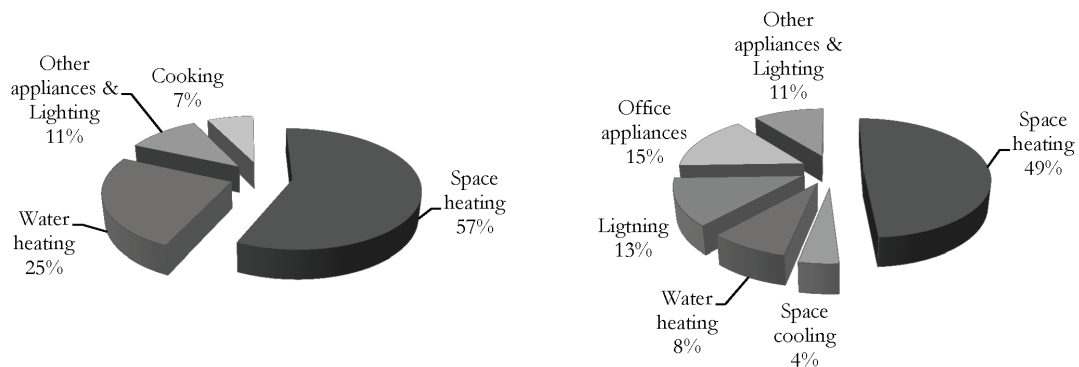
For example, in Sweden about 55% of the energy used in buildings. This is the equivalent of 20% of the total energy used in the country is used for space heating, Figure 3. In the US 46% of the energy used in buildings is used for heating and 8% for cooling, Figure 4. However, heating and cooling sums up to 54% being used for space conditioning in the US much like in Sweden.



**Figure 4: Delivered Energy End-Uses for an Average U.S. Household (left) in 2001 (EIA, 2004).**

Averaged across the EU the portion of the total energy used for space conditioning is 57% (heating) for housing and 53% (heating and cooling) for commercial buildings, Figure 5.

Even though they are invisible in the statistics that the present graphs are built upon, one must realize that portions of the energy placed in other sectors may also add to heating or cooling loads. For heated spaces excess heat dissipated from appliances and equipment may help heating the space, while in a cooling situation the excess heat may add to the cooling load. In appliances and equipment most of the energy is in its final form transformed into heat, which is released to the surrounding atmosphere. The conclusion is that the actual amount of energy used for space conditioning may be greater than the numbers indicated here.



**Figure 5: Energy consumption in buildings in the European Union, source (IEA, 2005b).** The Pie chart to the left show energy consumption for residential buildings in the EU and commercial buildings are represented in the chart to the right.

Large amounts of materials are used to construct buildings; hence, using minimum amounts of renewable materials with low embodied energy content in buildings results in a large potential to reduce total energy usage for construction; in a similar manner improving thermal performance of building enclosures will reduce energy usage for heating and cooling throughout the building for its usable life.

## **1.2 Comfort - durability – economy**

The buildings in society are a natural focus for several reasons; we spend a large portion of our lives indoors, in buildings, thus a large portion of our comfort is dependent upon our buildings and building systems.

### **1.2.1 Comfort, indoor environment, indoor air quality, human well-being and performance**

The indoor environment is again a broad term encompassing the physical, social and psychological environment in a building. Comfort is a subjective measure of how a human experience the indoor environment and is closely linked to air and surface temperatures, air velocity, indoor air quality etc. The indoor environment has a strong relation to energy performance since a large proportion of the building's energy consumption is used to amend the indoor environment particularly the indoor climate and the air quality. The definition of acceptable indoor environment that will be suitable for a particular purpose is therefore very important, as this is a key component of the specification for a building and a strong factor influencing the energy usage. A higher restriction indoor climate is often more energy consuming to maintain.

### **1.2.2 Durability**

The durability issue is linked to energy usage by degradation of materials and ultimately failure. For a vacuum panel it is obvious since the difference in performance between a good panel and a failed

panel is significant while for many other insulation materials the change may be a subtle creeping change that is not so obvious but still deteriorating the performance of the material and hence affect the thermal performance. The service life times of materials that degrade in a creeping fashion are rarely discussed even though the changes and the increase in energy loss may be significant.

### 1.2.3 Economy

A set performance requirement may be met by many conceptually different designs. It is the constraints placed upon the design, together with design team's experience, that will decide on the final design. There are limitless constraints many hard and measurable such as maximum allowed cost of erecting the building, maximal energy usage, maximum physical size and so on, but also soft constraints, hard to measure, such as the aesthetic beauty of the building, its fit into existing building styles and so forth.

## 1.3 Sustainable engineering

There are many scales in the built society, and energy saving is the requirement for all. It was established, above, that between 50-60% of the energy used in buildings is used for space conditioning. It is already established that we need to reduce the energy consumption globally, and that it seems like the building enclosure is a good starting point, but saving energy is not enough. We must do so maintaining good indoor environments and without depleting other natural resources, thus the development must be sustainable. Sustainable development has been defined as...

*"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs."*

...in the Bruntland Report, (WCED, 1987). For a building to be sustainable, it must be designed to use the least possible amounts of resources throughout its entire service lifetime. All of a sudden, the field of focus expanded tremendously. Not only must the day to day resources (mostly energy and water) used in the building be minimized, but also resources used for constructing the building. Important issues related to sustainability are:

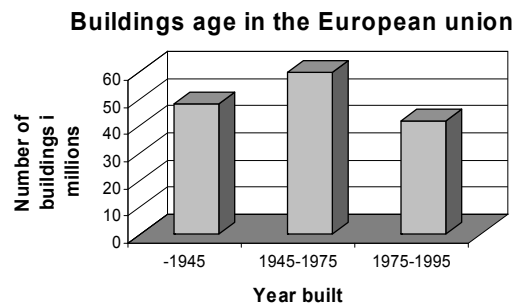
- The embedded energy in the materials
- energy used for transports, as well as
- the end usage of the building material after the building has been torn down;

To minimize resources, in the case of insulation for example, does not only require thickening the insulation layer to minimize energy usage. It also requires applying the insulation in such a way that the amount of insulation material used is minimal in relation to its performance, hence, the efficiency of the insulation must be maximized and the factors of its manufacture must be included in the whole.

To get to grips with this complex challenge a paradigm shift must take place in the building industry. It is a must to move away from thinking of a building as an assembly of independent components and instead start to design building systems looking at the combined performance of the building envelope, and the building systems, as well as the surroundings. Applying engineering practices to design building systems with sustainability in mind is the way of the future; Sustainable Engineering is in our best interest for the future.

## **1.4 What is being done by society to reduce energy usage in buildings?**

In context of the new European Product Directive for Buildings, the energy performance demands on new and existing buildings are increasing. If we assume that it is only the energy marked as heating energy that actually does the task of heating then, according to the IEA annex 39 report produced in part B of the project (IEA, 2005b), the European Union used 210 Mtoe of energy for space heating in 1997. It is stated further that this energy is used by the existing building stock which totals 150 million buildings in Europe, see Figure 6. New buildings erected are about 1-2% of the existing building stock, hence 1.5 to 3 million new buildings are erected every year.



**Figure 6: Millions of buildings built up to the year 1995 summed by building year, source (IEA, 2005b).**

The amount of new buildings every year is so small compared to the existing building stock that it would take centuries for improved insulation technologies to impact the total heating energy demand by only modifying the design of new buildings. Existing buildings are a major factor that needs to be addressed if the requirement of reduced energy usage is to be met.

### **1.4.1 How are increased demands met in the individual building?**

It is clear that buildings use large amounts of energy for space conditioning, thus, reducing heat loss through the enclosure is the most cost effective measure for reduced energy consumption. This is true in new construction and when renovating existing buildings; a fact already incorporated into the European Energy Regulation, a regulation considering a high degree of thermal insulation in the building enclosure as granted and a prerequisite to advance to more sophisticated energy saving measures (Papadopoulos, 2005). Papadopoulos further states that advanced insulation materials are necessary to meet the new stricter limits.

It is a challenge, but there are a few simple steps, in theory, to save on energy used for space heating:

1. Make the building envelope air tight
2. Insulate the building enclosure better
3. Recover the energy in the ventilation air

The next stage of reducing the impact buildings have on the environment would be to find renewable sources for those small amounts of energy buildings, improved according to the above list, would need to maintain the indoor climate.

## **1.5 How do we go about making the necessary progress?**

The components themselves must be improved by the use of better materials and designs that are more efficient as well as the integration between them. This matter must be addressed in every step

of the building process; during the design phase as well as actual construction of the building, when workmanship becomes a key issue. A poorly built house with a great design is likely to perform worse than a poorly designed house perfectly built. Quality must be sought both during design and during construction to meet the high set of standards needed. The end user also has a final impact on energy consumption as they may choose to use the building as designed or not, if not, it may result in excessive energy usage. If possible, automatic controls should be included in the design and barriers to misuse of the space should be embedded.

### **1.5.1 Improvements on every scale**

A traditional approach to enhance thermal performance of a building envelope is simply to increase the thickness of the insulation layer. This approach has limitations though; economical due to reduced living space if insulation is added on the inside of an existing building, or possible need for a new façade if the building is insulated on the outside. The option of external insulation may not be possible due to local building regulations, while the option of adding insulation to the inside may not be economically viable. The whole design of sustainable buildings must be seen as an organic creation. The entire building is a system and, as such, is part of a society system, meaning the city. All parts of the planet are subsystems of the planet itself. The buildings within the cities are themselves subsystems of the city subsystem of the overall planetary system. When viewed like this it becomes obvious that harmonization and optimization are necessary at every step on the scale. Some means must be devised to ensure harmonization of all components to enable them to become functional parts of the system they are placed in, from the overall system down to the smallest component system of the overall system.

#### ***1.5.1.1 Material scale***

Most traditional insulation materials are based on the isolative property of stationary air (e.g. air-based materials) fibers are added to prevent motion in the air. To develop insulation materials better than the air based, hence, with lower thermal conductivity, a number of techniques can be used. Some involves replacement of the gas contained in the material, addition of materials than can absorb radiation or create scattering, dispersing the radiation, or even evacuation of all air within the material. Each of these measures is aimed at reducing one or more of the thermal transport mechanisms: conduction, convection and radiation. One available, well known, example of a successful technology is the insulative multi pane window; low emission coatings are used to reduce radiative thermal transport and to reduce the conduction as well as the convective thermal transport, the entrapped air is replaced with low conduction gas less prone to convection. Another good example is the Thermos® flask, which utilize vacuum between two surfaces, since the gas between the two surfaces is evacuated, there cannot be any convection or conduction. The only transfer mechanism remaining is by radiation between the two surfaces which is minimized by polishing the two surfaces.

#### ***1.5.1.2 Component scale***

Components can and will become better in their own right by the use of new and improved materials and improved combinations. There will also be new components coming on to the market. A number of new components are discussed in section 2.3 were polymer skins and vacuum insulation glazing are discussed as two examples. However, it is not enough to improve only the component itself but manufacturers and designers should also be thinking about how the component will fit into the system already during research, development and design.

Some method must be devised to ensure the development of components, which go into any systems, will harmonize with the other components within those systems. The building industry should peek at other specialized industries that has developed in our society, where few

manufactured items are created all in one place by one craftsman. Materials and parts, which go into modern systems, come from many different manufacturers around the globe. The ISO 9000 and 9001 system of classifying helped to make it possible to match parts from anywhere. A similar approach could be a path forward in the building industry as well. However, it must be taken one step further and new categories of 9000 and 9001 need to be created for sustainability of parts which will go into buildings. If this is done properly, it can be extended to every manufactured item in the world. In this way all manufacturers around the world, and manufacturing countries, will be able to participate in global trade of their manufactured items. If the ISO 9000 and ISO 9001 systems of measurement were extended to cover sustainability, it would require a little more time for the assessment of the compliance within individual companies. However, that time would be well spent, because the ability to communicate detailed and exact true descriptions all the way up to the architect designing the building would result in more sales for companies that comply, assurance that design features will work with available parts, and a new sustainable standard of manufacturing.

#### ***1.5.1.3 Building scale***

However, the most important step is that a building cannot be looked upon as an assembly of non-interacting individual components instead it must be looked upon as the complex system it is. We can no longer ignore what happens in the spaces between components nor can we ignore the interdependence between sub systems within the building. For example, if the enclosure is improved then it is plausible that a smaller heating system can be used. Another example, slightly more complex, is that if the material of the inner layer of the wall has a large thermal capacity then it is possible to passively prevent large temperature swings but only if the temperature control system allows for some temperature swings, otherwise the wall will never load and unload.

### **1.5.2 Holistic approach**

A building envelope contains many different components; walls, doors, windows, roof and so on. Traditionally these parts have been seen as separate units and focus has been upon performance of the individual component while the interaction has been ignored. Joe Lstiburek, for one, showed that different parts of the building are interconnected by complex webs of leakage pathways with air flow driven by complex local air pressures, (Lstiburek, 2000). To meet the challenges of the future there must be a paradigm shift in attitude, and buildings must be looked upon as complex systems or large scale composites, not individual islands of performance with oceans of undefined and unaddressed matter between them. The previous idea of setting up a system to harmonize parts and systems becomes even more important in this context.

### **1.5.3 Workmanship**

Defects or imperfections in a construction, irregularities such as undefined volumes of air, leakage ways or closed drainage paths, create a stochastic variable, which is loosely dependent on the workers skill. This is referred to as workmanship. The list of possible deviating from the perfect case is endless.

A poorly built house with a great design is likely to perform worse than a poorly designed house perfectly built. This is because the perfectly built house will, at least, fit together well, with all the integrated systems perfectly aligned, especially if the parts in the systems and the systems themselves meet the new standards for sustainability and harmonization. The poorly built house, on the other hand, will have leaks and drafts and mismatched systems that cannot work together even as well as they were designed to do. Quality must be sought both during design and during construction to meet the high standards needed.

#### 1.5.4 End users

Another source that strongly effects the energy consumption of a building is the behavior of the final inhabitants, or users, of the building. One may not ignore the variation in interior loads created by the users of the building. There is no way to accurately predict their behavior, there are statistical approaches but it is impossible to accurately predict the behavior of a group of users in an office building or a family in advance.

#### 1.5.5 In the future

In the future as existing state of the art technologies improve and new technologies emerge, there may very well be a switch to self-supportive and energy producing buildings; but we are not there yet. The path could be by continuously improving our buildings; the steps could be:

1. Create a passive house through careful holistic design addressing every aspect of the building optimizing its geometry, enclosure, services, external environment utilizing solar energy, window placement and so on.
2. Utilize low grade energy such as geo-solar with seasonal storage
3. Move to renewable energy by solar panels and hence produce energy

Existing work, including this thesis, shows that we still have work to do in mainstream construction on 1 and 2.

### 1.6 Aim of the research

I have been interested in building construction and how buildings work as long as I can remember. I applied for my first building permit when I was five or six years old. I wanted to build a tree-house and my dad would not allow me to start building until I applied to him for a permit. This was followed by a number of summer breaks spent at a local construction company helping with everything from drafting to setting out. My future path was already paved then.

Papadopoulos states that advanced insulation materials are a prerequisite to achieve the set forth goals (Papadopoulos, 2005) of the European Union. There are a number of materials with lower thermal conductivity (advanced insulation) than traditional insulation materials, vacuum insulation panels is one example with about 6-8 times lower thermal conductivity than traditional air/fiber based insulation, Aerogel is another example. Vacuum Insulation builds on the same technology as in the Thermos® flask utilizing vacuum and could be one viable option for improving the thermal enclosure of our buildings; but it comes with its own set of challenges.

I studied civil engineering through graduate level with a minor in structural engineering and a major in building technology at the same time as I was working in our family consulting firm dealing with all aspects of building construction. It was in the final year of my master studies in an advanced course in building physics, when I realized that I was good at doing research and enjoyed it. I was given the opportunity to get involved with several international projects, all dealing with saving energy in buildings in one way or another. One of those projects was the project IEA Annex 39 on the subject of vacuum insulation panels.

During that project, I learned about various aspects of VIP, which was, at the time, a novel insulation material. There was a new material with better insulation properties of almost 10 times than the commonly used materials, and the question of if and how it could be used in buildings. It was understood that some of the keys to introduce VIP for use in buildings was the service life time and fragility of these panels.

A VIP is a composite with a flat core enclosed by an envelope preventing the core from filling with gas. The vacuum in the core is vital to push thermal conductivities down to the level of 0.004

W/(m·K). If the vacuum is lost the panel has reached the end of its service lifetime, and the thermal conductivity rises to about 0.020 W/(m·K). Metal sheets would be the preferred material to create an impermeable envelope but would create a large thermal bridge at the edges of the panel when it folds over them.

The problems were like puzzles, deeply involving. One path towards long service life is to use full metal enclosures, but then the thermal loss at the edges can ruin the overall performance of the panel. We had some experience with steel studs that was slotted to reduce the heat transfer, as most heat would be conducted along the metal skin, but then the length of the metal edge had to be made longer, and the serpentine edge was born.

#### *Aim of paper I and II*

***The aim of the research presented in the first portion of this thesis, paper I and II, was to find a way to reduce heat loss at the edge of a vacuum insulation panel. A serpentine edge was proposed and evaluated by numeric modeling and then by laboratory testing.***

The described edge effect may be dealt with on the material scale or the component scale. On the component scale multiple panels may be placed in a staggered pattern, (Ghazi Wakili et al., 2011), or by adding insulation layers adjacent to the vacuum panel, thus reducing the effects of the thermal bridge. On the material scale, the path of improvement may include the usage of other barrier materials or composites, reducing the thermal bridge or redesigning the edge.

In papers 1 and 2, the objectives were to optimize and evaluate such a serpentine edge design. We primarily wanted to prove the concept, and then let someone else manufacture it. As it turns out there exists a patent from 2001 on a range of designs which all aim at making the conduction path longer but it also stops further development effectively since manufacturers lose interest if they do not have the patent (Frederick, 2001).

Another direction in addressing the challenge of the thermal loss at the edge is taken in the development of the VIP barrier films. The development is towards using polymer based multilayer films incorporating very thin metal layers, metallization layers, or coatings. This creates barrier films with reasonably good barrier properties and only small thermal bridges. The challenge is that there are no gas diffusion models predicting the gas flux through such films with multiple coatings.

Existing models for flux through multi-coated films all assume that flux is only taking place through defects in the coating layers, that all defects are of the same size, and that all defects are positioned in square lattices.

It became clear that polymer barriers with multiple coatings was a promising technology which was thought to have potential to provide both a sufficiently air tight enclosure in combination with very limited extra heat transfer at the edges of the panel. In addition, it would be a more cost effective solution than a welded metal barrier. However, during the IEA project it was brought to the participants' attention that conventional methods for measuring permeability could not cope with such gas tight barrier films.

I was taking a course in mathematical modeling at that time, and soon realized that theories of resistance networks could be used to create a model for the gas diffusion through composite polymer films with multiple metallization layers incorporated into the matrix. A literature study on the matter showed that the diffusion was governed by the defects in the coatings, and that existing models addressing this type of films was using very coarse simplifications regarding defect sizes and positions. I saw a possible approach to the problem, and it led to the development of the hybrid model. Hybrid is referring to the fact that it combines numerical modeling for the diffusion

close to a defect in the coating with analytical field theory for the diffusion within the polymer substrate film. The objective for development of the hybrid model was to develop a tool for calculating gas diffusion through VIP barrier films. If the rate of gas diffusion through the barrier can be calculated, then the length of the service life can be estimated.

#### Aim of paper III

***The aim of the work leading up to paper III was to develop a model, which was more accurate than previously used models in predicting gas flux through multilayered films with more than one metallization layer.***

After a hybrid model has been proven, it can be used to evaluate and develop better barriers without having to make actual panels, and then test them in a long durability test. Instead, it is enough to characterize the materials and the coating quality of the film, and then calculate the diffusion, estimate service life, and continue. This is a much faster process of evaluation than durability testing.

In the path of searching for possible applications for VIP in the field of buildings, it was natural to look at placing VIP into other building components, such as doors, thin panels etc. The reason being that a panel with a polymer based enclosure is quite fragile. It is enough to step on it or lay it on top of a small rock or a nail to puncture it and immediately ruin it. Hence, it seemed like a good idea to protect the panels from the construction sites by incorporating them into other components at the factory. With this in mind, we explored the behavior of VIPs when incorporated into building components in paper 4, discussed later.

#### Aim of paper IV

***In paper IV and in the thermal efficiency chapter of this thesis the aim was to show how important it is to apply a holistic approach to the design of buildings in general and buildings and components in which vacuum insulation panels are integrated in particular.***

After working with VIP for several years, and finishing my Licentiate in January 2007 I wanted to switch over from materials research to look at the building in a larger scale. At a building conference in Montreal where I presented my second paper, I was approached by my co-supervisor Professor Mark Bomberg, and convinced to come to Syracuse University (SU) to research wall performance. My family and I moved there in the summer of 2008.

Here I was given the opportunity to join a research group who was working closely with industry on wall performance under heat, air and moisture loads. Some preliminary work had already been done with both modeling and full scale testing when I arrived, but the results were limited. At the time when I decided to make the move, there had been problems with externally insulated walls with stucco as a rain barrier. There had been numerous occasions with moisture and mold problems. This type of design was one that I believed would work very well, yet there were a lot of problems with it. Therefore, I was very interested in field performance especially under moisture loads. As I worked with what had been done previously at Syracuse University (SU) I came to realize that uncontrolled air flows could be one of the culprits in many of the Swedish cases. Therefore, air flows in and around building components became a main interest as a carrier of moisture.

All that was needed was a functioning model able to cope with simultaneous hygrothermal transports in combination with simultaneous natural and forced convection (HAM). Such a model could be used in combination with known material properties, known geometries, and known airflows. There was no model capable of the above available to the author, and there was little

knowledge concerning paths for air leakages, aside from the fact that they existed and they had an effect on the performance of the wall. I am no programmer, so instead my research was focused on airflows in walls, and the effect thereof, but still with future modeling in mind.

The research done within the research group at SU was done with a shotgun approach, walls were built with several components, and known defects were integrated into them. The walls were tested in a full-scale chamber under several steps with different loads similar to the procedure used for the tests presented in papers V-VII, discussed later. However since so many defects and components were incorporated into the test specimen, the produced data was very garbled, resulting in it being impossible to find cause-effect correlations.

#### Aims of paper V

***The aim of writing paper V was to give reasons for the chosen test methodology and argue for the benefits it brings over traditional averaging methods.***

***The first aim for the model development was to develop a test method, which would produce a performance indicator that more closely reflects the thermal performance of an assembly under service conditions than the currently used U-values (R-values used in North America). The other aim was to create a test procedure, which could be used, in medium scale testing to produce data for model validation.***

To get back on track it was decided to test the walls under very well defined conditions, which would allow the data to be used for model verification. A verified model could then be used to model the effects of the different defects, which were incorporated into the wall specimen in the first cases. By doing it this way the belief was that, more information of better quality would be gained. Such a model could also be used to model performance under different climates and different internal loads.

There was another need identified in the building market: the industry must move away from the simplified performance indicators that are being used today, such as U-values (R-value in the US) towards one that better reflects real performance. It was the realization that there are insulation materials that, in themselves, can cope with moisture by buffering (cellulose fiber), and others that create wind barriers by their properties (closed cell spray foam for example), while others need to be protected by separate wind or moisture barriers (mineral fiber insulation) to prevent system failure.

#### Aims of paper VI and VII

***The aim of the research reported upon in papers VI and VII was to test the developed test method by applying it on four different walls and seek verification for the assumptions that was made during the method development.***

A possible future usage of the approach, once an adequate model is available, could be as a standard test procedure, which produces a measure on how well a wall can cope with airflows and moisture, possibly with a base to which the reduction in thermal performance under the different loads is related to as thermal insulation efficiency. The performance of a wall design could be reported with a performance indicator, such as the U-value combined with the thermal insulation efficiency under dry steady state conditions. In addition, there could be two additional efficiencies one for efficiency reflecting performance when there is a pressure difference across the wall, and one after wetting and drying.

Aims for introducing thermal insulation efficiency

***The aim for introducing the concept of thermal insulation efficiency in the discussion chapter was to provide a quantitative indicator reflecting the degree of utilization of the insulation material. It is used to stress how important it is to design carefully to utilize materials to their full potential.***

These are facts that are not really communicated to the market today, especially not the end users who are to pay for the house in which these materials can be used. With such a more diverse performance indicator, buyers would be better informed and other systems would have a fair chance on entering the market. In the future of advanced building, it might be other aspects, aside from thermal insulation capacity, that govern the selection of material.

As the demands on building performance increase, buildings become more complex, and old materials are used in new configurations, or new materials are used, many times without satisfactory evaluation. Systems incorporating VIP can certainly move the performance of the building enclosure towards higher thermal resistances, or create equal thermal resistance in thinner constructions, but a holistic approach is necessary to optimize its overall performance and to prevent unnecessary risks.

For larger buildings new recurrent components may be built up and tested to ensure their performance as a system as well as the process of building it but for short series details or less expensive portions of a building enclosure the responsibility often lies upon the architect, structural engineer or building scientist to come up with working designs. The tools they rely upon are mostly experience and limited models. A large portion of the energy used in a building is used for heating and cooling in both cold and warm climates, therefore the precise evaluation of thermal losses and gains is a necessary first step towards improvement of building enclosures.

One example of limited thinking is the commonly used standard method for evaluating thermal performance of wall and roof assemblies, the so called hot box methods (guarded hot box and calibrated hot box). These methods determine average thermal performance under reference, steady state conditions. One can argue that determined under those conditions U-values (R-values in the US) represent a comparative indicator and are not designed to predict the real performance. Yet, those values are typically used in the energy analysis of buildings.

If the requirement of sustainability is applied the importance of using least amount of material comes into play the efficiency of the materials becomes more important since efficiency in combination with a performance indicator not only address how well a material perform the task assigned to it, but also how well utilized the material is.

When, for example, a super insulation material is placed in a wall system in an inefficient way, with thermal bridges or air leakages, the relative reduction in thermal efficiency would be greater than if less resistive traditional insulation was used. If used in a thought through design with high thermal efficiency and applied correctly the potential increase in over-all thermal resistance is substantial.

### 1.6.2 Scope

We must realize that the building is complex, it is a system placed in a larger system, like a city, placed in an even larger global system. Looking along the opposite direction of the scale a building is a composition of materials and subsystems working in synthesis to maintain a healthy and comfortable indoor environment. A building placed in a city will affect and be affected by surrounding infrastructure, which creates a microclimate different from the undisturbed climate outside the city. All issues raised in the list above are highly relevant to the built society but the rest

of the thesis does not deal with the political background or social issues but engineering solutions for building enclosures.

### ***1.7 Outline of the thesis***

The wide focus of this thesis is on improved performance of the building envelope since it has a large impact on the amount of energy used in buildings to maintain the indoor climate and buildings are responsible for a large portion of the total energy use in western countries.

Thus, the research presented in this thesis is on thermal performance of building enclosures on multiple scales. On the material level there are super insulating panels in the form of vacuum insulation panels (VIP), on the assembly scale the focus is on field thermal performance of a wall assemblies in contrast to its thermal performance determined under standard laboratory conditions.

In chapter 1 the focus goes from wide to narrow, starting in a global perspective and focusing on the building envelope in the end. The general context of why a reduction of energy is desired in the name of sustainability is described and some ideas on how to achieve the set goals are sketched.

The second and third chapter in this thesis reports on vacuum insulation panels and the full size wall testing in individual chapters by expanding upon the included articles. Each subject is treated as separate, with individual literature studies, methods and results.

In chapter 4 the results from the research presented in chapter 2 and 3 is used to underpin a discussion of future steps towards the ever-increasing global requirements. Thermal insulation efficiency is introduced as a means to quantify the efficiency of the thermal insulation layer in a chosen design. It is discussed how important a holistic approach is if we are to meet the challenge of energy savings and sustainability while maintaining good indoor environment and healthy buildings.

In chapter 5, the most important findings are summed up and a few final comments are made to point out conclusions that can be made.

Chapter 6 continues to propose a path of future research, and how it should build upon the findings presented here.

Finally, the research done herein is briefly reflected upon from a global but personal perspective in the last section: personal reflection.

## 1.8 Nomenclature

**Assembly:** Within the field of engineering assembly refers to a group of mated components before or after they are fitted together. Components in an assembly are not generally interdependent or interacting. If the components are interacting, the combinations of components should be referred to as a system.

**Building enclosure:** Refers to the whole system, or assembly of components that provides environmental separation between the conditioned space and the exterior environment.

**Building envelope:** Synonymous to building enclosure.

**Calibrated boundary layer (CBL):** The approach of using a calibrated boundary layer, as it was used in this research, was as an added layer of an insulation material on the surface of a wall sample. The author used 25 mm (1 inch) expanded polystyrene (EPS). The reason for using a CBL was to; on one hand allow for the usage of thermopiles made with the same material as the CBL without creating local three dimensional hygrothermal effects on the surface of the wall samples, and secondarily the CBL stabilized the conditions that affected the surface of the sample.

**Clear wall R-value:** Kosny and Christian (2001) describe the clear wall R-value as an estimation for the exterior wall area containing only insulation and necessary framing materials for a clear section of the wall without fenestration, corners, or connections between other envelope elements such as roofs, foundations, and other walls.

**Composite:** A composite is a complex material that is comprised of two continuous phases or materials, in the latter case, combined to produce structural or functional properties not present in any individual component. Examples of composite materials in the building industry are wood or fiberglass.

**EE-procedure:** the energy equivalence procedure.

**Film vs. Foil:** Film is used to describe very thin polymer sheets, which are the base material in many of the barrier composite films used for vacuum insulation panels. In this context the distinction is that a foil is a solid thin metal, the most common being aluminum foil, it is however, thicker than several molecules.

**Foil:** See Film vs. Foil

**Framing factor:** The term “framing factor” is widely used in the US to express a percent of the total wall area occupied by framing members (Kosny et al., 2001).

**Glass transition temperature:** Amorphous (non-crystalline) polymeric solids are either glasses or rubbers. The glass transition temperature,  $T_g$ , is the critical temperature that separates glassy behavior from rubbery behavior. Many amorphous solids such as polymers, organic liquids, biomaterials, some metals and alloys, and inorganic oxide glasses, exhibit glass transition temperatures. The dramatic change in the local movement of molecular chains at  $T_g$  leads to large changes in a host of physical properties, (Brandrup et al., 1999; 2005).

**Guarded hot box and calibrated hot box testing:** Typically one tests a wall section, 2.4 m x 2.4 m (8 ft. by 8 ft.) or larger, in either a guarded or a calibrated hot box that is placed tightly against the component on the room side. To perform a guarded hotbox measurement one must maintain a zero heat transport on all sides of the box, except through the tested wall. If this is not possible, a correction factor is determined as a function of temperature distribution and heat flux through the tested wall. This correction is applied to the measured necessary heat production inside the box to keep the temperature steady; hence, the assigned name “calibrated hot box”.

**Isohygron:** An isohygron is a contour line that connects points of equal moisture content.

**Nail popping:** Nail popping refers to the lifting or pulling of nail heads due to moisture and temperature movement in building materials (Platts, 1962). This may occur anywhere sheeting is attached to other materials by nails. The phenomenon is most easily observed in gypsum boards in houses where the gypsum sheeting has been fastened with nails.

**R-value:** The R-value is used as the measure for thermal resistance in the US. The R-value is related to both thermal conductivity and material thickness as  $R=d/\lambda$ . The R-value, as defined by ASHRAE, does not include surface transfer resistances when used for assemblies.

- **R-value in chapter 3** on testing full size walls represents air-to-air resistance to heat flow. It is an inverse of the U-value. Note that this definition is different from that used in ASHRAE. This definition permits us to avoid several measurements on the wall surface to establish an average surface temperature when multi-dimensional heat transfer causes large local differences.
- **Apparent R-value** in chapter 3 is a ratio between temperature differences between indoor and outdoor air to the local heat flux measured at the local point without subtracting the resistance of calibrated boundary layer (CBL).
- **Local R-value** in chapter 3 is a ratio between temperature difference between indoor and outdoor air to the local heat flux measured at the local point, when the resistance of calibrated boundary layer (CBL) is subtracted.

**System:** A system is group of interacting, interrelated, or interdependent elements forming a complex whole.

**Macro-pores<sup>3</sup>:** Pores with a diameter greater than 50 nm according to the IUAPAC classification for porous materials.

**Micro-pores:** Pores with a diameter less than 2 nm according to the IUAPAC classification for porous materials.

**Mean free path:** The mean free path in a gas is the probable length a gas molecule can travel before it collides with another molecule.

**Meso-pores:** Pores with a diameter of 2-50 nm according to the IUAPAC classification for porous materials.

**Thermal efficiency:** Thermal efficiency relates actual performance to maximum possible performance. Thermal Efficiency is defined in chapter 5.

**Thermopile:** A thermopile is multiple thermocouples connected in series' with junction points alternately placed on either side of a material with a known thermal conductivity through which heat flux will occur. The difference in temperature between the two sides (and the thermocouple junctions) will result in a voltage potential, which is quite linear to the heat flux. If more junctions are used then the signal will be stronger.

**U-value:** Overall heat transfer coefficient, (SI unit  $W/(m^2K)$ ).

**Vacuum insulation panels (VIP):** A Vacuum Panel is a composite of a core material in vacuum and a gas impermeable enclosure retaining that vacuum, together creating a panel with a

---

<sup>3</sup> In the hygrothermal analysis, the border between macro and micro-pores is the limit of validity of the Kelvin's law namely  $10^{-7}$  m or 100 nm. The difference between 50 or 100 nm is not significant but the meso-pores (that have a critical impact on freeze-thaw durability) in hygrothermal analysis are from 0.1 to 1  $\mu$ m (micron).

thermal conductivity that can be as low as  $0.004 \text{ W}/(\text{m}\cdot\text{K})$  or less. The extremely low conductivity is reached by optimization of the core material in combination with the low internal pressure which, if it is lost, will lead to panel failure and the thermal conductivity will raise to about  $0.020 \text{ W}/(\text{m}\cdot\text{K})$ , see chapter 2 for more in depth information.

***Vacuum insulation sandwich (VIS):*** A vacuum panel with welded all-metal barrier.

***Water resistive barrier (WRB):*** This is a barrier sheet, often polymer based and delivered on rolls, used in the US behind the cladding on top of the sheathing to prevent any wind-driven rain from affecting the sheathing

***Sensible heat/Latent heat:*** Sensible heat is the heat which can be sensed by touch, hence, the heat that changes the temperature while latent heat is the energy stored or released due to a phase change.

## 1.9 Acronyms

AIA	The American Institute of Architects
ASTM	ASTM International, formerly known as the American Society for Testing and Materials.
BEESL	Building Energy and Environmental Systems Laboratory at Syracuse University.
CB	In the chapter on testing walls CB refer to convection barriers.
CBL	Calibrated boundary layer, see nomenclature for explanation of the term.
CFC	Chlorofluorocarbon used as a blowing agent for foam products before the late 1970s and early 1980s, when it was discovered that chlorofluorocarbons would seriously destroy the ozone layer, (GTZ, 2000).
CFD	Computational Fluid Dynamics
CFW	Cellulose fiber insulated wall, Figure 45.
CHAMPS	Coupled Heat, Air, Moisture and Pollutant Simulation software
CIW	Cavity insulated wall
EE	Energy equivalent
EIW	Externally insulated wall
EPS	Expanded polystyrene
ETFE	Ethylene tetra fluoro ethylene is the polymer of choice in most polymer skin applications
GFP	Gas filled panels
GFW	Glass fiber insulated residential wall, Figure 44.
HAM	Heat, air and moisture
HFT	Heat flux transducer
HVAC	Heating, ventilation, and air conditioning
IAQ	Indoor air quality
IEA	International energy agency
IECC	International Energy Conservation Code
IUCN	International union for conservation of nature
MCWS	The industrial reference multi component wall system, Figure 42Figure 43.
Mtoe	Million tons of oil equivalent, the approximate amount of energy released by burning one tons of crude oil, approximately 42 GJ.
NLR	Normalized leakage rate

NLR <sub>75</sub>	Normalized Leakage Rate at an indoor-to-outdoor pressure differential of 75 Pa.
NRCC	National Research Council Canada
OSB	Oriented strand board
OTR	Oxygen transmission rate
ORNL	Oak Ridge National Laboratory
PE	Polyethylene
PET	Polyethylene terephthalate
PU or PUR	Polyurethane
RH	Relative humidity
SPS	The industrial test wall, selected panel wall system, Figure 42.
TWh	Terawatt-hour
UV	Ultra violet used to describe radiation with wavelengths between 100 and 400 nm.
VIP	Vacuum insulation panel
VIS	Vacuum insulation sandwich is a panel with a welded all-metal barrier
WRB	Water resistive barrier
WVTR	Water vapor transmission rate

## **Chapter 2: Air as an insulator has reached its useful limit**

### **2.1 Introduction**

Traditional materials used for building insulation, mostly developed before the 1960's, use air as the insulator (Bynum, 2001). Fibers and cellular structures are used in the material to prevent bulk movement of the encompassed air. When the air is motionless, heat is transferred by conduction and radiation within the gas and the skeleton, or fibers, while if the air is allowed to move the convective mode of heat transfer gradually replaces that of conduction with a higher thermal conductivity as the result. When air is the insulator the lowest possible value of conductivity is somewhat more than  $0.026 \text{ W}/(\text{m}\cdot\text{K})$  which represents the limit, namely the thermal conductivity coefficient of still air.

To develop materials with lower thermal conductivity than that of still air, a number of techniques can be used. Some involve replacing the air in the material by an alternative gas, and/or addition of materials which absorb or scatter radiation, or even evacuation of the contained gas in the material. Each of these measures is aimed at the suppression of one or several of the thermal transport mechanisms: conduction, convection, and/or radiation. To improve materials further it is necessary to address these mechanisms and to minimize each of them.

### **2.2 Physics of thermal insulation, thermal transport**

As already mentioned, thermal transport within materials takes place by three distinctive mechanisms: conduction, radiation and convection and their interaction. Typically the interaction between convection and conduction is added to the radiation to simplify calculations, and these different transport mechanisms are considered as additive. Particularly in foams and coherent solid skeleton materials, such as fumed silica, any coupling effect may be considered negligible, (Fricke, 2001). Below are the physics of heat transfer shortly described mechanism by mechanism freely based on the text by Eckert and Drake (Eckert and Drake, 1987).

#### **1.1.1 Solid conduction**

Conduction is mostly associated with solid materials, but occurs in still fluids as well, but is called gas conduction when in gas. Transfer of energy between molecules transfers thermal energy, which really is movement of molecules within materials, through the material as they collide with each other.

#### **2.2.1 Gas conduction**

Gas-conduction is heat transfer due to the interaction between molecules in the gas in the same manner as in solid conduction, hence the warm vibrating molecules collider with colder molecules and thereby transfer a portion of the inertia. To prevent gas conduction the mean free path (measure of the average distance traveled by a gas molecule before it interacts with other gas molecule) of the gas molecules has to be longer than the pore size of the core material. This means that in a material with pores smaller than the mean free path then the probability of the moving molecule striking the solid part of the material is larger than hitting another gas molecule. The transferred energy is then dissipated through the solid skeleton of the material. Hence, if a material with relatively smaller pores is used as core material, then the core pressure (amount of gas molecules left) can be allowed to be relatively higher before gas conduction occurs.

### 2.2.2 Convection

Convective heat transfer is due to bulk movement of gas or liquid molecules that carries energy. In buildings the most common medium is moist air. Convection occurs when bulk air moves from one point in a space to another point, thus transferring thermal energy.

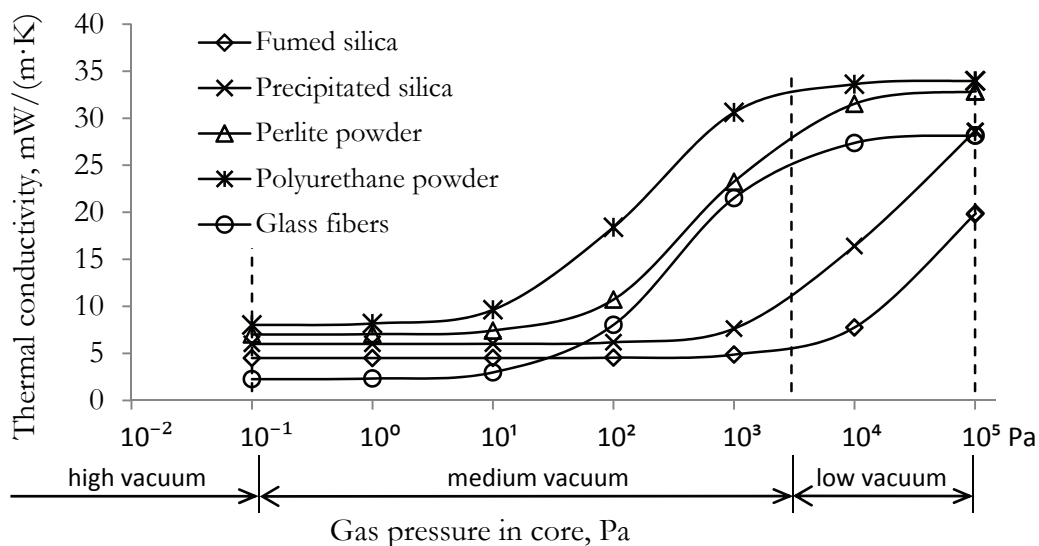
### 2.2.3 Radiation

Radiation is thermal energy transmitted by electromagnetic radiation caused by temperature differences between bodies. All surfaces emit and receive radiation. The radiation exchange between two surfaces depends on the surface temperature, surface properties and mutual geometric positions, but will occur independently of air pressure.

Many times a move to composites are necessary to create improved insulation materials. One available, well known, example of a successful improved technology is the window with double or triple panes with sealed volumes between them and low emission coatings. The surface coating is applied to reduce radiative heat transport and the volume is filled with low conduction gases to reduce the conduction and eliminate convective heat transport (Herrmann, 2001). Another example is the Dewar's vacuum flask, which, instead of filling the gap with a low conductance gas, simply removes most of the gas from the space.

### 2.2.4 Better thermal performance by vacuum

Sir James Dewar, a scientist at Oxford University, introduced the use of vacuum in 1892 when he invented the “vacuum flask” which later was refined by two glass blowers who formed the company Thermos GmbH. Thermos bottles were first commercially manufactured in 1902 by this company, (Fricke, 2005, Thermos, 2011). The design of the Thermos® flask is basically that of a bottle in a bottle concept. The empty space between the inner and the outer bottle is evacuated; since the gas between the two surfaces is evacuated, there cannot be any convection or gas conduction. The heat transfer due to radiation between the two surfaces is minimized by polishing the facing surfaces of the bottles.



**Figure 7: Heat conductivity of materials as a function of pressure within the material, redrawn from (Caps et al., 2008) with added material.**

Vacuum can be used to improve thermal properties of most available open porous materials. Different levels of vacuum are needed for different materials to reach low thermal conductivity. The particles of the core material have to be relatively small, and of a shape that creates small

points of contacts and thereby limits heat transfer by conduction. Actually, many of the currently used insulation materials can be used as core material for vacuum insulation as, for example, glass wool, which with its thin glass tubes will improve to similar values as a silica core at 0.1 mbar, as can be seen in, Figure 7. The thermal conductivity of a glass fiber core will rapidly increase as a function of increased pressure, whilst a core of silica or aerogel will maintain the low conductivity at higher pressure, up to a pressure of 1/10 of an atmosphere. This characteristic is essential in reaching lifetimes usable for the building industry. This issue will be discussed more in later chapters.

