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Assessment of Co-heating Test
A Practical Method to Evaluate the In-situ Heat Transfer Coefficient in Dwellings

Master's Thesis in the Master's Programme Structural Engineering and Building Technology

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Arrangement of equipment for the *Co-heating test method*.

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ABSTRACT

According to the National Board of Housing, Building and Planning in Sweden, a finished constructed building should be verified to ensure that the built performance fulfil the requirements set by *BBR*. For the transmission losses, only theoretical calculations are used as verification, as there are no standard methods used for practical measurements. This means that in reality when the building has been executed the theoretical value might not correspond with the actual in-situ performance, meaning that there is a gap between the theoretical value and the actual built performance. However, some few methods for measuring the built thermal performance exist but they have never been established since the research has not made sufficient progress. One of the methods that exist is the *Co-heating test*. Recently renewed interest regarding characterization of the energy performance of buildings has led to further research and development of the test methods, and it is also the driving force behind this study.

The purpose of this study was to assess the *Co-heating method* and examine the possibilities of measuring the built thermal performance of a building envelope by using the original *Co-heating method* as basis. The average heat transfer coefficient of a building was obtained and compared with a theoretical calculated value. The usability, the reliability and the future outlook of the method are the three different aspects that were focused on in this study. Practical measurements were performed on two test object as a part of the study. In addition to the *Co-heating test*, it was necessary to perform airtightness tests and thermographic tests on the objects in order to interpret and analyse the data.

The measurements and analyses conducted in this study showed that there is a promising potential for the test to be used in the future. However, the current status requires more research to eliminate some of the uncertainties associated with the test method, and also to be able to truly evaluate the potential in this test and the use of the test as a standard method.

Key words: Co-heating, average heat transfer coefficient, transmission-losses, infiltration-losses.

Utvärdering av Co-heating test
En praktisk metod för att utvärdera den verkliga värmeöverföringskoefficienten för en byggnad

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SAMMANFATTNING

Enligt Boverket byggregler bör en färdigställd byggnad verifieras för att kontrollera att den uppfyller de krav som finns i BBR. När en byggnad blivit färdigställd kan det också hända att det teoretiska värdet inte överensstämmer med det verkliga. Det finns därför ett intresse av att praktiskt kunna verifiera och kontrollera transmissionsförlusterna av en färdigställd byggnad. I dagens läge inte finns det dock inte några standardiserade metoder för att genomföra praktiska undersökningar av sådana mätningar, utan teoretiska beräkningar används. Det finns dock några få metoder för att mäta det praktiska värdet av en byggnads prestanda, varav en av dem är den så kallade *Co-heating metoden.* De praktiska mät-metoderna har emellertid aldrig fått något större genomslag, då intresse och forskning inom ämnet länge varit bristfälligt och inte nått några större framsteg. Nyligen har det dock väckts ett förnyat intresse gällande karakterisering av byggnaders energiprestanda, vilket har lett till ytterligare forskning och utvecklig inom ämnet, vilket också är drivkraften bakom denna studie.

Syftet med denna studie var att utvärdera *Co-heating metoden* samt att undersöka möjligheterna att praktiskt mäta värmeförlusten genom en byggnads klimatskal, genom att använda *Co-heating metoden* som utgångspunkt. Genom detta arbete kunde ett praktiskt värde för den genomsnittliga värmegenomgångskoefficienten erhållas för att sedan jämföras med ett teoretiskt beräknade värde. Användbarheten, tillförlitligheten och framtidsutsikterna är de tre aspekterna som varit i fokus för denna studie. Praktiska mätningar genomfördes på två testobjekt för att kunna utvärdera metoden. Förutom *Co-heating testet* utfördes även lufttäthetsprov och termografiska tester på objekten för att kunna tolka och utvärdera *Co-heating metoden.*

De mätningar och analyser som genomförts i denna rapport visade att det finns en lovande potential för att testet skall kunna användas i framtiden. Dock krävs det ytterligare forskning och tester för att kunna handskas med de utmaningar som testet innebär samt för att eliminera de osäkerheter som är förknippade med metoden.

Nyckelord: Genomsnittlig värmegeomgångskoefficient, transmissionsförluster, infiltrationsförluster.

Contents

Preface

This is a master thesis conducted during the spring of 2015, written for the master programme *Structural Engineering and Building Technology* at *Chalmers University of Technology*. The thesis was written as a collaboration between *NCC Construction Sweden AB* and *Chalmers University of Technology, Department of Civil and Environmental Engineering* at the *Division of Building Technology*.

The idea for this master thesis was developed by Angela Sasic Kalagasidis, *Associate Professor* at the *Divison of Building Technology*, research group *Building Physics* at *Chalmers University of Technology.* She has also been our supervisor from *Chalmers*, and we want to express our gratitude for her valuable guidance and helpful advices during the period we have worked with the master thesis.

Martin Sandberg, *Specialist Manager* at *NCC Construction AB, Sustainability Department*, has been our supervisor representing NCC. Martin Sandberg and his colleagues at the *Sustainability department* have contributed with helpful discussions and good advice, their knowledge has been of great assistance. We truly appreciate the help we have received at *NCC*.