## **2.3 New insulation materials and other energy preserving approaches**

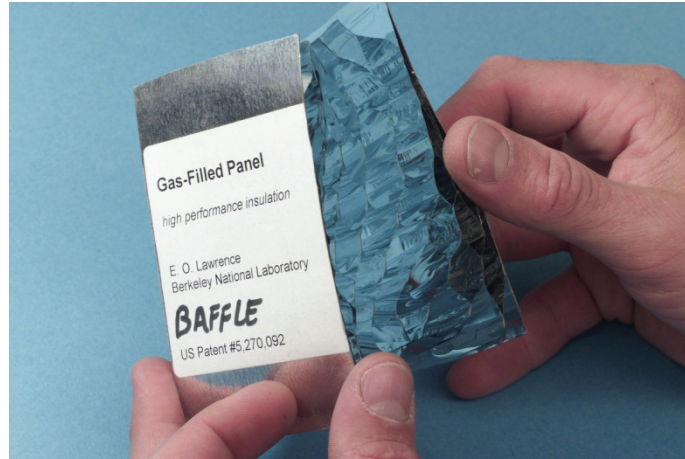
Aerogel is a product, which is a very good insulator just by its material properties; its pores are so small that it has better thermal resistance than still air. Still, on the scale of a material there is the vacuum panel technology, which uses a system of materials and vacuum in order to achieve high performance thermal insulation. Another example of a system, but still in the material scale, is the Gas-filled panels; a gas filled polymer construction which has a large number of closed cells filled with a low conducting gas, such as Argon, Krypton, or Xenon. These same gases can be found in multi pane windows.

Multi-pane windows are a good example, on a component scale, where replacement of gases has been utilized together with low emission coatings to improve thermal performance. The multi pane window is a known technology, but there is research on improving it even further by combining the existing concept with that of both aerogel and vacuum technology. In principal, a vacuum panel or an aerogel sheet is incorporated into the cavity between the different panes.

Another novel technology is using thin skins: very large pillows of a polymer films are mounted into structural frames and inflated. The number of skins and level of inflation determine the stiffness as well as the thermal properties of the component; hence, the component may be controlled to meet ever varying requirements.

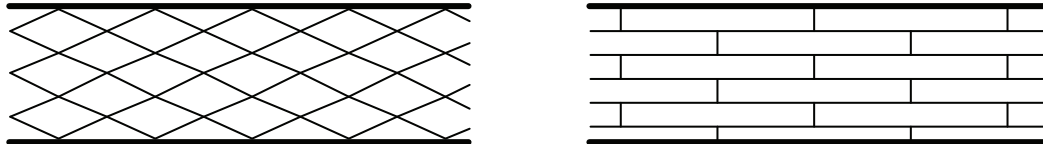
### **2.3.1 Gas filled panels**

As in insulating glazing, which uses low conducting gases, there are also experimental insulation materials that combine gases, such as Argon, Xenon, and Krypton with high gloss polymer baffles in a honeycomb geometry, Figure 8. The free space in the combs is filled with the gas of choice to improve the performance, and a barrier to keep the gas from escaping to the outside encloses the whole package. The thermal performance, if the baffles are designed correctly, is close to that of the selected filler gas, the thermal conductivity of a gas filled panel (GFP) with Xenon has been measured at  $0.008 \text{ W}/(\text{m}\cdot\text{K})$ . The same design, but with air filling the core, resulted in the measured conductivity being  $0.028 \text{ W}/(\text{m}\cdot\text{K})$ , hence, an improvement by a factor of three (Griffith et al., 1995).



**Figure 8: A small sample of the internals of a gas filled panel, photo courtesy of Lawrence Berkeley National Laboratory.**

The GFP is made up of three main components: the baffle (or the inner honeycomb), the encapsulating barrier and the gas filling. The baffle has multiple functions. Firstly, it creates cells small enough to suppress convection in the gas and second the low emission surface of the baffle material suppresses significant radiation. The conduction along the baffle web is limited due to the geometric format of the web, in Figure 8: the web has the basic shape of honeycombs and the conduction path from one panel face to the other is prolonged, hence, leading to lowered conduction. Rhomb shaped cells or even serpentine shaped baffles, as in Figure 9, would likely be even more effective in reducing the conductive part of heat transfer through such a panel. The narrow spaces in the serpentine example are likely to prevent conduction better as well.



**Figure 9: Alternative web geometries that would make the conduction path even longer than for the honeycomb alternative.**

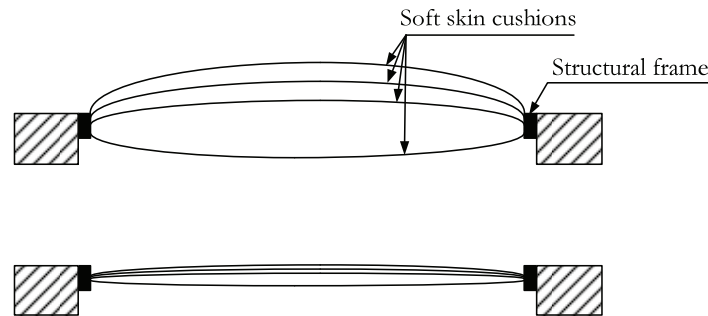
According to Griffith et al. (1992) the thermal conduction through the gas in the primary mode of heat transfer, and the conductivity of the chosen gas is most important for the overall performance. Gases with higher molecular weight typically have lower thermal conductivity, and monoatomic gases, such as Krypton and Xenon, have lower thermal conductivity than polyatomic gases of equal or greater weight.

Gas filled panels have not yet been introduced into the construction market, even though some preliminary testing and modeling was performed by Griffith et al. (1995); they discuss the possibility of using GFP in buildings. They presented some results from numerical modeling of wall sections with traditional insulation, and with GFP replacing the traditional insulation: calculations show an improvement of about 30% in a wall containing 45x120 mm studs with cavity insulation.

### 2.3.2 Polymer skins

A similar approach as for the GFP can be used on a larger scale as well. There are structures, which use thin polymer skins in a cushion like configuration. This technology was used in some quite large projects, such as the Beijing National Aquatic Center and the Allianz football (soccer) arena in Germany. The polymer film, mostly ETFE, is most commonly designed as a part of a pneumatic

cushion assembly, Figure 10, like inflatable pillows held in place by a structural frame, (Trubiano, 2011).



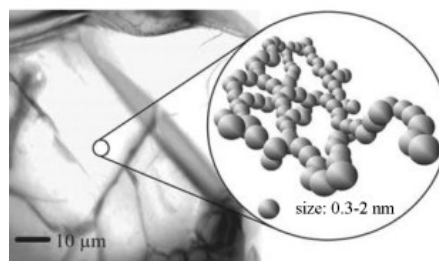
**Figure 10: Section sketch of a thin skin cushion mounted in a structural frame attached to a building. The top figure shows the element in an inflated state while the lower shows a deflated state.**

There are solutions with only two skins and with as many as five. The structural integrity as well as the thermal resistance can be altered by inflating or deflating the space between the individual skins, creating a dynamic system. Hence, if a storm is coming then raise the pressure for a more rigid construction or during a cold day all spaces may be inflated to increase the thermal resistance.

### 2.3.3 Aerogel

Returning to the material scale, aerogel is a state of the art material that is available on the market today. Aerogel is basically a dried gel and was first discovered in 1934 when Kistler and Caldwell reported about a material which had some amazing properties, (Kistler and Caldwell, 1934). This new material had, at the time of discovery, the lowest measured thermal conductivity in history. The found material was created from drying a gel under critical conditions. What this means is that the gel is dried in a way that prevents the pores of the gel from collapsing. In the same report Kistler and Caldwell suggest a vacuum panel construction for the first time using powdered aerogel as core material.

The structure of Aerogel is mostly empty; it has high specific surface area ( $500\text{--}1200\text{ m}^2/\text{g}$ ), high porosity (80-99.8%) and low density ( $\sim 3\text{ kg/m}^3$ ) and as a result a low thermal conductivity in the range of  $0.005\text{ W}/(\text{m}\cdot\text{k})$ , (Soleimani Dorcheh and Abbasi, 2008). The internal structure of Aerogel limits all three mechanisms of thermal transport, which leads to a material with exceptional thermal properties. Current aerogels for building applications have an overall density of  $70\text{--}150\text{ kg/m}^3$ . Silica Aerogel has quite high compressive strength of up to  $300\text{ kPa}$  but poor tensile strength making the material very fragile, (Baetens et al., 2011).



**Figure 11: Internal structure of Silica aerogel showing the SiO<sub>2</sub> network enlarged (Reim et al., 2005).**

There exist several patents, ranging from 1950's to the 1970's, regarding usage of aerogel in various insulation forms, vacuum panels are one of them, as well as in composites with polymers or fiberglass (Smith et al., 1998). Commercially available products based on aerogel granules reach

thermal conductivities as low as  $0.013\text{--}0.014\text{ W}/(\text{m}\cdot\text{k})$  and are available to the construction market in several forms, such as blankets and granules for loose fill or to be mixed into plasters, or other coating systems, (CABOT, 2011, Aspen, 2011, Baetens et al., 2011).

Monolithic aerogel as manufactured in its current process may be opaque, translucent or transparent, which opens up a wide array of additional applications besides as an insulation material. Instead, it may be used where good insulation is preferred and light penetration is a requirement. The added benefit makes the material interesting in specialty applications less cost conscious than for insulation of opaque parts of a building enclosure.

Since the common transparent area of houses are the windows, which also happens to be one of the major culprits in releasing heat to the exterior, it is the first place to apply aerogel in order to improve thermal performance. Research has been done on this type of window and it is called aerogel glazing.

#### 2.3.3.1 Aerogel glazing

Aerogel glazing is not a material but a component and a system of materials combined to improve the performance beyond the current. Since it is a window, thermal resistance is not the only parameter to be optimized but also light transmittance.

Aerogel glazing is in principal a traditional multi pane window where an aerogel material has been introduced into the gap/s between the glass sheets. As seen before, one way of lowering the thermal conductivity of a material is to evacuate the contained gas in the material. In the case of aerogel the pores are so small that only a rough vacuum of 1-10% of ambient pressure is required to eliminate gas phase conduction, (Smith et al., 1998).

The edge is then sealed and the aerogel-glazing unit may be used in a traditional frame. Prototypes have been built at DTU in Denmark with promising results. They have been able to make glazing units with a center-of-unit thermal conductivity of  $0.010\text{ W}/(\text{m}\cdot\text{K})$  on average (U-value  $\approx 0.066\text{ W}/(\text{m}^2\cdot\text{K})$ ) with an average solar transmittance of above 70%, (Schultz et al., 2005). A good standard 3-pane window of today has a U-value between  $0.8\text{--}1.0\text{ W}/(\text{m}^2\cdot\text{K})$  with a solar transmittance slightly above 60%, (Elitfönster, 2011).

#### 2.3.4 Evacuated glazing

The next step for super-efficient glazing could be to evacuate all gas in-between the glass sheets. The transparent evacuated insulation is an insulation material utilizing vacuum to eliminate convection and gas conduction.

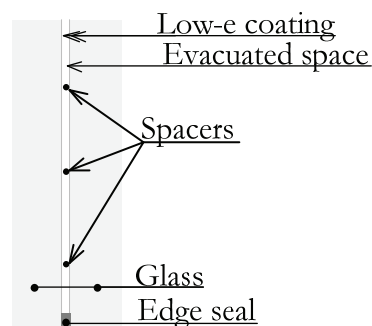


Figure 12: Principal sketch of Vacuum Insulation Glazing, redraw from (Weinläder et al., 2005).

The idea to create a flat material with vacuum inside was first applied for patent in 1913, only 20 years after the invention of the Dewar flask according to Collins, (Collins et al., 1992). Collins refers to a patent by Zoller A. from 1913, (Zoller, 1913). The insulation material described by Collins et

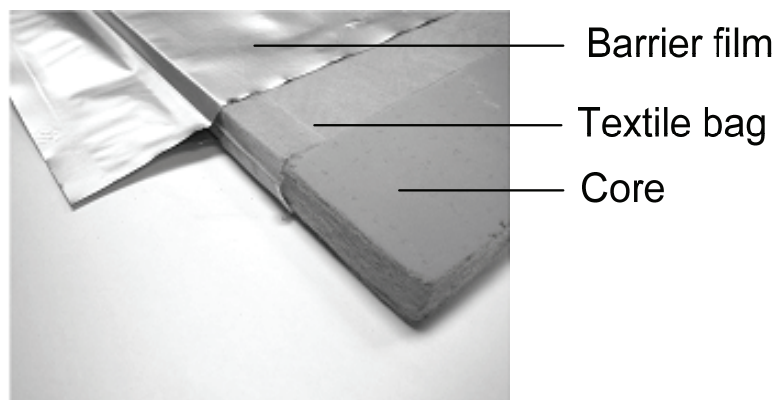
al. is basically a window unit with two glass sheets which are sealed tight around the edges and the intermediate space is evacuated of all gas to create a vacuum. The two glass sheets are kept apart by distances of different forms some spherical and some in the form of small pillars. The research in this area seems to be still ongoing with several recently published articles, (Weinläder et al., 2005, Dey et al., 1998). Vacuum is used for panels without glass sheets as well; in vacuum insulation panels.

### 2.3.5 Vacuum insulation materials

A vacuum insulation panel, Figure 13, is a composite, which has a core material enclosed by another material functioning as a barrier. The gas originally in the core is evacuated to reach extraordinary levels of thermal insulation. A thermal conductivity, at a core pressure of 1 mBar, of around  $0.005 \text{ W}/(\text{m}\cdot\text{K})$  is normal, Figure 7.

There are several steps included in manufacturing a VIP. The first step, in case of a core consisting of a powder, is to mix a small amount of fibers into a batch of the core material to create a material that after pressing can be handled without falling apart. The core is then enclosed by a fleece bag (textile bag in Figure 13) and placed in a pressing tool to be pressed into the form of a board similar in feel to a very low-density wood fiberboard. After the board is cut to desired dimensions, it is placed in a barrier bag and then all air is removed from the package and the enclosure is sealed under vacuum. The result reminds of a package of vacuum-packed coffee that has been flattened into a board shape. As long as the internal vacuum is withheld, the board will retain its stiffness and its low thermal conductivity.

There are panels with a wide variety of barrier types. Barriers may be metal sheeting, metal foil, polymer films, and combinations of polymer films and metal foils or polymer films with metallized layers which are composited into single films. Vacuum insulation is often divided into different sub categories depending on their structure.



**Figure 13: A vacuum insulation panel of a design readily available on the European market today.**

Panels with barriers of polymer and metal composite films are often referred to as vacuum insulation panels (VIP) whilst a panel with a welded all-metal barrier is referred to as a Vacuum Insulation Sandwich (VIS).

Replacing 40 cm of existing insulation with vacuum insulation maintaining the same level of thermal resistance can be reached with only 5 to 10 centimeters of VIP. Even stricter demands can be met without an excessive increase in thickness of the thermal shell in new buildings. Great care must be given to the design when such super materials are used since the impact of thermal bridging and other deficiencies is much greater. The use of VIPs is, of course, especially advantageous where space is scarce or where another benefits can be found.

## **2.4 Vacuum Insulation Panels**

There was strong interest in Vacuum insulation materials of different sorts during the end of the 20th century. Manufacturers of refrigerators and freezers had to replace the commonly used CFC blown foams that were used in appliances at that time. One of many possible replacement materials was vacuum insulation. Many different materials were tested and optimized for use as core materials in vacuum insulations during this time.

Materials that were evaluated and used for the core materials in vacuum insulation panels were glass fibers, (Michael, 1991) open pore foams, (De Vos et al., 1996, Tao et al., 1997), and powders such as perlite powder, precipitated silica, and fumed silica as described by Caps and Fricke (Caps and Fricke, 2000); many were discussed much earlier and summed up in a review article by Alan Fine in 1989, (Fine, 1989).

Vacuum panels with aluminum foil based envelopes are common on the Asian market where glass fiber as well as open cell foam is used as core materials; both core materials require a higher level of vacuum and thus require a tighter envelope, and getters (Ghazi Wakili et al., 2011) to maintain the vacuum. The trend in Europe is to use core materials with most pores smaller than 1  $\mu\text{m}$  making getters unnecessary and envelopes in thin (300 nm) metallized barrier composite films possible to use. The most common core material used in Europe is precipitated or fumed silica due to its characteristics at moderate levels of vacuum. The most common barrier material is a polymer laminate with two or more aluminum coatings, (Baetens et al., 2010).

As the vacuum technology was used in specific applications such as the aforementioned refrigerators and freezers as well as in transport packaging, cold storage and others, it became clear that this technology could become an effective mean to save energy. In the presence of the global strive to save energy and lower the amount of release greenhouse gases which is intimately connected to the amount of energy used for heating the building stock in the world; the interest for vacuum insulation in buildings has grown strong.

In 2002, a report prepared for the U.S. Department of Housing and Urban Development was published on the subject of vacuum insulation in buildings (NAHB, 2002) as the result of a research project spanning over three years. The aim of this report was to accelerate the use of VIP in building in the U.S.

In Europe an IEA project was started in 2001, the Annex 39-High performance thermal insulation. The work in this project was divided into two subtasks, subtask I dealt with the panel itself and its components, while subtask II dealt with applications which uses vacuum insulation panels in buildings. It was decided early in the project to limit the work to deal with vacuum insulation panels with silica powder core materials.

A VIP, a vacuum insulation panel, has two major components; the core and the envelope. Each component has a specific task, the barrier is to protect the panel from outside agitations as well as prevent, if possible, any gas from penetration into the core. Another important aspect of the barrier is its sealing properties, hence how impermeable the seams become when the enclosure is sealed. The innermost layer of the barrier composite film will govern this property. If the barrier is a metal sheet the preferred method would be welding, but in the case of polymer composite films, the common method is heat-sealing. The properties of the seam by heat welding were investigated by in the IEA Annex 39 work package, (IEA, 2005a).

The core on the other hand must be able to support the pressure created on the surface of the envelope when the core is evacuated. The core must also have an internal structure, which

minimizes heat transfer by conduction and radiation, as well as in the best possible way, utilizes the low pressure to prevent gas conduction.

The panel core is evacuated to a lower pressure than what is necessary to reach the target conductivity to allow for some gas leakage into the panel during its life time, such leakage will occur in any panel with polymeric barriers since no currently available polymeric film is absolutely gas tight. Another available means to improve service life is to add a desiccant or getter, which is a component or chemical inserted to the core to trap moisture or residual gas respectively, see subchapter on getters and desiccants.

## **2.5 Service Life Time**

The single most important component of a VIP with regard to its lifetime is the barrier properties of the enclosure in combination with the chosen core material. The surrounding environment influences the properties of a polymer barrier, and increased moisture and heat are contributing factors that rapidly increase diffusion through a polymer barrier into a VIP and, thereby, decrease the performance of the panel. Fumed silica, a commonly used core material in panels for use in buildings, has the capacity to bind both water vapor and air to some extent, which opposes performance loss due to permeation. This will obviously decrease initial effects on performance by diffusion of gas into the panel.

Sources for increase of the pressure in the VIP core are, (Della Porta, 1996):

1. Residual gas in the core
2. Out gassing from the core material
3. Gas permeation through the barrier and its seams

The prevailing gases diffusing into a VIP in a building application are oxygen, CO<sub>2</sub> and water vapor. The permeation of gas through the barrier is a very slow process and may be somewhat delayed, depending on application, while the outgassing from the core material may be much faster, and start immediately after evacuation of the core. The quantity of the outgassing from the core material will be much less, than the potential permeation from the outside atmosphere, but it may not be an unimportant factor concerning the degradation of the panel.

The service lifetime of a vacuum insulation panel is a function of:

- Minimum performance requirements
- Panel size
- Fabrication quality
- VIP component choices
- Use conditions
- Handling

The first five are identified in the U.S. Department of Housing, 2002 report, (NAHB, 2002). Each individual aspect will be discussed below but first discussed is the definition of service life time.

### **2.5.1 Definition of Service Life Time for VIP**

There are two approaches to define the service life times of vacuum panels, both are discussed in paper IV. The first one is a snap shot approach where the instant thermal conductivity is the deciding factor, while the second one uses a thermal conductivity averaged over time. The first approach has been incorporated into an American standard for vacuum insulation panels, (ASTM Standard C1484) while the second definition may be useful for calculations of life time energy usage.

Service life definition 1: The elapsed time from the moment of manufacturing until the moment the thermal conductivity of the material or component,  $\lambda_c$ , has increased to some limiting value<sup>4</sup>,  $\lambda_{lim}$ ; or in other words, the service life has expired if the following condition has been reached:

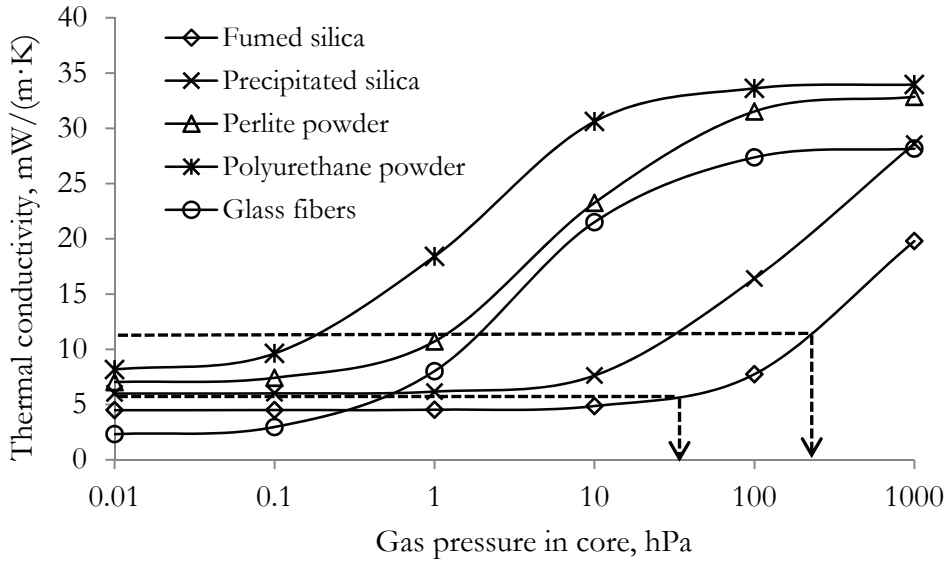
$$|\lambda_c|_{t=t_{SL}} = \lambda_{lim} \quad \text{Equation 1}$$

Service life definition 2: The time that expires from the moment the panel or material is manufactured until the moment the time-averaged thermal conductivity of the material or material equals some critical value,  $\lambda_{critical}$ ; or the service life has expired if

$$|\bar{\lambda}_c|_{t=t_{SL}} = \lambda_{critical} \quad \text{with} \quad \bar{\lambda}_c = \frac{1}{t} \int_0^t \lambda_c(t) dt \quad \text{Equation 2}$$

With this second definition, it is possible to take into account that the thermal conductivity increase rate varies over time due to possible non-linear correlation between thermal conductivity and pore gas pressure, as well as by a (theoretically) non-linear increase of pore gas pressure over time, at least over longer periods.

The second definition allows for a limit for the total heat loss through the building construction, including thermal bridges during the entire VIP service life, while the first definition just limits the instantaneous heat loss, (Tenpierik et al., 2007).



**Figure 14: Minimum performance criteria govern the allowable internal pressure of a VIP with fumed silica core.**

In the type of scenario where the instant performance is most important, then the first definition above is applicable. In a specific application it might suffice to have an insulation material that has a thermal conductivity of  $0.010 \text{ W}/(\text{m}\cdot\text{K})$ . If that is the case, more gas can be allowed to leak into the panel before it is deemed as having failed. If a thermal conductivity of  $0.005 \text{ W}/(\text{m}\cdot\text{K})$  is the limit value, then the allowed increase in thermal conductivity is very small and, hence, the allowable amount of penetrating gas is very much less than in the first case. The panel would reach the end

<sup>4</sup>This limiting thermal conductivity can arbitrarily be set at any value, but is generally set at  $8 \cdot 10^{-3} \text{ W}/(\text{m}\cdot\text{K})$ , SIMMLER, H. & BRUNNER, S. 2005. Vacuum Insulation Panels for Building Application: Basic Properties, Aging Mechanisms and Service Life. *Energy and Buildings*, 37, 1122-1131.

of its service lifetime in shorter time than in the first case if the gas intrusion rate was the same. That is if all other circumstances are equal. The two described cases are plotted in Figure 14. The case with a maximum allowable thermal conductivity of  $0.010 \text{ W}/(\text{m}\cdot\text{K})$  can allow five times higher internal pressure than in the second case before the panel reaches its end of life. This example reflects the case of panels with a fumed silica core.

## 2.5.2 Panel size

A larger panel will have a longer expected lifetime than a smaller panel. The effect of the panel size is simply because the relationship between volume and seam length, as well as the volume to barrier surface relationship changes. The seam, where the barrier film is sealed, is pointed out in several reports as an area of increased permeation, (NAHB, 2002, Binz et al., 2005, Alam et al., 2011, Baetens et al., 2010). Therefore, if the thickness in this case is increased in relation to the length of the seam then more gas can be allowed to penetrate into the core before the end of life criterion is fulfilled.

If the surface size of a panel is increased while the thickness is maintained then the ratio between volume and surface area decreases slightly while the ratio between seam length and volume reduces drastically, assuming the seams to be placed along the outer edges of the panel. Gases do penetrate through the barrier film itself as well, unless it is made of metal sheets or metal foils. In addition, in this case, a larger volume in relation to the surface area is helpful to increase the service lifetime of a panel. In the case of larger panels, the importance of diffusion through the barrier surfaces increasingly becomes more important than the leakage through the seam.

The size and form of the panels also affect the thermal performance of the panel, since there are additional heat losses at the panel edge; this is discussed further in the sub chapter on thermal performance of VIP as well as in section 4.2 where thermal efficiency is discussed.

## 2.5.3 Fabrication quality

Into this section goes all care that are being taken during the manufacturing of a panel as well as quality assurance to verify that panels leaving the manufacturer are as good as agreed upon with the buyer.

It is important that the enclosure film is not stressed by bending, wrinkling or pulling during evacuation or later handling, (Roderick et al., 2005). For example, some manufacturers fix the excessive barrier material onto one surface of the panel creating sharp bending as well as wrinkles at the panel's corners. Any break, bend, or indentation can be a source for increased permeation, due to micro cracks and other defects. See section on handling further down in the text for more information.

Another important aspect is quality assurance. There is a German company which has incorporated a small piece of open porous fleece on top of a piece of a metal plate into their panels which allows them to measure the internal pressure after manufacturing a step in quality assurance. This has been described in a paper presented by Caps R. at the 7<sup>th</sup> International vacuum insulation symposium in 2005, (Caps, 2005). Another company relies solely on visible inspection after the newly manufactured panels have been stored for a specific amount of time. One finding during the testing for the IEA, annex 39 project was that a fraction of panels would fail within a short period of time after manufacturing, (Simmler and Brunner, 2005).

## 2.5.4 VIP component choices

Different core materials need different levels of pressure inside to reach low thermal conductivities. For example fiber-glass reaches the lowest thermal conductivity of close to  $0.002 \text{ W}/(\text{m}\cdot\text{K})$ , but in order to do so the internal pressure must be below 0.05 mbar, whilst a fumed silica core does not reach as low, but it will maintain low thermal conductivity of  $0.004 \text{ W}/(\text{m}\cdot\text{K})$ , even at an internal pressure of 1 mbar. Some core materials that are used also release residual gases from the panels, even though pretreated before the envelope is sealed, (NAHB, 2002).

Another important component is, of course, the chosen barrier material. A better, hence a more gas tight, barrier material will do a better job at preventing atmospheric gas from entering into the core material. The gas permeation through polymer-based film with metallized layers is governed by defects in the metallized layers; the subject is discussed more in depth in later chapters as well as in Paper IV.

Yet another component that greatly influences the allowable amount of penetrating gas is the addition of getters or desiccants. These components can help in absorbing any incoming gas or moisture, thus preventing increased pressure, see later subchapter on the matter.

## 2.5.5 Conditions of use

The conditions under which a panel is used will also affect the life time of the panel. In the report of IEA it is shown that panels do fail under certain circumstances, (Simmler and Brunner, 2005). Similar conclusions are reached in the report from the (NAHB, 2002), both heat and moisture will affect the permeability of a polymer based barrier film, and both increased moisture and raised temperature will relax the polymer matrix and an increase in permeation will occur. The underlying mechanisms of molecular transport are discussed in the chapter on Polymer and coated polymer film barriers. Another environmental concern for any polymer is exposure to chemicals and short wave radiation. Ultra violet radiation is the most common in the building industry, which can lead to degradation as described in the chapter about polymer degradation.

## 2.5.6 Handling

When handling a panel, both during manufacturing and at a construction site, great care must be taken. During manufacturing excess barrier material is often folded; a practice that according to (Roderick et al., 2005) may lead to micro cracks and increased permeation. Any break, bend or indentation is said to be a source for increased permeation, which is why applying unprotected panels on a construction site is not advisable; a small piece of gravel or a sharp edge may create such an indentation or even a puncture. This is particularly true for composite films with thin metallization layers. Any defects no matter how small lead to increased gas permeation through the film, (Roderick et al., 2005).

## 2.5.7 Getters and Desiccants

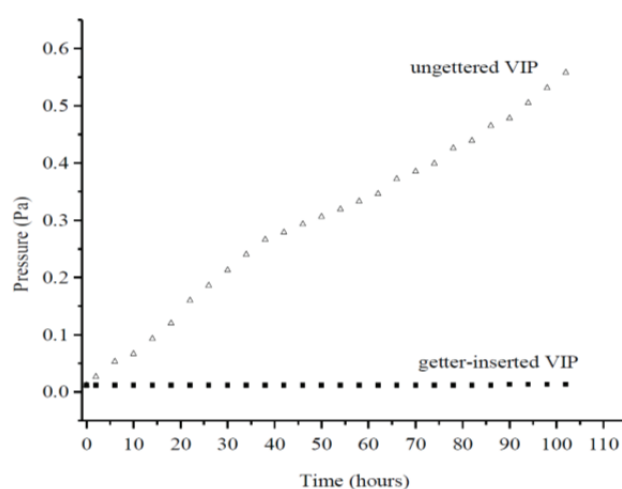
Desiccants, or “getters”, are components or chemicals inserted to the core to trap moisture or residual gas to prevent a pressure increase in the core. Both getters and desiccants are materials specifically designed to entrap molecules from the environment and may, therefore, be referred to as dryers or absorbers as well. The meaning of the terms seem to be used relatively interchangeably, but the difference, according to the report from U.S. Department of Housing, between a getter and a desiccant is that the latter removes moisture whilst a getter is designed to remove molecules from atmospheric gases, (NAHB, 2002). Getters are more complicated to produce and, therefore, more expensive.

Desiccants are commonly designed specifically to entrap moisture and thus are made of highly hygroscopic materials. Commonly encountered desiccants are made from solids and trap moisture by means of adsorption and subsequently absorption. Desiccants for other purposes may be in other forms and utilize other mechanisms.

Getters, in the meaning of gas trappers, are highly porous structures with large surface area that attracts and bonds with gases and volatile organic molecules, (Controls, 2011). Kwon et al describes the function of getters as small vacuum pumps, (Kwon et al., 2010).

One of the early applications for getters was for maintaining vacuum in electronic vacuum tubes. These getters were commonly small circular cavities filled with a material, often metal, that very rapidly oxidizes and by that binds oxygen molecules irreversibly. Barium was a common such metal. In this application the getter had to be activated by heat; it was evaporated and reacted with any residual molecules in the tube, leaving a silver colored deposit on the inside of the tube. If the tube was cracked the coating reacted with atmospheric oxygen and changed into a whitish color, (Wikipedia, 2011).

As earlier discussed, a rise in gas pressure degrades the performance of a VIP. The most common gases that enter into the core of a vacuum panel are nitrogen, oxygen, CO<sub>2</sub> and water vapor, (Della Porta, 1996). For some types of VIP core materials, it is necessary to add getters and/or desiccants to increase their service life. In the case of silica core VIPs, the core itself acts as a desiccant, thus, it is not necessary to add additional desiccant, but for other core materials, a small amount of desiccant/getter is required to continuously adsorb the gases (getters) and the water vapor (desiccants) penetrating into the core and prevent increased internal gas and vapor pressure, (Baetens et al., 2010, Alam et al., 2011). The characteristics of fumed silica, with its huge specific surface area, results in very high sorption capabilities; 1 kg of the material will adsorb 0.05 kg water at 75% relative humidity, (IEAa 2005).



**Figure 15: Show pressure increase for a panel without a getter material and one with a getter material in the core, (Kwon et al., 2010).**

Kwon et al. are working on a double envelope VIP, and they have also evaluated the results on internal pressure in a panel by using desiccant and getter material into a VIP. They used a commercialized product (COMBOGETTER) manufactured by SAES getters, which consists of BaLi<sub>4</sub>, CaO and Co<sub>3</sub>O<sub>4</sub>. However, the powder of CaO and Co<sub>3</sub>O<sub>4</sub> can provoke health problems and all components are put in a metal container in compressed form. Figure 15 shows the pressure increase curves of the ungettered VIP and gettered VIP. Note that VIPs used in this measurement

have a single polymer envelope. They conclude that the getter seems to be very effective, but a long-term measurement should be carried out to ensure that because the getter absorption capacity may be gradually degraded with time. This remains to be investigated in further research, (Kwon et al., 2010).

## 2.6 Thermal Performance of VIP

A vacuum insulation panel is not to be regarded as a single material: it is a composite of several different materials. There is the core, which by its properties under vacuum, is a very good insulator. Fumed silica has a thermal conductivity in the range of 0.005 W/(m·K) at an internal pressure of maximum 10 mbar. This value would be found if the conductivity was measured in the middle of a large vacuum panel (one-dimensional flow), herein called the center of panel value.

The barrier on the other hand is the key to the service lifetime of the VIP. If the barrier has very low gas permeability, the panel will have a longer service life than if the barrier has higher permeability, as discussed before. A core material with small pores will have a shorter mean free path, and will therefore, be less prone to conductive heat transfer, and the total thermal conductivity will be smaller than in a material with larger pores at a set internal pressure. Alternatively, the material with smaller pores allows a higher pressure in the core maintaining the low thermal conductivity. Independently of what material is used in the barrier or the core the barrier will create a thermal bridge when wrapped around the edge of a panel, even if an all-polymer barrier only creates a very small thermal bridge effect.

Also at the corners of the panel additional thermal bridges will occur, so called point bridges. To calculate the total transmittance through a panel all the thermal bridges have to be added to the center of panel transmittance times the area, see Equation 3. The point losses at the corners of the panel are so small that it is commonly neglected.

$$\Phi = \left( \sum (U \cdot A) + \sum (\Psi \cdot l) + \sum X \right) \cdot (T_i - T_e) \quad \text{Equation 3}$$

$\Phi$  = Total heat flow rate through the panel (W)

$U$  = Thermal transmittance in the center of the panel (W/(m<sup>2</sup>·K))

$A$  = Area of the panel (m<sup>2</sup>)

$\Psi$  = Linear thermal transmittance of the edge (W/(m·K))

$l$  = Length of the edge (perimeter) (m)

$X$  = Point thermal transmittance (W/K)

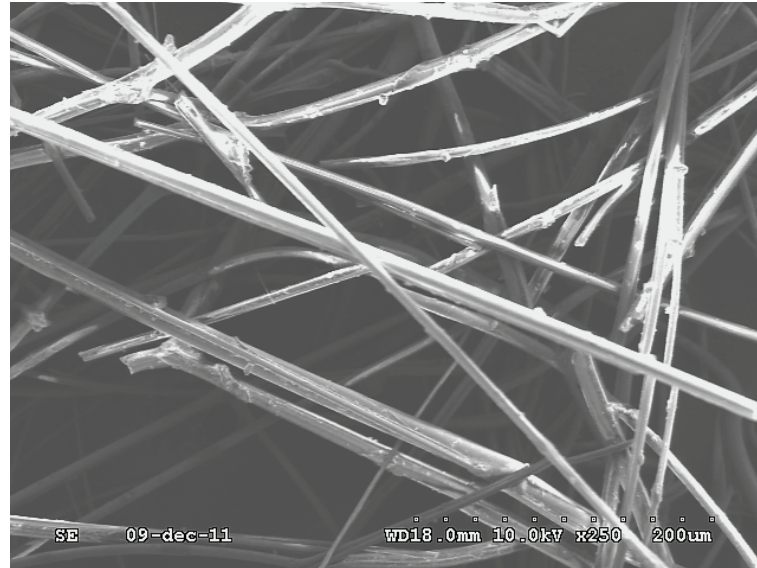
$T_i$  = Temperature on inside of the panel (°C)

$T_e$  = Temperature on outside of the panel (°C)

### 2.6.1 The Core

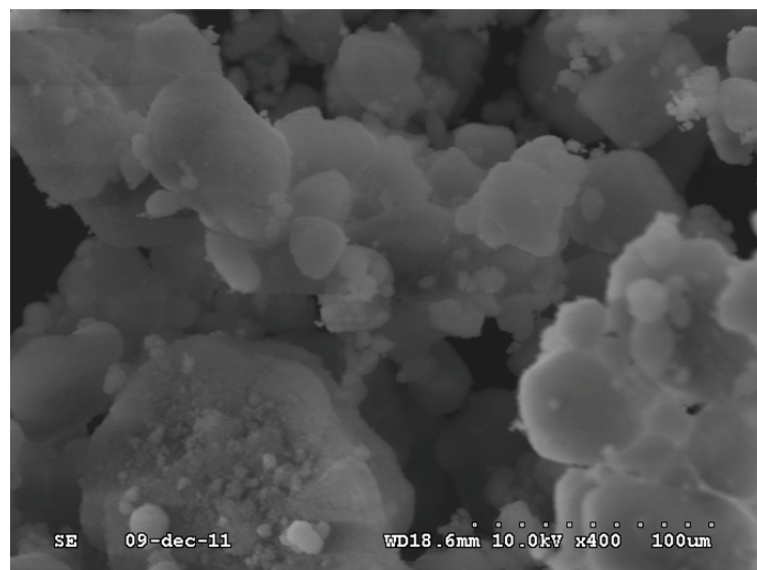
The core material within a vacuum insulation panel has to have a number of specific properties. It must have open pores to make it possible to evacuate the gas in the core; the pores must be small and the skeleton must have a geometry, which renders small points of contacts between the structures in the material to minimize conductive heat transfer; even under high load. Optimal shapes are spherical or cylindrical as in fumed silica, see Figure 17, and fiberglass respectively,

Figure 16. The material must be able to withstand high external loads without collapsing. The preload of a panel due to an internal pressure of 1 mBar is in the range of 100 kN/m<sup>2</sup>. This is due to the difference between the inside and the outside pressure of the panel. Finally, the core must reduce radiative heat transfer between the surfaces of the panel. The core material of choice in Europe was, in 2005, fumed silica, which has all the above properties.



**Figure 16.** This image is a SEM picture of glass fiber insulation. The shape of the glass fibers are cylindrical which lead to small areas of contacts and thus small conductive heat transfer even if the material is compressed.

Fumed silica is a product produced in a flame where  $\text{SiCl}_2$  is transformed into  $\text{SiO}_2$  aggregates. Fumed silica is stable enough to withstand the pressure of 10 tons per square meter as is created by the pressure difference when the core is evacuated. At the same time it has exceptionally small pores, pore sizes on the order of 10 to 20 nanometers, with a specific surface area higher than 200m<sup>2</sup>/g, the porosity is above 90% and the density is in the range of 160 to 190 kg/m<sup>3</sup>. This is data for the fumed silica material which was investigated in IEA, Annex 39, (IEA, 2005a).



**Figure 17.** This image is a SEM picture of fumed silica powder. The shape of fumed silica particle is basically spherical which lead to small areas of contacts and thus small conductive heat transfer. The small points of contact are maintained even when compressed.

The SiO<sub>2</sub> aggregate particles resemble spheres, Figure 17, which by its shape creates small contact surfaces. Since conduction needs to pass through these small points of contact between the spheres the total core conduction will be very small. The evacuation of the core reduces the amount of gas available for convection and the radiation heat transfer is minimized by the addition of opacifiers, for example carbon black, that block the radiation or of some molecules to act as scatterers which disperse the radiation to the skeleton of the material. A combination of opacifying powders with silica can, in vacuum, reach a conduction as low as 0.003 W/(m·K)(Caps and Fricke, 2000).

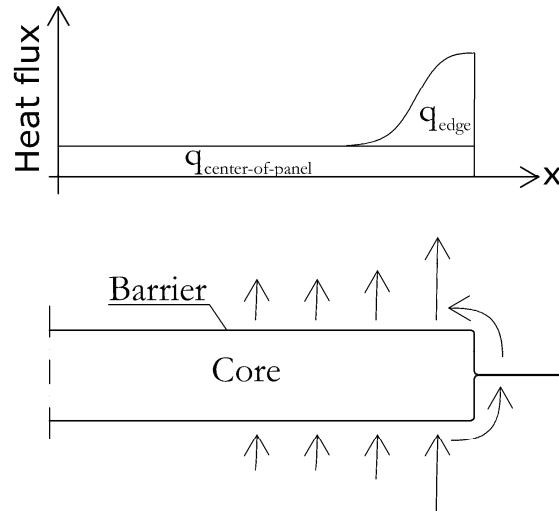
## 2.6.2 The Barrier

The most important objective of the barrier is to prevent atmospheric gas from entering the core. If gas is allowed into the core then the pressure will increase, this pressure increase results in an increased thermal conductivity in the core. When the thermal conductivity of the core rises above a certain level, the end of service life time has been reached if the instantaneous definition for service life time is used. There is great variety in materials that can be used as barrier materials, ranging from single layer polymer films to solid metal enclosures.

A panel with an enclosure made of metal sheets welded into one piece would be virtually gas tight. A gas tight panel would be advantageous for increased lifetime, but the added heat loss due to the material wrapping around the edge, thermal edge loss, would significantly reduce the overall thermal performance of the panel unless very large panels were used. A VIP manufactured with an all-polymer barrier manufactured with technologies available in 2005 would, in contrast, have a short service life but the thermal edge loss would be minimal. The most common solution for VIPs manufactured for buildings was a combination of polymer films and metal coatings sandwiched into a composite film. Such barrier films consist of several polymer layers with one or more metallization layers, or coatings, hence a metal layer a few molecules thick.

The gas flux, permeation, through the barrier must be small enough so that the panel will reach the designated lifetime in the range of 30 to 50, or even 100 years if VIP are to be used in buildings. It is stated in the IEA report, (IEAa, 2005), that the limiting value for the oxygen permeability is 10<sup>-2</sup> cm<sup>3</sup>/(m<sup>2</sup>·day·bar) in order to reach at least 30 to 50 years of service life time. The limit value depends on the size of the panel, so the number can only be used as a rule of thumb value. If the vacuum is lost and the internal pressure increases to the ambient pressure the thermal conductivity will increase to 0.020 W/(m·K). The seam of the envelope usually has larger diffusion than through the film itself, it is thought that the solution to this particular problem is through use of wider seams. Another way to decrease permeation through the seam would be to improve the quality of the seam or by improving the quantity of seams.

### 2.6.2.1 Thermal bridge effect



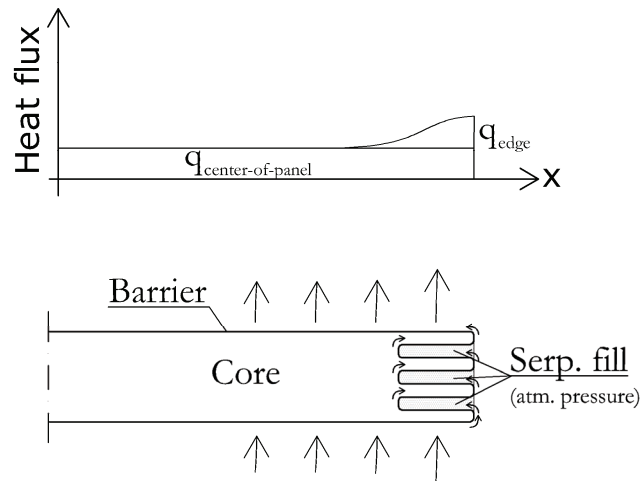
**Figure 18:** The image shows a graphic illustration of a section of a typical design of the edges of a vacuum insulation panel and the path for the heat to travel resulting in a linear thermal bridge around all edges of the panel, figure is originally found in Paper I.

As already stated the best construction with regard to lifetime is the all-metal enclosure. The downside of a metal enclosure is that metal is generally a good thermal conductor whereas the material binding the two panel faces together would create significant thermal bridges as drawn in, Figure 18. If the panel is small or the thermal bridge severe, the overall improvement over traditional insulation is often lost. On the other hand, an all-polymer barrier with low conductivity would be preferable in order to decrease the thermal bridge effect at the edge, but no current all-polymer film has good enough barrier properties for panels to reach the desired lifetimes necessary for a building material.

### 2.6.2.2 Serpentine edge

To make it possible to use the preferred thicker metal material for the edge of a VIP an alternative edge design was proposed in Papers I and II, a serpentine edge. The idea to form a serpentine edge came from an already existing design involving thin metal layers breaking through relatively thick insulation layers, namely the web of a steel stud, which in traditional wall design often breaks through an insulation layer<sup>5</sup>. Studs of sheet metal are being used in outer walls of buildings with good results. The web of the stud breaks through the isolative layer creating a thermal bridge. To minimize the thermal bridge of the stud web it has been slotted to prolong the path that heat has to travel from one side to the other. A similar strategy is proposed in papers I and II to deal with the edge effect of vacuum panels. By designing an edge element with material going back and forth as shown in Figure 19, the thermal bridge at the edge can be reduced significantly.

<sup>5</sup> During the finishing stages of this thesis, it has come to the author's knowledge that the idea of an alternative edge design was not new. There exist a patent filed in 2001 covering alternative edge designs for vacuum insulation panels; the idea of a sig-sagged edge is one of many (Frederick, 2001).



**Figure 19:** with a serpentine edge, the path for heat is prolonged with a smaller heat flow through the edge as the result.

Numerical calculations, presented in paper I, show that an optimized edge design, a serpentine edge, has the potential to reduce the linear heat loss to a third of the heat loss for a straight edge; both using of 0.1 mm stainless steel in the edges, Table 1. Laboratory experiments on prototype edges have shown strong improvements compared to the traditional straight edges. Unfortunately, it was not possible to make an edge element with 17 serpentes nor was the equipment available to manufacture a vacuum panel. Instead, a serpentine edge was formed with five slots and PU foam was used to fill the voids. The two edge versions, one straight and one serpentine were placed in a hot plate instrument at atmospheric pressure and surface temperatures were measured.

**Table 1: Linear heat losses for some different barrier configurations for panels with a thickness of 30 mm. Calculated values from Paper I. Values produced within the work of IEA, Annex 39 (IEA-b 2005).**

Barrier type	$\Psi_{\text{edge}}$ $\text{W}/(\text{m}\cdot\text{K})$
Serpentine 5 slots, depth 30 mm <sup>6</sup> thickness of steel 0.1 mm	0.015
Serpentine 17 slots, depth 30 mm <sup>5</sup> thickness of steel 0.1 mm	0.0096
Stainless steel, thickness of 0.1 mm	0.028
Stainless steel foil <sup>7</sup> , thickness of 50 $\mu\text{m}$	0.019
Aluminum foil <sup>6</sup> , thickness 6 $\mu\text{m}$	0.026
Metalized polymer film <sup>2</sup> , thickness 97 $\mu\text{m}$	0.0088

The measured temperatures show the same behavior as in the numeric model even though the measured temperatures show some deviation from the modeled temperatures, see Papers I and paper II for more details.

## 2.7 Polymer and coated polymer film barriers

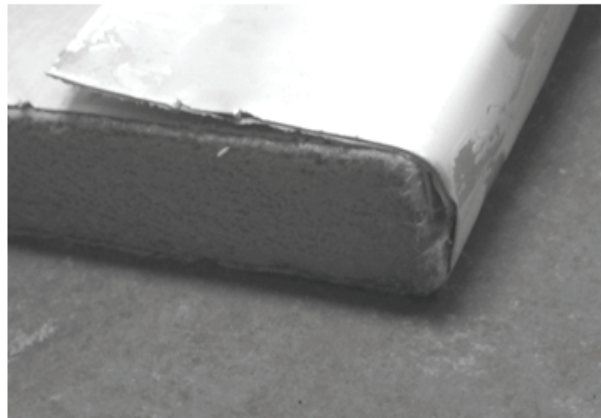
If an all-polymeric film is used then the thermal bridge effect is small but the gas permeability is much larger. Instead, polymer composite films are used. Composite films consist of a sandwich of multiple layers; each layer has its individual function hence one layer per needed function. Thin

<sup>6</sup> Calculated values from paper I

<sup>7</sup> Values produced within the work of IEA, Annex 39 IEA 2005b. Vacuum Insulation Panels - System Development and Applications with VIP (Subtask B). *In*: ERB, M. (ed.) IEA/ECBCS.

metal layers, so called metallization layers or coatings, are added to improve the barrier properties of the composite film. One such film from a VIP manufacturer (in 2005) is made of Nylon/Polyester/Polypropylene/Polyethylene, some layers with added metallization. The Nylon layer is there for mechanical protection and the polyethylene layer makes it possible to heat-weld the seam to seal the panel enclosure.

Some manufacturers wrap the excess material around the edge towards one surface of the panel as in Figure 20. The extra layers of barrier create an additional thermal bridge when wrapped in this way. These designs have flexible envelopes of composite types, and they are heat-sealed at the short edges creating a flange on at least two ends of the panel. When this flange is bent towards one of the surfaces the thickness of the highly conductive metal, the metallization layer, is tripled. Consequently, the thermal bridge effect is substantially increased. Even if a barrier film is used with ever so thin layers of aluminum, as when a polymer is metalized, it will create a thermal bridge that affects the total performance of the whole panel. In many cases, this will significantly impair the performance of the panel. Other manufacturers have developed technologies to reduce the number of seams to three and place the longest seam on the face of a panel instead of at the edge, (Ghazi Wakili et al., 2011).



**Figure 20 shows a cross section of a typical current vacuum insulation panel with excess material wrapped around the edge of the panel, which increases the thermal bridge.**

According to (Glicksman, 1991) this thermal bridge can decrease the overall performance by a factor of two compared with the center-of-panel value. A similar conclusion was reached by (Wakili et al., 2004) after thermally testing several vacuum panels from different manufacturers. It was also concluded in the same study that there is significant edge-effect due to the wrapping of the barrier material around the edge of the panel, a linear loss of about  $6 \cdot 10^{-3} \text{ W}/(\text{m} \cdot \text{K})$  to  $53 \cdot 10^{-3} \text{ W}/(\text{m} \cdot \text{K})$  was found; the size depends on material properties of the barrier layer. The best thermally performing barrier was a multi-layer metalized polymeric foil with an aluminum thickness of 90 nanometers and the worst performing barrier contained an aluminum foil with a thickness of 8 micrometers.

The thermal bridge at the edge may be dealt with on a material scale by alternative designs, such as by the serpentine edge design introduced above. The serpentine edge shows promise of reducing the edge loss significantly. Alternatively, the edge loss may be addressed on the component scale; for example, to place panels in multiple layers in a staggered configuration. Wakili et Al. has shown that in a configuration with panels double layers the improvement by staggering the panels was approximately 25% to over the same configuration without staggering, (Ghazi Wakili et al., 2011). However, the argument has been to use as large and thick panels as possible to maximize the

service life times<sup>8</sup>. It is a situation of opposing requirements, on one hand, the improvement in thermal performance by using multiple staggered layers and, on the other, the reduction in service lifetime by the usage of thinner panels in a staggered configuration compared with a single layer configuration of the same total thickness.

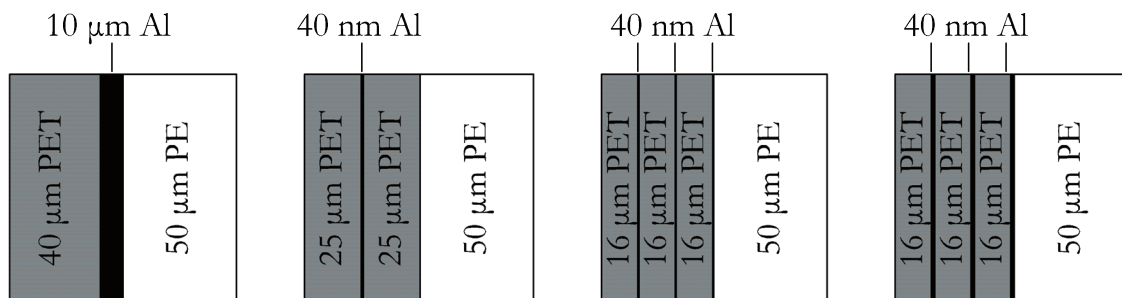
Yet another approach is to surround the VIP layer with other insulation materials to negate the additional heat loss, basically adding insulation layers intelligently to minimize the size of the heat loss, hence, the issue of the built in thermal bridge in the scale of the VIP is dealt with on the larger scale of the component. This was discussed in paper IV and in later sections regarding thermal efficiency.

It was mentioned earlier that moisture and heat are contributing factors to rapidly increased diffusion of atmospheric gas into a VIP. Fumed silica, however, has the capacity to bind both water vapor and air which, to some extent, delays performance loss due to permeation. This will obviously decrease initial effects on performance by diffusion of gas into the panel, but in the long run the internal pressure will increase and cause the center of panel conductivity to increase. It is also important to realize that materials degrade over time. This will, in the case of polymer barriers, result in an increased permeability through the barrier with a decreased over-all performance of the panel, (Simmler and Brunner, 2005).

### 2.7.1 Degradation mechanisms polymers in VIP

Materials in a building will be subject to very different and varying environments, depending on how and where the material is installed. It may be exposed to a number of potential degrading mechanisms, such as elevated and/or alternating temperatures, pollution via the air, alkaline environments that occur if in contact with concrete and mechanical stress during construction. Further, a material could potentially be exposed to UV radiation if installed or stored incorrectly at the building site, and in some specialty applications, such as hospitals and laboratories, there might be radiation with higher photon energies.

Independently of used lifetime definition, the key parameter is the thermal conductivity of the panel and the determining factor for it is the internal pressure in the core in combination with the material of the core. Hence, it is the rate of gas intrusion into the core that is the main mechanism of degradation of the panel as a system, while it is the enclosure material, seam quality etc. that determines the gas intrusion rate.



**Figure 21: Cross sections of some typical barrier films used for VIPs, redraw from Baetens et al. (2010).**

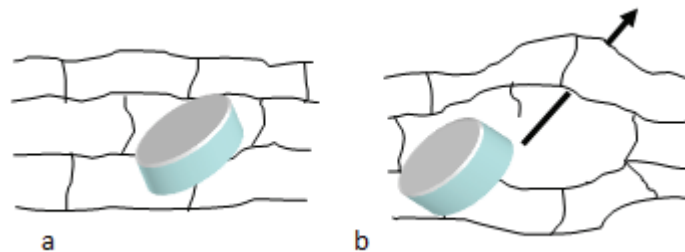
A very commonly used barrier material is composite films made with several layers of polymer films, some with metallization coatings on them, and some for heat sealing properties, Figure 21.

<sup>8</sup> The intrusion of gas takes place through the seam and the face of the panel, hence, decreasing surface and seam length to volume ratio should prolong life time.

The metallization is applied directly to one side of the polymer substrate, and the metalized films are then glued together. One type of glue used for this application is Polyurethane (PUR) glue, (Simmler and Brunner, 2005). The diffusion through an inorganic coating versus the diffusion through the bulk material of the substrate polymer film will be very different. Through the coating the main transport will take place through defects, (Jamieson and Windle, 1983, Da Silva Sobrinho, 1998, Chatham, 1996), this is discussed in a later chapter, while in the substrate the main transport is by diffusion from one defect to another or it may be concentrated to either the substrate film or the glue layer.

It was found in the IEA Annex 39 work that the permeability values increased with temperature and increasing moisture, (IEA, 2005a). There are many other mechanisms, which will lead to degradation of polymers, increased permeability of gas through the enclosure barrier and in accelerated degradation of a vacuum panel system.

Many environmental agents will affect a plastic material greatly through breaking up the backbone chains or by transforming pendant groups. The backbone chain can also be lengthened by reactions between polymers. If a branch in a networked polymer is broken off, it will cause a chain interruption that might allow increased transport through the material, see Figure 22.



**Figure 22: Degradation that breaks up networked polymers will increase diffusion by allowing greater mobility in the network illustrated in b. Original network illustrated in a.**

Some degrading mechanisms of polymers depend on the following factors, (Feldman, 1989):

- chemical environment
- heat and thermal shock
- ultra-violet light
- higher energy radiation

Different types of polymer degradation are often labeled according to the mechanism leading to degradation: radiation leads to photo degradation, chemical reaction with oxygen leads to oxidization and biodegradation is degradation induced by something biological, for example bacteria.

- Photo degradation is due to influence by radiation on the material. The energy of the photons interacts with the polymer, and for some polymers leads to yellowing, and for others, such as polycarbonate, the effect is a rearrangement reaction. For PET (Poly ethylene terephthalate) it is well known that the main degradation event due to radiation is chain scission, hence the long polymer chains are separated into shorter chains, (Fechine et al., 2004). In the building industry the UV radiation already constitutes a real threat; however, Torikai speculates that the reduction of ozone in the stratosphere and the partial depletion of the ozone layer observed over Antarctica in the 1980's may very well lead to the enhancement of UV and even shorter wave lengths solar radiation to reach the surface

of the earth, (Torikai, 2000). Shorter wave radiation contains more energy, Table 2, and hence may lead to accelerated photo-degradation. The impact of UV radiation may be blocked by ultraviolet light absorbers incorporated into the material but may lead to a less ductile material, (Fechine et al., 2004).

**Table 2** solar irradiances placed in categories and calculated photon energy.

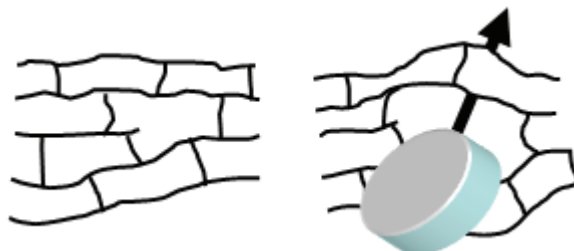
<b>Category</b>	<b>Acr.</b>	<b>Wavelength, <math>\lambda</math>, range [nm]</b>	<b>Wavelength range, SI</b>	<b>Energy per photon, <math>E</math>, [eV]</b>
Gamma rays		$1 \cdot 10^{-5} \leq \lambda < 0.001$	$1 \text{ fm} \leq \lambda < 1 \text{ pm}$	$124 \text{ MeV} \geq E > 1240 \text{ keV}$
X-rays		$0.001 \leq \lambda < 10$	$1 \text{ pm} \leq \lambda < 10 \text{ nm}$	$1240 \text{ keV} \geq E > 124 \text{ eV}$
Ultraviolet	UV	$100 \leq \lambda < 400$	$100 \text{ nm} \leq \lambda < 400 \text{ nm}$	$12.4 \text{ eV} \geq E > 3.10 \text{ eV}$
Visible	VIS	$380 \leq \lambda < 760$	$380 \text{ nm} \leq \lambda < 760 \text{ nm}$	$3.26 \text{ eV} \geq E > 1.63 \text{ eV}$
Infrared	IR	$760 \leq \lambda < 1 \cdot 10^6$	$760 \text{ nm} \leq \lambda < 1 \text{ mm}$	$1.63 \text{ eV} \geq E > 1.24 \text{ meV}$
Microwave		$1 \cdot 10^6 \leq \lambda < 15 \cdot 10^6$	$1 \text{ mm} \leq \lambda < 15 \text{ mm}$	$1.24 \text{ meV} \geq E > 82.6 \text{ } \mu\text{eV}$
Radio		$0.1 \cdot 10^6 \leq \lambda < 1 \cdot 10^{11}$	$0.1 \text{ mm} \leq \lambda < 100 \text{ m}$	$12.4 \text{ meV} \geq E > 12.4 \text{ neV}$

- Thermal degradation is degradation due to elevated temperature. Raised temperature leads to increased chemical activity. Van der Waals bindings between polymer backbone chains is loosened up to give the material more flexibility. Thermal degradation in its pure form does not include any chemical reactions.
- Chemical degradation in a strict sense is only chemical reactions with the polymer. The reaction is named depending on influencing chemical. If a polymer reacts with oxygen it is called oxidation, and if the influencing chemical is water it is called hydrolysis. Typically differentiating between thermal and chemical degradation is difficult. The rate of a chemical reaction is increased with increased temperature, and therefore, it is hard to know if degradation is due to increased temperature or if the higher temperature induces a chemical reaction.
- Biodegradation is degradation induced by something biological, for example bacteria. Biodegradation is not an imminent risk in a building as long as the material is used above ground.
- Mechanical stress can lead to mechanical degradation. Mechanical degradation in the case of VIP may be as abrupt as a nail penetrating the barrier with immediate pressurization or as subtle as a worker stepping on the material at the construction site without any visible damage which leads to micro-cracks in the barrier and increased intrusion of gas and possibly a premature failure. A VIP is such a fragile composite that one has to assume careful handling at both the manufacturing site as well as at the construction site. A recommended route to ensure safe handling of VIPs would be to never allow the bare material at the construction site, instead supply the material integrated into components where the VIP is already embedded by other materials and protected, for example encapsulated in the layer of closed cell polyurethane foam, (Feldman, 1989).

An important note when it comes to degradation of a polymer is that when exposed to more than one degrading factor at a time the sum of degradation is often greater than each factor summed up.

### 2.7.2 Gas permeation in polymers

Diffusion, permeation and sorption are driven by the difference in concentration or the chemical potential on either side of the barrier film, (George and Thomas, 2001). Polymers with low glass transition temperature possess greater segmental mobility and will have higher diffusivity. It was also reported that the molecular weight, significantly influences the transport process. As polymer molecular weight increases, the number of chain ends decreases. Every chain end represents a discontinuity and may form sites for permeant molecules to be adsorbed into the polymer.



**Figure 23: A polymer chain end can form site for a permeant to be adsorbed into the polymer.**

As shown in Figure 22 and Figure 23, the polymer grid influences permeation greatly. A more flexible grid leads to increased transport, and a disrupted grid does the same. Polymer grids can be softened through use of heat, solvents, or more permanently, by use of plasticizers. Independent of method, transport will increase as the grid is softened.

The size and shape of the penetrant molecule will influence its rate of transport within the polymer matrix as well, (Chaney, 1989). A smaller molecule will have a higher transport rate than a larger molecule. Also the permeants shape has noticeable effect on permeability, for instance flattened or elongated molecules have higher coefficient than spherical molecules of equal molecular volume, (Berens and Hopfenberg, 1982).

If inert filler is used and the filler is compatible with the polymer matrix, the filler will take up the free volume within the polymer matrix and create a more torturous path for the permeating molecules (Negulescu, 1990, Feldman, 1989). The degree of tortuosity is dependent on the volume fraction of the filler and the shape and orientation of the particles. When the filler is incompatible with the polymer, voids tend to occur on the surface, which leads to an increase in free volume of the system and consequently, to an increase in permeability, (Chaney, 1989).

### 2.7.3 Physics of gas permeation

The transport of small molecules through a polymer membrane occurs due to random molecular motion of individual molecules, (Chaney, 1989). Stannett reports that Graham formulated the “Solution diffusion process” as early as 1866 by observing and reporting the inflation of a wet pig bladder with CO<sub>2</sub>. This is, according to him, the first reported study of permeation through a polymer. The governing function proposed by Fick, in 1855, by analogy with Fourier’s law of heat conduction, of diffusion through a material is shown in Equation 4, (Stannett, 1978).

$$J_i = -D_{ij} \cdot \frac{dc_i}{dx} \quad \text{Equation 4}$$

$J_i$  = Gas flux of gas  $i$  through the matter  $j$  (mol/(m<sup>2</sup>·s)).

$D_{ij}$  = Diffusion coefficient of gas  $i$  in matter  $j$  (m<sup>2</sup>/s).

$c_i$  = Gas concentration of gas  $i$  (mol/m<sup>3</sup>).

$x$  = is the position (m)

The diffusion coefficient,  $D$ , gives a measure of how fast a molecule of a specific kind can move through a specific material. The diffusion process is driven by the difference in concentrations in the material. Thus, if there is a film with thickness,  $l$ , with high concentration,  $c_1$ , on one side and a low concentration,  $c_0$ , on the other side the steady state gas molecular flux will be:

$$J_s = \frac{D(c_1 - c_0)}{l} \quad \text{Equation 5}$$

$J_s$  = Flux of gas molecules (mol/(m<sup>2</sup>·s)).

$D$  = Diffusion coefficient (m<sup>2</sup>/s).

$c_x$  = Gas concentration at  $x$  (mol/m<sup>3</sup>).

$l$  = is the thickness of the film, (m).

Stannett continue and describes how Exner and Stefan (Exner, 1875, Stefan, 1878) showed that permeation through soap films was proportional to the product of the solubility of the gas in water and the diffusion constant as described by Fick's law (Stannett, 1978). In 1879, Wroblewski extended this work and showed that Henry's law of solubility, Equation 6, was valid for gas solubility in rubbers according to Stannett. The solubility,  $S$ , describes how many of a permeant gas's molecules will dissolve in the surface of, in this case, a polymer. This relationship only holds for low concentrations of permeant according to Chaney, (1989).

$$c_x = S_{ij} \cdot p_x \quad \text{Equation 6}$$

$c_x$  = Gas concentration at  $x$  (mol/m<sup>3</sup>).

$S_{ij}$  = Solubility coefficient of gas  $i$  in matter  $j$  (mol/m<sup>3</sup>·Pa).

$p_x$  = Pressure at  $x$  (Pa).

The diffusion coefficient,  $D$ , and the solubility coefficient,  $S$ , may be lumped together to yield the permeability coefficient,  $P$ , which can be combined with Equation 5 to derive the well-known permeation equation, Equation 7, which relates the permeation flux directly to the gas pressures in the atmosphere near the surface of the film at hand.

$$J_s = \frac{P(p_1 - p_0)}{l} \quad \text{Equation 7}$$

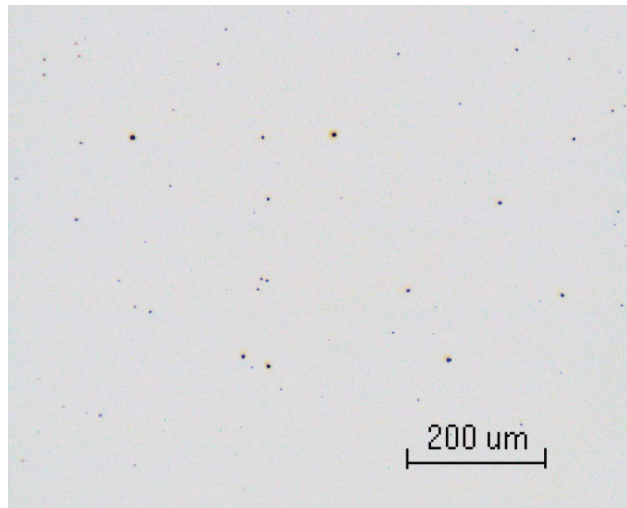
$J_s$  = Gas flux of gas (mol/(m<sup>2</sup>·s)).

$P$  = permeability coefficient (mol/(s·m·Pa)).

$p_x$  = Pressure at x (Pa).

#### 2.7.4 Gas permeation through films with more than one coating

Gas diffusion through an all polymer film could be modeled as flux in one dimension, but in the best available barrier films, polymer films are combined with metallization layers composited into a film. There is no all-polymer film that is impermeable enough to create a vacuum panel with an expected service lifetime of more than 30 years. It is a necessity to add metallization layers into the film matrix. The metallization layer could be regarded as gas tight if there were not any defects, but there are. See Figure 24 for the defects in an aluminum metallization layer of a barrier film from a VIP available on the market in 2005. The image is a photograph taken through a light microscope, the colors are inverted for clarity, and each black dot represents a defect.



**Figure 24: Shows an aluminum coating on the outside part of a VIP barrier including dual aluminum coatings.**

The diffusion of any non-reactive gas, such as oxygen, through a crystalline material, as in a non-organic coating, is very slow and the main diffusion through a coated membrane will take place through areas that lack coatings or through defects in the coating. A number of studies have found clear correlations between defect density and permeation, (Jamieson and Windle, 1983, Da Silva Sobrinho, 1998, Chatham, 1996).

Most measurement equipment struggles to measure films with very good air barrier properties. A state of the art instrument was developed within IEA Annex 39, (IEA, 2005a), with capabilities of measuring water vapor transmission rates as low as 10<sup>-5</sup> g/(m<sup>2</sup>·day). In the IEA project it was concluded that in order to reach lifetimes of 30-50 years in a building application the enclosure barrier needs as to have a maximum oxygen transmission rate (OTR) of 0.001 cm<sup>3</sup>/(m<sup>2</sup>·day·atm) and water vapor transmission rate of less than 0.0001 g/(m<sup>2</sup>·day·atm). During the same period a typical polymer film with three metallization layers was reported to have OTR of 0.003-0.005 cm<sup>3</sup>/(m<sup>2</sup>·day·atm) and WVTR of 0.001-0.002 g/(m<sup>2</sup>·day·atm) at 23°C and 50% RH even though manufacturers claimed OTRs as low as 0.00062 cm<sup>3</sup>/(m<sup>2</sup>·day·atm) in their declarations.

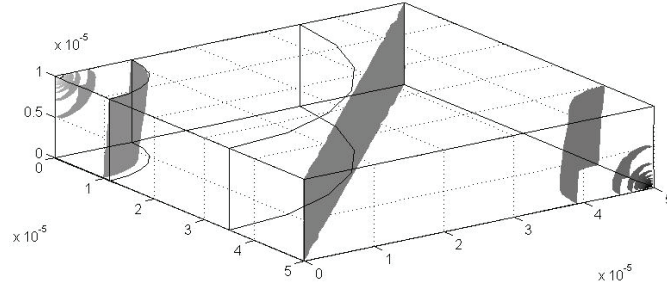
Recently the company va-Q-tec developed, tested and published some viable methods for testing gas intrusion into the core of vacuum panel systems (Caps et al., 2008). They have tested and proven the applicability of two methods with good results. The first uses a spinning rotor gauge, which measures the increase in friction between the residual gas in the panel and a rotating steel ball. The more gas there is the more friction is detected. With this method, they can detect a clear trend in gas intrusion after just a few days.

The other usable method is by a thermal method where the thermal behavior is measured and related to the pressure increase inside the panel. To test a regular state of the art panel with the best core material and the best available barrier it may take several hours just to establish steady state heat flux across a panel. Because of this, Caps et al. manufacture smaller and thinner panels with a coarser filler material to enhance the sensitivity of the panel to increased internal pressure. They showed that they could detect a gas pressure change of 0.002 hPa in two days in such panels with the best aluminum foil laminate barrier. To accelerate the tests they tried to store the panels in a Helium atmosphere between tests; since Helium has smaller molecules, the intrusion rate into the panel will be faster than for air and in addition Helium has higher thermal conductivity than air which will yield a larger change in thermal conductivity of the panel. Increasing the temperature of the storage atmosphere should increase the transmission rate as well, accelerating the ageing further.

For a manufacturing company, such as above, it is necessary to test actual panels for quality control, but this is not for all interested parties. It must be noted that what is measured above is not directly the gas transmission rate through the barrier film alone, but through the barrier and the seams and through any defects. It would be a strong advantage if the gas transmission through films with multiple coatings could be modeled with some degree of connection to reality.

## ***2.8 Modeling of gas transmission through barrier films with dual coatings***

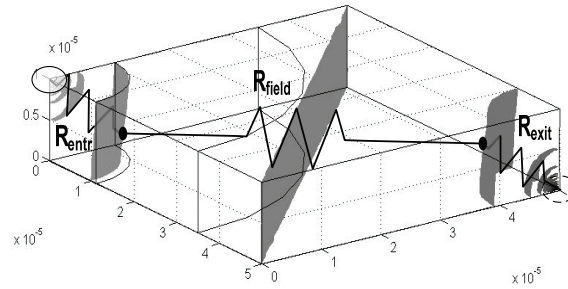
There are several models for gas flux through barrier films with only one coating, hence a polymer substrate film on which a thin layer of metal has been added on one side. There are numerical models for permeation through films with two coatings as well, one coating on either surface of the substrate film. Generalizations are necessary in any model also in purely numerical models, such as the models presented by Hanika et al. and Musgrave, (Hanika, 2003, Musgrave, 2005). In numerical models, mostly based on finite elements, generalizations regarding defect-to-defect distances and defect sizes are common. Many more assumptions and generalizations are made but these two are specifically addressed and removed in the model presented in paper III, in this paper a model is proposed for diffusion through a polymer film with two or more coatings which take data on defect size and distribution into account. The model combines numerical modeling, for the entry and exit resistance into and out from the film through the coating defects, with electrical field theory, for the permeation through the substrate polymer.



**Figure 25** show an isosurfaces plot from a numerical calculation in the software package, COMSOL Multiphysics, of the concentration between two interacting defects in two coatings on the opposite sides of a substrate film.

Figure 25 shows an isosurface plot of concentration for the case of a polymer with coatings on both sides. Both coatings have a quarter of a circular defect in opposing corners; the defect is in the top side coating on the left and in the bottom coating on the right side. The case is modeled in the numerical software COMSOL Multiphysics. The concentrations at which to plot an isosurface have been chosen so that one such isosurface falls at a radial distance of one substrate thickness from the corner where each defect is located. In this figure, it can be observed that the concentration at this distance is close to constant. This surface is, in the proposed model, taken as a potential point in a resistance network. A layer of resistances (in the field) then interconnects the potential points, denoted  $R_{\text{field}}$ , as can be seen in Figure 26 and an overview of the interaction between a numbers of defects are plotted in Figure 27.

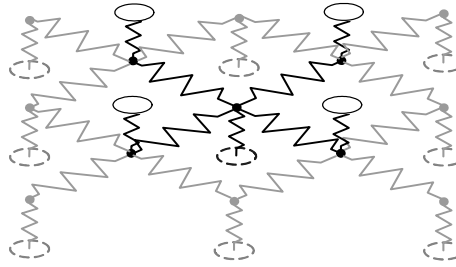
The resistance near the defect, through which the gas enters the substrate film as well as the resistance near the defect where the gas finally exits the substrate film, was modeled numerically; in Figure 27 those resistances are denoted  $R_{\text{entr}}$  and  $R_{\text{exit}}$ . The resistance between the two cylinders, which is formed around the two defects, is calculated by theories of magnetic fields around paired cylindrical poles, so called dipoles.



**Figure 26:** Is the same as Figure 25 but with the addition of the used resistances for the hybrid model.

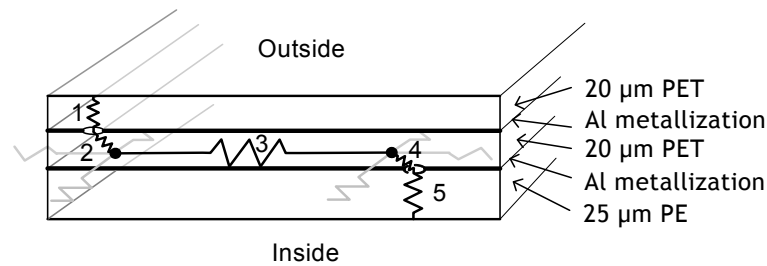
The total resistance for a typical diffusion path would be  $R = R_{\text{entr}} + R_{\text{field}} + R_{\text{exit}}$  but there are multiple field resistances connected to each potential node which results in a resistance network. Since every defect on the high concentration side will interact with several of the defects on the opposite side the resistance network may become very large. The number of field resistances that is to be included in the model has to be chosen by the user, the optimal would of course be to allow all entry defects interact with all exit defects but that creates a system unnecessarily large. In paper III, where this model is presented and used, four interactions per defect in the defect densest coating have been used because in a numerical calculation with evenly spaced positions of defects it is

assumed that each defect interact with four others. A representation of a part of such a resistance network is shown in Figure 27.



**Figure 27: Show a portion of the resistance network the interconnected defects create. This is the network that in the end is solved to calculate the total flux through the composite film.**

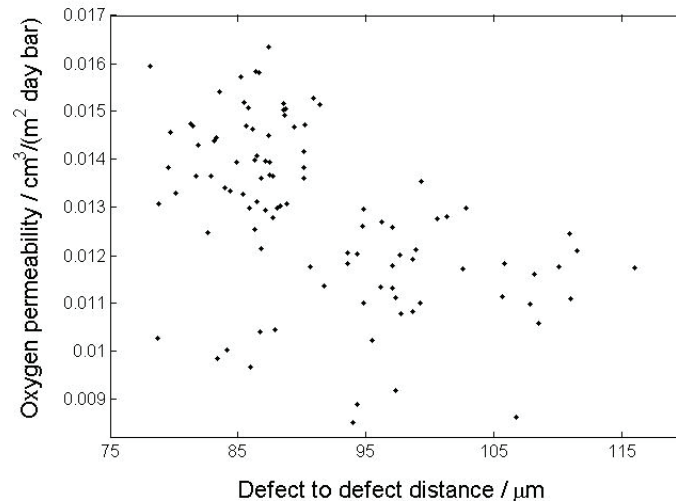
If additional polymer layers are added on either outside of the metallization layers then this will add one extra layer of resistances per added polymer layer. An image of such a common set up can be seen in, Figure 28, where a polymer layer have been added on either side of the original coating. Whilst if a coated layer is added then three layers of resistances would have to be added, one containing the resistance near the defects in the new coating, one containing the resistance near the defects in the existing coating and one layer containing the field resistances interconnecting the defect resistances.



**Figure 28: Image shows the basic buildup of the modeled VIP barrier film.**

The setup in Figure 28 is the same as one found as the barrier of a sample vacuum panel that was available to the author at the time Paper III was written (in 2005). Samples of the composite film from this panel were evaluated; the defect density, defect size distribution and the defect positions were found using light microscopy and image processing. This is a method that was previously used by Jamieson and Windle in their study. Permeation was measured on the samples both commercially coated as well as films coated in laboratory and good correlation was found, (Jamieson and Windle, 1983).

The found defect data was then used as input for the presented hybrid model with promising results. Ten samples of each coating, top and bottom, were analyzed, the data was fed into the model and the calculated fluxes are plotted in Figure 29.



**Figure 29: Plotted Oxygen permeability calculated for a combined film with 5 layers: 20  $\mu\text{m}$  PET–Al coat–10  $\mu\text{m}$  PET–Al coat–20  $\mu\text{m}$  PET. The defects are defined by the data from evaluated samples from real VIP barriers. The diffusion coefficient for oxygen in PET used is  $D = 1.407 \cdot 10^{-14} \text{ m}^2/\text{s}$ .**

The mean OTR of  $0.013 \text{ cm}^3/(\text{m}^2 \cdot \text{day} \cdot \text{bar})$  was compared with measured OTR values reported in the IEA report from Annex 39, (IEAa, 2005). The measured values from one institute range from 0.01 to  $0.02 \text{ cm}^3/(\text{m}^2 \cdot \text{day} \cdot \text{bar})$  which agrees very well with the results from our simulations.

Another institute reports, in the same report, transmission rates of  $0.07 \text{ cm}^3/(\text{m}^2 \cdot \text{day} \cdot \text{bar})$  as an upper estimate for one film with dual coating, this film however was said to have great variations in the measured transmission rate so therefore the value can only be considered an upper estimate. The other film tested by this institute was measured to  $0.00062 \text{ cm}^3/(\text{m}^2 \cdot \text{day} \cdot \text{bar})$  which must be a different very good dual coating film.

## 2.9 VIPs in buildings

Even though vacuum panels have been used in many industries other than the building industry it is no guarantee that they will work in a building. There are a completely new set of requirements for a material to be used in a building with projected life times longer than 25 years than for a material that is to be used in a refrigerator, which in best case may be expected to work for 15 years. The material will be exposed to new environments when used in buildings, new risks and challenges. A material that is to be used in buildings:

1. Needs to have a documented lifetime of at least 30-50 years but 100 years would be preferred. A shorter life time may be adequate if the panels are installed in a serviceable fashion.
2. Will be forgotten during its lifetime. Extra measures need to be made to ensure the integrity of the panels both at the construction site as well as in place during its lifetime.
3. Will be exposed to new climatic conditions, such as temperature and moisture content, which in turn may affect performance of the material.

Due to the extra cost of vacuum insulation panels, the areas of application are limited. For the same reason, there must be an added value of some sort to choose VIP instead of traditional insulation. In my opinion, the case where the space is limited will be the strongest case where vacuum panels will be used. Another case is if there are extreme demands of insulation performance. Other scenarios could be where a construction needs to be heavily altered in order to make room for a required amount of traditional insulation; then it might be more favorable to use vacuum insulation instead of altering the design.

### 2.9.1 Risk for abrupt damage

Panels, which have a film based on polymer layers and/or foils, are extremely sensitive. If punctured the panel loses the main portion of its thermal performance at the same time as it loses most of its stability.

At any work site where a building is being erected, remodeled or renovated there are a number of potential dangers to an exposed VIP. When placed flat on the ground a small rock can suffice to puncture the barrier, whilst the indentation of a foot stepping on the panel, even without shoes, will stress the material, which might result in a shorter lifetime for that particular panel.

After the panel is positioned and possibly covered, there are still risks of penetration by screws and nails, which might be used to hang things on a wall. It must be remembered that the tenants of a building usually change many times during the lifetime of a building. It is likely that sometime during the buildings lifetime the vacuum panel insulation will be forgotten so even if the initial tenants do not screw screws or drive nails into the wall, chances are that the third or fourth tenant will unless there is something in place to present this.

### 2.9.2 Possible application for vacuum insulation panels in buildings

In the report presented by the U.S. Department of Housing, (NAHB, 2002), a number of building components are identified as more promising than others. The ten most promising applications mentioned where:

- Precast concrete panels
- Manufactured housing floor plans
- Exterior doors
- Garage doors
- Manufactured housing ceiling panels
- Insulated metal roofing panels
- Rectangular duct insulation
- Retrofit exterior insulation
- Acoustical ceiling panels
- Attic access panels/stairway insulation

The selection was based on a number of criteria, such as cost of manufacturing, impact, required lifespan, risk of damages and additional installation costs. In a second step the market for each of the ten selected applications was evaluated. The largest market was for use in manufactured homes as floor and ceiling panels. This market was estimated close to one billion square feet, 88 million square meters annually. In a manufactured home, the floor panel is usually located between the floor framing and a bottom board that is installed underneath the chassis. This board protects the house during transport. The concept was dropped due to unwillingness of the manufacturers of such homes; the initial added cost by use of vacuum panels of \$3000 to \$5000 could not be justified in a pre-manufactured home.

In Europe the research the IEA/ECBCS Annex 39 project HiPTI-High Performance Thermal Insulation was ongoing during the same time. This project was divided into two parts, the first; subtask A, dealt with the Vacuum Insulation Panel itself and the second part; Subtask B dealt with applications of VIPs in buildings. The final reports were published in 2005,(IEA, 2005b, IEA, 2005a). Issues of the first part have been discussed throughout this thesis. In subtask B, the work dealt mainly with practical issues of vacuum insulation panels. It is clear that the most common application of vacuum panels is underneath terraced floors, especially in Switzerland, (IEA, 2005b), but there are a number of other applications that have been developed and used in Switzerland and

Germany. In Sweden there is, at this time, some usage. One use is in glass facades by Schüco and there are at least a couple of terraced floors where VIPs have been used for insulation.

In Germany and Switzerland, the market for VIP in building has emerged and a number of projects have been realized. In these countries, VIP with a metalized polymer film barrier and a fumed silica core is the only one used. Baetens et al, (2010), sums up the usage of VIP up to 2010 in their review article. They have searched available research publications for application of VIP and found applications within the following main types of usage;

- insulating existing buildings on the inside or on the outside of the existing building envelope,
- VIPs as vacuum insulated sandwich elements in door and window frames, in curtain walls and in non-load bearing walls,
- insulating flat roofs, loggias, terraces and internal floors, where the small thickness of the needed insulation layer enables a simple construction for a step less transition between the interior and exterior space,
- main insulation of the building envelope for new buildings,
- and building installations, e.g. pipe insulation, insulation for hot water cylinders, or under-insulation of floor heating.

It is challenging to incorporate VIP into buildings for many reasons: panels are fragile, panels must be pre-manufactured, and when installed in continuous layers they will act as a moisture barrier or alternatively concentrate any hygrothermal convection to gaps between panels. Incorporated in a well-engineered design VIP can contribute greatly to the thermal insulation of a building but if done wrong the thermal efficiency of the installed insulation can very well be reduced to less than 50%. Building enclosure design becomes increasingly complex to meet high set goals for thermal insulation. As progress is the goal, old materials may be used in new configurations or new materials, for example vacuum panels, may be used to replace old materials in traditional designs. The results are often good but there are examples where the results were not predicted<sup>9</sup>.

---

<sup>9</sup> For example the usage of traditional windows designed for use in wood stud walls failed in preventing moisture intrusion in the single stage sealed stucco walls that had so many problems in Sweden in the beginning of the 21th century.



## Chapter 3: Integrated Testing and Modeling

As shown in the introductory chapter, space heating and cooling constitute a large portion of the energy used in buildings, and thus occupancy cost in both cold and warm climates: therefore, the precise evaluation of thermal losses and gains is a necessary first step towards improvement of building envelopes. Commonly used standard methods for evaluating thermal performance of assemblies and materials was developed for designs with less complexity than many used today. In walls for example, 3-dimensional hygrothermal fluxes and interactions are becoming more and more important as every small defect may have a relatively huge impact. Despite the increasingly more complex assemblies, they are mostly tested by so-called hotbox methods described below, if tested at all. Thermal conductivity of materials is determined in a similar way by applying a steady state load in hot and cold plate device, which create a thermal gradient across the specimen. These methods determine average thermal performance under referenced, steady state conditions. One can argue that determined under those conditions U-values (R-values in the US) function as comparative indicators, and are not designed to predict real performance. Yet, those values are typically used in energy analyses of buildings for calculation of energy consumption as well as for heating and cooling loads when building systems are dimensioned.