For this master thesis a lot of equipment has been needed in order to carry out the practical measurements made in the study. *Chalmers* has been very helpful with providing equipment that we have needed and *NCC* has been generous by lending us available equipment, many thanks for this. To help us with the equipment we have had support from Marek Machowski, technician at *the Division of Building Technology*. We appreciate his support and wish to acknowledge him for everything he has helped us with.

Peter Lindblom, lecturer at *Chalmers University of Technology*, and *Eksta Bostads* made it possible for us to perform this master thesis by providing premises where we could conduct the practical measurements, this we are very grateful for. We also want to assign a special thanks to Niklas Christensson, *Energy controller* at *Eksta Bostads* who has helped us with equipment and measurement data for the test building in Vallda Heberg.

We also want to express our gratitude to our opponents Anna Göransson and Susann Götharson and to all the other people who have been involved during the process of this thesis. Finally, thanks to our families and friends for their support and encouragement.

Gothenburg, June 2015

Emma Brycke
Jannicke Nilssen

Notations

Roman upper case letters

A	Area, $[\mathrm{m}^2]$
A_{surf}	Enclosing area which is connected to the heated interior, $[\mathrm{m}^2]$
A_{sw}	Average solar aperture coefficient, $[\mathrm{m}^2]$
A_{temp}	Interior heated floor area, $[\mathrm{m}^2]$
$C_{p,a}$	Thermal heat capacity, [kJ/kg·K]
K_{tr}	Conductance for heat loss due to transmission, [W/K]
K_{inf}	Conductance for heat loss due to infiltration, [W/K]
Q	Stationary heat flow rate, [W]
$\dot{Q}$	Transient heat flow rate, [W]
Q_h	Stationary electric heating energy, [W]
Q_{heat}	Power supplied by heaters, [W]
Q_{inf}	Heat loss due to infiltration, [W]
Q_{latent}	Latent heat due to drying of moisture in the building, [W]
Q_{sky}	Radiative heat exchange from surfaces to sky, [W]
Q_{sun}	Solar gains through transparent surfaces, [W]
Q_{tra}	Heat loss due to transmission, [W]
$\dot{Q}_{\mathrm{inf}}$	Transient heat loss due to infiltration, [W]
$\dot{Q}_{tr}$	Transient heat loss due to transmission, [W]
R	Thermal resistance, $[\mathrm{m}^2\cdot\mathrm{K/W}]$
R_{se}	External surface resistance, $[\mathrm{m}^2\cdot\mathrm{K/W}]$
R_{si}	Internal surface resistance, $[\mathrm{m}^2\cdot\mathrm{K/W}]$
T	Temperature, [K]
T_e	External temperature, [°C]
T_i	Internal temperature, [°C]
U	Heat transfer coefficient, $[\mathrm{W/m}^2\cdot\mathrm{K}]$
U_m	Average heat transfer coefficient, $[\mathrm{W/m}^2\cdot\mathrm{K}]$
$U_{m,meas}$	Measured average heat transfer coefficient, $[\mathrm{W/m}^2\cdot\mathrm{K}]$
$U_{m,meas,corr}$	Corrected measured average heat transfer coefficient, $[\mathrm{W/m}^2\cdot\mathrm{K}]$

Roman lower case letters

d	Thickness of a material layer in a component, [m]
l	Length of thermal bridge, [m]
n	Airflow, [m^3/s]
n_{50}	Airflow at 50 Pascal, [m^3/s]
$n50$	Air changes per hour at 50 Pascal, [1/h]
$q50$	Airflow at 50 Pascal, [l/s·m^2 surface area]
q_{sw}	Global solar radiation, [W/m^2]
t	Temperature, [K]
$v50$	Airflow at 50 Pascal, [l/s]
$w50$	Airflow at 50 Pascal, [l/s·m^2 floor area]

Greek upper case letters

ΔT	Delta T, temperature difference, [K]
Σ	Sigma, summation, [-]

Greek lower case letters

λ	Lambda, heat conductivity of a material, [W/m·K]
ρ_a	Rho, density of air, [kg/m^3]
χ	Chi, heat transfer coefficient, point-shaped thermal bridge, [W/m·K]
ψ	Psi, heat transfer coefficient, line-shaped thermal bridge, [W/m·K]

Abbreviations

BBR	Boverket’s Building Regulations
BREEAM	Building Research Establishment Environment Assessment Method
DVUT	Design winter outdoor temperature
HLC	Heat loss coefficient
LEED	Leadership in Energy & Environmental Design
SCNH	Sweden's Centre for zero-energy buildings
VFT	Heat loss number (Värmeförlusttalet)

Glossary

Adiabatic surface
No heat transfer occurs through the boundary of the surface.

Blackbody
An ideal surface which absorbs all incident radiation regardless of wavelength and direction. It emits more energy than any other surface.

Building envelope
Includes all the building components that make up the shell of the building that separates the indoor and outdoor climate from each other. It is important that the building envelope is able to withstand various kinds of weather conditions.

Conduction
Heat transfer mechanism where the temperature difference is the driving force.

Convection
Heat transfer mechanism where difference in air pressure is the driving force.

Emissivity
The effectiveness of the surface of a material in emitting energy.

Heat transfer
Transmission of energy from one region to another as a result of a temperature difference between them. There are three modes of heat transfer: radiation, convection and conduction.