The reality is that a construction assembly under field conditions will only very rarely, if ever, experience steady state conditions: instead, it will be subject to constantly changing conditions due to weather and usage. Some of the most common driving forces are the varying temperatures, air pressure and moisture. The weather is the main contributor to creating diverse loads on a building enclosure. There are more loads, the loads on the interior created by the users of the building, such as the added moisture due to cooking or showering and the changing of the pressure situation in the building due to windows and doors opening and closing.

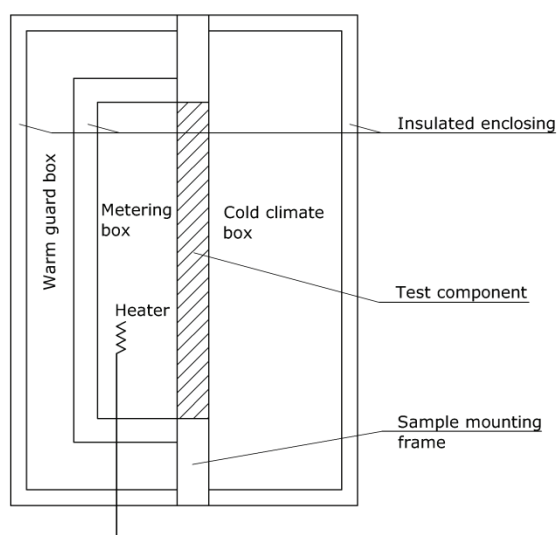
### 3.1 Literature study

#### 3.1.1 Building enclosure performance

As designs become more complex, our understanding of interactions needs to keep pace. We must be able to predict building performance under field conditions, as it is necessary for dimensioning heating and cooling systems correctly, and assessing the functionality of a design. This is also needed because the Swedish building code energy performance in practice (BBR18) requires it. It would appear that knowing the energy use of building enclosure under real conditions of exposure is the first step to achieving the efficient passive houses, which are our first step on the path to the future +energy houses. Yet, despite the many tools available we often fail in accurately predict the energy performance of the actual building enclosure. Why? The answer to this is that we do not know. We have several test methods, some mentioned above, that measure separate aspects of thermal performance. We have several models of the whole house energy performance. Yet, it is reported repeatedly that buildings and their components are performing differently than model predictions (Wilkes, 1982, Greason, 1983, Kalamees and Vinha, 2003).

The standard way of reporting thermal performance of materials and components is to use the thermal conductivity for materials and U-values for components in Europe (in the U.S. the R-value is used for both). The R-value is the thermal resistance, which is equal to the thickness divided by the thermal conductivity measured in a lab by a standardized method, ASTM C518, C177 or C687. For components, the R-value can be established by measurement according to ASTM method C236, C976, or C1363, (ASTM Standard C518, 2010, ASTM Standard C177, 2004, ASTM Standard C687, 2005, ASTM Standard C1363, 2005, ASTM Standard C236, 1993, ASTM Standard C976, 1996). Typically one tests a wall section, 2.4 m x 2.4 m (8 ft. by 8 ft.) or larger in either a guarded or

a calibrated hot box (see principal drawing in Figure 30), that is placed tightly against the component on the room side. To perform a guarded hotbox measurement one measures the amount of heat added to the metering box while zero heat transport on all sides of the metering box (insulated enclosure) must be maintained except through the tested wall. If this is not possible, a correction factor is determined as a function of temperature distribution and heat flux through the tested wall. This correction is then applied to the measured heat production inside the box that is needed to keep the temperature steady; hence, the assigned name “calibrated hot box”. The amount of added heat together with known temperatures can then be used to calculate the average thermal resistance of the sample.



**Figure 30: Principal drawing of the hot box setup.**

As stated, the hotbox methods have been developed to measure the average thermal resistance, including additional heat flow due to thermal bridges in the component, hence the clear wall R-value. The method is mainly used for testing of wall assemblies that are not affected by the presence or movement of moisture or by air convection inside the assembly. This restriction has been known for many years; though it is not always possible to eliminate it from the test set-up. For instance, Wilkes (1982)<sup>10</sup>, discussing block and frame walls, stated that non-insulated block walls exhibited 15 to 19% lower performance than predicted. Greason (1983) stated that while good agreement was found for all solid walls, walls with air spaces showed lower performance than predicted.

Another problem in this approach is uncertainty introduced by air movement within the metering box parallel to the wall surfaces. In this context, however, the calibrated hot box measures an average value of thermal resistance on the central portion of the test wall. This may, or may not, provide results that are representative of actual wall performance. Furthermore, the average energy rating from a hotbox test does not allow for separation of various flow mechanisms i.e., so one cannot measure how thermal performance changes because of airflow or moisture movement. Effectively, this approach is neither suitable for academic research, nor for industrial R&D when one wants to optimize designs and materials used for controlling heat, air and moisture performance of walls.

<sup>10</sup>Referred to in the book: Fundamentals of Building Energy Dynamics, By Bruce D. Hunn, Edition: illustrated, Published by MIT Press, 1996, ISBN 0262082381, 9780262082389, 550 pages.

An alternative approach for addressing this complex problem is to take advantage of the capabilities of heat flux transducers to secure R-value measurements and measure local heat fluxes and temperatures. Papers V through VII propose and use a method that entirely relies on local measurement with a calibrated boundary layer, thermopiles and temperature measurements. When thermopiles<sup>11</sup> of the right size in combination with temperature sensors all placed in well thought through patterns it is quite easy to measure energy loss through a wall at least as accurate as with a box method with the added benefit of local data. Here 100x100 mm<sup>2</sup> thermopiles and minimum 5 thermocouples across each half of a cavity width was used to capture three dimensional effects due to thermal bridges as well as effects due to convection, both natural and forced, in the cavities.

### 3.1.2 Conduction on the component scale

Scaling up from the material scale to the scale of a building component, or even the whole building, the internal heat transfer mechanisms of the finer scale becomes blurred and all that can be seen is the resulting sum of the heat transfer mechanisms. They are all, except for penetrating forced convection and mass transfer, summed up in the term thermal conductivity, which is seen as an integrated material property. For steady state calculations, without airflow or moisture flow, it is enough to know the geometry, boundary conditions and thermal conductivities of the materials in order to calculate heat transfer.

Thermal bridges are caused when material with higher thermal conductivity breaks through, or partially breaks through, a layer with higher thermal resistance (lower thermal conductivity) creating a pathway of lesser thermal resistance causing an increased heat loss. We have already seen thermal bridges in the chapter on VIP where the wrapping of the barrier film created an increased heat loss at the edges of the panel, hence bypassing the lower conductivity material (the core) by a material with higher conductivity (the barrier).

In building components, such as walls and roofs, thermal bridges are commonly found reoccurring in the form of evenly spaced beams or studs. Their effect on average thermal resistance of the wall can be expressed as a percentage reduction in R-value, which is called the framing factor (or framing correction), and can be described by the impact it has on the thermal insulation efficiency, as discussed in section 4.2.

Hence, thermal bridges may be separated into groups based on types. The reoccurring type described above being the first one; the commonly used groups are:

- Reoccurring thermal bridges,
- local thermal bridges (linear or point),
- geometrical thermal bridges.

The second type of thermal bridge, typically not reoccurring, is usually found at intersections of components; the connection between an intermediate floor connecting with the external wall usually create a linear thermal bridge while a fastener is an example of a point loss. Finally, the third type of thermal bridge is not related to differences in material properties, but is created by geometry and will occur, for example, at external corners of an exterior enclosure. This is caused by the geometrical relationship between inside and outside surface areas, see review of Thorsell and Bomberg (2007). The authors highlight that the impact of a thermal bridge depends not only on the materials, but also on the relative position of the thermal insulation and heat collecting layers. They state:

---

<sup>11</sup> Thermopiles as used in this project are explained in later chapters on sensing.

*The construction technology has changed significantly. Firstly, the levels of thermal insulation and air tightness of buildings are much higher than they were 20 years ago that makes effect of thermal bridges more severe. On the other hand, a trend to use exterior air barrier systems and exterior thermal insulation makes the design process easier (Thorsell and Bomberg 2007).*

Table 3, quoted from Oak Ridge National Laboratory (ORNL) research, shows the thermal significance of mechanical fasteners and air gaps between boards (Petrie et al., 2000). Laboratory experiments were carried out to examine the thermal performance of metal-deck, low-slope roofs with polyisocyanurate insulation. The effects of fasteners mounted through the roof insulation and gaps between insulation boards were measured. It was found that the effects of fasteners and gaps increased simulated annual heating and cooling loads by percentages about equal to the percentage reductions in thermal resistances.

**Table 3: Reduction of R-values, in percent, caused by the mechanical fasteners and gaps between insulation boards (from Petrie et al., 2000).**

Mean temp °C (° F)	Fasteners in 4 in. polyiso	Air gaps in two 2 in. polyiso	Air gaps in 2 in. polyiso
-1 (30)	8.6%	14.5%	16.7%
24 (75)	7.0%	12.2%	15.3%
51 (123)	5.6%	10.2%	14.0%

The ASHRAE handbook presents methods to manually calculate the impact of thermal bridges on R-value (ASHRAE, 2005). Two models are discussed: the parallel path and the isothermal planes model. The parallel path model assumes all heat to take perfect parallel paths with no lateral transmission; it overestimates the R-value. In the isothermal planes method the thermal resistance of all materials in each layer of the construction is weighted and the total resistance calculated as a series of resistive layers resulting in an underestimated thermal resistance.

$$R = R_1 \cdot m + R_2 \cdot (1 - m) \quad \text{Equation 8}$$

$R_1$  = thermal resistance calculated from the parallel path model ((m<sup>2</sup>·K)/W).

$R_2$  = thermal resistance calculated from the isothermal planes model ((m<sup>2</sup>·K)/W).

$M$  = is a weighting factor between 0 and 1. If  $m=0$  then the heat flow is perfectly parallel and with  $m=1$  mean that the heat is perfectly equalized within every plane.

The real thermal resistance of the construction will be somewhere between the upper limit given by the parallel path method and the lower limit given by the isothermal planes method, Equation 8. Carpenter states that a real thermal resistance of the wall is restrained by these two limits, (Carpenter, 2001). The lower the value m is, the higher the R-value will be. The limitation for this method is that it only works for plane structures, hence it cannot cope with geometrical thermal bridges such as at a corner, and it cannot handle highly conductive layers such as in steel studs.

Additional heat loss through thermal bridges are, under simplified conditions, quite straight forward to calculate by numerical methods in the case of pure conduction in steady state. There are

several numerical codes available for such problems. Kosny and Desjarlais (1994) compared a number of available codes to a series of critically reviewed experimental results. The average difference between the simulations and experiments was less than 4%. This is less than the stated uncertainty of the test method.

In reality however, it is not as simple as that. Heat conduction is not the only transfer mechanism occurring in a component: we often have convection, moisture transport and/or radiative interaction as well. As stated before, in reality, a steady state is very rarely the case.

### 3.1.3 Air leakage (convection)

Convection on a building scale is the same mechanism as in the material scale. The mode of convection is commonly separated into natural or forced convection.

- Natural convection is movement due to temperature differences: warmer air is lighter and will tend to rise above cold. This effect may be referred to as buoyancy or stack effect. Natural convection may occur in empty voids in components or in low-density insulation materials.
- Forced convection covers cases where the flow is forced by external force; on the scale of a building, it may be fans in a building or even the wind blowing around the building.

However if the scale of interest is the atmosphere, then the wind should be seen as a natural convection. However, looking at airflows inside components, hence on the component scale, fans pressurizing the building and wind driving the forced convection is not the only considerations necessary. In addition, there are the stack effect inside the building, but, outside the component, is a driver for the forced convection, and must be included. Hence, the scale of the problem dictates the roles of the driving forces.

Mechanical ventilation in buildings is driven by fans forcing air through ducts to exchange air between the inside and the outside in a controlled manner, allowing for heat recovery, filtration and/or other air conditioning. Air leakage, on the other hand, is the unplanned additional air exchange across the building enclosure. Leaking air flowing from the outside into the building is often referred to as infiltration and the opposite, leakage from inside to outside, is called exfiltration. When leaking air enters a wall at one point and travels several feet through the wall before entering the house, it is termed "diffuse" leakage; air which enters the building, such as through cracks around a door, and penetrates in a straight through fashion is termed "concentrated", (Bhattacharyya, 1991).

The uncontrolled airflow finds its way through imperfections in the envelope; the path of the flow will be the one of least resistance and the amount of flow will depend on local pressure difference, characteristics of the flow and the resistance of the flow path. There are several driving mechanisms creating pressures or creating pressure differences on or across the building enclosure; the most common and most significant are:

- Mechanical fans; kitchen fans, ventilation system, moisture removal fans in the bathroom.
- Wind
- Stack effect
- Air conditioning; dehumidification, temperature changes

#### 3.1.3.1 Mechanical fans

Mechanical fans are one of the more potent pressure creators found in buildings. Bornehag, (Bornehag, 1991), studied 87 Swedish apartments built between 1978 and 1982 and measured

pressure differences between inside and outside. He found pressure differences ranging between +10 to -60 Pa under normal running of the mechanical ventilation systems. When the kitchen fan ran, he found negative pressures of up to 100 Pa in some apartments. Levin made the same observation regarding kitchen fans when he measured pressures in more than 100 relatively new apartments (in 1991), (Levin, 1991). These are quite different findings than what Sherman and Chan indicate when they say that the average pressure across a leak in a building envelope is closer to 1 Pa than to 50 Pa, (Sherman and Chan, 2004). It also contradicts Abadie (Abadie et al., 2002) who found a typical indoor and outdoor pressure differences to be within the range of 0.1 Pa to 10 Pa for residential buildings.

### **3.1.3.2 The wind**

Uvsløkk, (1996) measured pressure differences in the gap behind a façade due to wind. At a wind speed of 10 m /s (at 10 m above ground), he found a pressure drop in the gap of 13 Pa/m. Some of the data he measured are presented in table Table 4. With facade height of 2.5 m the total pressure drop would be 32 Pa from top to bottom of the gap, hence, potentially higher pressure differences than the 1-4 Pa or closer to 1 than 50 Pa brought forward earlier.

**Table 4 shows the highest pressure differences along the air gap behind rain screens as well as the increase in heat transmission due to the induced air flow in the gap and the insulation material, as tested by (Uvsløkk, 1996).**

Wind speed	Max Press Gradient	No barrier	Best barrier
m/s	Pa/m	%	%
5	3	20	1
10	13	70	2
15	28	>140	5
20	52	>>200	10

The wind has potential to create much higher pressure differences than 5 Pa as seen in Uvsløkk's work. The pressure difference produced by wind will not only depend upon the wind speed but also building geometry, wind direction and the exposure to the wind, hence where the building is situated with nearby buildings, building orientation, ground roughness etc.

### **3.1.3.3 The stack effect**

The stack effect, or buoyancy, exists due to differences in air density, which depend on air temperature. The different conditions between inside and outside or between zones in a building, or even within a room, creates small pressure differences leading to air movement. The magnitude of the pressure difference will increase with building height due to the increasing height of the pressure stack. The measured pressure differences above, from Bornehag and Levin, most likely include stack effects, which however are small in comparison with the pressures created by mechanical means, such as a kitchen fan.

For example, if the temperature inside is kept at 23°C and the outside temperature is 0 °C ; the density of the outside air is 1.292 kg/m<sup>3</sup> and the maximum stack effect in a 10 m high building is 9.8 Pa calculated by the formulae given by Walker and Wilson, (Walker and Wilson, 1993). This is true if the neutral pressure plane is at the bottom of the building. The neutral pressure plane is the plane where the pressure inside the building is the same as the outside pressure.

#### ***3.1.3.4 Air conditioning***

Air conditioning of the air within the building is one largely overseen source for changing pressures in a building. The explanation may be that temperature changes and moisture content change is a slow process mostly done in the heating, ventilation, and air conditioning (HVAC) system but still, changes in temperature or moisture content of the air may lead to changes in pressures. Some examples where the treatment of the air directly affects the conditions in the room is the free standing dehumidifier that is promoted for use in crawlspaces in Sweden and basements in North America, or the air-air heat pumps with separate units that are becoming more and more popular.

Just as an example; let us consider a relatively moist day when it is 23 °C outside at 80% relative humidity (RH) and the desired indoor temperature is 20 °C at 40% RH. The outdoor air contain 16.44 g water/m<sup>3</sup> as it enters the building and after long time, when steady state has been reached, the moisture content of the room air would become the same unless the air is dehumidified and cooled. Such cooling by 3°C from 23°C to 20 °C leads to a decrease in pressure of more than 1 kPa if done in an absolutely air tight room. All calculations are done by using the ideal gas law and by treating air as an ideal gas. Dehumidification has a similar effect: removing 9.5 grams per m<sup>3</sup> is equivalent of a pressure reduction near 1 kPa, thus an order of magnitude higher than the maximum found from a kitchen exhaust fan by Levin.

If the conditioning of the air is done within the HVAC unit it is likely that the unit compensates for hygrothermal changes. If separate units such as a freestanding dehumidifier or a cooling unit working with recirculation only does the conditioning, then the effects will occur in the room where the unit is placed. Hence, the usage of a dehumidifier in the basement of a building may create a potential for unwanted air leakage through the construction, from the living space down to the basement. In modern super tight buildings these secondary effects may become important even though the process of dehumidification or temperature change are slow in comparison with air pressure equalization taking place in the relatively leaky existing buildings.

#### ***3.1.3.5 Combined pressure difference***

The combined pressure differences is the driving potential for air flow, and it does not matter if it is in the ventilation system, the kitchen fan and through holes, cracks and gaps in the building enclosure. To model air leakage accurately in a building the minimum amount of information is:

1. Known characteristics of the HVAC system
2. Known wind characteristics, speed, direction and exposure
3. Known pressure distribution across the surface of the building for the wind direction being studied.
4. Temperatures inside the building and outside
5. Position and flow characteristics of all openings in the building(Awbi, 2003)

To calculate a local particular pressure distribution in a building all driving mechanisms must be combined and the height of the neutral plane found. It is also important to understand that as buildings are being built more and more airtight, it will be harder to maintain a set pressure difference, and easier to create larger pressure differences, and even the effects of dehumidification and temperature changes may become more important.

### **3.1.4 Characterization of air leakage**

Air leakage characterization may be done on the scale of an individual flow, a component, or on the scale of a whole building. On the scale of individual defects the flow may be laminar, turbulent, or in transition between the two. Since the overall leakage in a building involves a combination of

laminar and turbulent flows, the non-linearity of the process may lead to challenging measurement and interpretation problems.

The fundamental form of the air leakage equations is not known, but there is general agreement that a power-law formulation is theoretically and empirically justifiable (Nylund, 1980, Sherman and Chan, 2004, Peterson, 1982). For component and whole buildings, the flow is often characterized by determining the coefficients,  $C$  and  $n$ , for the power law, **Equation 9**.

$$Q = C \cdot \Delta P^n \quad \text{Equation 9}$$

Where  $C$ ,  $\text{m}^3/(\text{s} \cdot \text{Pa}^n)$ , is the flow coefficient which has the physical meaning of the flow rate at a pressure difference of 1 Pa and  $n$  is the pressure coefficient. The pressure coefficient is often found to be in the range between 0.65 and 0.70 but has the limiting values of 0.5 (turbulent flow) and 1 (laminar flow). The flow coefficient is dependent on the geometry of the actual leakage paths, air velocity, and surface roughness in the path etc.

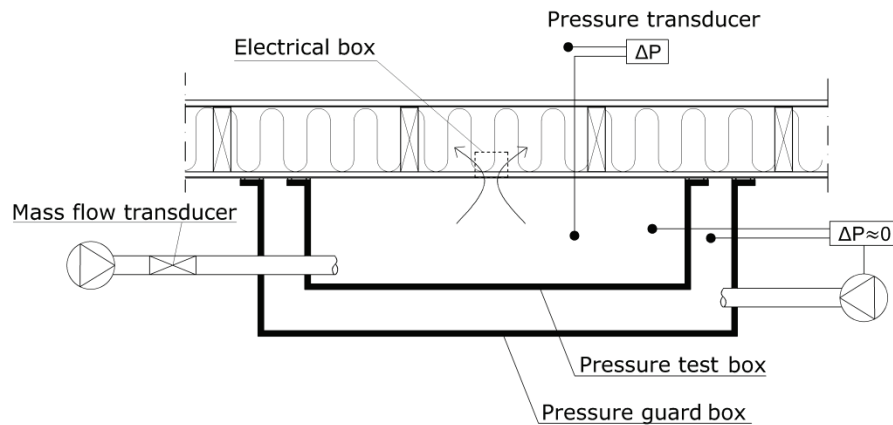
Walker et al. (1997) examined the validity of the power law for describing the leakage through a building envelope. His work was done through theoretical analysis, laboratory measurements of crack flow, and detailed field tests of building envelopes. The results of the theoretical considerations and field and laboratory measurements indicate that the power law is valid for low pressure building envelope leakage. They found experimental and theoretical evidence that showed the power law function to be appropriate for developing flow in cracks. Because the flow in building leaks is mostly developing flow, this evidence, therefore, shows that the power law should work well for building envelope leakage. They also proved that the leakage exponent,  $n$ , can be considered independent of flow rate,  $Q$ , and pressure difference,  $\Delta P$ , for a single large leak as well as the array of smaller cracks in the building envelope. Below 0.1 Pa, the measurements showed a slight trend towards more laminar flow, however, these low flows are insignificant in air infiltration calculations, and the measurement uncertainties are large.

These results imply that the assumption of a power law relationship used by many standards and measurement procedures is valid. In addition, extrapolation of results from tests at high pressures to those typically experienced by a building envelope does not introduce a bias in infiltration predictions.

### 3.1.5 Air leakage measurements

Most air leakage-testing use one of two basic approaches: tracer gas methods or air pressurization methods. Tracer gas methods are more common for measuring ventilation systems while blower pressurization methods are more common for testing buildings, but there are examples of using tracer gas for building testing and there is research on combining the two methods.

The general approaches of the referenced air leakage methods are all by box methods, similar to those used for the thermal resistance tests done by hotbox methods described earlier. The concept is to bring in an air tight chamber (box), mount it to the component, pressurize the chamber, and then measure the air flow necessary to withhold a desired pressure difference across the component (the inner box in Figure 31). The test can be performed by attaching a temporary pressure chamber to either the external or the internal side of the component. A similar method is used for testing buildings, but then the building itself is used as the box. The amount of air flowing into the box, and the pressure differences between inside and outside are recorded, and then the power law is fitted to the data.



**Figure 31: Principal test set up for leakage measurements using a measurement box and a guard box as described by Levin, (Levin, 1991).**

Since the overall leakage in a building involves a combination of laminar and turbulent flows, the non-linearity of the process makes it hard to measure and the measured data is challenging to interpret. According to Sherman and Chan (2004) it is not atypical to see large variations of the same magnitude as the measured mean value. The large variation can be attributable to variations in workmanship, variations in constructions and maintenance, and variations in renovation and repair activities. Dimensional changes of materials often alter air tightness as well. Onysko showed how moisture effects affected the air leakage between studwork and sheeting. This will be described in more detail below, (Onysko, 2001, Onysko and Jones, 1989).

#### **3.1.5.1 Component**

On the component scale, air leakage is typically measured according to the methods outlined in ASTM<sup>12</sup> standards. Of interest are methods for determining air leakage across components, which is described in ASTM E1424 for leakage under a differential temperature condition, (ASTM Standard E1424, 2008). Test Method ASTM E283 describes a similar test at ambient conditions while ASTM E783 describes leakage tests of components such as doors, windows and curtain walls in the field, (ASTM Standard E783, 2010, ASTM Standard E283, 2004). The intention of these methods is to measure the leakage rate through the component only, and not through any faults in the connections between the component and the wall in which it is mounted. The result of each method is an average leakage across the tested component.

In cases when there is a need to separate zones, or when it is hard to seal a box to the sample satisfactorily, one may use a guard pressure. What this means is that the pressure in the adjacent zone, to be removed from the test or outside the pressure box is maintained at the same pressure as in the test pressure test box in order to eliminate the flow between the guard box and the test box. Levin refers to the work of Höglund et al. (1969) who describes a method with an outer and inner box that are placed against the test object. The pressure in the space between the two boxes is maintained at the same pressure as in the test box, hence no air should flow between the outer guard box and the inner test box as shown in Figure 31. Figure 31: Principal test set up for leakage measurements using a measurement box and a guard box as described by Levin, (Levin, 1991).

There are very few test methods concerned with the path of the air leakage, and most are limited to measuring the pressure difference and the amount of leaking air. However, Desmarais et al. (2000) did a feasibility study of using temperature and moisture measurements to map leakage paths inside wall sections. They tested several full size walls in which air flow with a different temperature than

<sup>12</sup> ASTM International, formerly known as the American Society for Testing and Materials.

the bulk temperature of the wall was introduced, and the temperatures were logged over time. The temperatures were measured in a 3D grid and the moisture content in the sheathing materials were measured on the surface of the sheathing. Temperatures without the impact of air leakage were also calculated using a three-dimensional conductive heat transfer model. The results from the conduction model were then subtracted from the measured temperatures to isolate temperature changes due to the flow of air. The resulting moisture and temperature maps do show the trends in the airflow quantitatively. The results show that two-dimensional moisture content monitoring, and to some extent three-dimensional temperature monitoring, can be used to document air paths inside a wall in a lab setting.

### ***3.1.5.2 Whole building***

On the scale of a whole building, a commonly used technique to establish whole building air leakage is the blower door test. This test procedure is described in a number of standards (ISO, 2006, CAN/CGSB, 1986, ASTM Standard E1827, 2007, ASTM Standard E779, 2003). These methods measure average air leakage rates through the building envelope. All methods use a fan mounted in an opening in the building enclosure, usually a door, thus “blower door test”, to induce a pressure difference across the building envelope. During the test, the pressure difference and the air flow necessary to uphold it is logged. The data of the pressure differences and the amount of injected air is then used to determine air tightness and other leakage characteristics of the envelope.

The difference between methods is the analysis of the collected pressure and flow data. In the simplest standards, the flow is measured at a single pressure difference: 50Pa pressurization is the most commonly reported for whole building leakage tests but there are others that are used. 50Pa pressure difference, as it is used, is good for the reason of repeatability. 50 Pa is large enough to render wind-induced variations insignificant at moderate wind speeds, but on the other hand, it is higher than the pressures normally found in buildings. As discussed earlier, there are reports that say that the normal pressure difference found in buildings is closer to 1 Pa than 50 Pa, (Sherman and Chan, 2004) while some reports that pressures of up to 60 Pa have been found under normal running conditions of mechanical HVAC systems. Up to 100 Pa under pressures have been found when the kitchen fan is running, (Levin, 1991, Bornehag, 1991). However, if such low pressure differences as 1-4 Pa were used for tests in the field fluctuating wind effects would make it very difficult to get accurate results. Higher pressure difference is used to overcome the natural variations and make measurements more reliable and comparable. However, more elaborate test methods require measurements at several different pressures, which are fitted to the power law. The fitted power law can then be used to calculate leakage at the pressures of interest (Sherman and Chan, 2004).

It needs to be noted that it must be expected to see higher momentary pressures in modern buildings due to the increased air tightness of the envelope. As the envelope gets tighter it will take less effort to raise the pressure difference between in and outside to higher levels than what is indicated in existing literature.

As mentioned, Höglund (as described by Levin, (Levin, 1991)) used a guard pressure box to maintain a matching pressure across a test box to prevent unwanted flow. Shaw (1980) used a similar approach to measure leakage through exterior walls in multi-story buildings. He describes how an enclosure is built up against the wall that is to be tested, and then the pressure in the room is maintained at the same pressure as the test enclosure to avoid air exchange between the enclosure and the room. A secondary set of fans are used to maintain the pressure in the room. While correct in principle, the balanced fan depressurization method is not practical in a transient situation. Proskiw and Parekh (2001) improved this approach by a, so called, 2 blower method. By adding a second blower door between two zones and doing a series of measurements, they

introduced a method to separate leakages in two different zones without having the challenge of creating a precise guard pressure.

Another method is to use tracer gas: three methods are described in (ASTM Standard E741, 2006) which covers techniques using tracer gas dilution for determining a single zone air change with the outdoors, as induced by weather conditions and by mechanical ventilation. The tracer gas theory they describe assumes well mixed conditions within a zone. These techniques are:

- (1) concentration decay,
- (2) constant injection, and
- (3) constant concentration.

Yet another variant involving tracer gas measurements was described by (Persily and Axley, 1990, Axley and Persily, 1988). They describe a variation on the concentration decay method. Instead of loading up a concentration, a known amount of tracer gas is added as a pulse, hence the method is referred to as a pulse injection tracer gas technique. They describe a multi zone technique for measurement of air exchange between different building zones within a building. The basic approach is to measure concentration responses within a network of interconnected volumes by injecting tracer gas as a pulse into one volume at a time, and measuring the responses in the connected volumes. This is done at least once in each volume to create a set of mass balance equations. The solution yields the airflow between the individual volumes for the specific conditions under which the tests were conducted. In a three zone example in the 1988 paper by Axley and Persily, (Axley and Persily, 1988), they suggest dealing with the connectivity with the outdoor zone by assigning it an infinite volume and assuming that all tracer gas not measured elsewhere went to the exterior.

### 3.1.6 Measured air leakages

There is unwanted air leakage in most buildings: thousands of field studies were performed in the U.S. by pressurization tests and by tracer gas methods to quantify air leakage. The results have been compiled in a series of reports several researchers (Sherman and Dickerhoff, 1998, Sherman and Chan, 2004, Sherman and Matson, 2002). They report on factors correlating with building air tightness, some factors being reported as significant are local governing regulation, construction type and age of the building, but there are many other factors.

#### 3.1.6.1 Buildings

Proskiw (2001) located, documented and summarized existing air tightness data for large buildings with the objective of compiling the air tightness data. He found 75 references containing quantitative air tightness data. From these, air tightness data were identified for 192 individual buildings, predominantly in Canada and the United States, and air tightness data were reported using the Normalized Leakage Rate (NLR) at an indoor-to-outdoor pressure differential of 75 Pa ( $NLR_{75}$ ).  $NLR_{75}$  is equal to the total air leakage in liters per second divided by the total envelope area, including above-grade and below-grade components. His results were assembled into a table, Table 5, where the data has been sub divided into three categories:

- Type 1 Data: Test performed on whole building; total envelope area used to calculate  $NLR_{75}$ .
- Type 2 Data: Test performed on whole building; alternate area used to calculate  $NLR_{75}$ .
- Type 3 Data: Test performed on individual floors or suites; exterior wall area of floors or suites used to calculate  $NLR_{75}$ .

**Table 5: Mean NLR by building and data type. Data selected on large buildings in the U.S. and Canada (Proskiw, 2001), MURBS = Multi-Unit Residential Buildings.**

Building type (N° in Sample)	Mean NLR75 (l/(s·m <sup>2</sup> ))		
	Type 1 Data	Type 2 Data	Type 3 Data
<b><i>MURBS</i></b>			
Canada (12)	3.19		
Canada (3)		4.00	
Canada (6)			3.23
<b><i>Office Buildings</i></b>			
Canada (8)	2.48		
U.S. (7)	5.91		
Great Britain (12)	7.55		
Great Britain (13)		6.67	
<b><i>Schools</i></b>			
Canada (11)	1.48		
U.S. (14)	2.44		
<b><i>Commercial</i></b>			
Canada (11)	1.35		
U.S. (68)	6.18		
Canada (10)		13.95	
<b><i>Industrial</i></b>			
Great Britain (5)	6.95		
Great Britain (2)		22.52	
Sweden (9)		1.45	
<b><i>Institutional</i></b>			
Canada (2)	0.86		

### 3.1.6.2 Components

Onysko and Jones (1989) summarize a large number of tested walls in a similar exercise with an average leakage at 10 Pa as 0.25 l/(s·m<sup>2</sup>) for green wood and 0.96 L/(s·m<sup>2</sup>) for dry wood. (Hui, 2007) reports full-scale test with mean airflow at 10 Pa about 0.1 L/(s·m<sup>2</sup>) with 2/3 coming through the top of the wall and 1/3 through the bottom. So laboratory measurements at 10 Pa vary from 0.1 to 1 L/(s·m<sup>2</sup>).

To put all these numbers into perspective there are a few examples of requirements placed upon buildings: the R2000 Standard in Canada require maximal air exchange rate of 1.5 ACH at 50Pa while the German passive house standard requires the exchange rate to be below 0.6 ACH/hour, (FEBY, 2009), for a building to be called a passive house. In the US there are two commonly used model codes: the ASHRAE/IES Standard 90.1-2010 (90.1-2010) and the commercial provisions of the 2012 International Energy Conservation Code (IECC). They both require buildings to be designed for limited air leakage. Limit values are for assemblies 0.040 cfm/ft<sup>2</sup> (~0.20 L/(m<sup>2</sup>·s)) and for the whole building 0.40 cfm/ft<sup>2</sup> (~2.03 L/(m<sup>2</sup>·s)) at a pressure difference of 0.2 in wg (~50 Pa), (DOE, 2011). In Sweden the Forum for Energy Efficient Buildings has set a maximum limit of 0.30 L/(s·m<sup>2</sup>) at a pressure difference of 50 Pa, (FEBY, 2009) for a building to meet their definition of a passive house.

This work was followed up by Antretter and Karagiozis (2007) who investigated a limited number of occupied homes in the mixed climate of eastern Tennessee and in the cold climate of south-central Wisconsin. Individual homes were measured on a seasonal basis. The objective of their investigation was to find the factors in the building stock influencing the leakage rate of the buildings. They found that, as reported by Chan (2003), new homes tend to be tighter than old homes because of improved materials, better building and design techniques, and lack of age-

induced deterioration. They concluded that buildings built in the last five years (2002-2007) were the most air tight in their investigation. The age effect is dependent of the used construction, Proskiw and Eng (1997) reports on 20 year old homes with PE air-vapor barrier which have retained the original level of air tightness.

Sherman and Chan (2004) found in their review article that dwellings of different construction types have different envelope air tightness properties. However, some air leakage pathways are common among many dwellings, such as the connections between building materials and components. Leakage to attics, basements, crawl spaces, and garages is significant and raises additional, energy and health concerns. Many studies have addressed the effectiveness of air barriers and building materials to minimize leakage, but it is often the quality of workmanship and careful design that are the determining factors in achieving desirable air tightness.

There is an important point to repeat regarding the standardized leakage measurement methods: they all measure an average. There is no data collected regarding the details of the flow. The only reference dealing with the difficult task of mapping the path of air flow inside a component is the exploratory testing done by Desmarais et al. (2000). In the standardized methods, measuring component leakage, it is clearly stated that the measurement is only on the component, excluding the leakage at the intersection between the component and the rest of the building, even though this is pointed out to be one of the major pathways of air flow. Therefore, in the case of whole building tests an average across the whole envelope is calculated, while in reality, most air flow may flow through a number of flow paths distributed very unevenly across the envelope.

Typical paths for airflow include:

- Terminations of the undisturbed parts of the wall, such as electrical boxes, connection boxes, and other penetrations connecting the wall cavity to the room
- Joints and junctions of walls with other elements, such as windows, doors, etc.
- Penetrations through the exterior walls
- Lateral flow within exterior walls, partitions, and ceilings caused by pressure difference in remote areas.

In addition to the four paths of air leakage one must add leakage from the duct systems and air flows through floors, roofs/attics, exterior walls or internal partitions, where air flows are often caused by the pressure differentials associated with HVAC or other mechanical devices active in the building.

The pathway of the airflow in a building envelope is through a network of cavities in different scales. Three types of air cavities frequently found in construction are:

- A contact plane between two materials either by design, e.g., two layers of water resistive barrier (WRB) or by use of materials with different thickness. Typical thickness of such an air gap would be less than 1-2 mm (1/16 inch).
- A gap between spray applied insulation (cellulose fiber, foam) and the drywall or drainage cavity. Typical thickness of such an air gap would be between 2-20 mm (1/16 and 3/4 inch).
- Air cavities behind cladding or unfilled frame wall cavities. Typical thickness of such air cavities would be between 45-250 mm (1.5 to 10 inch).

The first type of air gap is abundant in any construction and found important in regard to heat, moisture, and air flows. For conduction, the small gap provides a discontinuity in the conduction path and the heat must be transferred by other mechanisms, by radiation and convection if the air is moving, or by radiation and conduction in the air if the air is standing still. This creates what is

called contact resistance. The contact resistance can be neglected for most structures except for metal constructions. Conversely, contact resistance cannot be neglected for most of moisture transport cases (Brocken, 1998). Furthermore, a thin gap provides an opportunity for diffusion-dominated drying and is a pathway for airflow connecting adjacent cavities.

The most important works on leakage paths are summarized by Sherman and Chan (Sherman and Chan, 2004) finding that the most severe air leakage paths was found in suspended ceilings<sup>13</sup> where there were electrical, lighting, and ventilation equipment was housed. A study by the Florida Solar Energy Center (Cummings et al., 1996) also found similarly conclusions regarding smaller commercial buildings. Perhaps more surprising is that some studies from the UK have shown even the roof tops of large buildings are not guaranteed to be impervious to air infiltration (Perera and Parkins, 1992, Potter et al., 1995). This is somewhat surprising for those who think that air goes straight through the building partitions, but not surprising at all when considering the work of (Lstiburek et al., 2002, Lstiburek et al., 2000, Lstiburek, 2000), who showed the impact of lateral air flows between and through building enclosures.

Potter (1995) found that exposed wall cavities create more problems than windows. This means that electrical and service penetrations through the structure into the cavity are in need of careful sealing. Cummings et al. (1996) found this problem may be considered disastrous in small commercial buildings where wall cavities are commonly used as ducts or plenums<sup>14</sup>.

It can be inferred from the reported papers that we are not dealing with leakage from one side of the partition directly to the other (even though this type of leakage also occurs), but rather the flow which is more likely to take place through a network of defects, gaps, orifices or cavities.

To complicate matters further, one must realize that the geometry of the gaps does not need to be permanent: Onysko and Jones (1989) showed how the stud-sheeting gaps change with moisture content and explained the difference in air tightness between “green” and dry walls. They found some interesting results when OSB was used as the sheathing material and stated that:

*“The results shown here are directly contrary to what was initially expected. A wall built air dry and dried further, leaked more than a wall built green which then dried to same final moisture content as the other.”*

This was found for 4 wall pairs, a total of almost 72 joints. All of these walls used oriented strand boards (OSB), Figure 32. Comparable walls built with plywood sheathing behaved in the expected manner, i.e., green lumber joints leaked more than air dry lumber joints after drying both of these further.

---

<sup>13</sup> Suspended ceilings are often used as exhaust ducts in the US.

<sup>14</sup> It is common practice in the US to use the wall cavities as ducting for ventilation air.

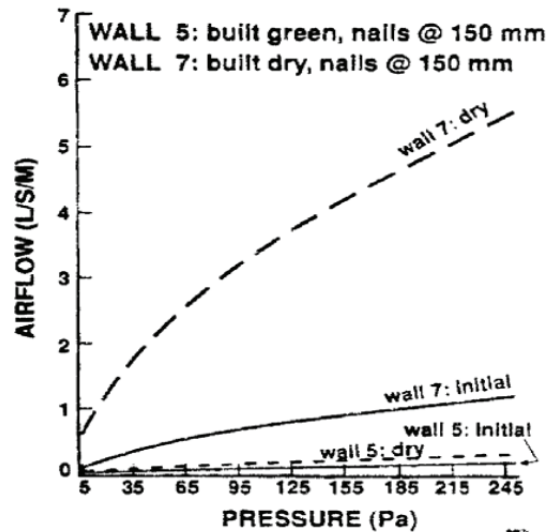


Figure 32: Change in mean air leakage for a wall built with green lumber compared with a wall built with dry lumber, both with OSB sheathing, (Onysko, 2001).

The difference was attributed to the irreversible expansion of OSB when it was contacting moist wood that caused it to swell more than plywood. This drew the joints tighter and caused the OSB to conform to the lumber surfaces better. There was also some pre-stress in the driven nails so that even when nail popping occurred because of lumber shrinkage, the OSB sheathing was held more tightly to the studs than other materials. The significance of this cannot be determined by inspection. Depending on the other materials with which the sheathing is used and the relative properties of the materials, this may, or may not, be significant.

Most of the leakage paths described here is caused by workmanship. For example there is a huge difference in air leakage around an electrical box installed in a stud wall with a Polyethylene (PE) membrane if the hole in the PE membrane is cut for a press fit or if the hole is over sized for a loose fit, this was one of the most significance leakage paths according to (Potter et al., 1995). As a typical workmanship issue that displays the importance of quality control and commissioning just as concluded by Dalglish and Surry (2003) they state that one of the key components of successful wall design for HAM considerations will be quality control: the best predictive tools will fail in the presence of detailing and installation deficiencies. This is the prime reason why in-situ full-scale testing will remain important to successful methodology development.

### 3.1.7 Effects of air leakage

Air leakage affects not only the energy consumption but also impact indoor air quality. Leaking air is bypassing the air conditioning if there is such. Air leakage may also affect indoor air quality and thermal comfort by changing the surface temperatures of walls and creating drafts. The major risk, however, is the risk of elevated levels of moisture on surfaces of thermal bridges or inside the enclosure components. The air flowing through a single small defect can carry with it many times more moisture than transported by diffusion. Increased moisture inside a wall may lead to mold, rot, and premature failure. In severe climates with warm humid air on either side of the envelope, air flowing towards the colder side of the envelope can also lead to condensing water inside the wall.

On the building level, air leakage will alter the mass balance of the building and may constitute an energy loss, or gain, that must be taken into account in an overall energy calculation. Air leakage has historically been accounted for as concentrated leakage by simply adding the mass flow rate

times the enthalpy difference between indoor and outdoor air, Equation 11, to the energy balance of the building. For this method to be valid the air flow must be penetrating through the envelope just as through an orifice plate without any hygrothermal interaction with the materials through which it passes. If there is any exchange of heat and/or moisture then the assumption is invalid and the interaction should be included in the calculation.

In reality, the flow will almost always be diffusive in the sense that the path will rarely be straight through the construction. It is more likely that it will enter into a construction in one place, flow along in a gap in-between two materials or penetrate through permeable material, and then find a path to the lower pressure. In this scenario, the air will have transferred, in the best case, only sensible heat between the air and the surrounding wall, and in worst case, some of the moisture in the air will condense in the surrounding materials.