Heat transfer coefficient
A measure of the ability of an object to allow the flow of heat from its warmer surface through the object to its colder surface.

Homogeneous material
A material of uniform composition throughout, that cannot be mechanically separated into different materials. The material has the same properties at every point.

Infiltration
The unintentional or accidental leakage of outside air into a building, typically through cracks in the building envelope and through use of doors for passage. The mechanism is also called air leakage.

Inhomogeneous material
A material that is composed of several different materials than can be mechanically separated. The material has not the same properties at every point.

Irradiation
Is the process when an object is exposed to radiation from the sun.

Passive house
Buildings built after the passive house standard; higher indoor comfort, reduced energy use, and reduced emission of carbon dioxide, compared with normal standard.

Performance gap
The difference between the actual as-built performance and the predicted calculated performance.

Radiation
Heat transfer mechanism where heat is radiating from warmer surfaces to colder surfaces.

Steady state
Surrounding temperatures are stable for a long period of time.

Stratification
When the temperature of the air increases with the height as a result of the stack effect.

Stationary
When a parameter is independent on time.

Thermal bridge
A part of a construction with increased heat flow rate and decreased internal surface temperature compared with the rest of the construction. Occurs generally at junctions between building components, or where the building structure changes composition.

Thermal mass
A property of the mass of a building which enables it to store heat and provide inertia against temperature fluctuations.

Thermal pillow
The warm region just below foundation of a building with foundation of the type slab on ground.

Transient
When a parameter changes as a function of time.

Transmission
The heat that is transferred through solid structures, and is mainly caused by heat conduction in the building envelope materials.

1 Introduction

A building should be designed and constructed in a way that the environmental footprint is at its minimum. However, it is also important to make sure of that the building is able to maintain its main function and provide a satisfying indoor climate, at the same time as obtaining low energy consumption.

Boverket (National Board of Housing, Building and Planning) publishes the Swedish building code *BBR* (*Boverket's building regulations)* which contains mandatory provisions and general recommendations that needs to be followed when designing and constructing a building. *BBR* requires among others that a building should be designed so that the energy consumption should be limited by low heat losses, low cooling demands, efficient heat and cooling usage, and efficient electrical usage. *BBR* suggest the total heat loss to be most effectively decreased by reducing the transmission losses, the infiltration losses and the ventilation losses (Boverket, 2015).

According to the National Board of Housing, Building and Planning in Sweden, a finished constructed building should be verified to ensure that the built performance fulfil the requirements set by *BBR*. The verification is normally done through testing, measuring or inspection, depending on which property is to be verified. For the infiltration loss, this is usually done by performing a *Blower door test* or *Tracer gas decay*. However, for the transmission losses, only theoretical calculations are used for the verification since there are no standard methods used for practical measurements (Boverket, 2015). In reality when the building has been executed the theoretical value might not correspond with the actual in-situ performance.

Although there are currently no standard methods for measuring the in-situ transmission loss, there exist some few methods. However, they are not so prevalent and the research has not made sufficient progress for the tests to be introduced as standardize methods. One of the existing methods is the *Co-heating test*. The *Co-heating test* has actually existed since the late 70s. However, the need for such a test has not been so present before now (Bauwens & Roels, 2014). Recently renewed interest in the characterization of the energy performance of buildings has brought a revival. This has led to interest in further research and development of the *Co-heating test method*, and is also the driving force behind this study.

1.1 Purpose

The purpose of this degree work is to examine the possibilities of measuring the built thermal performance of a building envelope by using the original *Co-heating method* as basis. The usability, the reliability and the future outlook of the method are the three different aspects of this research, and the following questions are to be answered.

Usability

- What knowledge is required in order to perform the test?
- How manageable is the equipment used for the test?
- What are the economic aspects of the test?

Reliability

- What are the preferred conditions in order for the test result to be as reliable as possible?
- Is it possible to gain reasonable results from the test method?
- What are the known uncertainties with the test?

Future outlook

- What further research is recommended to make this method more reliable?
- Is it possible to use the test as a standard method in the building industry?

1.2 Method

In order to fulfil the purpose of this study, both theoretical approaches and practical methods were applied. Literature studies were carried out to achieve a better understanding of the standard *Co-heating tes*t and its procedures. These studies were based on previously released research papers concerning this subject. After reading and amassed knowledge of the original *Co-heating method* and its interrelated test methods, a more suitable and feasible method for this study was developed, based on the original test. The original test was adapted in order to be applicable to the test objects and due to the prevailing limitations. However, due to significant similarities the original *Co-heating test method* can still be evaluated.

Practical measurements were performed on two different buildings; a minor construction called *Friggebod* and a community building built after *passive house* standard. In the *Community building* the measurements were performed as two different test scenarios; one single room measurement, and one for the whole building. The measurements consisted of performing an adapted *Co-heating test* for both the *Friggebod* and the *Community building*. The *Co-heating test* was performed one time in the *Friggebod*, and twice in the *Community building*.

In order to interpret the results from the *Co-heating test*, execution of *Blower door tests* and thermographic imaging was done in addition. The *Blower door tests* were done to be able to separate the transmission losses from the air infiltration losses and the thermographic tests were performed in order to find possible poor performance of the building envelope.