### 3.1.7.1 Thermal effects

The nominal steady state heat loss through a wall, hence without thermal bridges or air flow, is calculated as:

$$\Phi_{nom} = U \cdot A(T_{ins} - T_{out}) \quad \text{Equation 10}$$

$\Phi_{nom}$	Nominal heat flow, W
$U$	Thermal transmittance, W/(m <sup>2</sup> K)
$A$	Area of the wall, m <sup>2</sup>
$T_{ins}$	Temperatures inside, °C
$T_{out}$	Temperatures outside, °C

If the wall is completely air tight or has only straight through leakages then the transmission heat loss is  $\Phi_{nom}$  as calculated by **Equation 10**. The heat loss due to an air leakage through the wall without any hygrothermal interaction between the air and the wall can be quantified by **Equation 11**, if the wall is completely air tight then  $\dot{m}$  is zero and hence no heat loss. However, many researchers have shown that it is a rare case that air flows through a wall without any interaction with the materials within the wall. The case that comes closest to this assumption is flow with a straight through path.

$$\Phi_{air} = \dot{m} \cdot (h_{in} - h_{out}) \quad \text{Equation 11}$$

$\Phi_{air}$	Energy loss due to air flow, W
$\dot{m}$	Mass flow of leakage air, kg/s
$h_{in}$	Specific enthalpy of the air flowing into the wall, J/kg
$h_{out}$	Specific enthalpy of the air flowing out of the wall, J/kg

The air flowing through may change both the temperature distribution as well as the moisture distribution within the wall. The enthalpy of the air as it passes through the wall will change as well. As air is filtrating through the wall the second law of thermal dynamics dictates that the air and the penetrated material will strive to come into balance, hence the air, as well as the materials, will change temperature, and any moisture content will redistribute to become in balance in a long flow path. By changing the temperature field in the insulation the temperature gradient will change and thus the heat fluxes across the surfaces will change as well.

For example, assume we have air infiltrating through the building enclosure, hence, moving from the outside towards the inside. The building is in a cold region and the room is heated. The air coming from the outside would be cold and as it penetrates through the wall, it would heat up by taking up thermal energy from the materials within the wall. This would result in a larger temperature gradient across the wall surface on the room side, and in decreased gradient across the outer surface of the wall. The increased thermal gradient will lead to higher heat flux into the wall from the room, and the decreased gradient on the outside of the wall will lead to a decreased heat loss out of the wall. Theoretically, the difference is the heat picked up by the airflow, hence the amount of recovered heat.

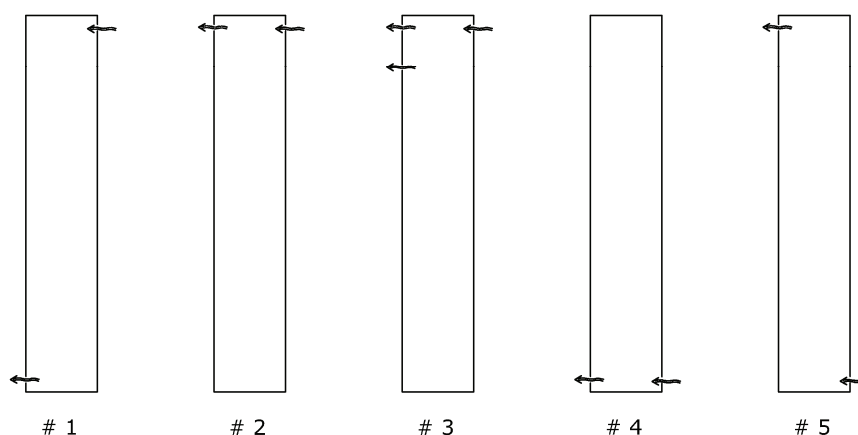
The described behavior was found by Baker, (Baker, 2003), when he tested a stud wall configuration with cellulose fiber insulation in the cavities. The system was set up with air permeable fabric on both sides of the studs holding the insulation in place and air gaps creating pathways for the air to reach the whole surface of the wall: hence, the airflow was thought to be mostly 1-dimensional and equal across the whole surface of the wall. He could see the heat flux across the inner parts of the wall increase and the heat flux through the outer surface decrease as the mass flow of air increased. He also found that the temperature change in the penetrating air was larger with lower flow rates and the suppression of the inside surface temperature was larger for larger flows. The temperature increase of the infiltrating air constitutes a recovery of the heat being conducted out through the wall, and unless the heat recovery effects are accounted for in a load calculation, the actual energy load seen by the room may be lower than the calculated due to the heat recovery within the wall, according to Sherman and Walker (2001).

Bhattacharyya and Claridge, (Bhattacharyya and Claridge, 1995), both measured and modeled the case of infiltrating air flow through walls, altering the length of the flow path, as well as the flow rate of the air, they found that the actual amount of energy loss due to the air leakage was less than what Table 11 states in every case. They found through experiments that the infiltrating air may recover up to 34% when penetrating the wall in a concentrated straight through leakage and up to 70% when the flow takes place through a longer path allowing more contact between the wall and the air. This is not the 1D type of flow described by Baker but a bottom to top flow as in Figure 33 #5.

Buchanan and Sherman (2000) used Computational Fluid Dynamics (CFD) to simulate sensible heat transfer for the long flow path case, the same as Bhattacharyya and Claridge, as well as a number of other configurations possible in typical envelope constructions similar to the ones shown below in Figure 33. The extent of heat recovery was found to be dependent upon the leakage path geometry, the infiltration flow rate, and the wall construction. In some cases with low infiltration rates and long leakage paths, bottom to top as mentioned earlier, the heat recovery can be substantial, well over 80 percent. In these cases, the classical method of heat load calculation would over-predict the extra heating load due to infiltration. According to their findings, under typical leakage conditions for most residential buildings the heat recovery could be around 40 percent.

Qiu and Haghighat (2005) produced a numerical model for conduction and air flow (ignoring moisture) through the porous insulation (assuming perfectly applied insulation) commonly found in a cavity of a wall. The particular objective of this study was to look at the impact on inside surface temperature and energy loss through the building envelope. They used similar defect configurations, in Figure 33, to those previously used by Ojanen and Kumaran, (Ojanen and Kumaran, 1996) in their study of hygrothermal behavior of timber frame walls. Qiu and Haghighat's main conclusion was that this type of air leakage and heat recovery that occurs with

infiltrating air must be taken into consideration in order to accurately estimate heat loss through a building envelope.



**Figure 33: Simulation scenarios used by Ojanen and Kumaran, (Ojanen and Kumaran, 1996). The figure has been redrawn from their article.**

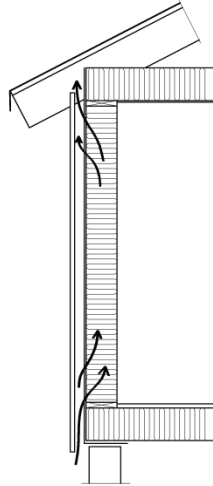
They first looked at the surface temperatures of the wall, and concluded that the straight through path impacted the surface temperature the least, while the long path flow shown in Figure 33 #5 impacted the temperatures of the wall surface the most. Therefore, as noted in the introductory analytical discussion, the heat exchange is less significant when the flow path is of the straight through type. This might seem obvious but they further conclude that even though the average interior surface temperature decreases under a longer infiltration path this does not necessarily mean that this kind of configuration will have more obvious influence on the occupants' thermal comfort, since the entering air is heated during the passage through the insulation material. This reasoning assumes that the heat recovered by air flowing through the wall is somehow made available to the room either fed into the room directly or through a heat exchanger. This is called a dynamic wall or dynamic insulation system. The concept of dynamic insulation proposes to use the heat exchange capability of air flowing through a permeable insulation material to reduce heating loads in a building. Bhattacharyya (Bhattacharyya, 1991) explains/defines dynamic insulation as:

*"It is a means of reducing building heat loss significantly without the use of massive thermal insulation. It is achieved by recycling the heat conducted through the fabric or reducing the temperature gradient across the wall section by means of a suitable heat transport fluid - usually air."*

Dynamic insulation was one of many technologies treated within the IEA Annex 44 project on "Integrating Environmentally Responsive Elements in Buildings". It is stated there as an approach to lowering enclosure heat loss and at the same time achieving better indoor air quality. Within the IEA project the concepts of dynamic insulation was divided into two types: One with air flowing in a cavity parallel to the surface of the wall and the second when the air is actually penetrating the insulation layer which is called a breathing wall design. The second type of system is what has been described above.

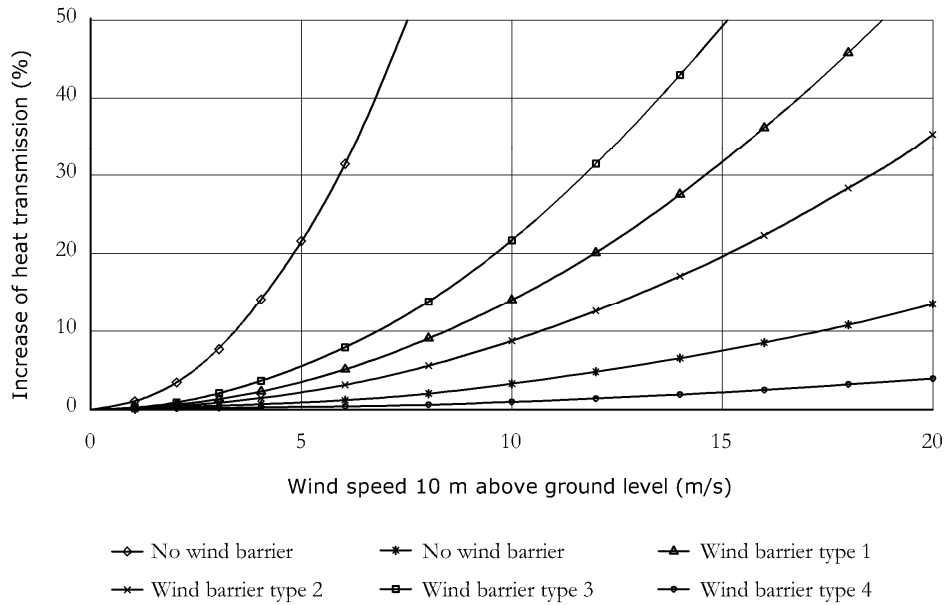
So far, we have found that airflow in general in a material will affect the thermal performance of the material but there need not to be a forced convection induced through the material for air movement to occur. An external convective flow across the surface of a permeable material or a temperature difference across the material may induce airflow in the material as well. This is highlighted in a review article by Wahlgren (2007). This review focuses on the onset of natural convection in porous insulation materials in attics, and briefly discusses airflows in the insulation

induced by forced flow along the surface of the insulation layer. Airflow in the attic insulation is a very complex phenomenon. This is shown by the difficulty found in predicting when natural airflows will initiate and what impact it will have on the thermal performance of the insulation. This is partly attributed to large variations in the tests, such as sample size, attic or chamber size above the specimen, material properties, workmanship, and boundary conditions. She does wish for a full-scale test chamber for parameter variation tests, but concludes that models have to be used, as it is not feasible to test every small variation of a design.



**Figure 34: Show the principal of wind washing in a wall as tested by a hot box by Uvslokk, (Uvslokk, 1996), the figure here is redrawn from the original due to poor quality of the copy available to the author.**

Uvslokk (1996) on the other hand researched the impact of air flow induced by the wind in insulation positioned behind a rain screen in the cavities of a wood frame wall and covered with a wind barrier. The aim was to evaluate the importance of the wind barrier permeance and recommend a maximum limit for the same. The research commenced in three major steps. First, pressures induced by the wind in the gap behind the rain screen were measured. Then boundary conditions were established by doing in situ measurements of the pressure gradients in three types of gaps behind rain screens at different wind speeds (results can be found in Table 6) (wind speeds were measured at 10m above ground). Finally, a hotbox method was used to measure heat transfer through similar walls in a laboratory with fan induced pressure gradients in the gap. The worst case results are presented in Table 6 and graphically represented in Figure 35. Secondly, hotbox measurements were conducted and calculations were made. The project was limited to air flows due to the pressure differences in the ventilation gap behind the rain screen and the air movement in the insulation induced by it. Figure 34 show a conceptual drawing of the anticipated airflows behind the cladding into and out of the insulation layer. Permeable insulation materials, such as glass fiber and mineral wool insulation, were tested.



**Figure 35: Estimated increases in heat loss, as affected by different degrees of air tightness of the wind barrier. The estimation is based on measurements performed in a Calibrated Hot Box and wind velocities measured in the experimental house, (Uvsløkk, 1996). This graph is redrawn from a graph in a scanned original of poor quality therefor the data should be regarded as qualitative only.**

The vertical axis in Figure 35 shows the average percentage increase in heat transmission caused by wind. The permeance of the four wind barriers, including joints, measured at 75 Pa were as follows: (1)  $0.049 \text{ l}/(\text{m}^2 \cdot \text{s} \cdot \text{Pa})$ , (2)  $0.019 \text{ l}/(\text{m}^2 \cdot \text{s} \cdot \text{Pa})$ , (3)  $0.0073 \text{ l}/(\text{m}^2 \cdot \text{s} \cdot \text{Pa})$ , and (4)  $0.0022 \text{ l}/(\text{m}^2 \cdot \text{s} \cdot \text{Pa})$ .

Table 6 show the highest pressure differences along the air gap behind rain screens as well as increase in heat transmission due to the induced air flow in the gap and the insulation material, as tested by (Uvsløkk, 1996).

Wind speed	Max Press Gradient	No barrier	Best barrier
m/s	Pa/m	%	%
5	3	20	1
10	13	70	2
15	28	>140	5
20	52	>>200	10

### 3.1.7.2 Moisture effects

The thermal effects of airflow may increase energy needed for heating or cooling which leads to increased running costs. The real danger of air leakage, however, is the air carrying moisture or pollution with it. Amounts of moisture carried by air movement (convection) are much higher than those carried by water vapor diffusion, several researchers have concluded this: (Ojanen and Kumaran, 1996, Gudum, 2003, Mattsson, 2005, Janssen, 1998, Sandberg and Sikander, 2004) to name a few.

The danger occurs when moist air from warmer conditions enters into to colder conditions. This type of flow is common in cold and in hot, humid climates. In cold climates, where the inside air is warmer and moisture is added to the air by such activities as by breathing, showering and cooking, or in hot, humid climates, where the colder climate is actually inside the cooled building. In these

cases, increasing relative humidity due to cooling of the leaking air may lead to accumulation of dampness, and in worst cases, condensation within the building.

High moisture content in combination with fair to warm temperatures will probably lead to mold and rot. It does not matter if the moisture gets into the wall by convection, as in the case of air leakage, diffusion, or by direct water leakage: any moisture accumulation is equally dangerous. The diffusion case is easier to cope with and has been with us for a while.

The effect of pure diffusion on mold growth has been evaluated by Simonson et al. (2005), they found that, in cold climates, the diffusive moisture can be coped with as long as the diffusion resistance of the internal surface is high enough. Hence, greater than that of the external surface (typically recommended ratio of 3:1 or 5:1), but that the vapor resistance of the vapor retarder can be significantly lower if a number of prerequisites were fulfilled:

- convection is eliminated
- initial moisture content of the building envelope is low
- the average moisture production in the house is moderate (2–3 g/m<sup>3</sup> above the outdoor humidity), and
- other failure mechanisms are not important
- the envelope must be airtight (e.g., 3 ach at 50 Pa)



**Figure 36: Condensation on the inside of a plexiglass plate under a stress test of a standard industrial wall under hot and humid conditions, 40 °C and 80% RH and an induced air flow of 2 liters per second from the hot and humid side to the room via a long bottom to top path.**

Vinha however wrote his doctoral thesis on the subject of hygrothermal performance of timber-framed external walls in Finnish climatic conditions. He came to contradictory conclusions. He showed that the matter was much more complex and depending on the placement of the internal diffusion barrier in combination with the chosen insulation material and type of exterior sheathing the required ration could be as high as 110:1 for the wall to function without extended risk of condensation or mold growth, (Vinha, 2008, Vinha, 2007).

The risk of high humidity with condensing water became obvious to the author when a standard industrial wall design was stress tested<sup>15</sup> under hot and humid conditions. The climate was 40 °C and 80% RH and an air flow induced through orifice plates from the hot and humid side to the room via a long bottom to top path, as in Figure 33 sub figure #5. The airflow was controlled and

<sup>15</sup>The objective of a stress test is to subject the wall to conditions that may lay beyond what is expected in a normal installation. The aim is to see how the wall performs under exaggerated conditions.

introduced through plexiglass orifice plates as can be seen in Figure 36. The orifice plates were designed for airflow of 2 liters per second at 50 Pa pressure difference. It cannot be stressed enough that this test was set up to create severe moisture loads. Still, the risk of condensation is evident and the risk of mold as well: the wall was torn down after a week of the most severe conditions and large amounts of mold were found on the inside of the gypsum board as can be seen in Figure 36.



**Figure 37: Mold growth on the inside of the gypsum of the wall in Figure 36 after one week's exposure to hot and humid air drawn through the wall towards the colder inside.**

Airflow in buildings, components and materials affect both moisture and heat flows in the building. Research indicates that the energy performance of buildings or of components are not as simple as adding the heat transmission measured by a hot box and the air exchange multiplied by the enthalpy difference of the indoor and outdoor, as discussed above. Air movements are reported to be the main moisture transport mechanism affecting moisture balance within the building envelope. As a concluding remark on the subject of how air flow impacts a building one can only agree with Sandberg and Sikander (2004) who stated that the air movement has a key role for the moisture transport and moisture balance in the envelope. Further elevated amounts of moisture promote mold growth and material emissions affect the indoor air quality. Air leaking through the envelope impacts the controlled ventilation rate directly by reducing the amount of air that goes through the air conditioner, thereby reducing control of the indoor air quality. The thermal performance is affected directly by altering the ventilation rate, and secondarily, by impairing the function of the insulation material or bypassing it completely.

The risk of surface mold on the inside walls due to temperature depression is highlighted. This is a phenomenon that is rather well known, and often, its occurrence is due to a number of coinciding factors: a thermal bridge in the wall, locally reduced convection, such as in corners between wall and floor or behind furniture, and relatively high moisture content in the air. The slow moving air in combination with a thermal bridge may bring down the surface temperature to the dew point of the air, when water condenses and, after some time, mold develops.

Furthermore, one finds that the effects of conduction, convection, and moisture transport cannot be separately evaluated and then super-positioned. All three effects need to be integrated into an integrated model simulating simultaneous heat, air and moisture flows. Just as stated by Bomberg

and Pazera (2006) in the summary of 20 years of research on the performance of spray polyurethane foam roofs:

*“The underlying theme of the paper is that R-value as it is measured today cannot predict the total energy efficiency of a roof system. For a real prediction one must consider three effects together: **heat, air, and moisture**”*

Using the example of roofs, they listed a number of effects that must be included in the estimate of thermal resistance of a roof assembly in Table 7.

**Table 7: Factors affecting energy performance R-value of low slope roofs:**

1. Mean temperature variation between seasons
2. Aging of gas-filled foams (thermal drift)
3. Thermal bridges (thermal shorts) created by mechanical fasteners used for insulation boards
4. Thermal shorts created by air gaps and air movements between insulation boards
5. Effects of moisture contained in the roof
6. Effects of moisture that is carried by air movements between the insulation boards
7. Lowering surface temperature by reflective coating (cool roofs)

This study was done on spray foams, which have closed cells and are impermeable for air which means that for permeable insulation materials the impact of airflow through the material must be added to the list as a major affecting factor.

### 3.1.8 Modeling

Heat conduction calculations are commonly done; moisture flow and modeling thereof have been studied for at least 70 years while modeling the combined impact of heat, moisture and air flows have now become a subject for building researchers. Studies on heat, air and moisture effects combined, so called HAM models, have verified that leaking air is more capable of moving large amounts of moisture than water vapor diffusion, (Gudum, 2003, Mattsson, 2005, Janssen, 1998), and it has been found that air, much like sound, travels through and along connected building partitions and may connect seemingly separate regions of the building (Lstiburek et al., 2002). In addition to this air is not limited to carrying with it moisture but also energy and pollutants leading to moisture problems, excessive energy loss, and unhealthy air respectively. Moisture transport may lead to high moisture content in places with relatively high temperatures, creating incubator conditions for mold, and in the long run rot, hence air flow can indirectly be a major culprit in seriously damaging buildings.

HAM models are increasingly being used to study hygrothermal performance under a wide range of loads. Current models are hampered by the lack of material properties and no model is better than the data used, thus the accuracy of the input data will strongly affect the results of the model. Needed material properties are somewhat dependent on the model, but some worth noting include: density, thermal conductivity, heat capacity, moisture permeability and moisture storage, as functions of moisture content. Material properties are often assumed constant, even though it is well established that both temperature and moisture content is likely to affect a materials properties, radical changes take place if freezing and thawing is taken into account. Material properties need to be assessed and completely mapped separately by laboratory testing. Another key input is the boundary conditions, which is dependent upon several parameters. One possible approach to meet this challenge, that is currently being researched, is to use CFD tools to model

the environment mainly consisting of air and couple it with HAM tools, which model the component or building.

The development of computer based HAM models has been ongoing since beginning of the computer era. Kalamees and Vinha (2003) used three different codes to test the accuracy of the hygrothermal models, they simulated Nordic climatic conditions from autumn to spring. The results produced by the used models, 1D-HAM, MATCH, and WUFI 2D, were compared with the results of laboratory tests to determine the heat and moisture performance of timber-framed building enclosures. The results show that these programs are useful tools in assessing the moisture behavior of building components as regards moisture diffusion and heat conduction but there were cases where differences between measured and calculated values were observed as well.

Kalamees and Vinha (2003) postulate that all three models can indicate general tendencies even though deviations are expected in some cases. For a hygroscopic material with exaggerated sorption hysteresis effect the only program which incorporated hysteresis gave the best results as expected. Other possible reasons for deviations are reported to be the accuracy of the measurement system used as well as the difference in initial moisture content in the tested materials. Yet these are heat and moisture models for predominantly 1-D transport and prediction relates to an overall performance.

The conclusion of Kalamees and Vinha is that although today's hygrothermal models are advanced and accurate, they cannot replace laboratory and field tests completely. Real buildings and laboratory tests are never as ideal as mathematical models. There are always defects and weaknesses in real buildings. The materials never conduct ideally as in models. Therefore, to assess hygrothermal behavior of a building envelope we need laboratory and field tests as well as models. Kalamees continues his work along the outline in the conclusions of his previous work (Kalamees and Kurnitski, 2007). To evaluate the moisture convection at the connection between roof trusses and the wall; they tested designs in full scale to validate their model and expand the analysis. In this article, they used the CHAMPS model developed at Building Energy and Environmental Systems Laboratory, BEESL at Syracuse University<sup>16</sup>. The difference between CHAMPS and the model that Kalamees used earlier is that CHAMPS model in 2D and include forced airflows in the material, which of course is essential if the objective is to evaluate convection. The used boundary condition related to the airflow in this case is the pressure difference across the component. The methodology he used was to do full scale testing to produce data that could be used for model verification. After a validated model was established, they expected to use it for expanded analysis and application of various boundary conditions. Their work show that the simulation program CHAMPS-BES showed good performance and is a useful tool in assessing the moisture behavior of building components including moisture convection. There were some discrepancies between the results of laboratory measurements and computer simulations but the results generally agreed.

Another promising modeling approach developed within the package COMSOL Multiphysics<sup>17</sup> was used by Li et al.(2008). They used the COMSOL as a numerical tool to predict combined heat, air, and moisture transport in building envelopes, abbreviated as HAM-BE. HAM-BE is a research tool for simulating transient HAM responses in multi-layer and multi-dimensional building envelope systems. The heat transfer mechanisms are conduction and convection of sensible and latent heat. The moisture transfer mechanisms are vapor diffusion driven by the water vapor pressure gradient, vapor flow with air convection, and liquid flow driven by the capillary pressure

---

<sup>16</sup>The program is an outcome of a joint effort between BEESL and Institute for Building Climatology (IBK) at University of Technology Dresden (TUD) in Germany.

<sup>17</sup>COMSOL Multi Physics is described by its developer as a simulation environment hosting all necessary components for solving arbitrary systems of differential equations.

gradient. The material properties used were derived from laboratory measurements and include thermal conductivity, thermal capacity, sorption isotherm, water retention curve, vapor permeability, liquid diffusivity and air permeability for each material.

There is a common consensus (Ojanen and Kumaran, 1996, Kalamees and Kurnitski, 2007, Karagiozis, 2001) that HAM models are necessary to analyze the hygrothermal behavior of any type of construction detail subjected to any given sets of boundary conditions. Research models are now being expanded to account for boundary conditions and connected to multi zone models for IAQ modeling. The CHAMPS model has within different research projects been expanded to include both pollutant and salt transport in materials.

#### ***3.1.8.1 Boundary conditions***

Limiting the argument to HAM modeling of building enclosure component the question is what are the necessary boundary conditions? The obvious ones for heat, air and moisture is temperatures, pressures and humidity, respectively, but there are more, there may be free water from rain and wind driven rain, hence water and pressure combined, there might be frozen water (ice) on the surface changing the properties of the surface and so on. The information that is needed is the conditions on the surfaces of the component, at every point. The question is how do we find them by modeling of the environment surrounding the component such as with CFD models or do we measure them in the field. It depends on the purpose of the exercise, if we are designing or analyzing. For design there is nothing to take measurements on so we are forced to assume or model our boundary conditions or maybe test on a prototype if one is available. In the case of analysis we have an existing component and we could very well do measurements in the field to see if any of boundary conditions are such that they need extra evaluation. In both cases, it is very advantageous to be able to couple climate data to the boundary layer and to derive usable data for HAM modeling.

Li and Holmberg (Li and Holmberg, 1994) states in their introduction that a difficulty when attempting to predict effect of the indoor air flow is that there are many factors which influence and govern the flow. It is affected by the details of the air distribution design, building construction, outdoor environment, the inhabitants and many others. When designing and analyzing heating, ventilation and air-conditioning systems, engineers and scientists generally have at their disposal an array of tools to study indoor air flow patterns: analytical methods, full-scale or small-scale model measurements and computational fluid dynamics (CFD). Analytical methods are restricted by the need for severe simplifying assumptions and simplistic configurations. Full-scale measurements may provide the most reliable data, but are more expensive and difficult to perform and will only give information on performance under the specific conditions used for the test. Currently CFD seems to be the most general and accessible method. This is evident from the fact that over the last 20 years, prediction methods for indoor airflow have increasingly relied on CFD, based mostly on finite-difference and finite-element solutions of the Navier-Stokes equations in their time-averaged form, with the addition of some turbulence models. The major challenges for the application of CFD on indoor airflow include modeling the physics of the flow, including turbulence, specifying realistic boundary conditions, representing the complex geometry of the room, and developing accurate and efficient numerical algorithms.

#### ***3.1.8.2 Material properties***

Lack of reliable material characteristics remains a major roadblock in modeling. Material data is missing for many materials and very detailed information is available for some variation of others. The data is most often collected by standardized test methods with standardized environments and constant gradients where only one parameter is changed at a time (Gudum, 2003). Even the best

test method with a well-defined measurement uncertainty, will not provide precise results if the material tested (specimen) is not adequately characterized. In such instance, the variability attributed to differences in test specimens cannot be separated from the measurement errors. Hygric characteristics measured in different laboratories (Roels et al., 2004) showed that some frequently used tests, considered to be well standardized, e.g., water vapor permeance or free water uptake tests, were not as accurate as initially thought. However, even if the material characteristics are well defined and all boundary conditions are known there are still issues of workmanship to consider which adds a stochastic variable loosely correlated with workers skill.

### **3.1.9 Conclusions from the literature study**

The clear wall R-value as measured by a hotbox method is limited: it is only acceptable as a crude indication of an average thermal performance under reference laboratory conditions and the resulting data does not provide any detailed information. There is a clear need for a better indicator to make decisions on envelope design.

It has been found that one decisive factor for both energy performance and moisture safety of construction is convective airflow. The amount of leakage and the pathway of the airflow are most important for the impact on the energy side while the moisture content is very important for durability. The diffusive moisture transport can be coped with by proper application of vapor retarders. Nevertheless, convective moisture transport is difficult to prevent. It may be argued that to eliminate the effects of workmanship we must require all construction details to be drawn up in detail and explained, as well as being subjected to mock-up testing used in most cases of complicated construction.

The whole-house air leakage measurements use pressurization, e.g. a blower door method. The building is pressurized to a certain pressure and the needed airflow to maintain the pressure is measured. There is a common acceptance of fitting measured data to the power law expression, Equation 3.

The only method found that maps the actual flow paths inside the wall is by mapping secondary effects such as moisture buildup or temperature change. One feasibility study addressing the use of temperature measurements for air flow mapping was found (Desmarais et al., 2000).

It is necessary to recognize that heat, air and moisture transport are all three-dimensional mechanisms. This is one of the reasons for the reported difficulties with modeling metal studs. Airflow can very well give very different results depending on where the least resistance flow paths are located.

Since we cannot test every wall design under every boundary condition, we must use models to evaluate performance under realistic conditions but our models cannot address the issues of workmanship, we need to integrate modeling with testing, in situ and in labs.

## **3.2 Enclosure component testing**

As the need to be able to predict performance of materials, components and buildings increases the decision whether to test them all, to model everything or to keep using simplified models basically ignoring more complex issues arises?

It is evident that we need to be able to predict hygrothermal performance on all scales of a building to correctly size heating and cooling units, to prevent moisture problems, and to maintain good indoor air quality. The ongoing development of modeling environments is constantly improving and will certainly reach, if they are not already there, a level of accuracy satisfactory for such use.

However, even with a completely correct model there are still issues of material characteristics and workmanship as well as deviations due to the use and users of the building.

It is equally evident that that a performance indicator that is used as a basis for purchase, simplified heat and cooling load calculations or just for material or component comparison should reflect the performance of a material or a component with more depth than in steady state at laboratory conditions, such as thermal conductivity, U-value and R-values do today. The performance as measured by a hotbox method is limited: it is only acceptable as a crude indication of an average thermal performance under reference laboratory conditions. There is a clear need for a better indicator to make decisions that are more informed on envelope design.

Results from hotbox test methods, be it for thermal testing or for air leakage testing, does not produce data with the required resolution to be used for R&D or for academic research. As discussed earlier, when materials improve the relative importance of the smallest detail may make or break the whole. These are the small details, which would disappear, in an averaging method like the box methods as well as in simplified models. The conclusion is that testing and modeling is not interchangeable but is complementary.

### 3.2.1 Test procedures

As the need for a wider performance indicator became evident, work begun on a more appropriate indicator spanning performance of wall systems under a diverse set of loads. The work arose from reports highlighting differences between values determined in laboratory by calibrated hot boxes, and tests done in the field. It was decided that the loads should include thermal, pressure and moisture loads, as those are the main loads in the field. During early work at BEESL at SU the approach was to test walls that had defects and sub-components in them, such as windows, electrical boxes, and other sources of malfunction. The idea was to test walls as built in the field under four main loading steps.

Eight residential walls were tested during the preliminary work with a variety of test conditions to evaluate both the procedure and instrumentation. This work was performed under a 3-year project sponsored by an industrial consortium<sup>18</sup> by Professor M. Bomberg<sup>19</sup> and several students<sup>20</sup>. The author joined this Syracuse University team in July 2007 to continue the work.

As work led up to the what is presented in this thesis a change was made from the all-inclusive approach to testing to a separated approach; separated in the sense that all the defects of uncontrolled nature, such as installed windows, electrical boxes, and so on were taken out and replaced with well-defined inlets and outlets for air. The quantification of the leakages due to those types of defects was left for others to research.

The test procedure, that included the main four steps shown in Table 8, was developed to produce a better performance indicator. It is the nominal conditions for each individual step that are shown in Table 8. The resulting indicator was called the energy equivalent R-value,  $R_{EE}$ , and the procedure is referred to as the energy equivalence procedure, EE-procedure, within this document.

---

<sup>18</sup>Members of the consortium were: Huber Engineering Wood Inc and Centria Corporation for 3 years and Honeywell Corporation, Huntsman Corporation, Jeld-Wen Corp, and Greenfiber Corp., for 2 years.

<sup>19</sup>Syracuse University, 263 Link Hall, Building Energy and Environmental Systems Laboratory

<sup>20</sup>Graduate students who participated in the initial development work of these concepts were: Henrik Martinell, M. Sc, Stockholm, who spent a year as a visiting researcher at SU; Shrinidhi Shetty and Ernest Blaszczyk who earned their M. Sc during this project. Finally, Marcin Pazera (through his PhD dissertation) contributed to the material characterization for HAM models used in this work.

The test procedure was applied to four different wall types within the scope of this thesis, two residential and two industrial. The two industrial walls were run through the test procedure twice, hence, this work reports on three series of tests, each series including at least the four main steps, on four different types of walls.

**Table 8: Nominal conditions during each step in the EE-procedure.**

Step	Pressure drop across the wall	Nominal temp. in chamber	RH outside	Nominal temp. in lab (indoor climate)	Nominal RH inside
1	0 Pa	-20 °C	N/A	25 °C	50%
2	50 Pa	-20 °C	N/A	25 °C	50%
3	50 Pa	40 °C	80%	25 °C	50%
4	50 Pa	-20 °C	N/A	25 °C	50%

Step 1 aims at determining the steady state R-value under standard reference conditions without inclusion of moisture or air flows. This first step of the test allows for comparison with calculated R-values, and gives the opportunity to adjust the base value, if necessary. It is the measured R-value from this first step that the results from continued testing relate. Hence, the measured thermal resistance in this step is used as the base to which the thermal performance of the walls is compared in later stages.

Step 2 continues with the same RH and Temperature conditions on the weather side, but introduces air pressure of 50 Pa in the opposite direction of the temperature gradient. The intent of the second step is to evaluate the impact of airflow on the measured R-value measured at the room surface of the wall. The 50 Pa pressure difference may seem high, but not unheard of. We can remember that Bornehag, Levin and Uvslokk all found pressures in the region or even higher than 50 Pa in their field tests, (Bornehag, 1991, Levin, 1991, Uvslokk, 1996). In addition, 50 Pa is a commonly used pressure to measure the air leakage of buildings by a blower door test. On one hand, it is low enough to be generated by standard blower door equipment in most residential buildings. Moreover, it is high enough that the dependency on weather influences is little (Antretter et al., 2007).

Step 3 of the procedure includes changing the direction of thermal gradient and using the exterior climate as a source of moisture. The hot and humid climate is continued for 3 days to permit observations on how well, or how poorly, the exterior weather barrier is performing. When this step was applied to walls provided with exterior WRB that was considered to be also an air barrier material, most of the eight residential walls tested in previous tests gained substantial amounts of moisture.

With moisture introduced by the air infiltration from the exterior, the measurements begin to involve transient contributions of moisture, and its phase change – the multitude of effects cause the need to involve modeling capability to a much greater extent. Therefore, Step 3 is preceded by a period of temperature stabilization at ambient conditions, (typically one or two days).

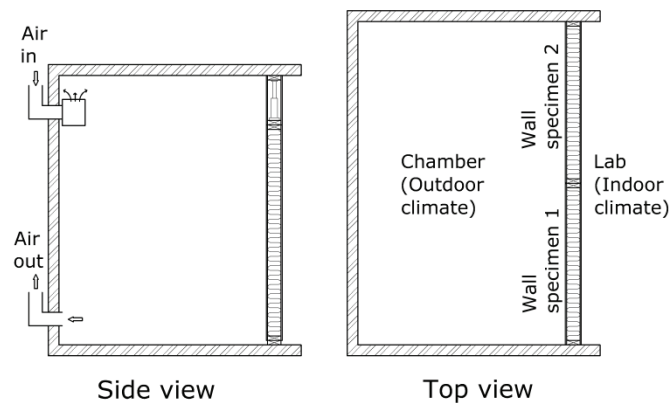
In step 4 we revert to the conditions of step 2. This is done to compare the drying ability of walls as well as to see if drying of the moisture introduced during step 3 can be modeled effectively. Obviously, using a fixed period of wetting and looking at the thermal performance after three days of drying, gives different responses of various wall constructions, yet, the initial response of the wet wall combined with that after three days of drying is an important benchmark. It indicates the

drying potential for the tested wall and the measured data may be used for verification of the moisture transfer in any HAM model.

### 3.2.2 General test layout

The environmental chamber at BEESL is large, 2.0 m (6.5 ft.), deep with a an opening of 3.7 m (12 ft.) wide and 3.0 m (10 ft.) high, enough to host two wall assemblies side by side for simultaneous testing. The principal design of the chamber is a dual shell with closed cell insulation as the distance material. Stainless steel is used for all surfaces of the chamber.

The environmental test chamber is placed in a lab in which both temperature and humidity is controlled. This allows the lab to represent the room side of the test walls, and the chamber was used for the weather (outdoor) side. The principal spatial configuration of the wall samples in the chamber is shown in Figure 38. To simulate the loads from a roof construction, the walls were put under vertical load, which was achieved by hydraulic jacks as can be seen on top of the walls in the side view in Figure 38. The setup of the samples, the sensors and the DAQ equipment is done before the testing takes place, and are kept the same throughout the test procedure.



**Figure 38: The spatial layout of the test setup in the full scale chamber tests consist of two wall specimens with dimensions 1.8 m by 2.4 m (70 in. by 96 in.).**

It is common to assume the principle of symmetry planes in modeling will limit the model to one zone stretching between the center of reoccurring thermal bridges and the center of the space between these thermal bridges. Since only the wood or steel frame walls have been tested so far, the assumed planes of symmetry are in the center of each stud and in the center of each cavity. One such zone was instrumented per tested wall, as shown in Figure 41.

The experience from earlier full-scale wall tests in the same chamber indicated that the boundary conditions varied both horizontally as well as vertically across the wall surface. The high velocity in the air inlet in combination with a small distribution box was identified to be a part of the problem. The BEESL chamber was designed for the high degree of mixing of the air that is required for VOC experiments. The main drawback of the described configuration was that the temperature distribution on the chamber side of the specimen walls was inverted in relation to the one expected under field conditions. To reduce this effect, a new air distribution box was designed, covering the full width of the chamber and mounted on the air inlet of the chamber. The implemented solution reduced the fluctuations of the temperature on the wall surface to a satisfactory level, although small differences were still seen in the measurements.

### ***3.2.2.1 Introduction of sensors in the air for surface resistance measurements***

Another feature added was sensors (for temperature and moisture) in the air, 100 mm outside of the surfaces of the walls. The purpose for these sensors was to estimate the thermal and the mass transfer resistance across the boundary layer.

### ***3.2.2.2 Introduction of orifice plates***

In the preliminary work leading up to the testing presented here, test walls included multiple defects resembling those that can be found in the field due to poor workmanship. The stated objective was to test real walls under field conditions, By doing so there were so many unknowns that the results was only valid for that particular case, since no separation of the phenomena was possible.

To permit generalization of the results well defined air inlets and outlets were introduced, while the remainder of the wall was sealed. Plexiglas sheets with holes drilled in them, functioning as orifices, Figure 39, were used instead of real, but less well defined, defects. The calibrated plates with two rows of 4 orifice openings (8 holes in total per plate) were designed to allow a flow of 0.5 liters per second per opening at 50 Pa pressure difference across the plate. Two orifice plates, (Figure 39), were mounted on each side of the wall, one at the top above the upper sensing level, (Figure 40), and one at the bottom below the lower sensing level as shown in Figure 40. This allowed relating measured performance to measured air flow through the wall.

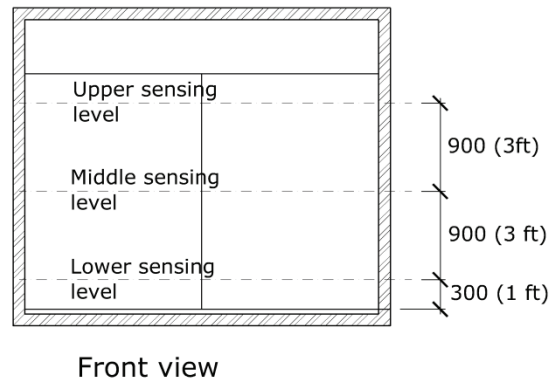


**Figure 39: Orifice plates used to introduce known amounts of air flow into the sample wall.**

### ***3.2.2.3 Sensing***

The sensing plan decided on after the review of earlier work, (Hui, 2007), included measurements at three heights of the wall samples, e.g. sensing levels; see Figure 40, one foot up, 120 cm (4 ft.) up and 30 cm (1 ft.) from the top edge of the 2.4 m (8 ft.) high wall. The reason for measuring at three levels was to capture changes in temperature and humidity, due to convection, both inside the cavity as well as on the surface of the wall.

The main measurements used in the procedure are temperature, moisture and heat flux. Sensors for measuring the pressure in the cavities where added in a second run of tests on the two industrial walls to investigate the pressure distribution inside the cavities.



**Figure 40: Three main levels of measurements**

The horizontal placement, at each level, was across one zone ranging between two symmetrical planes, to cover the whole span of temperatures, and heat fluxes from the best case in the center of the insulated cavity to the worst on top of the thermal bridge, created by the stud, as is shown in Figure 41.



**Figure 41: Symmetry plane concept (on the left) and sensor placement across a zone (to the right).**

The pattern of temperature and humidity sensors was repeated in several material interfaces inside the wall, as well as on the surface, and 100 mm (4 inch) out in the air (normal to the wall surface), altogether creating a 3-dimensional grid of measurement points.

The following sensors were used;

1. thermocouples for surface temperatures,
2. Honeywell wireless sensor boards with onboard temperature and humidity sensors for combined temperature and humidity sensing and
3. Thermopiles made in-house for heat flux sensing.
4. In some tests, as mentioned before, pressure was monitored as well: the sensors used were differential pressure transducers from the medical line of the company Aschcroft.

The use of thermocouples is probably the most common method of temperature measurement when there is a need for a high amount of measurement points. This type of sensor is cheap, relatively accurate, and most data loggers have built in technology for taking measurements with them.

The wireless sensor boards from Honeywell were developed for placement inside window frames for quality assurance. They are very simple to use, and they seem to be able to cope fairly well with the high stress level of the hot and humid climate to which they are subjected in the third step of the procedure. This very moist step has posed a problem for several sensor types used during the early tests at BEESL. Unfortunately about 40% of the wireless sensors do fail in the cold climate used in steps 1, 2 and 4 when placed to measure air or surface conditions on the cold side. The other flaw is that these boards are battery driven with soldered batteries. Many of them were reaching the end of the battery life and had to be cabled to a power source in order to function.