After the measurements, the collected data was processed and analysed in the computer software programmes *MathWorks Matlab* and *Microsoft Excel*, in order to find a practical value for the average heat transfer coefficient, U_m.

For the theoretical studies, the *U-values* and the thermal bridges was calculated and simulated according to associated *ISO International Standards.* When the thermal bridges and the *U-values* for the different building parts were obtained, a theoretical U_m was calculated according to *SS-EN ISO 13789:2007* (Swedish Standards Institute, 2008).

The average U-value for the *Community building* had already been calculated by *NCC*, as these calculations were done in conjunction with the design process of the building. However, the U_m*-value* that *NCC* has projected is a value which is based on an approximate value for the thermal bridges; an increase of the U_m*-value* by 20 %. Therefore more detailed calculations of the thermal bridges were done for the *Community building* also.

Finally, a comparison between the practical and theoretical result was done, and the usability, reliability and the future outlook of the method was evaluated based on the findings.

1.3 Scope and limitations

This study is based on practical and theoretical results. Measurements are performed on two objects; one minor construction and a passive building.

The two test objects where measurements take place are chosen due to their relevance for the study and their accessibility during the period of this study. The two buildings differ from each other with regard to size, shape and construction and they are located in different environments. The test is not performed on more than two test objects due to time and access limitations.

The measurements that are performed are based on the original *Co-heating test*. The original method has been adapted based on the two test objects and the prevailing limitations. In order to understand and interpret the average heat transfer coefficient of the building, *Blower door tests* and thermographic tests are done as well.

2 Environmental Initiatives

The awareness regarding the global warming has during the recent years increased significantly. This has resulted in more attention concerning a sustainable development for the future. Today the building sector is responsible for 40% of the total energy consumption in Sweden, and about 50% of the total electricity use in Sweden. More than 60% of the total energy consumption in the sector is used for room heating and hot water (Statens energimyndighet, 2012). The building industry is thus one of the most important pieces to reduce greenhouse gas emissions today.

2.1 International goals for the future

To cope with the climate changes that the world is facing today, the *EU commission* have taken action to limit the changes to a manageable level. Different goals for the future have been proposed by the commission and approved by *EU* leaders, resulting in a set of binding legislation (European Comission, 2015). The first goal to be set was *The 2020 climate and energy package*, where the key objective for 2020 is a 20% reduction in *EU greenhouse gas emission* compared to 1990 levels (European Commission, 2014). The next goal introduced was the *Roadmap for moving to a low-carbon economy in 2050*. The roadmap suggests that by 2050, the *EU* should cut its emission by 80% compared to 1990 levels through domestic reductions alone (European Commission, 2014). The most recent goal presented was *The 2030 framework for climate and energy policies*, where the binding target is to reduce *EU domestic greenhouse gas emissions* by at least 40% compared to the 1990 level by 2030 (European Commission, 2015).

Building regulations in Sweden are strongly influenced by the *EU*. Sweden is committed to implement the *EU Directives* into its legislations. This means that the legislations need to be changed so that it will correspond to the purpose of the directives. The future depends on energy efficient buildings to be able to reduce the emission gases. As a result of the policy developed by *EU* and as an action towards a more sustainable future, Sweden has among many other countries introduced stricter building requirements to ensure reduced emissions in the future (Boverket; National Board of Housing, Building and Planning, 2014).

2.2 Certification systems

In addition to the laws and regulations, there also exist a number of certification systems worldwide. The most commonly used systems in Sweden are *Miljöbyggnad*, *BREEAM*, *Green Building* and *LEED*. An energy certification system is an optional arrangement that provides an assessment of how environmentally sustainable a building is (Sweden Green Building Counsil, 2014). There are many benefits with certifying a building, and it is going to be more and more common in the future with the growing environmental awareness. By using an energy certification system the building will automatically achieve a quality assurance, which will increase the marketability, the asset values, and the attractiveness for tenants and buyers. Energy certification system is also a good way for companies to profile themselves in a positive way (Wallbaum, 2014).

3 Fundamental Theory of Thermal Performance

The properties of a building and the physical processes that occur in the building, together with the construction and composition of materials of the building envelope, are significant factors for determining the performance of the building. Knowledge about these factors is essential to be able to construct a durable and energy efficient building. It is also essential for understanding the theory of the thermal performance of a building, which in turn enables a better understanding of how to interpret and analyse the *Co-heating method*.

3.1 Heat transfer mechanisms

Heat transfer is a physical phenomenon that is important to have knowledge about when designing building constructions as well as for maintenance of a building. The heat transfer can occur in different forms and can be divided into three main groups (Petersson, 2009):

- **Radiation**- The driving force is the temperature difference. Heat is transferred from warm surfaces to cold surfaces (Petersson, 2009).
- **Convection**- This heat transfer mechanism occurs due to air pressure differences (Petersson, 2009).
- **Conduction**- The driving force for this mechanism is the differences in temperature. Heat is transferred from warmer to colder parts in homogeneous materials (Petersson, 2009).

3.1.1 Radiation

When radiation occurs, heat is radiating from warmer surfaces to colder. Radiation affects the temperature, the moisture condition and the heat balance. Radiation can be divided into three parts, one part that is transmitted through the material, another part is absorbed and a third that is reflected.