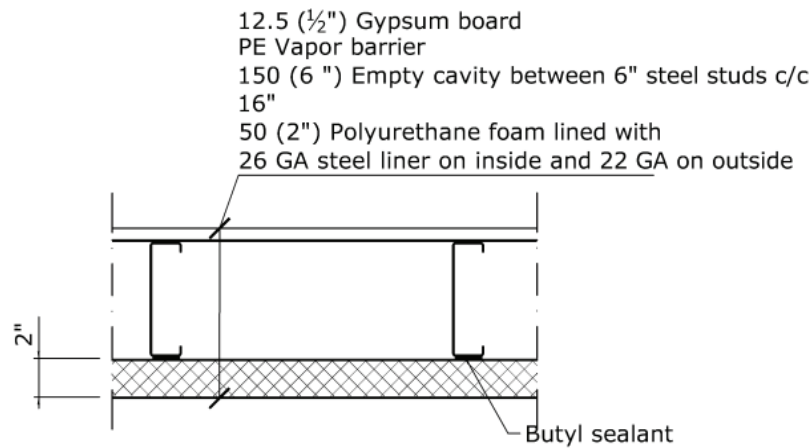
There were 4 walls that were tested, 2 of the walls was tested twice. The repeat was because the commercial heat flux transducers (HFT), which were used for the first test, proved to be too unstable. In following test thermopiles combined with calibrated boundary layers (CBL) were used instead. The calibrated boundary layer approach has been used in many studies. It includes a uniform and continuous layer of the known insulation placed on the room side. Medium density mineral fiberboards were used as CBL material in the first series of preliminary tests with the CBL approach at BEESL. Historically, convection was supposed to affect only the low density mineral fiber products, and this material was assumed to be non-convective while having a high permeability for air and vapor. In other words, it does not create a vapor barrier similar to that of a standard HFT made of a polymer film. Yet, during the pilot tests a substantial difference between thermocouples and thermopiles used compared to the HFT were observed. The CBL approach was applied during several years of field testing at National Research Council Canada (NRCC) (Bomberg et al., 1994) and was proven effective, yet, there were no air flows involved in those tests. When finding out that thermal performance of the medium density, semi-rigid mineral fiber board was affected by air flows, this material was replaced by EPS, and a new set of results was determined. Shetty (2007) improved the design of HFT and eliminated effects of radiation by covering the sensor with Kraft paper. By doing so the calibration of HFT exposed to air and that in HFT apparatus (sandwiched between black plates) became practically identical. An improvement over early versions was that the calibrated boundary layer contained several thermopiles previously calibrated in a heat flow meter apparatus. The thermopiles were made of the same material as the CBL. In this manner, the approach can be as precise as the thermal conductivity measurements performed well with the ASTM C518 test method, (ASTM Standard C518, 2010).

For the test of the residential walls, and the second run with industrial walls, the chosen material for the CBL as well as the thermopiles was 25 mm EPS. The thermopiles were 100 mm x 100 mm (4" by 4") in size made with calibrated pieces of the same material and thickness as the remaining part of an added layer on the surface of the wall. The size was changed from earlier tests, because numerical simulations of the conduction alone showed that a 300 mm x 300 mm (12"x12") transducer would not be able to capture the spatial variation of the flux with enough resolution to be usable. Kraft paper was glued to the surface of the EPS to modify the emittance of the surface and allow calibration of the sensors in the heat flow meter apparatus as a function of the mean temperature. To be able to decouple the wall from the CBL, temperatures were measured both on the surface of the CBL as well as underneath it in the interface between the CBL and the gypsum board.

### 3.2.3 Tested walls

The work reported on in this thesis includes tests on four walls: two industrial and two residential. The industrial walls were quite different in design: one traditional wall with steel studs and the cavity filled by glass fiber insulation, which was tested in parallel with a steel stud wall with external insulation panels and the cavities between the studs left empty. The residential walls were wood frame walls, one with glass fiber insulation in the cavities, and one with cellulose fiber insulation in the cavities. All four walls had an unpainted gypsum board as the finishing layer on the room side. The industrial walls had to be tested through the test program twice due to malfunctioning heat flux sensors during the first run as mentioned before.

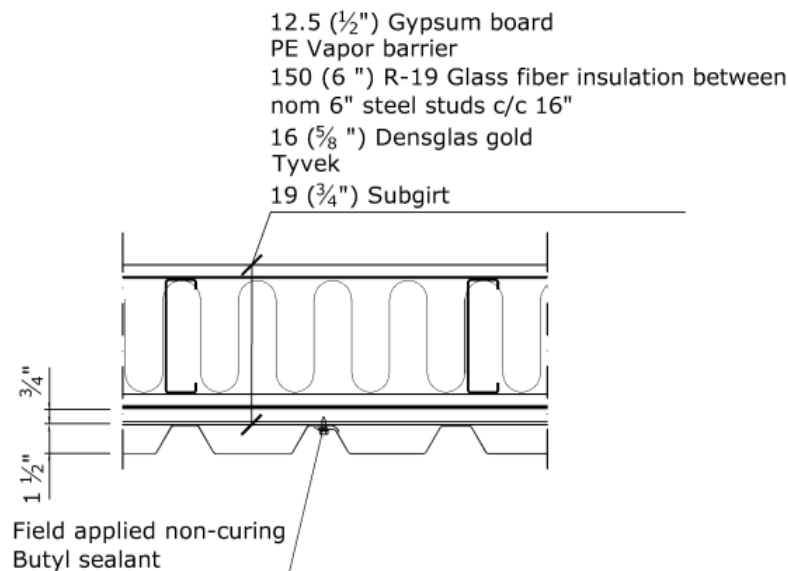
### 3.2.3.1 Tested industrial walls



**Figure 42: Horizontal cross section of the selected panel wall system, SPS.**

Figure 42 shows the industrial wall with external insulation panels. The insulation panels are made with a core of closed cell PU foam lined with metal sheets. This wall will be called a selected panel system, (SPS). The insulation panels were oriented horizontally and stacked on top of each other while attached to the vertical steel studs; while the interface between the insulation panels and the steel studs was sealed with butyl sealant to ensure that no air would leak from the cavities to the outside of the wall. The inside rendering consisted of a gypsum board, which was not sealed in any particular way.

The industrial reference wall, Figure 43, tested in parallel with the SPS was a design commonly used in industrial buildings; we will refer to it as a multi component wall system, (MCWS). The MCWS is with the structural element being steel studs with the cavities filled with glass fiber insulation.



**Figure 43: A horizontal cross section of the industrial reference, the multi component wall system, MCWS.**

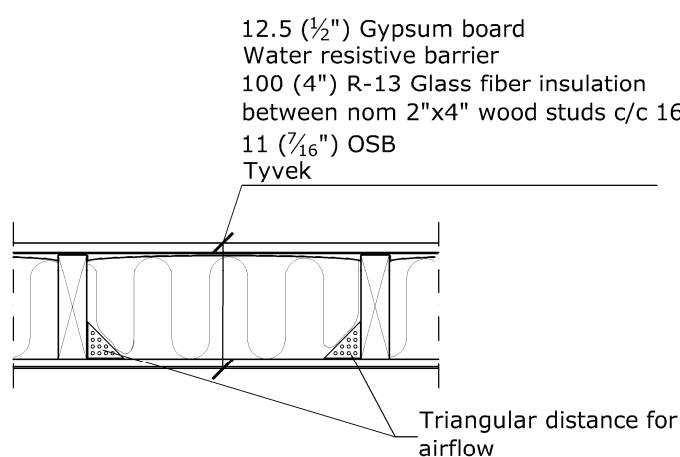
The outside of the wall has a rain screen of corrugated metal sheeting mounted on horizontal subgirts. The wind barrier protecting the insulation material is made of plastic house-wrap placed on the top of a mineral board. The inside finishing was a gypsum board with a vapor retarder

underneath. One of the most important aspects of this type of system is that the soft barriers are seldom perfect.

### 3.2.3.2 Tested residential walls

Both residential walls that were tested had nominal 2" by 4" (1.5" by 3.5" real dimensions, 38 mm x 89 mm in SI units) wood stud walls with gypsum board on the inside and a vapor barrier underneath. On the outside, an OSB was used and plastic house wrap was applied for wind protection. The only difference between these two walls was the type of the insulation material that filled the wall cavities, and the manner in which it was applied.

The reference wall system used glass fiber insulation for cavity insulation. This wall specimen had already been used in earlier tests, and was used again without alteration. The glass fiber insulation was of a commercially available type with Kraft paper facer stapled to the side of the studs (as recommended by manufacturer). The batt corners on the weather side were unfilled to simulate a small but measurable degree of deficiency, see Figure 44.

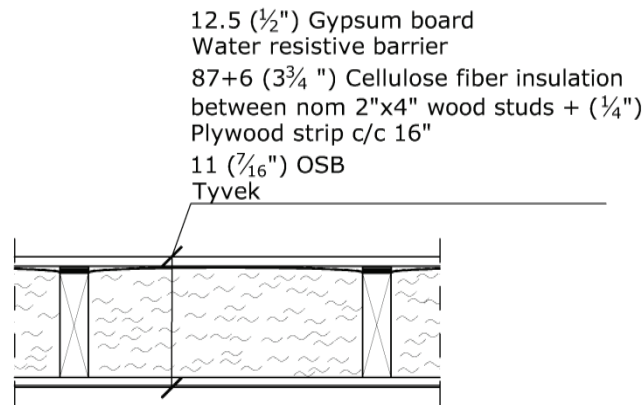


**Glass fiber wall system**

**Figure 44: A horizontal cross section of the residential reference wall with glass fiber insulation between the wood studs, GFW.**

The reference wall was tested in parallel with a similar wall, but with blown cellulose fiber insulation in the cavity, Figure 45. The important difference is that this insulation is blown in place between OSB and the interior membrane, and fills every nook of the cavities, not leaving any air channels in the material. The interior barrier film used in this wall was a type of water resistive barrier (WRB) similar to common house wrap but a major manufacturer did not manufacture it, it was an R&D product manufactured by a smaller firm and it that had been evaluated at BEESL. The evaluation showed that the barrier allowed higher airflow through it than traditional WRB films but had a much lower water vapor permeance than, on the US market, commonly available WRB membranes. CFI walls do not advocate the use of PE on any side of the insulation, instead, the argument is that the wall needs to allow for drying.

To avoid difficulties with the thermal insulation material bulging the gypsum board, an additional 1/4 inch plywood strip was stapled to the studs bringing the total thickness of the cavity space in the frame wall to 3 3/4 inch. The inside finishing layer in the form of a gypsum board was then applied on top of the plywood strips and secured by screws to the stud.



Cellulose fiber wall system

Figure 45: The second residential wall with cavities filled with cellulose fiber insulation, CFW.

### 3.2.4 Test results

The four walls described were tested in pairs. First out were the two industrial walls followed by the two residential walls, and finally the two industrial walls once again. Here the tests on the residential walls will be discussed first, and the test of the industrial walls, run 1 and run 2, second.

The procedure itself and the reasoning leading up to the test program are published in Paper V, and results from the tests are published in the two following papers. Results from tests on the residential walls are presented in Paper VI and results on the industrial walls in Paper VII, which also discusses some of the uncertainties that were encountered during testing. The methodology and some results have also been presented in a number of conferences in the US (Bomberg and Thorsell, 2008a, Thorsell and Bomberg, 2008b, Thorsell and Bomberg, 2009).

#### 3.2.4.1 R-value definitions

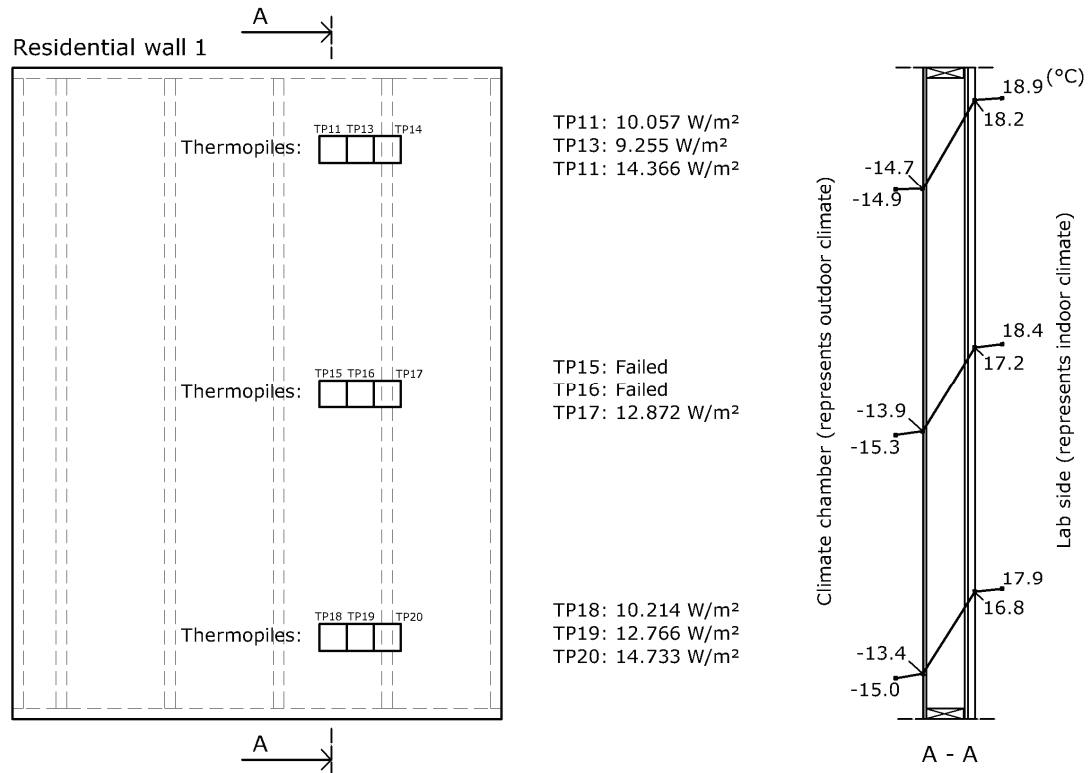
To continue the analysis of the measured data (temperatures and heat fluxes) with a view to establishing thermal resistance of the wall, we need to define a few terms that were used in the included papers, and will be used here as well:

- 1) R-value *in this document* represents air-to-air resistance to heat flow. It is an inverse of the U-value. Note that this definition is different from that used in ASHRAE in that it includes the thermal resistance of the boundary layers. This definition permits us to avoid several measurements on the wall surface to establish an average surface temperature when multi-dimensional heat transfer causes large local differences.
- 2) Apparent R-value = a ratio between temperature difference between indoor and outdoor air to the local heat flux measured at the local point without subtracting the resistance of calibrated boundary layer (CBL).
- 3) Local R-value = a ratio between temperature difference between indoor and outdoor air to the local heat flux measured at the local point when the resistance of calibrated boundary layer (CBL) is subtracted.

#### 3.2.4.2 Residential walls

Let us start with the general results of the tests. Figure 46 shows results of measurements performed during the first step on residential glass fiber insulated wall under standard conditions

namely room temperature nominal 20°C and 50% RH; weather -16°C<sup>21</sup>, uncontrolled RH and no air pressure gradient.



**Figure 46: Results of heat flux and temperatures measured on the residential wall with glass fiber insulation during step 1 of the test procedure.**

As can be seen, the heat flux measurements are missing in the cavity center in the mid height level. This is due to malfunctioning thermopiles, and the results presented in Table 9 do not include heat fluxes in this position. It can be noted, however, that there is a nonlinear vertical temperature variation present in the chamber air. If the values in Table 9 are compared with Table 10, it can be seen that there is even stronger variation horizontally over the surface of the two walls. Before an air distribution box was introduced, the difference was much more severe.

**Table 9: shows local R-value through the insulation section (in the middle of the cavity) in the residential wall with glass fiber insulation in the first step of the test procedure.**

Wall location	Cold side air (°C)	Warm side air (°C)	ΔT (°C)	Heat flux (W/m <sup>2</sup> )	Apparent R-value (m <sup>2</sup> K/W)	R-value excl CBL (m <sup>2</sup> K/W)
<b>Top</b>	-14.9	18.9	33.8	10.06	3.36	2.72
<b>Middle</b>	-15.3	18.4	33.7	N/A	N/A	N/A
<b>Bottom</b>	-15.0	17.9	32.9	10.21	3.22	2.58
<b>Average</b>	-15.07	18.40	33.47	10.135	3.291	2.650

Table 9 and Table 10 present surface temperatures measured on both wall and heat fluxes measured at interior surface of each wall. Since a 25 mm layer of EPS was placed against the inner surface of each wall, its effect was included in the measured apparent R-value, and when its thermal resistance is subtracted one obtains a local, R-value of the wall itself as indicated by the HFT.

<sup>21</sup> The test plan called for colder temperature than what was reached in the actual tests. The reason was that the used chamber was not able to provide a stable climate below -16 °C.

The objective of the first step of the proposed procedure was to measure the R-value corresponding to the clear wall R-value, as it can be measured by a hotbox method. However, if we look at the resistance in the center of the cavity insulation, and calculate the nominal R-value from material properties by summing up the individual resistances, namely OSB, Glass fiber insulation (R13), gypsum board, and the surface resistances, we get  $R \approx 2.65 \text{ m}^2\text{K/W}$  including standard surface resistances. This is the same as the mean of the measured center of cavity value for the reference wall with glass fiber insulation

$$R_{Tot} = \frac{1}{h_i} + \sum \frac{t}{k} + \frac{1}{h_e} = \frac{1}{7.7} + \frac{0.013}{0.14} + \frac{0.087}{0.039} + \frac{0.013}{0.17} + \frac{1}{25} \approx 2.65 \frac{\text{m}^2 \cdot \text{K}}{\text{W}}$$

For the cellulose fiber wall, however, the calculated 1D R-value is in the region of  $2.78 \text{ m}^2\text{K/W}$  (based on material properties established in a previous project). Compared with the measured R-value in step 1 of  $3.22 \text{ m}^2\text{K/W}$ , shown in Table 10, the difference is 16%. Due to this discrepancy, step 1 was done over again. The thermal resistance of the glass fiber insulated wall was measured to be the same, while the thermal resistance of the cellulose wall was found to be reduced to  $R=3.03 \text{ m}^2\text{K/W}$  from the previous  $3.22 \text{ m}^2\text{K/W}$ , as measured in the first test.

**Table 10: R-values through the insulation section in the residential wall with cellulose fiber insulation in the first step of the EE-procedure: hence, the only load is a thermal gradient.**

Wall location	Cold side air (°C)	Warm side air (°C)	$\Delta T$ (°C)	Heat flux (W/m <sup>2</sup> )	Apparent R-value (m <sup>2</sup> K/W)	R-value excl CBL (m <sup>2</sup> K/W)
<b>Top</b>	-17.0	19.0	36.0	8.90	4.04	3.40
<b>Middle</b>	-16.6	18.9	35.5	10.15	3.50	2.86
<b>Bottom</b>	-15.1	17.8	32.9	8.15	4.04	3.40
<b>Average</b>	-16.23	18.57	34.80	9.067	3.860	3.219

The reason for the difference may be explained by moisture transport in the material towards the cold. Similar behaviors have been seen in earlier work in heat flux measurements performed in an apparatus built for testing in accordance to ASTM C518, (ASTM Standard C518, 2010), but performed on a sealed specimen with moisture content of  $9.4 \text{ kg/m}^3$ . Models in CHAMPS show similar behavior as well, see Paper VI for more on the matter.

The cellulose fiber insulation was applied in a nom. 2x4 frame wall, Figure 45, covered by a WRB membrane on the warm side. The membrane was bulging in the center part, and to facilitate the application of the gypsum board a 6 mm thick wood strapping was stapled to the wood frame and the gypsum board was attached through the strapping, forming a partial air gap near the wood studs. In this situation, the air bypass bringing moisture into the wood frame wall caused condensation on the surface of WRB and release of heat, which in turn reduced heat flux entering through the calibrated boundary layer and increased the apparent thermal resistance measured. This external effect of moisture carried by air was getting smaller and smaller while thermal gradient pushed the moisture to flow through the cellulose fiber insulation (involving latent heat transfer) until at the certain moment in a quasi-steady state the error caused by air bypass and the effect of latent heat flow became equal producing an unbiased estimate of the wall performance. As shown in Paper VI, the results of measurements and calculations agreed.

**Table 11: Measured center of the cavity thermal performance in the EE-procedure applied on residential walls. On the second row of each wall type is a simplified thermal efficiency calculated by dividing the reduced R-value with R-value as measured in the first measurements step.**

Wall	Calculated 1D R-value (m <sup>2</sup> K/W)	Measured Step 1 2D R-value (m <sup>2</sup> K/W)	Measured Step 2 2D R-value (m <sup>2</sup> K/W)	Measured Step 3 2D R-value (m <sup>2</sup> K/W)	Measured Step 4 2D R-value (m <sup>2</sup> K/W)
<b>Glas fiber insulation wall</b>	2.64	2.65	2.27	0.53	2.40
		100.0%	85.9%	19.9%	90.8%
<b>Cellulose fiber insulation wall</b>	2.80	3.08	3.00	0.84	2.74
		100.0%	97.3%	27.2%	88.8%

The tests on the two residential walls was expanded to include two levels of air leakage: the standard flow was created by having 1 row of openings (4 openings in total) in the orifice plate open and the doubled flow by opening the second row as well (8 holes open per plate). As expected the cellulose fiber insulation could cope better with the double defect. The results from this comparison are presented in Table 12.

**Table 12: Measured thermal resistance in the center of the cavity under two amounts of air flow through the cavities.**

Wall	Measured, Step 2 STD Flow 2D R-value (m <sup>2</sup> K/W)	Measured, Step 2 Double flow 2D R-value (m <sup>2</sup> K/W)
<b>Glas fiber insulation wall</b>	2.27	0.90
	85.9%	34.2%
<b>Cellulose fiber insulation wall</b>	3.00	1.42
	97.3%	46.0%

The results from the EE-procedure are presented in Table 11. The conclusions to be drawn on the matter of thermal performance are:

- The impact of air flow is the most severe in glass fiber insulation
- The cellulose insulation copes with moisture better, but
- Cellulose fiber takes longer to dry out and regain initial performance.

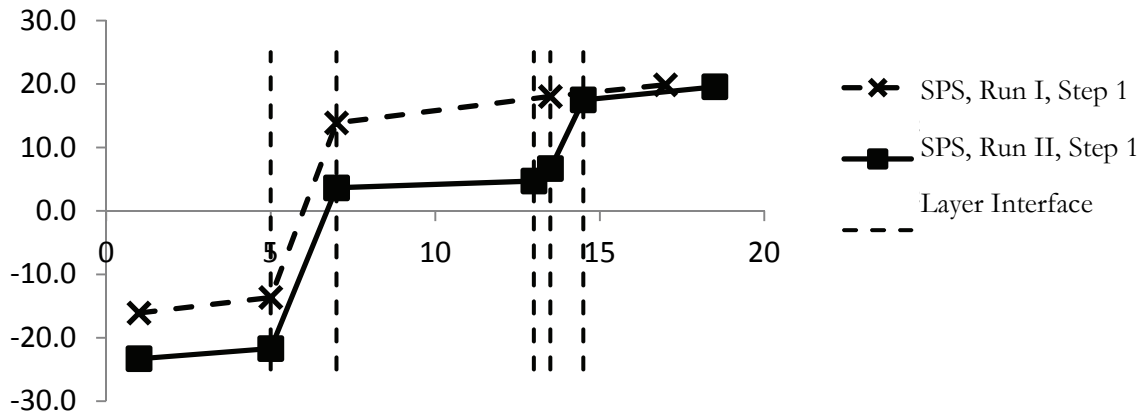
The conclusion to be made regarding designs incorporating glass fiber and cellulose fiber insulation is that the insulation needs to be protected from air flows as well as intruding moisture.

#### **3.2.4.3 Industrial walls**

The two test runs of the industrial walls will be referred to as industrial run 1 and run 2. The main difference in approach between run 1 and run 2 was that in run 1 there was no CBL since the heat flux was planned to be measure with commercial heat flux transducers. The commercial HTF failed and the CBL approach was reintroduced in the second run. The industrial run II allowed for some additional studies to be made outside the scope of the established test-procedures. The additional studies were on:

- The repeatability of the procedure.
- The pressure distribution in the walls and the major leakage paths of the assemblies

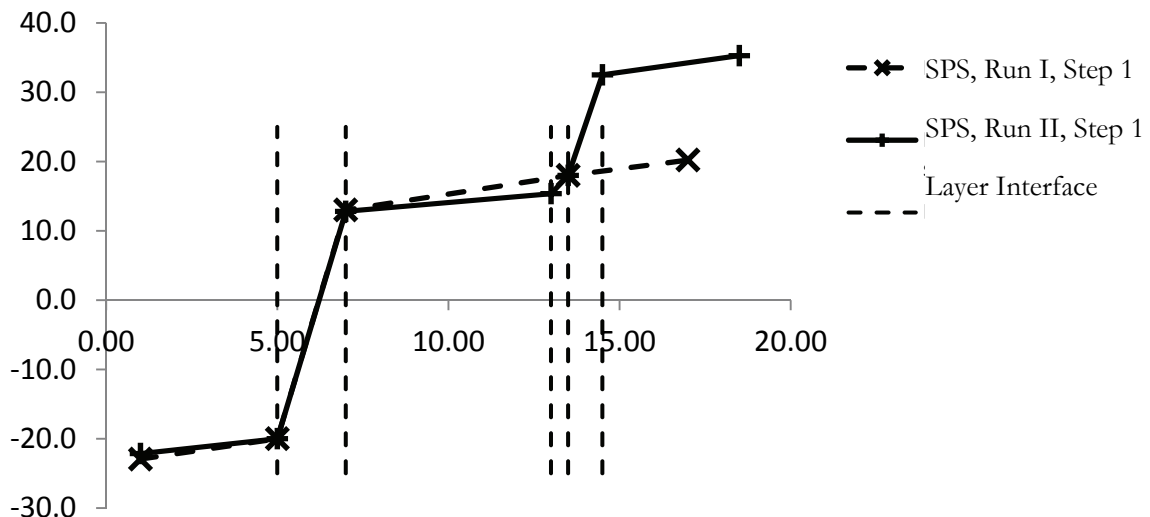
- How the air leakage at the edges of the gypsum boards affected the thermal performance of the walls, and
- Effects of a reduction in gap height.



**Figure 47: The averages of measured temperatures in the top, middle and bottom level in the same cavity of the SPS wall**

Data shown in this section includes both measured and normalized values. Figure 45 shows the average temperatures profile across the SPS from run I and run II in step 1 (the only applied load is a temperature gradient). As we can see the temperatures profiles are different, mainly because of the use of CBL and the difference in the weather chamber temperature between these two runs. Temperatures were measured with wireless sensors with the exception of the surface temperature on the cavity side of the insulation panel, which was measured with thermocouples.

To allow for easier comparison, of the temperatures in Figure 47 they are recalculated to reflect an inside temperature of 18 °C (surface between the gypsum and the CBL) and outside surface temperatures of -20 °C and are presented in Figure 48. This figure shows that after normalization, the agreement is within a degree C which is the accuracy of the sensors, and must therefore, be judged as good.



**Figure 48: A normalized temperature distribution across the SPS.**

After the repeatability has been established, we can look at the results from the whole EE-procedure. In Table 13 we can see the mean of the local R-values in the center of the cavity. We notice that the wall with an external panel kept a higher efficiency throughout the procedure, even

though the initial thermal resistance is much lower than for the multi component wall. Thermal efficiency is the subject of chapter 4.2. The SPS wall performs better than the reference wall during the moisturizing step as well.

**Table 13: Measured thermal performance in the center of a cavity during the test procedure applied on two industrial walls. The thermal efficiency is presented on the second row of each wall type.**

Wall	Measured				
	Measured Step 1 2D R-value (m <sup>2</sup> K/W)	Measured Step 2 Open 2D R-value (m <sup>2</sup> K/W)	Step 2 Sealed 2D R-value (m <sup>2</sup> K/W)	Measured Step 3 2D R-value (m <sup>2</sup> K/W)	Measured Step 4 2D R-value (m <sup>2</sup> K/W)
<b>External panel wall</b>	1.77	1.63	1.62	1.47	1.68
	100.0%	92.3%	91.5%	83.3%	95.2%
<b>Multi component wall</b>	2.63	2.27	2.37	1.15	2.45
	100.0%	86.4%	89.9%	43.7%	92.9%

Furthermore, during run II testing additional investigations were made. One was that the edges of the gypsum boards facing the room were either sealed by tape or left un-taped (open), to examine the difference in wall performance caused by air tightness on the interior finish. As can be seen by comparing data from the cases *Step 2 Open* and *Step 2 Sealed*, there is a slight difference. The unexpected result is that the multi component wall behaved better in our tests with the edges unsealed. At this stage, the difference is attributed to changed behavior of the airflow inside the cavity, bringing warmer air to the inside of the gypsum board, hence reducing the heat flux across the thermopiles. This led us to look at the pressure distributions in these two cases. Table 14 shows measured pressures behind the gypsum board in the cavity, and the last column shows the total pressure difference across the wall.

**Table 14: Measured pressure in Pa in the cavity behind the gypsum board averaged over the chosen steady state period.**

	SPS-CB Top (Pa)	SPS-CB Mid (Pa)	SPS-CB Low (Pa)	SPS Top (Pa)	SPS Mid (Pa)	SPS Low (Pa)	MCWS Top (Pa)	MCWS Mid (Pa)	MCWS Low (Pa)	Chamb (Pa)
<b>Stage 2, Sealed</b>	21.3	23.9	25.2	20.6	15.0	15.8	14.2	15.0	15.8	46.6
<b>Stage 2, Open</b>	6.6	8.4	10.1	4.1	3.2	4.1	2.7	3.4	4.3	53.3
<b>After stage 3</b>	5.0	5.0	4.4	2.3	1.1	0.7	1.6	1.3	0.8	50.0
<b>6 days into stage 4</b>	4.2	5.6	6.8	2.8	2.2	2.9	1.8	2.4	3.0	47.1

The differential pressures were measured between an outside common pressure box and the individual cavity at the three distinctive measuring heights. By reviewing the measured pressures in the multi component wall, it can be noted that initially with the gypsum sealed, a large portion of the pressure drop takes place over the gypsum board, about 1/3. When unsealed the OSB on the weather side constitutes most of the resistance, and less than 1/10 of the pressure drop is across the gypsum board. The relative pressure drops are all presented in Table 15: here the local pressure drop is related to the total pressure drop across the whole structure.

Yet another observation, which can be made from the pressure measurements in the cavity, is that the distribution of pressure loss changes after the structure is subjected to the wetting step, stage 3, and the drying step, stage 4.

**Table 15:** Shows the relationships between pressure drops across Gypsum board in relation to the total pressure difference between the chamber and the lab. SPS-CB reflects measurements in the cavity with convection barriers.

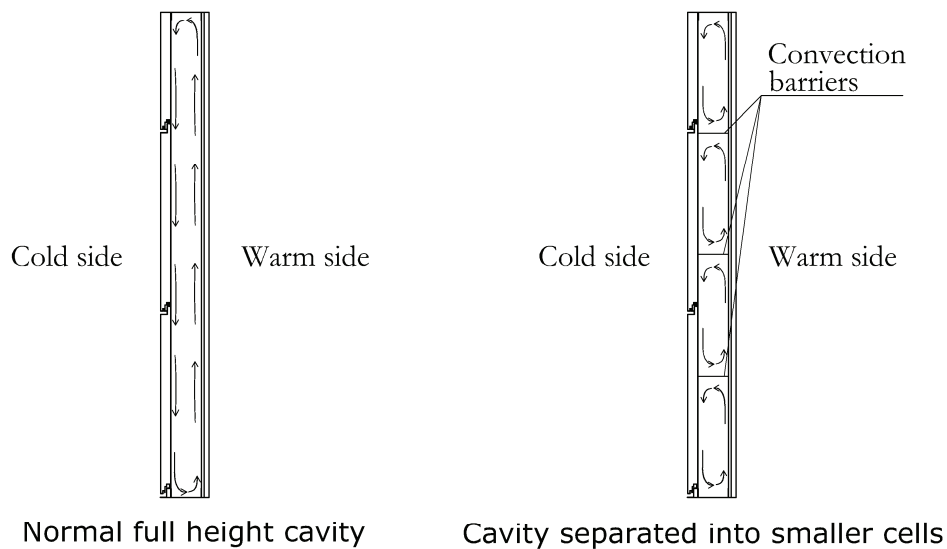
	<b>SPS-CB Top</b>	<b>SPS-CB Mid</b>	<b>SPS-CB Low</b>	<b>SPS Top</b>	<b>SPS Mid</b>	<b>SPS Low</b>	<b>MCWS Top</b>	<b>MCWS Mid</b>	<b>MCWS Low</b>	<b>Chamb</b>
<b>Stage 2, Sealed</b>	0.458	0.512	0.541	0.442	0.321	0.339	0.305	0.322	0.339	1.000
<b>Stage 2, Open</b>	0.124	0.158	0.189	0.078	0.061	0.077	0.050	0.064	0.080	1.000
<b>After stage 3</b>	0.100	0.099	0.088	0.046	0.022	0.015	0.033	0.026	0.015	1.000
<b>6 days into stage 4</b>	0.089	0.119	0.144	0.059	0.046	0.061	0.038	0.050	0.064	1.000

We saw the same behavior in the cavity marked SPS-CB, which was yet another side test that was added in the second run on the industrial walls, involving convection barriers.



**Figure 49:** One of the SPS cavities had convection barriers installed.

In the second run on the commercial walls, the one performed with CBL, two cavities in the panel wall were instrumented with thermocouples. One with and one without additional horizontal barriers placed in four levels, Figure 49. Thermocouples were placed in a vertical row to measure temperatures on the insulation panels inside surface facing the cavity. The intention of the horizontal convection barriers (CB) was to reduce the air movement within the cavity to reduce the convective heat transfer across the cavity. The measured R-values are presented in Table 16. As can be seen, the cavity with the convection barriers performs worse in every step of the procedure.



**Figure 50: Change in convective behavior due to the added convection barriers.**

This was not expected, but in retrospect, physically understandable. What the barriers actually do, in addition to creating a thermal bridge, is to modify the airflows to create shorter flow loops, see Figure 50 (right). In the case of the whole height cavity, the expected behavior of the air is that as it cools down the density decreases and sinks down near the cold surface, creating a rotation utilizing the full height of the cavity. In the smaller cavities the same behavior will develop, but the loop length will be shorter and the heat from the warmer side will be transferred to the cold side more efficiently than with the long loop. This is noteworthy, since many houses in the US have horizontal studs strengthening the frame in the middle of the cavities, and the cavity underneath a window will perform worse than a regular full height cavity if there is convection within the cavity.

**Table 16: Measured thermal performance of two cavities in the external panel wall. Convection barriers were added in the second cavity.**

Wall	Measured Step 1	Measured Step 2 Open	Measured Step 2 Sealed	Measured Step 3	Measured Step 4
	2D R-value (m <sup>2</sup> K/W)	2D R-value (m <sup>2</sup> K/W)	2D R-value (m <sup>2</sup> K/W)	2D R-value (m <sup>2</sup> K/W)	2D R-value (m <sup>2</sup> K/W)
External panel wall	1.77	1.63	1.62	1.47	1.68
	100.0%	92.3%	91.5%	83.3%	95.2%
External panelWall w. Conv Barriers	1.69	1.47	1.41	0.97	1.44
	100.0%	86.8%	83.5%	57.5%	85.4%

## Chapter 4: Discussion

To produce sustainable buildings in the broadest sense we need a design process that incorporates all disciplines and addresses the whole system of the building and improvement instead of the current approach, where individual components are designed and defined by individual consultants to be assembled into a building. It was shown in the full wall tests how important the connection between wall elements was for air leakage. The VIP insulation in its own complexity would not be viable unless looked upon as a system. The complexity increases yet again as such, if a super performing material is to be incorporated into a building, maybe a wall design for example.

### ***4.1 An holistic Approach and Sustainable Engineering***

We are in the midst of a paradigm shift: buildings must be looked upon as systems and not simply as assemblies. Every component is one piece of the puzzle, and all pieces must fit together and interact to meet the challenge of zero energy or even +energy buildings. A system approach may lead to many small actions undertaken in concert to achieve a major impact. On the other hand, the quick fix efforts for one or more components in the building envelope, at best, may not achieve enough, and at worst, may cause damage. The systems approach requires advice from, and interaction of, experts and experienced practitioners from all fields of the building industry. During the design process, integration between disciplines is necessary.

Throughout the text, so far, energy consumption has been used as the main quantity that needs to be saved, and it has been shown that small flaws and/or lack of workmanship may lead to large impact in energy loss through the building enclosure. This holds true on the scale of materials (VIP) as well as the full-scale walls. It is not so simple that if energy consumption is significantly reduced then all is well. There are a number of additional requirements to becoming sustainable such as:

- durability; required level of performance over service life
- indoor environment, IAQ, human wellbeing and performance.
- resource efficiency

#### **4.1.1 Durability**

The durability issue is linked to energy usage by degradation of materials and ultimately their failure. For a vacuum panel it is obvious, since the difference in performance between a good panel and a failed panel is significant, while for many other insulation materials the change may be a subtle creeping change that is not so obvious, but is capable of still deteriorating the performance of the material, hence affecting the thermal performance. The service life times of materials that degrade in a creeping fashion are rarely discussed, even though the changes and the increase in energy loss may be significant.

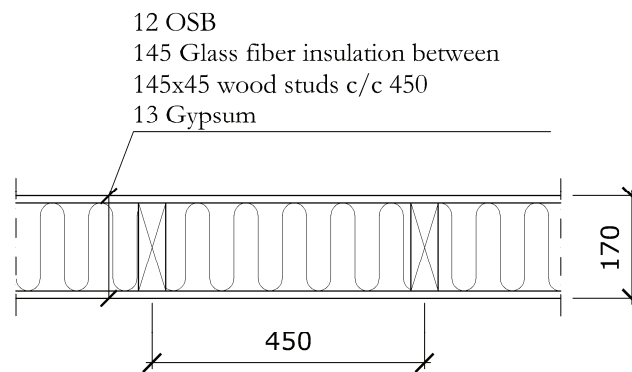
#### **4.1.2 Indoor Environment, IAQ, human well-being and performance**

The indoor environment is again a broad term encompassing the physical, social and psychological environment in a building. Indoor environments have a strong relation to energy performance, since a large proportion of the building's energy consumption is used to amend the indoor environment, particularly the climate and the air quality. The definition of acceptable indoor environment that will be suitable for a particular purpose is, therefore, very important, as this is a key component of the specification for a building, and a strong factor impacting the energy usage. A more restricted indoor climate (less flexible) often requires more energy to maintain.

### 4.1.3 Energy and resource efficiency

A set performance requirement may be met by many conceptually different designs. It is the constraints placed upon the design, together with design team's experience, that will decide on the final design. There are limitless additional constraints, many of which are difficult and measurable, such as maximum allowed energy usage, maximum physical size, and so on, but also soft constraints, hard to measure, such as the aesthetic beauty of the building, its fit into existing building styles, and so forth. Let us put the soft constraints aside and take a look at the energy and resources efficiency of a regular wood stud wall.

A stud wall, let us call it the cavity insulation wall (CIW), with 145 mm of glass fiber insulation ( $\lambda=0.033$  W/mK) in the cavity between wood studs placed at a cent-to-center distance of 450 mm, see Figure 51. The wall have an average thermal resistance of  $3.124$  ( $\text{m}^2\text{K}$ )/W (U-value of  $0.304$  W/( $\text{m}^2\text{K}$ )) including standard surface transfer coefficients), numerically calculated in COMSOL Multiphysics in 2 dimensions (horizontal section as in the figure). This wall is 170 mm thick and uses  $0.130$   $\text{m}^3$  insulation per  $\text{m}^2$  wall.

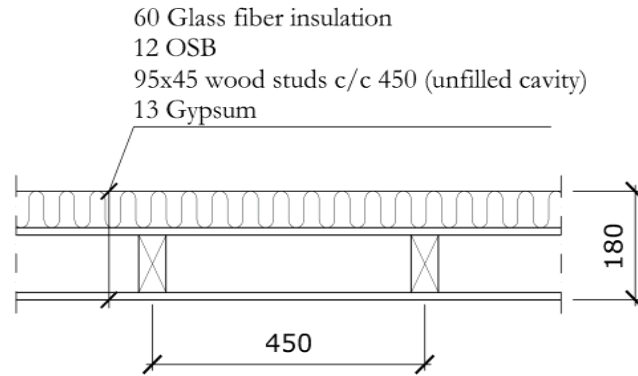


**Figure 51: Simple stud wall with 145 mm fiberglass insulation with a nominal thermal resistance of  $3.124$   $\text{m}^2\text{K}/\text{W}$ .**

If the materials are reconfigured, and a portion of the insulation is placed outside the studs without significantly changing the thickness of the wall then we get the wall in Figure 52. Let us call this wall the exterior insulation wall (EIW). Here a 60 mm batt of insulation is placed on the outside of the studs replacing the 145 mm thick cavity insulation. The wood studs used are still placed at a c/c distance of 450 mm, but are now 45x95 mm studs, which in most cases, should be enough for loads in a regular house. The average thermal resistance of the wall is then  $2.104$  ( $\text{m}^2\text{K}$ )/W (U-value of  $0.440$  W/( $\text{m}^2\text{K}$ ), modeled in COMSOL, but uses only  $0.054$   $\text{m}^3$  insulation per  $\text{m}^2$  wall. The cavity was modeled with an equivalent thermal conductivity of  $0.5$  W/(mK)<sup>22</sup>, (ASHRAE, 2005).

---

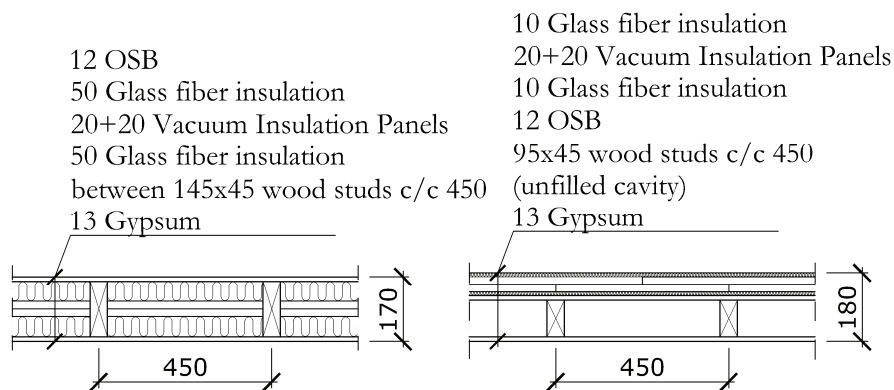
<sup>22</sup> derived from the thermal resistance given for plane air spaces of 90 mm, effective emissivity of 0.82, mean temp  $10$   $^{\circ}\text{C}$  and temperature difference  $5.6$   $^{\circ}\text{C}$  in table 3, chapter 25 of the ASHRAE Fundamentals Handbook, ASHRAE 2005. *ASHRAE Handbook: Fundamentals*, Atlanta, GA, American Society of Heating, Refrigerating and Air-conditioning Engineers Inc.



**Figure 52: Exterior insulation wall with a thermal resistance of 2.104 m<sup>2</sup>K/W.**

By this example, it is shown that by reconfiguring the materials in a stud wall 67% of its thermal resistance can be maintained with only 46% of the insulation by placing it in a continuous layer outside the studs. This would have been detected if thermal efficiency were used as design parameter. The gain in this example is due to the thermal bridge the stud creates in the CIW. The significance of the thermal bridge effect is even greater if an insulation material with lower thermal conductivity, such as the VIP, is used.

If the thermal insulation in the cavity of the CIW were to be improved by incorporating dual layers of standard VIP (20+20 mm) into the cavity insulation, as in Figure 53 (left), then the thermal resistance rises to 5.980 (m<sup>2</sup>K)/W ( $U=0.167$  W/(m<sup>2</sup>K)), almost doubling (an improvement of 91%), compared with the original CIW. If instead, the materials were to be applied in the most efficient manner, as in the EIWs, then the thermal resistance increases another 86% to a thermal resistance of 11.151 (m<sup>2</sup>K)/W ( $U=0.090$  W/(m<sup>2</sup>K)), thus an improvement of 250% compared to the CIW with only traditional insulation in the cavities (from 3.124 to 11.151(m<sup>2</sup>K)/W). In both cases a portion of the traditional insulation materials was replaced with two VIPs.