The radiation from a material is depending on the properties of the material (Petersson, 2009). A perfect so called blackbody surface absorbs all incident radiation regardless of wavelength and direction, and emits more energy than any other material (Hagentoft, 2001).

Night radiation
During cold and clear nights the sky radiates with a much colder temperature then the temperature of the air itself. As a result, the surfaces of buildings get a lower temperature than the air (Petersson, 2009).

The night radiation also affects the relative humidity due to strong connection between temperature and the moisture content in the air. Condensation may occur due to lower surface temperatures and higher relative humidity caused by the night radiation (Petersson, 2009).

Solar radiation

The solar radiation has great impact on the heat balance in buildings. If a building consists of a large amount of windows the solar radiation can have a large influence on the indoor temperature, especially if there are a lot of south facing windows (Petersson, 2009).

3.1.2 Convection

Convection is a phenomenon that occurs due to heat transfer between a surface of a material and surrounding air, and which in turn is transferred to other places (Petersson, 2009).

Two different types of convection can occur. The first one is *natural convection*, which occurs due to differences in density caused by differences in temperature. The second one is *forced convection*, which can occur due to external parameters such as a mechanical fan or the wind (Hagentoft, 2001).

3.1.3 Conduction

Through a homogeneous material heat is transferred by conduction, heat is transported from warmer to colder parts of the material. The heat transfer capability depends on the properties of the material as well as the temperature difference. The thickness of the material has also an influence (Petersson, 2009).

The heat transfer capacity may be denoted as λ [W/m·K], and varies for a material depending on the temperature and content of moisture. For example for walls and floors, it is also important to take into account the heat conduction of the surfaces in order to get a proper result of the heat conduction.

3.2 Thermal bridges

A thermal bridge is a phenomenon that can occur where different building parts connect or in a building structure where different materials meet (Hagentoft, 2001).

The thermal bridges can perform as point-shaped or line-shaped. A point-shaped thermal bridge may for example be concrete columns penetrating an insulating layer and a line-shaped one can appear along a connection between two components (Hagentoft, 2001).

The consequences of a thermal bridge can be decreased surface temperatures, increased heat loss, reduced comfort, and surface condensation (Hagentoft, 2001).

3.3 Thermal pillow

When a building is built with foundation of the type slab on ground, heat is transmitted through the ground plate and further down in the soil. Below the building a so called thermal pillow is created. This pillow consists of a warm area below the floor slab caused by the heat loss from the building. The warm area decreases with the distance from the house (Hagentoft, 2001).

3.4 Thermal mass

The thermal mass affects the heat capacity of a building which in turn influences the heat balance. The weight and performance of the materials in a construction decides the ability to store heat. A heavy building has a large capacity to store heat while a lightweight building has poor capacity to store heat (Petersson, 2009).

The heavy weight building’s ability to store heat reduces the influences of a fluctuating outdoor condition and by that the indoor temperature becomes more stable. The stored heat can be utilized when the outdoor temperature is lowered (Petersson, 2009).

Lightweight buildings are more influenced by the outdoor temperature variations and in order to fulfil the requirements for comfort, cooling and heating are needed in a higher degree than for heavy buildings (Petersson, 2009).

3.5 The stack effect

Stack effect is a phenomenon that occurs due to density differences in the air on account of temperature differences between the indoor and outdoor air.

First looking into the phenomenon that takes place inside the building. Warm air has lower density than cold air, therefore the colder air drops to the ground due to gravity, while the warmer air rises. The result of this will be a temperature gradient within the building; the temperature increases with the height (SINTEF Byggforsk, 1994).

Then looking at the building in connection to the outside air. The density differences between inside air and outside air makes the warm air inside the building press against the roof and upper part of the walls, while the cold outdoor air will try to press from the outside towards the walls at the lower part of the building (Hagentoft, 2001).

The stack effect phenomenon enables movements of air in a room. When cold air enters a room either by supply air terminals or through natural leakage paths due to the pressure from the outside air, the air heats up and then rises (SINTEF Byggforsk, 1994); (Abel & Elmroth, 2012).

3.6 Importance of construction work

A factor that is crucial in order to achieve a well-functioning building is the construction work. Poorly executed work can result in adverse construction defects which may, if fortunate, be inconsequential, but in worst case highly destructive. These defects may result in major economic losses, poor indoor quality or high energy losses (Josephson, 1994).

The reason for poor construction work may be economics, lack of time, lack of experience or other unexpected circumstances (Josephson, 1994). It can also occur due to deficiencies in the materials or lack of communication (CIB, 1993).

A common spot for failure is in the building envelope and its associated parts, such as roof, walls, windows and doors. Defects in the building envelope are shown to have a large impact on the stability of the building as well as the duration and maintenance (Bonshor & Harrison, 1982). Particularly prone to building failure is the connection details between the building components. However, an increased heat transmission due to poor thermal bridges can be avoided by a careful design, as well as detailed and accurate construction work (Johansson, et al., 2005).

4 Methodology of the Co-heating Method

Few methods exist for testing the in-situ heat loss of a building. The performance of a building is usually based on the designed value. However, the so called *Co-heating test* is one of the methods that have been developed to identify the actual in-situ heat loss of a building (Bauwens & Roels, 2014).

In order to test and evaluate the *Co-heating test* in this study, the method has been adapted with regard to current limitations. However, the purpose of the adapted test, is as well as for the original, to perceive a heat loss factor for a studied building.

In this chapter a review of the standard test as well as a description of the adapted test is presented.

4.1 Application and purpose of performing a Co-heating test

Used with other measurement techniques, the *Co-heating test* can be used as a building diagnostic tool. By using infrared thermal camera, heat flux surveys, and airtightness tests in addition to the *Co-heating test*, the performance gap between expected and measured heat loss can more easily be identified (Butler & Dengel, 2013).

In the recent past, the *Co-heating test* has primarily been used to assess the thermal performance of a building, but there are several other investigations that can be carried out by performing the *Co-heating test*.

The *Co-heating test* can be used for quality assurance of new buildings. By performing such a test, the users of the building may be guaranteed that the building fulfils the expected qualities of standard (Butler & Dengel, 2013).

A *Co-heating test* can also become handy in a refurbishment project. The test can be performed after each renovation step, in that way the impact of each renovation step becomes more evident. In the end, it will also show the total impact of the whole refurbishment (Butler & Dengel, 2013).

4.2 The original Co-heating test

The *Co-heating test* has existed for several decades and is still in development. The following sections give an introduction to the original *Co-heating method*.

4.2.1 History of the original Co-heating test

Sonderegger and Modera have written the earliest dated publication found concerning the *Co-heating test method* (Sonderegger & Modera, 1979). The publication dates back to 1979 and was published in *Berkley, USA*. Since the dawn of the *Co-heating test* further development of the test has been performed during the years, and conclusions can be drawn that there is a clear connection between the development of the test and the contemporary concerns in the society.

For those interested in earlier publications associated with the *Co-heating test*, reference is made to Appendix A.

The following section provides an overview of possible connections to the development of the test.

Awakening of the test

The 1970s energy crisis was a period when the petroleum shortage affected the economy in many industrial countries in the world. The worst crises in this period were the oil crises in 1973 and 1979. When the energy crisis and the increasing oil prices became a reality, the need to decrease the energy consumption and the quest for new alternative energy sources arose (Levin, 2014). It was during the energy crisis *Sonderegger and Modera* started the investigation of the *Co-heating method*, and the main purpose of their research paper was to find the efficiency of installed furnaces and fireplaces in dwellings by using the test (Sonderegger & Modera, 1979). However, already in their publication they also recommended the method for other application purposes. They proposed for example the test to be used for measuring the average heat loss coefficient, and if air infiltration measurements is planned to be carried out, the test can also be used to find the transmission loss through the building envelope (Sonderegger & Modera, 1979). During the period from 1979 and until the end of the 1980s numerous publications were released where the *Co-heating test method* was applied and further developed.

During the 1990s the oil consumption decreased drastically as new alternative energy sources made their appearances and more energy efficient ways to build were developed. The economy in the industrial countries began to stabilize, and the anxiety concerning energy conservation was decreasing (Levin, 2014). The use and development of the *Co-heating test* during this period was minor compared to the earlier years, and as it is knowledge about, there were few publications related to the test in this period.

Resurgence of interest in the test

In the last 10 years there has been awakened a new interest in the test and many new publications have been released, especially the last 5 years. The revitalization of the test can be explained by the growing attention regarding sustainable development that has arisen during the last decade. Actually, already in the early 1990s the Swedish political ambition was to become world leading within environmental and climate issues, an ambition that became very popular. However, it was not until many years later that the environmental aspect became influential (Levin, 2014).

4.2.2 Related test methods

Since the introduction of the *Co-heating test*, many new methods have been developed on the basis of the test, and can be categorized as ramifications of the original *Co-heating method*. These methods vary from the original *Co-heating method* with various degree of detail.

The list of ramifications is long, but some methods that are worth to mention are:

- *Princeton Scorekeeping Method (PRISM)* (Fels, 1986)
- *Short-term energy monitoring (STEM)* using the *primary and secondary terms analysis and renormalisation (PSTAR)* (Subbarao, et al., 1988)
- *Measured performance rating (MPR)* (Howard & Saunders, 1989)
- *Estimating building performance parameters* using *neural network* (NN) (Lundin, et al., 2004)
- *Quick measurements of energy efficiency of building (QUB)* (Mangematin, et al., 2012).

4.2.3 Performance of the test

The original *Co-heating test* involves heating the indoor environment of a building to a steady state temperature of about 25°C by using an electrical heater. A temperature difference of at least 10 ℃ is desirable. This to make sure that the majority of the heat flow through the building envelope during the test, is transferred from the inside to the outside (Johnston, et al., 2012). The time span of the measurement differs, but the most common duration is between 1-3 weeks. It is beneficial to use fans to distribute the heat evenly to achieve a uniform temperature gradient. It is important that all factors that potentially could interfere with the test result are removed from the site or shut down, while the test is in progress. In addition the building shall be unoccupied and all unintentional air leakage paths need to be sealed. Unintended air leakage paths can be windows, doors, ventilators, flues and siphons (Butler & Dengel, 2013).