**Figure 53: Stud wall with VIP. To the left VIP incorporated into the cavity insulation,  $R=5.980$  (m<sup>2</sup>K)/W and to the right all insulation is placed on the outside of the studs,  $R=11.151$  (m<sup>2</sup>K)/W.**

These two examples highlight the potential savings of using materials efficiently. In the first comparison the material reduction was significant while the thermal resistance reduction was reasonable, and in the second example with the VIP, the reduction of traditional insulation was substantial and the improvement in thermal resistance was huge. In the latter case the first design with VIP in the cavity looks good if one only looks at the R-value, but it is very poor for reasons of low surface temperatures and poor utilization of the added VIP, so it should never be used. This can be easily seen if thermal efficiency is used as an evaluation parameter. This comparison was a

good example of poor application, while in the case with externally applied VIP the improvements are exceptional. Thermal efficiency should be used as a design parameter as it places a value of how well the insulation materials are utilized, and it is necessary for a truly organic efficient system design.

## **4.2 Thermal Insulation Efficiency**

Thermal Insulation Efficiency is proposed as a necessary design parameter to be used when designing building envelopes, since it gives a measure of how well utilized the potential of the insulation material is used, and thereby is a partial indirect measure of sustainability. Here, thermal efficiency is used to reiterate across and expand upon results from research presented in the included papers. Thermal insulation efficiency can be derived from models, as in the example above, or from tests, as in the testing done and presented in papers V through VII. Thermal efficiency should be taken into account when designing building envelopes since it gives a measure of utilization of a material, and thereby is a partial measure of sustainability.

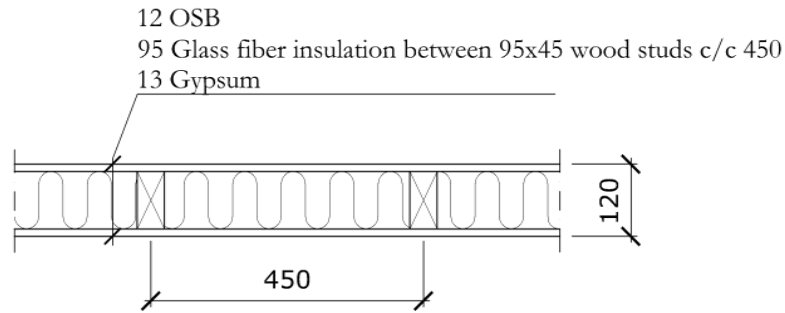
## **4.3 Definition of Insulation Efficiency**

Efficiency is traditionally defined as the percentage of usable energy compared with the energy inserted into a system. Hence, for an electric motor it is the amount of the rotational energy at the axis divided by the energy inserted into the motor. In mathematical terms, the motor efficiency can be expressed as in Equation 12.

$$\eta_m = \frac{P_{out}}{P_{in}} \quad \text{Equation 12}$$

Where, in the example of an electric motor,  $P_{out}$  is the shaft power in watts and  $P_{in}$  is the electric power put into the motor in watts, and the energy difference is due to friction and other losses in the motor. The maximum efficiency is 1 which would mean that all power fed into the motor is usable at the shaft.

To translate this to thermal resistance, it is assumed that for a perfect unbroken layer of insulation without any 3D hygrothermal fluxes, the thermal efficiency would be unity, hence the material performs at 100% of its potential. If the maximum possible performance is given the value of 1, then anything that increases energy loss through the insulation layer would yield efficiency lower than 1. For insulation materials or looking at the insulation capacity of a building enclosure component such as a wall the parameter of importance is the thermal resistance, hence thermal insulation efficiency.



**Figure 54: Example wall with wood studs 45 mm X 95 mm c/c 450 mm and glass fiber insulation filling the cavities.**

The normed value for the insulation layer is the nominal R-value,  $R_{nom}$ , of the component and the comparative value is the apparent R-value,  $R_{app}$ , including any thermal bridges, effects of air leakage, moisture flux, or any other mechanisms lowering the thermal resistance of the material, the composite, or the assembly. The thermal insulation efficiency,  $\eta_i$ , can then be defined as in Equation 13.

$$\eta_i = \frac{R_{app}}{R_{nom}} \quad \text{Equation 13}$$

The nominal thermal resistance can be often be calculated by manual methods, as is the case for the examples in this chapter or by testing which is the case in the first step of the EE-procedure when the data from the full wall testing is the subject. The apparent thermal resistance can be calculated by numerical modeling software or measured on real assemblies. Let us look at an example of a regular stud wall with glass fiber insulation filling the cavities and gypsum coverings on the inside and a sheet of OSB on the exterior side very similar to the wall discussed earlier and apply the concept of thermal insulation efficiency as defined here. All other but nominal resistances are numerically modeled in COMSOL Multiphysics.

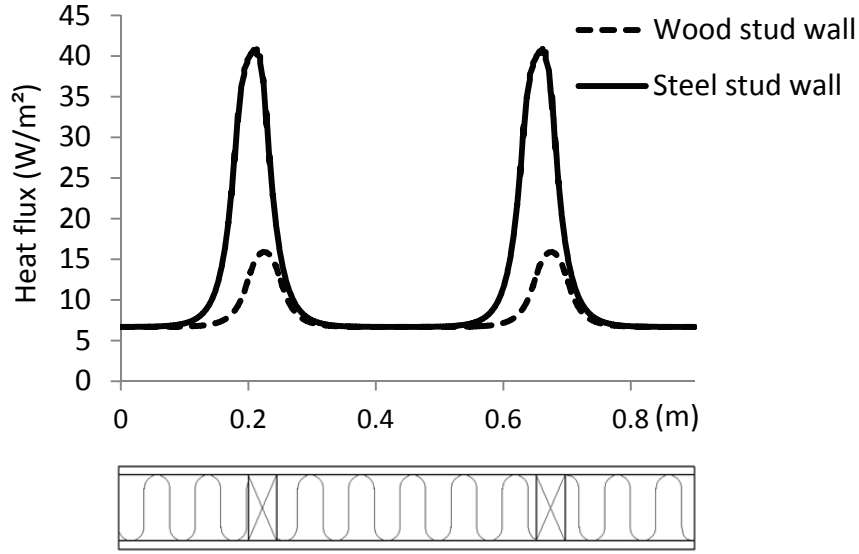


Figure 55 show calculated heat fluxes graphically from both the wall with steel studs (solid line) and wood studs (dashed line).

For this case the nominal thermal resistance can be found in the middle of the cavity, and is simply the sum of the thermal resistances of the individual layers plus the assigned boundary conditions, which were convective heat transfer with surface transfer coefficients of  $8.0 \text{ W}/(\text{m}^2 \cdot \text{K})$  on both sides. The thermal conductivities used for the calculation are shown in, Table 17, and the nominal thermal resistance becomes:

$$R_{nom} = \frac{1}{8} + \frac{0.012}{0.14} + \frac{0.095}{0.036} + \frac{0.013}{0.74} + \frac{1}{8} = 2.992 \text{ m}^2 \text{K}/\text{W}$$

This is to be related to an average thermal resistance for the wall including thermally degrading elements, in this case thermal bridges, which are taken from a numerical calculation. The total heat flux,  $Q$ , through the section was calculated to  $6.66 \text{ W}$  assuming the dimension of  $1 \text{ m}$  in the  $z$ -direction. The heat flux graph is shown in Figure 55 and the sum is then the result of integration along the boundary length of the wall ( $0.9 \text{ m}$ ). The air temperature used in the simulation was, for the inside  $20^\circ \text{C}$ , and outside  $0^\circ \text{C}$ . The apparent thermal resistance may then be calculated as:

$$R_{app} = \frac{A \cdot \Delta T}{Q} = \frac{0.9 \cdot 1.0 \cdot 20}{6.66} = 2.703 \text{ m}^2 \text{K}/\text{W}$$

This yields the thermal insulation efficiency of this configuration to be:

$$\eta_i = \frac{R_{app}}{R_{nom}} = \frac{2.703}{2.992} = 0.903 = 90\%$$

If the same exercise is done for a similar wall, but the wood studs are replaced by steel studs, then the total heat flux,  $Q_{steel}$ , is calculated to  $10,981 \text{ W}$  in COMSOL and:

$$R_{app} = \frac{A \cdot \Delta T}{Q} = \frac{0.9 \cdot 1.0 \cdot 20}{10,981} = 1,639 \text{ m}^2 \text{K}/\text{W}$$

This leads to a thermal insulation efficiency of:

$$\eta_i = \frac{R_{app}}{R_{nom}} = \frac{1,639}{2,992} = 0,548 = 55\%$$

Material	Thermal conductivity (W/m·K)
OSB	0.14
Studs	0.14
Glass fiber insulation	0.036
Gypsum	0.74
Steel (stud)	43

**Table 17: Thermal conductivity used for the calculation.**

Applying the definition of thermal insulation efficiency to the wood stud walls in the previous chapter, we understand that the wall with standard insulation filling the cavities, the wall in Figure 51, has a thermal efficiency of 0.75. The efficiency of the wall improves to 0.90 if the insulation is placed on the outside of the studs instead, as in Figure 52, thus an improvement of 20% in efficiency. For the example with incorporated vacuum panels the increase is from 0.46 for the poorly designed wall with VIP between the studs, Figure 53 (left), to an efficiency of 0.99 for the wall with two staggered 20 mm VIP layers on the outside of the studs, Figure 53 (right), an improvement in efficiency of more than 100%.

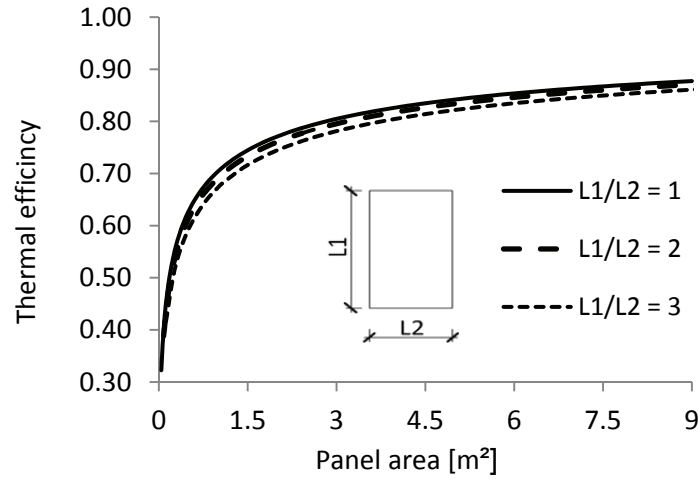
The reason for the larger improvement is that the relative impact of deficiencies increases when the resistance of the insulation layer increase, thus, a super insulation is more sensitive to flaws in the design. In the examples above the deficiency that negates the thermal resistance is the thermal bridge wall design created by the wooden stud. The described testing in papers V to VII includes testing of several walls and the results show that the thermal efficiency is strongly reduced by airflows in the walls due to leakages and buoyancy.

## **4.4 Effects of Thermal bridges**

### **4.4.1 Example of VIP edge**

For a vacuum panel one could argue that the thermal efficiency of the vacuum panel is  $>1$  if the  $R_{nom}$  is selected to be the resistance of unevacuated core material. However, for this discussion the evacuated value will be used as the nominal R-value. Using the instantaneous service life definition, Equation 1, with a limiting value of the center of panel value of  $0.008 \text{ W}/(\text{m}\cdot\text{K})$  and edge losses from paper I and II the thermal efficiency of a whole panel can be studied.

Barrier composites that were used in the market in 2005 had a linear loss of about  $6\cdot 10^{-3} \text{ W}/(\text{m}\cdot\text{K})$  to  $53\cdot 10^{-3} \text{ W}/(\text{m}\cdot\text{K})$  depending on material properties of the barrier layer. A 0.1 mm thick straight stainless steel edge was modeled on a 30 mm thick panel, and was found to add a linear loss of  $28\cdot 10^{-3} \text{ W}/(\text{m}\cdot\text{K})$ , while the serpentine edge on a similar panel was found to reduce this loss to  $9.6\cdot 10^{-3} \text{ W}/(\text{m}\cdot\text{K})$  for a serpentine design with 17 serpentines of 20 mm depth.

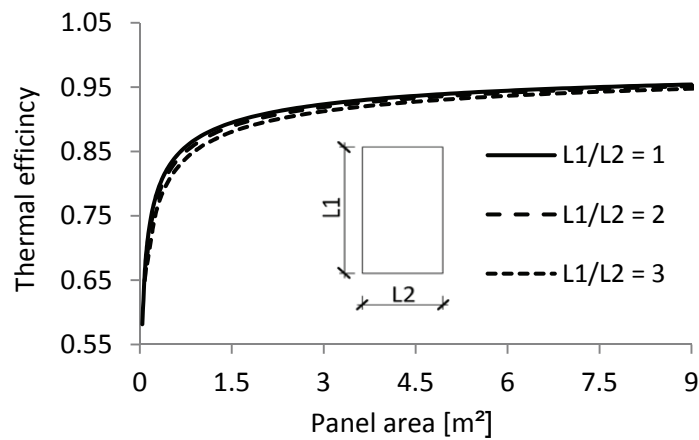


**Figure 56:** Thermal efficiency of vacuum panels with stainless steel barrier of thickness 0.1 mm with a straight edge solution with a linear heat loss of 0.028 W/(m·K).

If the concept of thermal efficiency is applied on a complete VIP of thickness 30 mm and. Assuming the nominal resistance of the core to be 3.75 (m²K)/W (center of panel resistance) and the barrier as above (stainless steel 0.1 mm), then it can be deduced that the panel size (relative to the panel surface and edge length) is a more important factor than the format of the panel.

$$R_{mean} = \frac{A}{U \cdot A + \Psi \cdot L} \quad \text{Equation 14}$$

Equation 3 was used as a base to calculate the mean resistance including the added losses through the edge, which yields the equation for the mean resistance,  $R_{mean}$ , Equation 14. The results of the calculation exercise are presented in Figure 56 for the straight edge solution of the panel edge, and for the 17 serpentine edge solutions in Figure 57. It is very clear that it is thermally advantageous to choose large panels, even though the relative importance becomes small for sizes larger than 2.5 to 3 m². The efficiency for the straight edge panel of 1 m² is around 70%, somewhat less for a rectangular panel compared with a square panel, but the difference is small, while for a 2.5 m² the efficiency has increased to near 80%, yet increasing the size to 4 m² only increases the efficiency a few percent above 80%.



**Figure 57:** Thermal efficiency of vacuum panels with stainless steel barriers of thickness 0.1 mm with a serpentine edge solution with a linear heat loss of 0.0096 W/(m·K), thermally comparable to the composite barriers that were used for panels in 2005.

When the edge on the panel is replaced with a serpentine edge (17 serpentines, 20 mm deep,  $\Psi=0.0096 \text{ W}/(\text{m}\cdot\text{K})$ ), which is comparable to the composite barriers that were used for panels in 2005, then the efficiency of a 1 by 1 m panel increases to 87% to be compared to 70% for the straight edge. The increase in efficiency by choosing a larger size of 4 m<sup>2</sup> only increases the efficiency to 93%, thus 6%. This exercise reinforces the recommendation of selecting as large panels as possible; however, the discussion on the thermal efficiency of the panel itself is of somewhat limited interest since the important performance is that of the whole system in which the panel is placed.

#### 4.4.2 Example of VIP in walls

Previously, two walls, Figure 53, with vacuum panels in them were used to exemplify how the relative importance of careful design increases as material performance improves. The thermal efficiency for the standard wall with vacuum insulation incorporated into the fiberglass insulation in the cavity is only 46%, which is very low, and this design must be deemed as being inadequate. If the vacuum panels are instead placed on the outside of the studs, neutralizing the thermal bridges, then the efficiency becomes 99%, neglecting fasteners, which is excellent.

The very same wall with traditional insulation in the cavity between the studs but no VIP, Figure 51, has a thermal efficiency of 75%. The thermal resistance of the wall with incorporated VIP in the cavity, Figure 53 (Left), has higher mean thermal resistance of 5.98 (m<sup>2</sup>K)/W to be compared to only 3.12 (m<sup>2</sup>K)/W without VIP, hence the wall with VIP in the cavity has higher thermal resistance on average, but the utilization of the insulation is extremely poor. This comparison drives the point that use of high performance materials requires design that is more thorough. Super performance materials have the potential of improving performance tremendously, but make designs incorporating them much more sensitive to deficiencies in design, as well as in workmanship.

It is also worth noting that the overall efficiency of a wall can be improved by adding additional layers to the existing wall, as when external insulation is added to an existing building when renovating it, thus thermal efficiency is a valid parameter to use when building new and for renovation. The relative importance of the existing insulation is decreased by the addition of more insulation.

The impact of workmanship on a construction with VIPs in them is, in the case of a VIP puncture, obvious since this will cause a failure. This type of abrupt failure is not the subject here, but poor workmanship may create defects and pathways for hygrothermal transport within a construction. Hygrothermal transport has the potential of reducing thermal efficiency by bypassing materials and/or degrading material performance.

#### 4.5 Effects of Air leakages

The notion of walls not working as well, thermally, as expected was the underlying reasons for the work presented in papers V through VII. Several walls were tested under a defined test procedure, which was designed to apply all main loads a wall may be subject to in the field. The idea was to explore the impact of three dimensional hygrothermal flows on thermal performance of walls, and reflect the performance in a performance indicator which expands the one traditionally used in the US, the R-value (the U-value in Europe). The proposed indicator is meant to reveal information on performance under loads, other than the dry, no airflow and constant temperatures that is used today.

#### 4.5.1 Example from Wall tests

For both the residential wall types dealt with in paper VI the wooden studs lowered the thermal insulation efficiency about 14% to an efficiency of 0.86, compared to the calculated and measured mid cavity value. When a pressure gradient was applied across the walls the efficiency was decreased further. For the wall with glass fiber insulation the efficiency was lowered another 15%, reaching an efficiency of 0.73, while for the wall with cellulose fiber insulation the averaged reduction was 4.5%, resulting in an insulation efficiency of 0.82. The difference is likely due to the difference in air permeability of the two materials. The fiberglass insulation was a very lightweight quality, common in the US, while the cellulose insulation was a denser insulation, which in this case helped in reducing the effects of airflow.

Steps 3 and 4 of the procedure presented in paper V, aimed at wetting the walls by applying pressure combined with hot and humid conditions on the high pressure side, and in the following climate step reversing back to cool and dry conditions. The drying period was chosen to be the same length as the wetting period. The measured data from the tests on residential walls showed that the effect of wetting was larger in the wall with fiberglass insulation than in the wall with cellulose insulation. The efficiencies from step 3 of testing were 0.29 and 0.41 respectively, and after drying, 0.17 and 0.21 respectively. The results from testing steps 3 and 4 are to be looked upon as qualitative only, because there were multiple sensor failures that prevented complete assessment. Both the residential walls had the same design with the exception of the type and installment of the insulation materials, and yet the efficiencies were quite different. The tested industrial walls, on the other hand, were two of very different design, even though both used steel studs as the load bearing elements.

The industrial reference wall (MCWS) had the insulation positioned between the studs, as in the residential walls, while the industrial test wall (SPS) had the insulation placed outside the studs in steel faced panels. For the reference wall, the reduction in thermal resistance due to air flow when a 50 Pa pressure was applied was 16.3%, while it was 7.9% for the wall with exterior insulation panels. The measured thermal insulation efficiency in this step was 0.53 and 0.80 respectively.

The results from the wall test show the importance of preventing unwanted airflows in order to maintain the efficiency of the insulation layer. One can understand that airflow penetrating through a material has the potential of compromising its function by enforcing the convective component of heat transfer. What may come as more of a surprise, is the fact that there exists a reduction in thermal resistance, even in the wall with insulated panels placed externally on a system of studs. Here the effects of heat collecting layers and cooling fin effects come into play as the air movement changes in the empty cavity behind the layer of insulation.

## Chapter 5: Conclusions

### 5.1 Material Scale

In the scale of individual materials, the focus in this thesis was on vacuum insulation panels. Vacuum insulation panels have advanced, well beyond air as the main insulator, to a complex construction comprised of a system of an evacuated core and a barrier maintaining the vacuum. This type of composite can reach a thermal performance of 6 to 8 times better than traditional fiber insulation.

#### 5.1.1 Serpentine Edge

- *Numerical modeling shows that a serpentine edge design reduces the thermal loss from  $0.028 \text{ W}/(\text{m}\cdot\text{K})$  with a straight steel edge to  $0.0096 \text{ W}/(\text{m}\cdot\text{K})$  for a serpentine design with 17 serpentines of 20 mm depth, hence a reduction by 65%. Calculations show that a stainless steel edge with 11 serpentines with a depth of 20 mm has a linear heat loss as low as  $0.01 \text{ W}/(\text{m}\cdot\text{K})$ . This linear heat loss is to be compared with measured values of existing panels with linear heat loss of up to  $0.05 \text{ W}/(\text{m}\cdot\text{K})$  (aluminum foil) or for metallized polymer multi-layer films that have a linear loss of  $0.006 \text{ W}/(\text{m}\cdot\text{K})$  (Wakili et al., 2004). For a panel of one square meter the additional heat transfer due to the loss at the edge is less than 30% for a panel with a serpentine edge.*
- *Testing of a serpentine edge with 5 serpentines in a hot and cold plate device shows that the numerical model reflects real behavior well. Both testing and modeling show significant heat collecting effects from the metal surfaces of the panel. However, testing indicated that the real effect is smaller than what was indicated by numerical modeling.*

#### 5.1.2 Hybrid Diffusion Model

- *Inspection of metallization layers from real VIP barriers shows that the defects in the coatings are often clustered into groups with high defect density. This speaks against using diffusion models which use an average defect to defect distance as a simplification.*
- *Modeling a film built by three polymer layers, 20  $\mu\text{m}$  PET-Al coating-20  $\mu\text{m}$  PET-Al coating-25  $\mu\text{m}$  PE and two coatings, as described in the Annex 39 report of IEA, (IEA, 2005a), indicates a mean oxygen permeability of  $0.013 \text{ cm}^3/(\text{m}^2\cdot\text{day}\cdot\text{bar})$  which can be compared to measured OTR values reported in the IEA project. The measured values from one institute range from 0.01 to  $0.02 \text{ cm}^3/(\text{m}^2\cdot\text{day}\cdot\text{bar})$  which agrees very well with the results from our simulations. Another institute reports, in the same report, transmission rates of  $0.07 \text{ cm}^3/(\text{m}^2\cdot\text{day}\cdot\text{bar})$  as an upper estimate for one film with dual coating, this film, however, was reported to have great variations in the measured transmission rate therefore the value must be considered an upper estimate. The other film tested by this institute was measured to  $0.00062 \text{ cm}^3/(\text{m}^2\cdot\text{day}\cdot\text{bar})$  which must be considered a very good dual coating film. Still our model is not completely out of range in comparison.*
- *It is stated in the IEA report, (IEA, 2005a), that for a VIP to be useful in a building it needs to reach service life times of 30-50 years. It is also stated that in order to reach those lifetimes the use of getters is necessary in combination with barriers with oxygen permeability below  $1\cdot 10^{-2} \text{ cm}^3/(\text{m}^2\cdot\text{day}\cdot\text{bar})$ . The diffusion model presented indicates that such low permeability is within reach with only two metallization layers if a quality found in the best metallization layer inspected in this study could be reached in both coatings.*

## 5.2 Component scale

### 5.2.1 Energy equivalent R-value

- *It is clear that the U-value (R-value) is very restricted as a performance indicator.*
- *It can be concluded that different walls behave differently under different loads, a point which was proven by the performed testing. Energy performance R-value or energy equivalent R-value ( $R_{EE}$ ) or whatever we call the proposed performance indicator, aside, it is clear that the proposed test procedure does reflect differences in performance under a variety of loads.*

To have an indicator that reflects performance under several types of loads would extend the information beyond that of a U-value or an R-value; information that may inform a designer of the challenges ahead. A material that shows large changes when exposed to a pressure difference probably requires that system air tightness is created by other means, while for a material for which performance is maintained under the same circumstance may not need this extra measure.

### 5.2.2 Thermal insulation efficiency

- *The proposed usage of thermal insulation efficiency as a design parameter when designing building envelopes is a way of assigning a measurable quantity to how efficiently the insulation portion is incorporated into a wall, and in the EE-procedure it reflects how well the insulation copes with the different loads.*

## 5.3 Building Scale

### 5.3.1 Holistic Approach to Building Design

- *The challenges that come with improved material performance may be dealt with on a materials scale, as with the serpentine edge negating the linear heat loss for the VIP, or on a system scale by intelligent design. One example of the latter is placing VIPs in staggered double layer configuration of VIP outside the load bearing structure which yields a near 100% thermal insulation efficiency.*
- *A holistic approach to building design must be employed to progress towards the sought after reduction in environmental impact. Flaws in a design that includes a super effective insulation material will be greatly enhanced: a thermal bridge or air leakage for example will have a relatively profound impact as opposed to when lesser performing materials are used. It was shown in chapter 4 that, depending of design, the thermal efficiency may very well be halved if VIP is incorporated poorly into a design.*
- *Hygrothermal performance of walls with different types of insulation was significantly affected by air ingress to the air gap between the insulation and drywall during the performed testing. It was found to be cumbersome to seal this gap sufficiently in a lab setting, and one can suspect that it will be even more difficult in situ. The conclusion of Kalamees and Vinha (2007) that there will always be defects has been reinforced through this work. A combination of numerical modeling and testing is necessary to assess hygrothermal performance of building systems.*
- *In paper IV and in the thermal efficiency chapter of this document it was shown how important it is to apply an integral approach to designing building components and constructions in which vacuum insulation panels are integrated. This is a conclusion valid for any high performance design we are to develop; a holistic approach is necessary.*

A method or a model to gain knowledge of the performance of such a design is another prerequisite for success in such an endeavor.

### 5.3.2 Integrated Testing and Modeling

- *Without air pressure, applied measurements performed showed a good consistency and agreement of average values with computer calculations for 2-D models independently of the workmanship and sealing of the*

*perimeter. It can be concluded that local measurements may be used and yield results on par with results from hot box methods.*

The approach used for the walls in this study with local measurements show, however, that the detailed information gained was significant and there were mechanisms taking place, which would have been missed if an averaging method, such as a hotbox method, were used. Results presented enforces that for research and development one must use local measurements in combination with modeling while the traditional hotbox methods merely produces a limited performance indicator.

- *The foremost important conclusion from the full size wall testing was that air ingress into the wall cavity has significant effects on thermal performance of the wall. The reduction in thermal resistance due to air leakage in regular stud walls, as used in the US, have been found to range from only 1 or 2% when airtight foam filled the whole cavity to 20% reduction when insulation was permeable for air and moisture, or a large unfilled air space existed in the cavity. Obviously these numbers were lower (e.g., 4.5 and 14.5% shown in this study) when the wall construction was more airtight.*
- *To address field performance of an assembly one must combine testing and hygrothermal modeling. Hygrothermal models are necessary to be able to address the wide spectrum of parameters deciding building performance; include the effect of climate and service conditions, thermal mass and moisture movement, workmanship and usage. Testing is necessary to validate our models; the test protocol presented here is sufficient for model validation on the three major transport mechanisms heat, air and moisture, hence for HAM models.*

Assessment of new designs, assembly methods and workmanship issues may be dealt with by mock up testing combined with workforce training. In some cases, it might be necessary to overhaul the whole construction process; it could be necessary to invent new processes to neutralize particular risks of failure due to on site work. The other side of the reaching the target performance is quality control. As mentioned by Dalglish and Surry (2003) the best predictive tool will fail in the presence of detailing and installation deficiencies. Hence, even if we model every part of a building, the quality issues are not addressed in HAM models and such models will not predict real hygrothermal performance since they do not model the real in situ situation.



## **Chapter 6: Future work**

### **6.1 Vacuum insulation panels**

#### **6.1.1 Serpentine edges**

Manufacturing the serpentine edge is a challenge especially sealing the serpentine at the corners of the panels may prove hard, if not impossible. However, stainless steel of a thickness 0.1 mm is virtually gas tight so if the edges and corners could be completely sealed, such a panel will have a practical lifetime many times longer than that of panels with metallized polymeric barriers, thus accomplishing the desired lifetimes of buildings. Further possibilities with a gas-tight envelope are to use other core materials, which require lower pressures in the core to reach the desired thermal resistance. The lower cost for the core material could thereby at least partly balance out a higher cost for the barrier materials and manufacturing.

If the challenges of manufacturing can be overcome, then the serpentine edge enables the usage of stainless steel barriers for vacuum insulation panels in smaller panels. Using metal as the barrier material would create sturdy panels less sensitive on the work site.

Another upside of using perfectly air tight all metal encapsulations would be that it would allow for the usage of a wide array of other core materials with potentially better core performance due to material properties, glass fiber is one example, or the option of using and maintaining a higher vacuum.

#### **6.1.2 Hybrid diffusion model**

The results from the diffusion model was compared to barrier films that was thought to be of the same design as the ones that were measured, this is not, however, sure since film manufacturers were not willing to supply films. This insecurity of whether this really being the case downgraded the conclusions significantly why it is recommended to continue work to verify the accuracy of this model. It would be preferred to do laboratory testing to gain knowledge of real permeability of samples, which are then evaluated for defect data used in the model. Only then real confidence can be built to trust the results from this hybrid model. However the results are promising, and a strong indication that polymer based composite film barriers with metallized coatings have a future as barrier materials and is likely to be able to meet the permeability requirements.

#### **6.1.3 VIP in building construction**

In paper IV two significant contradictory requirements were identified for implementation of vacuum insulation panels in buildings;

- thermal performance versus functional service life,
- and thermal performance versus structural performance.

However, the argument in the chapter on barrier materials was to use as large and thick panels as possible to maximize the service life times. It is, again, a situation of opposing requirements, on one hand, the improvement in thermal performance by using multiple staggered layers and, on the other, the service lifetime of the thinner panels that have to be used for a staggered configuration compared with a single layer configuration of the same thickness.

But, there are more challenges to the usage of VIP in buildings; for example issues of handling the panels on the construction site or protecting the panels so that they may be handled at the site or issues of fastening the VIP to the structure without risking the integrity of the panel. What is the

correct application approach for VIP? Do we assume that some will fail and use several layers of VIP for redundancy; do we make the VIP layer accessible to allow for replacement of failed panels or maybe even use large sturdy panels with easily accessible evacuation valves, which allow for re-evacuation? There are still many questions to address in the field of vacuum insulation panels in particular or other new types of super insulation.

The diffusion model that was presented in paper III used the theory of resistance networks to solve the overall gas diffusion through a VIP barrier film; a similar approach may very well be used to calculate air leakage in complex leakage systems in buildings. The challenge is to find the leakage pathways by combined measurements and modeling of the inner cavities of a lightweight wall.

## **6.2 Integrated testing and modeling**

The proposed indicator was called energy performance R-value in one paper and an energy equivalent R-value in another. It could be enough just to report thermal insulation efficiency under the different loads to reflect the system performance.

Through the full-scale tests, a proposal for a test procedure was developed in the form of four major steps, beginning from the equivalence of the clear wall R-value as measured by a hot box in the first step. It continued via the second step with applied pressure and a conditioning step which wet the structure, then a final drying period after which the thermal performance was evaluated. Thus, one obtains a history of R-value changes under different conditions. The performance of the wall is to be calculated from local measurements on three levels of the walls: at 30 cm (1 ft.), 120 cm (4 ft.) and 210 cm (7 ft.) height. At these levels temperatures, humidity and heat fluxes are measured. The initial work as well as the tests under the author's control show significant differences in the measured performance under the different loads. The procedure shows a promise in separating performance of different types of walls. However, there are a number of questions to resolve before it can be submitted as a proposal for standardization.

1. **What is the best approach for separation of different effects without producing biased results?**
2. **What need to be measured and at what locations?**

An advanced HAM model is needed to extrapolate from local measurements to the full wall performance. So far, a number of models have been used but the measured thermal performance as only determined as an average for the assembly. There is an obvious need for a model capable of addressing heat, air and moisture flows simultaneously and linking the local and average performance. The important question is:

3. **How do we go from the selected local measurements, via modeling, to calculate the performance of the whole component?**

The literature shows a large amount of work on the subject of modeling heat and moisture flux and air flows in different configurations. Hens (2002) lists nearly 40 models, however very few of them combined all three transport mechanisms into one model. In later years there are a limited number of combined heat, air and moisture models available: the two most promising, in the authors eyes, are the CHAMPS model developed at BEESL, and the HAM-BE developed at Concordia University within the simulation package COMSOL-Multiphysics. Both are said to include buoyancy and forced convective flows as well as heat and moisture fluxes in the model. Yet, the limited amount of verification work on these models (while positive in the sense that there are deviations between measurements and model results are small) does not include simultaneous interaction of all three transport mechanisms. The existing verification work is either by a

comparison to benchmark tests or by a comparison to averages from far too complex field measurements. A question arises:

**4. How well do existing models deal with three simultaneously acting heat and mass flow mechanisms? In what respect do the model and the measurement deviate?**

One definite factor affecting the accuracy of any model is the data input into the model. In the literature study, it was found repeatedly that lack of the available material properties was a limitation. In the full size chamber tests discussed in the section on earlier work the variations of the boundary conditions was of concern as well as the data input for defining the calculated problem. Temperatures, humidity and airflows on the surface of a component are relative easy to measure but how about the air leakage into and through the component. Three types of air cavities were identified earlier which are all more or less common in a building, depending on design, and they are:

- contact plane between materials either by design, e.g., two layers of water resistive barrier (WRB) or by use of materials with different thickness. Typical thickness of such an air gap would be less than 1-2 mm (1/16 inch).
- gap between insulation (cellulose fiber, foam) and the drywall or drainage cavity. Typical thickness of such an air gap would be between 2-20 mm (1/16 and 3/4 inch).
- air cavity behind cladding or unfilled frame wall cavity. Typical thickness of such an air cavity would be between 45-250 mm (1.5 to 10 inch).

A future research question regarding thin gap airflows is:

**5. How do these thin air gaps influence flow patterns of air and moisture in walls?**

- a. Can the day and night shifts in thermal gradient cause condensation and evaporation that together with gravity or airflow would affect the rate of transport? More specifically,
- b. Can a short path airflow across the wall e.g., at the wall-window interface change the flow pattern in a wall?
- c. If a second air gap is located on the inner side of the wall, the questions relate to the effect of airflow on moisture transfer through the walls. Specific interest is focused on highly porous materials such as fibrous insulations and moisture collection in the sill plates.
- d. If this air gap is placed as a drainage cavity behind insulation (currently a frequent solution used to drain windows) there are a number of questions related to reduction of thermal and moisture performance of the assembly. From building science point of view, this design may be not acceptable for selected assemblies in some climatic regions of the country.

The next set of issues to be examined, relates to conditions on air entry into the wall. How much air comes through the contact between OSB or drywall and wood frame?

There are studies on the impact of airflows in components both relating to thermal impact as well as moisture impact due to convective flows. Studies on actually measuring airflow in a component are very scarce and no standard method could be found. There are also studies on leakage paths location, there are methods for whole house leakage quantification as well as for components, but the data gathered from these test are not suitable as input into a HAM model as they are averaged and imprecise. The very wide and imprecise question summing all the small ones mentioned above is:

**6. How can component leakage be quantified in a manner that would yield input data for HAM modeling?**

As the questions raised are addressed, the final question is the obvious one. If we have a verified HAM model, correct input data in the form of material properties, measured boundary conditions and mapped air leakage the grand question arises:

**7. How well can a validated HAM model predict performance of full size walls under a range of climate conditions?**

## Personal Reflection

In this study, I have covered most of the current issues of the insulation layer in building envelope design. However, I have connected this work to the rest of the building design by virtue of connecting it with the materials, description of the spaces, the testing, workmanship, quality issues, and design issues. While not touching upon all the other subsystems within a building system, it was suggested more than once that all of these are connected as a system, namely the building. In order to progress in sustainable building design, we must change our perspective on exactly what a building is and what it provides. It has been seen in the past as a collection of different parts stuck together for a variety of purposes other than providing good sustainable living quarters. Unfortunately, that concept has led to the current situation where we have some stunning buildings that are veritable dinosaurs, gobbling energy as fast as we can capture it.

More than just within the building trade, we must begin to look at this planet as a system and the human centers of activity as subsystems, along with the other subsystems on the planet. The human centers of activity are mostly our cities, subsystems that interact with the planetary environment. Within the cities may be thousands of building subsystems, transport subsystems, separate weather subsystems, electrical and communication subsystems etc. Within the building subsystems are the subsystems of that building, which interact in order to maintain an interior environment comfortable for human habitation. In looking at buildings as systems and the various parts of the building as subsystems, we can see that no subsystem can be designed without consideration of all the other subsystems. To do so, would be equivalent to putting a jet engine in a Volkswagen, or vice versa. Just as all the parts within a jet airplane must interact or the plane does not fly or maintain safety, all the parts within the building must interact to maintain the interior environment, the exterior integrity and the safety of the enclosure. They do interact, whether we recognize this fact or not. Therefore, if we are to reach the goal of sustainable building design, we must design buildings as systems. This is reiterated here, because all of the information presented here after years of study, experimentation, analysis and design will be useless unless it is combined with other systems about which there is an equal amount of information available. Just as the testing was shown to be of vital importance to this paper, testing for model validation must be developed in order to properly evaluate efficiency of the new building system design as well as to develop the necessary retrofit systems to address the huge existing building stock.

Maybe it is time to think about changing the process of erecting buildings, instead of calling for increased commissioning. A revision of engineering designs aiming at creating designs that by default creates airtight building systems would be favorable. Instead of trying to implement new materials within the existing process, maybe future construction demands improved processes to meet requirements of precision, usage of superior materials, such as the VIP technology, basically requires a changed building process due to the fragility and required pre-manufacturing of the insulation elements.



## References

- ABADIE, M. O., FINLAYSON, E. U. & GADGIL, A. J. 2002. Infiltration Heat Recovery in Building Walls: Computational Fluid Dynamics Investigations Results. Berkeley, CA: Lawrence Berkeley National Laboratory.
- ALAM, M., SINGH, H. & LIMBACHIYA, M. C. 2011. Vacuum Insulation Panels (VIPs) for Building Construction Industry – A Review of the Contemporary Developments and Future Directions. *Applied Energy*, 88, 3592-3602.
- ANTRETTETTER, F., KARAGIOZIS, A., TENWOLDE, A. & HOLM, A. 2007. Effects of Air Leakage of Residential Buildings in Mixed and Cold Climates. *Buildings X Conference*, . Clearwater Beach, Florida.
- ASHRAE 2005. *ASHRAE Handbook: Fundamentals*, Atlanta, GA, American Society of Heating, Refrigerating and Air-conditioning Engineers Inc.
- ASPEN. 2011. *Building & Construction* [Online]. Aspen Aerogels, Inc. Available: <http://www.aerogel.com/markets/building.html> [Accessed 11 Oct, 2011 2011].
- ASTM STANDARD C177 2004. Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus. West Conshohocken: ASTM International.
- ASTM STANDARD C236 1993. Standard Test Method for Steady-State Thermal Performance of Building Assemblies by Means of a Guarded Hot Box (Withdrawn 2001). West Conshohocken: ASTM International.
- ASTM STANDARD C518 2010. Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus. West Conshohocken: ASTM International.
- ASTM STANDARD C687 2005. Standard Practice for Determination of Thermal Resistance of Loose-Fill Building Insulation. West Conshohocken: ASTM International.
- ASTM STANDARD C976 1996. Standard Test Method for Thermal Performance of Building Assemblies by Means of a Calibrated Hot Box (Withdrawn 2002). West Conshohocken: ASTM International.
- ASTM STANDARD C1363 2005. Standard Test Method for Thermal Performance of Building Materials and Envelope Assemblies by Means of a Hot Box Apparatus. West Conshohocken: ASTM International.
- ASTM STANDARD C1484 2009. Standard Specification for Vacuum Insulation Panels. *Thermal Insulation Standards*. West Conshohocken, PA: ASTM International.
- ASTM STANDARD E283 2004. Standard Test Method for Determining Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors Under Specified Pressure Differences Across the Specimen. West Conshohocken: ASTM International.
- ASTM STANDARD E741 2006. Standard Test Method for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution. West Conshohocken, PA: ASTM International.
- ASTM STANDARD E779 2003. Standard Test Method for Determining Air Leakage Rate by Fan Pressurization. West Conshohocken, PA: ASTM International.
- ASTM STANDARD E783 2010. Standard Test Method for Field Measurement of Air Leakage Through Installed Exterior Windows and Doors. West Conshohocken: ASTM International.
- ASTM STANDARD E1424 2008. Standard Test Method for Determining the Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors Under Specified Pressure and Temperature Differences Across the Specimen. West Conshohocken: ASTM International.
- ASTM STANDARD E1827 2007. Standard Test Methods for Determining Airtightness of Buildings Using an Orifice Blower Door. West Conshohocken, PA: ASTM International.

- AWBI, H. 2003. Air Infiltration Calculation and Measurement. *Ventilation of Buildings*. Abingdon and New York: Spon Press.
- AXLEY, J. & PERSILY, A. 1988. Integral Mass Balances and Pulse Injection Tracer Techniques. *Effective ventilation; 9th AIVC Conference*. Gent, Belgium: National Bureau of Standards.
- BAETENS, R., JELLE, B. P. & GUSTAVSEN, A. 2011. Aerogel Insulation for Building Applications: A State-of-the-Art Review. *Energy and Buildings*, 43, 761-769.
- BAETENS, R., JELLE, B. P., THUE, J. V., TENPIERIK, M. J., GRYNNING, S., UVSLØKK, S. & GUSTAVSEN, A. 2010. Vacuum Insulation Panels for Building Applications: A Review and Beyond. *Energy and Buildings*, 42, 147-172.
- BAKER, P. H. 2003. The Thermal Performance of a Prototype Dynamically Insulated Wall. *Building Services Engineering Research and Technology*, 24, 25-34.
- BERENS, A. R. & HOPFENBERG, H. B. 1982. Diffusion of Organic Vapors at Low Concentrations in Glassy PVC, Polystyrene, and PMMA. *Journal of Membrane Science*, 10, 283-303.
- BHATTACHARYYA, S. 1991. The Measured Energy Impact of Air Leakage on Frame Wall Systems.
- BHATTACHARYYA, S. & CLARIDGE, D. E. 1995. The Energy Impact of Air Leakage Through Insulated Walls. *Journal of Solar Energy Engineering*, 117, 167-172.
- BINZ, A., MOOSMANN, A., STEINKE, G., SCHONHARDT, U., FREGNAN, F., SIMMLER, H., BRUNNER, S., GHAZI, K., BUNDI, R., HEINEMANN, U., SCHWAB, H., CAUBERG, H., TENPIERIK, M., JOHANNESSEN, G., THORSELL, T., ERB, M. & NUSSBAUMER, B. 2005. Vacuum Insulation in the Building Sector-Systems and Applications. *HiPTI - High Performance Thermal Insulation*. IEA/ECBCS Annex 39.
- BOMBERG, M. & ONYSKO, D. 2008. Energy Efficiency and Building Durability at the Crossroads. *Journal of building enclosure and design*, 27-35.
- BOMBERG, M. & PAZERA, M. K. 2006. Energy Performance of SPF Roofs: Documentation and Review. Spray Polyurethane Foam Contractors Alliance.
- BOMBERG, M. & THORSELL, T. Energy Performance R-value: Part 1 - Development of Integrated Evaluation Methodology for Building Enclosures. BEST 1: Building for Energy Efficiency and Durability at the Crossroads, June 10-12 2008a Minneapolis. Building Enclosure Council BEC-Minnesota.
- BOMBERG, M. & THORSELL, T. 2008b. Integrated Methodology for Evaluation of Energy Performance of the Building Enclosures: Part 1-- Test Program Development. *Journal of Building Physics*, 32, 33-48.
- BOMBERG, M. T., MUZYCHKA, Y. S., STEVENS, D. G. & KUMARAN, M. K. 1994. A Comparative Test Method to Determine Thermal Resistance under Field Conditions. *Journal of Building Physics*, 18, 163-181.
- BORNEHAG, C.-G. 1991. Inomhusmiljö i Dalen - Tekniska mätningar i 90 lägenheter i Enskededalen, Stockholm. Statens råd för byggnadsforskning, Stockholm.
- BRANDRUP, J., IMMERGUT, E. H., GRULKE, E. A., ABE, A. & BLOCH, D. R. (eds.) 1999; 2005. *Polymer Handbook (4th Edition)*: John Wiley & Sons.
- BROCKEN, H. J. P. 1998. *Moisture Transport in Brick Masonry : The Grey Area Between Bricks*. PhD, Technische Universiteit Eindhoven.
- BROWN, W. C., BOMBERG, M. T., ULLETT, J. M. & RASMUSSEN, J. 1993. Measured Thermal Resistance of Frame Walls with Defects in the Installation of Mineral Fibre Insulation. *Journal of Building Physics*, 16, 318-339.
- BUCHANAN, C. R. & SHERMAN, M. H. A Mathematical Model for Infiltration Heat Recovery. AIVC 21st conference, 2000 The Hague, Netherlands. 49.
- BYNUM, R. T., JR. 2001. *Insulation Handbook*. McGraw-Hill.
- CABOT. 2011. *Building Insulation Products* [Online]. Available: <http://www.cabot-corp.com/Aerogel/Building-Insulation>.