During the test the indoor temperature and the external weather conditions shall be monitored. The outdoor air temperature and the solar radiation as well as the wind direction and its speed shall be measured (Bauwens & Roels, 2014). In addition, the electrical energy use from the electrical heater shall be monitored. Preferable is also to measure the indoor relative humidity (Johnston, et al., 2012).

The best conditions for measurements are when the difference in temperature between the inside and outside is as large as possible, i.e. winter conditions are most preferable. The benefit with testing in the winter is also reduced influence from the solar radiation, which is good since solar radiation can be challenging to cope with (Butler & Dengel, 2013).

When the data is collected, the overall heat loss will be found by plotting the mean daily input against the mean daily inside to outside temperature difference. The resulting slope of the curve gives the heat loss coefficient (Butler & Dengel, 2013).

The heat loss coefficient that can be gained by this test is a combination of the transmission losses and the infiltration losses. In order to separate these parameters to gain the average heat transfer coefficient, additional practical measurements has to be done, such as a *Blower door test* or a *Tracer gas test* (Bauwens & Roels, 2014).

For more detailed information about the procedure for the measurement see Appendix B.

4.2.4 Data processing methods

When investigating various papers published concerning the *Co-heating method* it can be concluded that the method for performing the practical part of the test is somewhat consistent. The data analysis method however varies to a large extent between the different publications, however the foundation of them is the same. The most common data processing methods used are the *simple* and *multiple linear regression analysis* on averaged data. Below a brief description of the basis of the data processing methods can be found.

The *Co-heating* test involves heating a building to a desired elevated temperature. When the desired temperature is achieved, the building is considered to be in a steady state condition as long as the desired temperature is maintained (Butler & Dengel, 2013). The pre-heating period before the building has reached a steady state condition, it is hereafter referred to as the *Co-heating* interval as illustrated in Figure 4.1. During this interval the building is heated up until it reaches a stable temperature. When the building is in balance the *Co-heating* period is over and the building is said to be in heat balance (Bauwens & Roels, 2014).

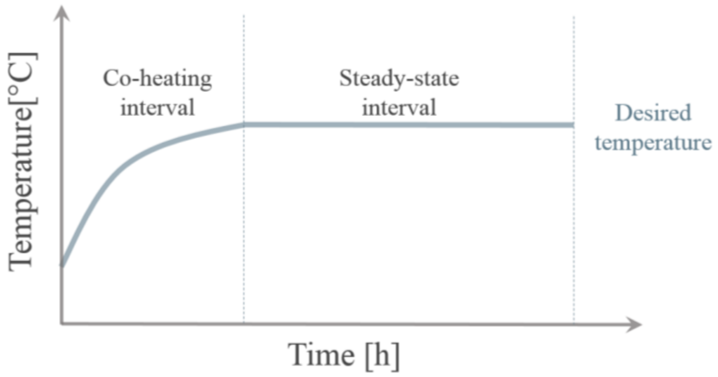

Figure 4.1 Illustration of the Co-heating interval.

By assuming a simplified stationary heat balance of a dwelling, following equation can be obtained (Bauwens & Roels, 2014):

$$Q_h = HLC \times \Delta T \tag{1}$$

Where the parameters can be explained as:

- Q_h the electric heating power in $[W]$
- HLC the overall heat loss coefficient in $[W/K]$
- ΔT the temperature difference between the outside and inside in $[K]$

This equation actually only describes a thermostatically controlled zone sheltered from outside weather conditions. In reality however, this is not the case. By investigating the building heat balance, a more comprehensive formula can be obtained (Bauwens & Roels, 2014).

When the building is in heat balance, the amount of energy going in to equals the amount of energy that going out of the building. During the *Co-heating test*, the balance equation can be expressed as following (Bauwens & Roels, 2014):

$$Q_{sun} + Q_{heat} = Q_{tra} + Q_{inf} + Q_{sky} + Q_{latent} \qquad (2)$$

Where the parameters can be explained as:

Q_{sun}	the solar gains through transparent surfaces in $[W]$
Q_{heat}	the power supplied by heaters in $[W]$
Q_{tra}	the transmission heat loss through the building envelope in $[W]$
Q_{inf}	the infiltration heat loss through the building envelope in $[W]$
Q_{sky}	the radiative heat exchange from surfaces to sky in $[W]$
Q_{latent}	the latent heat due to drying of moisture in the building in $[W]$

The heat loss and the heat gain terms in equation (2) needs first to be rewritten so that they become functions of the corresponding driving forces. Thereafter, major simplifications needs to be performed since aggregated *Co-heating* measurement data only allows for a stationary model of limited complexity to be identified. Finally, what is left is then this equation (Bauwens & Roels, 2014):

$$Q_h + ({A_{sw}}^* \times {q_{sw}}^*) = HLC \times (T_e - T_i) = HLC \times \Delta T \qquad (3)$$

Where the parameters can be explained as:

A_{sw}	the average solar aperture coefficient in $[m^2]$
q_{sw}	the global solar radiation in $[W/m^2]$
$T_e - T_i$	the temperature differences between the outside and inside.
sw	the direction of the solar radiation, south west
$*$	the solar radiation projection that is actually measured