- CAN/CGSB 1986. CAN/CGSB Standard 149.10-M86 Determination of the Airtightness of Building Envelopes by the Fan Depressurization Method
- CAPS, R. Monitoring Gas Pressure in Vacuum Insulation Panels. 7th International Vacuum Isolations Symposium, 28-29 September 2005 2005 Dübendorf, Schweiz.
- CAPS, R., BEYRICHEN, H., KRAUS, D. & WEISMANN, S. 2008. Quality Control of Vacuum Insulation Panels: Methods of Measuring Gas Pressure. *Vacuum*, 82, 691-699.
- CAPS, R. & FRICKE, J. 2000. Thermal Conductivity of Opacified Powder Filler Materials for Vacuum Insulations<sup>1</sup>. *International Journal of Thermophysics*, 21, 445-452.
- CARPENTER, S. Advances in Modeling Thermal Bridges in Building Envelopes. eSim 2001, June 13th - 14th, 2001 2001 Ottawa, Canada. 7.
- CHAN, W. R., PRICE, P. N., SOHN, M. D. & GADGIL, A. J. 2003. Analysis of U.S. Residential Air Leakage Database. *Paper LBNL-53367*. Lawrence Berkeley National Laboratory.
- CHANEY, M. 1989. Transport Phenomena in Polymer Films. In: CHEREMISINOFF, N. P. (ed.) *Handbook of Polymer Science and Technology*. New York and Basel: Marcel Dekker, Inc.
- CHATHAM, H. 1996. Oxygen Diffusion Barrier Properties of Transparent Oxide Coatings on Polymeric Substrates. *Surface and Coatings Technology*, 78, 1-9.
- COLLINS, R. E., FISCHER-CRIPPS, A. C. & TANG, J. Z. 1992. Transparent Evacuated Insulation. *Solar Energy*, 49, 333-350.
- CONTROLS, A. C. 2011. Desiccant Performance Data.
- COOK, E. 1971. The Flow of Energy in an Industrial Society. *Scientific American*, 225, 135.
- CUMMINGS, J. B., WITHERS, C. R., MOYER, N. A., FAIREY, P. W. & MCKENDRY, B. B. 1996. Uncontrolled Air Flow in Non-Residential Buildings. Florida Energy Solar Center.
- DA SILVA SOBRINHO, A. S. Transparent barrier coatings on PET by single- and dual-frequency PECVD. Society of vacuum coaters 41<sup>th</sup> annual Technical conference proceedings, 1998. 115-120.
- DALGLIESH, W. A. & SURRY, D. 2003. BLWT, CFD and HAM Modelling vs. the Real World: Bridging the Gaps with Full-scale Measurements. *Journal of Wind Engineering and Industrial Aerodynamics*, 91, 1651-1669.
- DE VOS, R., ROSBOTHAM, D. & DESCHAGHT, J. 1996. Open-Celled Polyurethane Foam Based Vacuum Panel Technology: A Fully Polyurethane Based Composite Technology for Vacuum Insulated Appliances. *Journal of Cellular Plastics*, 32, 470-484.
- DELLA PORTA, P. 1996. Gas Problem and Gettering in Sealed-off Vacuum Devices. *Vacuum*, 47, 771-777.
- DESMARAIS, G., DEROME, D. & FAZIO, P. 2000. Mapping of Air Leakage in Exterior Wall Assemblies. *Journal of Thermal Envelope and Building Science*, 24.
- DEY, C. J., SIMKO, T. M., COLLINS, R. E. & ZHANG, Q. C. 1998. Design and Validation of Guarded Hot Plate Instruments for Measuring Heat Flow Between Evacuated Plane-parallel Glass Surfaces. *Review of Scientific Instruments*, 69, 2939-2947.
- DOE, U. 2011. Meeting the Commercial Continuous Air Barrier Requirements for ASHRAE 90.1-2010 and the 2012 ICC IECC. U.S. Department of Energy.
- ECKERT, E. R. G. & DRAKE, J. R. M. 1987. *Analysis of Heat and Mass Transfer*, Hemisphere Publishing Corporation.
- EIA 2004. A Look at Residential Energy Consumption in 2001. Energy Information Administration.
- ELITFÖNSTER. 2011. *Elit Extreme 0.9* [Online]. Available: [http://www.elitfonster.se/Documents/Produktblad/Produktblad\\_Extreme.pdf](http://www.elitfonster.se/Documents/Produktblad/Produktblad_Extreme.pdf).
- EXNER, J. 1875. Sitzungber. d. Wien Akad.
- FEBY 2009. Kriteriejämförelse av Passivhus enligt PHI och FEBY. *Positioning Paper-Background on implementation of Passive House in Sweden*. LTH rapport

- FECHINE, G. J. M., RABELLO, M. S., SOUTO MAIOR, R. M. & CATALANI, L. H. 2004. Surface Characterization of Photodegraded Poly(ethylene terephthalate). The Effect of Ultraviolet Absorbers. *Polymer*, 45, 2303-2308.
- FELDMAN, D. 1989. Polymer Degradation. *Polymeric Building Materials*. London and New York.
- FINE, H. A. 1989. Advanced Evacuated Thermal Insulations: The State of the Art. *Journal of Building Physics*, 12, 183-208.
- FREDERICK, G. 2001. *Improved Edge Insulation for Vacuum Insulation Panels*. Great Britain patent application PCT/GB01/04309.
- FRICKE, J. Physical Aspects of Heat Transfer and the Development of Thermal Insulations. High Performance Thermal Insulations (HiPTI) – Vacuum Insulated Products (VIP), January 22 - 24 2001. 13-21.
- FRICKE, J. 2005. From Dewars to VIPs - One Century of Progress in Vacuum Insulation Technology. 7th International Vacuum Insulation Symposium: Bavarian Center for Applied Energy Research (ZAE Bayern).
- GEORGE, S. C. & THOMAS, S. 2001. Transport Phenomena Through Polymeric Systems. *Progress in Polymer Science*, 26, 985-1017.
- GHAZI WAKILI, K., STAHL, T. & BRUNNER, S. 2011. Effective Thermal Conductivity of a Staggered Double Layer of Vacuum Insulation Panels. *Energy and Buildings*, 43, 1241-1246.
- GLICKSMAN, L. R. 1991. Two-Dimensional Heat Transfer Effects on Vacuum and Reflective Insulations. *Journal of Building Physics*, 14, 281-294.
- GREASON, D. M. 1983. Calculated Versus Measured Thermal Resistances of Simulated Building Walls Incorporating Airspaces. *ASHRAE Transactions*.
- GRIFFITH, B. T. & ARASHTEH, D. Gas-filled Panels: A Thermally Improved Building Insulation. Thermal performance of the exterior envelopes of buildings V 7-10 December 1992 1992 Clear Water Beach, Florida. ASHRAE/DOE/BTECC, 1-13.
- GRIFFITH, B. T., ARASHTEH, D. & TÜRRLER, D. Gas-filled Panels: An Update on Applications in the Building Thermal Envelope. BETEC Fall Symposium, 14 November 1995 1995 Washington, District of Columbia, . 1-13.
- GTZ 2000. Natural Foam Blowing Agents: Sustainable Ozone- and Climate-Friendly Alternatives to HCFCs. In: HASSE, V. (ed.) *GTZ Proklima - a programme to save the ozone layer*. Proklima International.
- GUDUM, C. 2003. *Moisture Transport in Building Envelopes: Ventilation in Light Weight Outer Walls*. PhD, Technical University of Denmark.
- HANIKA, M. Simulation and Verification of Defect-Dominated Permeation Mechanisms in Multiple Structures of Inorganic and Polymeric Barrier Layers. Society of vacuum coaters 46<sup>th</sup> annual Technical conference proceedings, 2003. 592-599.
- HENS, H. S. L. C. 2002. Heat, Air and Moisture Transfer in Highly Insulated Building Envelopes (Hamtie). Hertfordshire: International Energy Agency Energy Conservation in Buildings and Community Systems Programme.
- HERRMANN, V. Insulated Glazing / Current Status of Technology. High Performance Thermal Insulation (HiPTI) – Vacuum Insulated Products (VIP), January 22–24 2001. 23-26.
- HÖGLUND, I., ELMROTH, A., LINDKVIST, H. & MATTSSON, B. 1969. Undersökning av luftlackning genom fasadelement (in Swedish). Stockholm: Department of Building Technology, Royal Institute of Technology.
- HUI. 2007. *A Modeling and Experimental Investigation of Coupled Heat, Air, Moisture and Pollutants Transport in Building Envelope Systems*. Ph. D., Syracuse University.
- IEA 2005a. Vacuum Insulation Panels - Study on VIP-components and Panels for Service Life Prediction of VIP in Building Applications (Subtask A). *IEA/ECBCS*.

- IEA 2005b. Vacuum Insulation Panels - System Development and Applications with VIP (Subtask B). In: ERB, M. (ed.) *IEA/ECBCS*.
- IEA 2010. Key World Energy Statistics. International Energy Agency.
- IPCC 2007. Summary for Policymakers. In: SOLOMON, S., D. QIN, M. M., CHEN, Z., MARQUIS, M., AVERYT, K. B., M. TIGNOR & MILLER, H. L. (eds.) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge.
- ISO 2006. ISO 9972:2006 Thermal Performance of Buildings - Determination of Air Permeability of Buildings - Fan Pressurization method. In: 1, C. I. T. S. (ed.). International Organization for Standardization.
- JAMIESON, E. H. H. & WINDLE, A. H. 1983. Structure and Oxygen-barrier Properties of Metallized Polymer Film. *Journal of Materials Science*, 18, 64-80.
- JANSSEN, A. 1998. *Reliable Control of Interstitial Condensation in Lightweight Roof Systems; Calculation and Assessment Methods*. PhD, Katholieke Universiteit Leuven
- KALAMEES, T. & KURNITSKI, J. Moisture Convection Performance on the Joint of External Wall and Attic floor - Laboratory Tests and Two-dimensional Simulation Model Validation. In: SEPPÄNEN, O. & SÄTERI, J., eds. *Clima 2007 Well Being Indoors*, 2007 Helsinki, Finland.
- KALAMEES, T. & VINHA, J. 2003. Hygrothermal Calculations and Laboratory Tests on Timber-framed Wall Structures. *Building and Environment*, 38, 689.
- KARAGIOZIS, A. N. 2001. Moisture Analysis and Condensation Control in Building Envelopes. In: TRECHSEL, H. R. (ed.) *Chapter 6: Advanced Numerical Models for Hygrothermal Research*. West Conshohocken, PA: ASTM International.
- KISTLER, S. S. & CALDWELL, A. G. 1934. Thermal Conductivity of Silica Aëroge. *Industrial & Engineering Chemistry*, 26, 658-662.
- KOSNY, J. & CHRISTIAN, J. E. 2001. Whole Wall Thermal Performance. Available: [http://www.ornl.gov/sci/roofs+walls/research/detailed\\_papers/Whole\\_Wall\\_Therm/index.html](http://www.ornl.gov/sci/roofs+walls/research/detailed_papers/Whole_Wall_Therm/index.html).
- KOSNY, J. & DESJARLAIS, A. O. 1994. Influence of Architectural Details on the Overall Thermal Performance of Residential Wall Systems. *Journal of Building Physics*, 18, 53-69.
- KOŚNY, J., YARBROUGH, D. W. & CHILDS, P. 2001. Couple Secrets about How Framing is Effecting the Thermal Performance of Wood and Steel-Framed Walls. [Accessed 20110928].
- KWON, J. S., JANG, C. H., JUNG, H. & SONG, T. H. 2010. Vacuum Maintenance in Vacuum Insulation Panels Exemplified with a Staggered Beam VIP. *Energy and Buildings*, 42, 590-597.
- LEVIN, P. 1991. *Building Technology and Air Flow Control in Housing*. Doctor, KTH The Royal Institute of Technology.
- LI, Q., RAO, J. & FAZIO, P. 2008. Development of HAM Tool for Building Envelope Analysis. *Building and Environment*, In Press, Corrected Proof.
- LI, Y. & HOLMBERG, S. 1994. General Flow and Thermal Boundary Conditions in Indoor Air Flow Simulation. *Building and Environment*, 29, 275-281.
- LSTIBUREK, J., PRESSNAIL, K. & TIMUSK, J. 2002. Evaluating the Air Pressure Response of Multizonal Buildings. *Journal of Thermal Envelope and Building Science*, 25, 299-319.
- LSTIBUREK, J. W. 2000. *Toward an Understanding and Prediction of Air Flow in Buildings*. PhD, U. of Toronto.
- LSTIBUREK, J. W., PRESSNAIL, K. & TIMUSK, J. 2000. Transient Interaction of Buildings with HVAC Systems - Updating the State of the Art. *Journal of Thermal Envelope and Building Science*, 24, 111-131.
- MATTSSON, B. 2005. A Sensitivity Analysis of Assumptions Regarding the Position of Leakages when Modelling Air Infiltration Through an Attic Floor. *7th Nordic Building Symposium*.

- Reykavik, Iceland: Div. of Building Technology, Department of Civil and Architectural Engineering / Royal Institute of Technology.
- MICHAEL, R. 1991. Fiber Glass for Use in Evacuated Thermal Insulations. *Journal of Building Physics*, 14, 195-210.
- MUSGRAVE, S. D. Finite Element Analysis Used to Model VIP Barrier Film Performance. 7<sup>th</sup> International Vacuum Insulation Symposium September 28-29 2005 Duebendorf, Switzerland. 99-104.
- NAHB, R. C. I. 2002. Accelerating the Adoption of Vacuum Insulation Technology in Home Construction, Renovation, and Remodeling.
- NEGULESCU, I. I. 1990. Polymeric Building Materials, by Dorel Feldman, Elsevier, London and New York, 1989, 575pp. Price: \$140.00. *Journal of Polymer Science Part C: Polymer Letters*, 28, 385-385.
- NYLUND, P. 1980. Infiltration and Ventilation. *BFR-D22*. Stockholm, Sweden: Swedish Council for Building Research.
- OJANEN, T. & KUMARAN, K. 1996. Effect of Exfiltration on the Hygrothermal Behaviour of a Residential Wall Assembly. *Journal of Building Physics*, 19, 215-227.
- ONYSKO, D. M. Air Tightness of Joints in Wall Sheathing as a Function of Lumber Drying. ICBEST, 2001 ON, Canada.
- ONYSKO, D. M. & JONES, S. K. 1989. Air Tightness of Wall Sheathing as a Function of Lumber Drying. *ASHRAE/DOE/BTECC/ CIBSE Conference. Thermal performance of the exterior envelopes of building IV*. Orlando, Fla.: ASHRAE.
- PAPADOPOULOS, A. M. 2005. State of the Art in Thermal Insulation Materials and Aims for Future Developments. *Energy and Buildings*, 37, 77-86.
- PERERA, E. & PARKINS, L. 1992. Airtightness of UK buildings: status and future possibilities. *Environmental Policy and Practice*, 2, 17.
- PERSILY, A. & AXLEY, J. 1990. Measuring Airflow Rates with Pulse Tracer Techniques. West Conshohocken, PA: ASTM International.
- PETERSON, F. 1982. On flow in Narrow Slots Applied to Infiltration. *Energy efficient domestic ventilation systems for achieving acceptable indoor air quality. 3rd AIC Conference*. London, UK.
- PETRIE, T. W., ATCHLEY, G., DESJARLAIS, A. O. & CHRISTIAN, J. E. 2000. Effect of Mechanical Fasteners and Gaps between Insulation Boards on Thermal Performance of Low-slope Roofs. *Journal of Thermal Envelope and Building Science*, 292-317.
- PLATTS, R. E. 1962. Nail Popping: Moisture is the Trouble-Maker. Canadian Builder.
- POTTER, I. N., JONES, T. J. & BOOTH, W. B. 1995. Air Leakage of Office Buildings. Building Services Research and Information Association.
- PROSKIW, G. 2001. Air Leakage Characteristics, Test Methods and Specifications for Large Buildings. Ottawa.
- PROSKIW, G. & ENG, P. 1997. Variations in Airtightness of Houses Constructed with Polyethylene and ADA Air Barrier Systems Over a Three-Year Period. *Journal of Building Physics*, 20, 278-296.
- PROSKIW, G. & PAREKH, A. 2001. A Proposed Test Procedure for Separating Exterior Envelope Air Leakage from Interior Partition Air Leakage. *Performance of Exterior Envelopes of Whole Buildings VIII: Integration of Building Envelopes*. Clearwater Beach, Florida, USA: ASTM.
- QIU, K. & HAGHIGHAT, F. Assessment of Impact of Building Envelope Porosity on Energy. Ninth International IBPSA Conference, August 15-18, 2005 2005 Montreal, Canada.
- REIM, M., KÖRNER, W., MANARA, J., KORDER, S., ARDUINI-SCHUSTER, M., EBERT, H. P. & FRICKE, J. 2005. Silica Aerogel Granulate Material for Thermal Insulation and Daylighting. *Solar Energy*, 79, 131-139.
- RIEBEEK, H. 2010. Global Warming. [Accessed 07112011].

- RODERICK, K., GLOVER, B. & SMITH, D. Applications of Vacuum Insulation Panels in Extrem Environments. 7th International Vacuum Insulation conference, 2005.
- ROELS, S., CARMELIET, J., HENS, H., ADAN, O., BROCKEN, H., CERNY, R., PAVLIK, Z., HALL, C., KUMARAN, K., PEL, L. & PLAGGE, R. 2004. Interlaboratory Comparison of Hygric Properties of Porous Building Materials. *Journal of Thermal Envelope and Building Science*, 27, 307-325.
- SAID, M. N. A., BROWN, W. C. & WALKER, A. I. S. 1997. Long-Term Field Monitoring of an EIFS Clad Wall. *Journal of Building Physics*, 20, 320-338.
- SANDBERG, P. I. & SIKANDER, E. 2004. Lufttäthetsfrågorna i byggprocessen – Kunskapsinventering, laboratorie- mätningar och simuleringar för att kartlägga behov av tekniska lösningar och utbildning. *Luftförelser i och kring konstruktion*.
- SCHULTZ, J. M., JENSEN, K. I. & KRISTIANSEN, F. H. 2005. Super Insulating Aerogel Glazing. *Solar Energy Materials and Solar Cells*, 89, 275-285.
- SHAW, C. Y. 1980. Methods for Conducting Small-scale Pressurization Tests and Air Leakage Data of Multi-storey Apartment Buildings. *ASHRAE Transactions*, 86, 241-250.
- SHERMAN, M. & DICKERHOFF, D. 1998. Air-tightness of U.S. dwellings. *ASHRAE Transactions*. ASHRAE.
- SHERMAN, M. H. & CHAN, R. 2004. Building Airtightness: Research and Practice. *LBNL report 53356*. Berkeley CA 94720: Lawrence Berkeley National Laboratory.
- SHERMAN, M. H. & MATSON, N. E. 2002. Air Tightness of New Houses in the U.S.: A Preliminary Report. *LBNL report 48671*. Lawrence Berkeley National Laboratory.
- SHERMAN, M. H. & WALKER, I. S. Modeling, Cavity, Component, XAX, CFD, Energy, Impact. Heat Recovery in Building Envelopes. ASHRAE/DOE/BTEC Thermal Performance of the Exterior Envelopes of Buildings VIII, 2001 Atlanta, GA. ASHRAE.
- SHETTY, S. K. 2007. *Development of Test Procedure to Measure Effects of Moist Air Flow on Thermal Performance of Wood Frame Walls*. MsC, Syracuse University.
- SIMMLER, H. & BRUNNER, S. 2005. Vacuum Insulation Panels for Building Application: Basic Properties, Aging Mechanisms and Service Life. *Energy and Buildings*, 37, 1122-1131.
- SIMONSON, C. J., OJANEN, T. & SALONVAARA, M. 2005. Moisture Performance of an Airtight, Vapor-permeable Building Envelope in a Cold Climate. *Journal of Thermal Envelope and Building Science*, 28, 205-226.
- SMITH, D. M., MASKARA, A. & BOES, U. 1998. Aerogel-based Thermal Insulation. *Journal of Non-Crystalline Solids*, 225, 254-259.
- SOLEIMANI DORCHEH, A. & ABBASI, M. H. 2008. Silica Aerogel; Synthesis, Properties and Characterization. *Journal of Materials Processing Technology*, 199, 10-26.
- STANNETT, V. 1978. The Transport of Gases in Synthetic Polymeric Membranes — An Historic Perspective. *Journal of Membrane Science*, 3, 97-115.
- STEFAN, J. 1878. Sitzungber. d. Wien Akad.
- TAO, W.-H., SUNG, W.-F. & LIN, J.-Y. 1997. Development of Vacuum Insulation Panel Systems. *Journal of Cellular Plastics*, 33, 545-556.
- TENPIERIK, M. J., CAUBERG, J. J. M. & THORSELL, T. I. 2007. Integrating Vacuum Insulation Panels in Building Constructions: an Integral Perspective. *Construction Innovation*, 7, 38-52.
- THERMOS. 2011. *Our history* [Online]. Available: <http://www.thermos.com/history.aspx> [Accessed 17 October 2011].
- THORSELL, T. 2005a. Edge Loss Minimization in Vacuum Insulation Panels - Model Verification. *3rd International Building Physics Conference*. Montreal, Canada: A. A. Balkema Publishers.
- THORSELL, T. 2005b. Edge Loss Minimization in Vacuum Insulation Panels. *7th Nordic Building Symposium*. Reykavik, Iceland: Div. of Building Technology, Department of Civil and Architectural Engineering / Royal Institute of Technology.

- THORSELL, T. & BOMBERG, M. 2007. Hygrothermal Performance of Building Enclosures; Part 1: Thermal Bridges. *submitted to J. of Building Enclosure Design*.
- THORSELL, T. & BOMBERG, M. 2008a. Integrated Methodology for Evaluation of Energy Performance of Building Enclosures: Part II -- Examples of Application to Residential Walls. *Journal of Building Physics*, 32, 49-65.
- THORSELL, T. & BOMBERG, M. Integrated Methodology for Evaluation of Energy Performance of Building Enclosures; Part 2: Examples of application to residential walls. BEST 1: Building for Energy Efficiency and Durability at the Crossroads, June 10-12, 2008 2008b Minneapolis. Building Enclosure Council BEC-Minnesota.
- THORSELL, T. & BOMBERG, M. 2009. The Need for Evaluation of Energy Performance of Building Enclosures. *Healthy Buildings*. Syracuse, NY.
- THORSELL, T. & BOMBERG, M. 2011. Integrated Methodology for Evaluation of Energy Performance of the Building Enclosures: Part 3 – Uncertainty in thermal measurements. *Journal of Building Physics*, 35, 83 - 96.
- THORSELL, T. I. 2011. A Hybrid Model for Diffusion Through Barrier Films with Multiple Coatings. *Journal of Building Physics*, 35, 83-96.
- TORIKAI, A. 2000. Wavelength Sensitivity of Photodegradation of Polymers. In: HAMID, S. H. (ed.) *Handbook of Polymer Degradation*. New York and Basel: Marcel Dekker, Inc.
- TRUBIANO, F. 2011. Nano-Materials and Building Envelopes – ETFE + Aerogel. *Submitted to Journal of Building Physics*.
- UVSLOKK, S. 1996. The Importance of Wind Barriers for Insulated Timber Frame Constructions. *Journal of Building Physics*, 20, 40-62.
- VINHA, J. 2007. *Hygrothermal Performance of Timber-Framed External Walls in Finnish Climatic Conditions: A Method for Determining the Sufficient Water Vapour Resistance of the Interior Lining of a Wall Assembly*. Doctoral, TUT.
- VINHA, J. Analysis method to determine sufficient water vapour retarder for timber-framed walls. The 8th symposium on Building Physics in the Nordic Countries, , was arranged in June 16-18th 2008 Copenhagen, Denmark.
- WAHLGREN, P. 2007. Overview and Literature Survey of Natural and Forced Convection in Attic Insulation. *Journal of Building Physics*, 30, 351-370.
- WAKILI, K. G., BUNDI, R. & BINDER, B. 2004. Effective Thermal Conductivity of Vacuum Insulation Panels. *Building Research & Information*, 32, 293-299.
- WALKER, I. S. & WILSON, D. J. 1993. Evaluating Models for Superposition of Wind and Stack Effect in Air Infiltration. *Building and Environment*, 28, 201-210.
- WALKER, I. S., WILSON, D. J. & SHERMAN, M. H. 1997. A Comparison of the Power Law to Quadratic Formulations for Air Infiltration Calculations. *Energy and Buildings*, 293-299.
- WCED 1987. Our Common Future. The World Commission on Environment and Development.
- WEINLÄDER, H., EBERT, H.-P. & FRICKE, J. VIG - Vacuum Insulation Glass. 7th International Vacuum Insulations Symposium 2005 Zürich-Duebendorf, Switzerland.
- WIKIPEDIA. 2011. *Getter* [Online]. The Chemistry Encyclopedia. Available: <http://www.chemistrydaily.com/chemistry/Getter> [Accessed 19 Oktober 2011].
- WILKES, K. E. Dynamic Thermal Performance of Walls and Ceilings/Attics. Thermal Performance of the Exterior Envelopes of Buildings II: Proceedings of the ASHRAE/DOE Conference, 1982 Las Vegas, NV. ASHRAE, 436-455.
- ZOLLER, A. 1913. *Hohle glasschiebe*. 387655.

## Summary of included articles

Included are five already published journal articles and two conference papers produced over a period of 7 years. Below is first a short introduction to the papers followed by individual summaries.

Four publications (the two conference papers and two of the published articles) talk about aspects of Vacuum Insulation Panels (VIP) and their application in the built environment. This material was also included in my Licentiate thesis, which was defended in November 2006 at KTH. The two conference papers discuss an alternate design, a serpentine edge, proposed to improve thermal performance, the proposed design was, in the first paper (Thorsell, 2005b), evaluated by numerical modeling and expanded with laboratory testing in the second (Thorsell, 2005a). The first journal article (Tenpierik et al., 2007) was written in collaboration with colleagues from the IEA Annex 39 project, in which I was one of the participants, and discusses the possibilities and pitfalls of using vacuum panels integrated into buildings. In this article, I was responsible for the portion dealing with thermal performance of the VIP itself. The last article on the subject of VIP (Thorsell, 2011) deals with the diffusion of gas through multilayered metallized polymer films, which closely relates to performance and service lifetimes of VIPs.

The remaining three articles all report on a set of full-scale wall tests performed in a climate chamber at Syracuse University during 2007-2008. Four walls were tested according to a strict test protocol spanning almost 2 weeks per test. The protocol included heat, air and moisture loads as well as a drying period; initially the aim was to develop a performance indicator that more closely reflects the thermal performance of an assembly under service conditions, as well as produces data for validation of heat, air and moisture computer codes.

These tests, presented in a series of articles, were the first (Bomberg and Thorsell, 2008b) give background and validation to the test protocol and the measurement setup that was used. I am the second author for this article, because others did much exploratory work leading up to the test procedure before I became involved.

The second article (Thorsell and Bomberg, 2008a) in the series report on test results for two residential wall types as well comments on the thermal efficiency of the tested wall designs.

In the third article (Thorsell and Bomberg, 2011), the test results from the testing of two conceptually different industrial wall systems are presented and discussed in parallel with a discussion of errors and uncertainties encountered during this work.

## **Vacuum Insulation Panel (VIP)**

### Edge Loss Minimization in Vacuum Insulation Panels

*Thorsell, Thomas I. and Källebrink, Ingemar. Proceedings of the 7th Nordic Building Physics Symposium, IBRI / KTH, Reykjavik, Iceland, June 13-15, 2005, pp. 945-952.*

This paper is on the subject of Vacuum insulation panels (VIP). VIPs composed of a nano-porous core material enclosed by a gas barrier material designed to separate the internal parts of the panel from the surroundings. The gas in the core is evacuated to create a vacuum to suppress any gas convection or conduction. The result is a panel with very low thermal conductivity compromised only by a thermal bridge, which is created when the barrier material is wrapped around the edge of the panel. The center of panel thermal conductivity of  $0,004 \text{ W}/(\text{m}\cdot\text{K})$  is normal for this type of panel, but it depends on the level of vacuum and the type of core material (Caps and Fricke, 2000). The barrier itself needs to be gas tight to keep the low pressure inside the panel at the same time as

it creates a linear thermal bridge around all four edges, recognized by Glicksman (Glicksman R. 1991).

The gas enclosure is commonly produced of metallized polymer laminate films, metal foils, or combinations of these. Pure metallic foils provide a non-permeable enclosure, but the thermal bridge at the edges is large and compromises the overall thermal performance. With metallized foils, the thermal conductivity is lower and the thermal bridges are more limited, but the gas permeability, even though it is very low, limits the service life of the element beyond what is suitable for use in buildings. A thermal bridge in a thin layer can be dealt with in different ways. Steel studs as commonly used in Sweden can constitute a similar problem. The web of the steel stud breaks through the surrounding insulation layer, the thin metal-web leads the heat from warm to cold. One approach to lower heat loss in steel studs is to cut slots in the meta-web to prolong the distance the heat will have to travel from the warm side to the cold side. This paper will propose a similar technique to be applied to the edge of a VIP, a serpentine edge. This new edge design is evaluated and optimized numerically in COMSOL. It is shown that the thermal bridge can be limited in this way and therefore it should be possible to create hermetic enclosures with long service lifetime maintaining good thermal properties beyond what is needed for buildings.

## Edge Loss Minimization in Vacuum Insulation Panels – Model Verification.

*Thorsell, Thomas I.* Proceedings of the third international building physics conference, Concordia University, Canada, August 27-31, 2006, pp. 251-256

Vacuum insulation panels have, by design, a thermal bridge at each of the edges of the panel. This paper presents results from continued work on an edge design that reduces this effect. This serpentine edge was introduced in a previous paper. Results presented herein include numerical modeling as well as laboratory measurements on two different edge designs. It is shown that the serpentine edge has the potential to reduce the thermal bridge greatly compared to a traditional straight edge design. A serpentine edge could enable designs with metal foil or thin metal sheet barriers. Panels made with metal foil or sheet barriers, with its superior gas tightness, are likely to reach lifetimes of 50 years and more. They would also allow for core materials other than the commonly used fumed silica, for example glass fibers, or open cell polyurethane, even though most other materials require even lower inside pressure to reach desired super insulative properties. Fumed silica or aerogel that have pore-sizes in the nano-region might not need stainless steel barriers to reach technical lifetimes of several decades, but can still benefit from a sturdier shell. A welded stainless steel envelope helps to create a panel that will withstand handling and other loads in a construction much better than panels with polymer based barriers.

## A Hybrid Model for Diffusion through Barrier Films with Multiple Coatings

*Thorsell, Thomas.* *Journal of Building Physics* Volume 34 Issue 4, April 2011

*First published online November 18, 2010*

This article was written mainly in 2006 and it makes more sense to present it before the article on integration of VIP in building construction. It was submitted and accepted into the Nordic Journal of Building Physics in 2006, but was never published; instead it was resubmitted to Journal of Building Physics in 2010 and subsequently published in 2011.

The service lifetime of a VIP is directly linked to the amount and at what rate gas penetrates the panel enclosure, which in turn depends on type of barrier used. Therefore, in order to model and predict vacuum insulation panels life times it is necessary to model the diffusion through its barrier. The best barriers on the market today with reasonable thermal properties are composed of multiple

polymer layers with several aluminum coatings (metallization layers). In such films, it is accepted that the main part of diffusion takes place through defects in the coating layers. There are only a limited number of numerical models for this geometry with more than a single coating. This paper presents a hybrid model for gas permeation through film geometry with two or more coatings on polymer substrates. Numerical calculations are combined with analytical to create a model that does take individual defect sizes, as well as actual defect positions, into account. The defects in the metallization layers from a commercial VIP were statistically evaluated by microscopy, and the data was fed into the model with promising results.

## **Integrating Vacuum Insulation Panels in Building Constructions: An Integral Perspective**

*Tenpierik, Martin J., Cauberg, Johannes J.M., Thorsell, Thomas I. Construction Innovation: Information, Process, Management, 2007; vol. 7: pp. 38 – 53*

This article was written in collaboration with colleagues from the IEA annex 39 on vacuum insulation. My portion of writing was focused on the technical, primarily thermal, aspects of VIPs. The article is written to show the importance of applying an integral approach to designing building components and constructions, including vacuum insulation. Especially, two important interactions between performance requirements on complete building components, i.e. thermal insulation requirements, versus structural performance and thermal insulation requirements versus functional service life, was thoroughly investigated, since they can be considered of special interest for VIP integrated building components. Based upon this holistic view, a number of recommendations for designing such panels were derived.

In general, due to thermal bridging of high barrier films enveloping a VIP, and due to the importance of edge seams on the total envelope permeance for atmospheric gases, panels must be designed as large as practically possible with a ratio of surface area to panel perimeter length as high as possible. The thermal bridge effect can also be minimized by developing vacuum insulation panels without edge seams (seams along the surface), or by using an alternative edge design such as the serpentine edge discussed in earlier articles. A reduction of the envelope permeance, however, would require both a barrier film with a reduced permeation coefficient and a longer overlapping seam, which is contradictory to the aforementioned thermal performance requirement unless better low conducting, low permeance, barrier materials are developed. A similar contradiction exists for the type of barrier film chosen for a vacuum insulation panel. The best performing high barrier films are thick metal-based foils, therefore resulting in long expected functional service lives on the one hand, but in large energy losses through the panel edge due to the high thermal conductivity of these foils on the other hand. It is, therefore, necessary to find the optimal solution for each application regarding service life and thermal requirements.

Contradictory requirements exist, not only for thermal performance versus functional service life, but also for thermal performance versus structural performance. Edge spacer constructions, similar to multi-pane windows, do not impose requirements on the mechanical properties and behavior of vacuum insulation panels, and structural action is completely fulfilled by the edge spacer. However, the spacer needs to be designed accordingly, generally leading to high thermal edge losses. Although sandwich constructions have edge spacers to protect the VIP from external impact forces, these spacers however do not have a structural function, therefore, they can be thin in construction and can be based on low thermal conductivity materials. The application potential of sandwich components, however, stands or falls with the ability of attaching the component facings onto the VIP properly. Until now, this has been the limiting factor for a successful application of VIP integrated sandwich components. Another important contradictory effect is caused by a loss of vacuum inside the panel, resulting in an increase in thermal conductivity of a factor of

approximately 1 to 5, depending on the stage of aging. Structural safety is, however, not reduced, notwithstanding a decrease in flexion modulus of the VIP with a factor of approximately 1.7.

As a conclusion, an integral approach to the design of VIP integrated building components and constructions have the potential to generate design solutions that are optimal for a certain application.

### **Wall Component Performance**

This trio of articles report findings of a 2-year research project sponsored by an industrial consortium that aimed at developing a performance indicator that more closely reflects the thermal performance of an assembly under service conditions. In addition to the authors, several students participated in this work. The need for this work arose from several studies that reported significant differences between thermal resistances (R-value) of walls as measured in the laboratory as opposed to those measured in the field (Said et al., 1997, Brown et al., 1997).

### **Integrated Methodology for Evaluation of Energy Performance of the Building Enclosures - Part 1: Test Program Development**

*Bomberg, Mark and Thorsell, Thomas. Journal of Building Physics, July 2008; vol. 32: pp. 33-48.*

The first article of the series focuses on justification of the chosen test regimen. It promotes a transition from test methods based on hot boxes, guarded and calibrated hot box, into methods with local measurements combined with computer modeling. The major limitation of hot box methods is that the results are average values while with local measurements one can look at the whole component as well as study details.

The procedures that are used traditionally to define the thermal performance of, for example a wall, are typically based on averaging tests performed on dry materials without consideration of air and moisture movements. In other words, these tests represent arbitrary rating conditions because we know that the energy performance of materials and building assemblies are affected by moisture and air flows. It is believed that to improve their energy performance one must have a more precise means of evaluation of their field performance that would also include the consideration of air and moisture transfer conditions.

In the first part of this article, a background for the evaluation of thermal performance by traditional testing with calibrated boxes shows that use of these tests is limited. The average heat flow that they measure is sufficient to rate the wall assemblies, but insufficient to calculate its thermal performance under field conditions. To include the effect of climate in combination with varying defects on thermal performance one must use computer models that are capable of simultaneous calculations of heat, air, and moisture transfer. Effectively, to characterize energy performance of the building enclosure one must simultaneously use assembly testing and modeling, i.e., an integrated methodology.

The proposed procedure introduces a stepwise approach. Step 1 aims at determining the steady state R-value under standard reference conditions with no intended moisture or air flow. This step is used as a reference and benchmark for a wall with newly installed dry insulation. The outcome of this step allows us to compare the measured R-value with the current state-of-the art value, i.e., the so called 'clear wall R-value' as developed by the ORNL. This R-value will later be used as the basis for comparing changes in R-value that occur when air flows are introduced through the test wall (Step 2), or under hot and humid conditions (Step 3), or when drying of the wall after exposure to moisture (Step 4).

## Integrated Methodology for Evaluation of Energy Performance of Building Enclosures: Part II - Examples of Application to Residential Walls

*Thorsell, Thomas and Bomberg, Mark. Journal of Building Physics, July 2008; vol. 32: pp. 49-65*

In this study, the integrated testing and modeling methodology proposed in article 1 of the series was applied to a few selected residential walls to highlight the magnitude of air flow effects compared with steady-state thermal resistance without air flows.

The two wall systems are typical stud walls by US design, one with glass fiber insulation (GFI) filling the cavities, and the other one with prototype hydroscopic cellulose fiber insulation (CFI). In step 1 of the test, measured thermal resistance of the first wall was close to the nominal while for the wall with the experimental cellulose fiber elevated thermal resistance was shown, which required additional exploration. The same walls were tested once again after a period of storage in the lab space. In the second run of tests on the two walls, the R-value of the glass fiber wall was unchanged while the CFI wall showed a decrease in the thermal resistance of about 5%. This change warranted an extension of research into the stability of the thermal resistance in relation to the CFI wall.

It was shown by numerical calculation that the change in the measured thermal resistance could be explained by the CFI collecting moisture from the air, and increasing in temperature, thereby causing this instability. Adjusting the measured values according to results of the numerical simulation yielded measured thermal resistances in accordance with numerically calculated data, including thermal bridges; hence, one can measure the clear wall R-value for both wall types as defined by ASHRAE by the use of local measurements.

The conclusion is far more surprising - a short-term thermal resistance measurement using a calibrated hot box of hygroscopic systems may give an overrated R-value result. While we are familiar with the situation when movement of moisture towards the cold side of a material increased the apparent conductance of heat and reduced the thermal resistance, we are not familiar with the opposite situation. We have not seen any report on the situation when an air bypass brings moisture to the hygroscopic material and thereby reduces heat flux entering the wall.

Further on it is shown that the tested walls are both sensitive to air leakage and a reduction in thermal resistance was registered in the region of 14% for the GFI wall and 4% for the CFI wall with a standard leakage averaged across the wall; locally in the walls we measured much larger changes.

Currently in the Building Physics domain, there is insufficient capability to characterize the ingress of moisture carried by air or the capability of calculating moisture removal under simultaneous heat and airflows. To build confidence in the use of models we need to verify them by comparing with the experimental that are related to the rate of those processes versus time. More research in this area is urgently required.

In the meantime, it is proposed that an energy performance R-value indicator can be used that only includes two effects:

1. The effect of thermal bridges (framing correction).
2. The effect of standard airflow conditions on apparent R-value.

We also propose to use a concept of thermal insulation efficiency to reflect the reduction in thermal insulation performance.

## Integrated Methodology for Evaluation of Energy Performance of the Building Enclosures: part 3 – Uncertainty in Thermal Measurements

*Thorsell, Thomas and Bomberg, Mark. Accepted for publishing by Journal of Building Physics, 2011*

This article presents testing of full-scale light-gauge steel framed walls. One of them, called a multi-component (MC) wall was built with glass fiber insulation in a metal stud system with a metal facade. It was provided with a vapor retarder on the interior, and an air barrier that also functioned as a water resistive barrier was placed on the exterior of the wall. The second wall used an exterior panel system (PS). This wall did not have any insulation in the cavities but had 50 mm (2 in.) of closed cell foam in a cassettes lined with metal sheeting.

The differences between these two walls are in two areas:

- Electrical outlets and structural brackets or floor edge detailing most likely disrupts continuity of moisture control - The vapor retarder. In contrast, the metal skin of the PS wall functions as uninterrupted plane of moisture control.
- Thermal efficiency - The PS wall is efficient because a great effort was made to establish continuity in the exterior insulation. In contrast, the MC wall has continuity of the primary insulation layer disrupted by metal studs at every 400 mm (16 in.), which act as thermal shorts.

This article presents both results from numerical models and measurements performed on these metal frame walls that introduce additional sources of uncertainty in the experimental results. It is clear that the PS wall with its exterior insulation is less sensitive to imperfections. The thermal insulation efficiency of the insulation in the MS wall was only 53% including thermal bridges from framing and airflow due to a 50 Pa pressure across the wall while for the PS wall with a sealed exterior insulation the thermal insulation efficiency was 80%. We end with a discussion of the need for improvements to testing procedures for evaluation of energy performance of building enclosures.