Since the total heat loss coefficient constitutes both transmission loss and infiltration loss, either a *Blower door test* or a *Tracer gas test* has to be performed in order to separate the parameters. The air change rate is often assumed constant over the test period. After separating the transmission loss from the infiltration loss, equation (3) can be written as (Bauwens & Roels, 2014):

$$Q_h + ({A_{sw}}^* \times {q_{sw}}^*) = HLC \times \Delta T = (\sum AU + c_a G_a) \times \Delta T \qquad (4)$$

Where the parameters can be explained as:

$\sum AU$	the transmission heat loss in $[W/K]$
$c_a G_a$	the infiltration heat loss in $[W/K]$

The parameters in the equation above can be determined by applying linear regression analyses. The expression above can be rewritten into the equation below where c stands for the divergence between measured data and the *regression fit model* (Bauwens & Roels, 2014).

$$Q_h = HLC \times \Delta T - ({A_{sw}}^* \times {q_{sw}}^*) + c \qquad (5)$$

From this point there are different methods of how to treat the data. One method is to correct the heating energy for the solar gains by making an assumption for the solar aperture and then plot the result. Another method is to divide the equation above with ΔT and plot or by multiple regression study the $q_{sw} *$ as an independent parameter and plot (Bauwens & Roels, 2014).

For more information about how to handle and treat the data for the *Co-heating test* the following reports are recommended for further reading:

- *Review of Co-heating test methodologies* (Butler & Dengel, 2013)
- *Co-heating test-state-of-the-art and application challenges* (Bauwens & Roels, 2014)

4.2.5 Predicted expenses with the test

On account of the need of equipment, accessibility to the test object, and expenses due to labour, the *Co-heating test* entails a number of costs (Butler & Dengel, 2013).

In order to perform the test, the building needs to be unoccupied throughout the whole test period. This means that for a newly built dwelling the test is preferably performed before people move into the house. The rental or sale of the house is then likely to be delayed, which in turn results in reduced or delayed revenues (Butler & Dengel, 2013).

The measuring equipment that is to be used for the test has to be bought or be rented, which will create an expense. There will also be a cost for the work of mounting the equipment. Then there will be an additional cost for the work regarding removing the apparatus after the test. When the test is in progress, the electrical energy use for heating up the interior to an elevated temperature will be an expense (Butler & Dengel, 2013).

After the test, the data has to be analysed and processed. This requires manpower and will therefore result in an additional cost (Butler & Dengel, 2013).

4.2.6 Reliability and challenges with the test

There are several parameters that influence the measurements and it is important to consider them already before executing the test to ensure a measurement procedure which generates as reliable results as possible. Some of the parameters might be easy to cope with, while others might be more challenging and require more work and planning in order to be dealt with.

From previous research regarding the *Co-heating test* it has been found that it is hard to perform the measurements under steady state conditions. The weather is a parameter that has a significant influence of the result, as well as the properties of the building. Some of the most influencing and challenging factors that affect the reliability of the test is discussed more in detail below (Bauwens & Roels, 2014).

Solar radiation

For the *Co-heating test* it is desirable to reduce or avoid the solar radiation as far as possible. This is due to that the radiation increases the internal temperatures on account of transmission through windows as well as the storage in the building envelope. Particularly prone are well-insulated houses which have a lot of glazed areas towards south. The consequence from the sun might be a higher indoor temperature than the desired elevated temperature provided by the radiator. Additionally, since the solar radiation varies during the day, it is difficult to attain steady-state conditions, which diminish the accuracy of the test (Johnston, et al., 2012), (Butler & Dengel, 2013).

Shadowing of the windows is discussed as a solution, in order to reduce the effect of the solar radiation. This may require additional work, but it may be worth it since the influence of the sun decreases. However, this will not reduce the affect from the irradiation on the external walls (Butler & Dengel, 2013).

Another possibility for avoiding the influence of the sun is to perform the measurements during night-time. By that, the influences of the direct sun are eliminated. However, if the sun has been shining during the day it may still have some effects on the measurements due to the thermal capacity (Butler & Dengel, 2013).

The effect of the sun can also be reduced by choosing the time for the measurements over a period of the year when the solar radiation is reduced, this in order to reduce the dynamics of the thermal mass and the radiation through the windows (Bauwens & Roels, 2014).

Sky radiation

The sky radiation is an unmeasured parameter in the current *Co-heating* methodology. Research shows however that this parameter has a noticeable influence on the measured heat loss coefficient (Stamp, et al., 2011).

The sky radiation varies depending on which time of the year the test is performed, but also the weather on a day-to-day basis. Under ideal conditions the heat loss will be unaffected. However, with optimal conditions for sky radiation there will be an increase of the heat loss coefficient (Stamp, et al., 2011).

To reduce this factor a possibility is to measure the sky radiation locally during the time of measurement, and then extract the intervals with high radiation from the measurement data (Stamp, et al., 2011).

Wind speed
A variable wind speed is affecting the infiltration as well as the external surface resistance. It is relatively complex to take a varying wind speed into consideration (Stamp, et al., 2011).

If the wind direction and its speed are measured, it will be possible to extract the most deviant intervals from the measurement data here as well.

Thermal pillow
The heat loss through the ground is also a parameter that reduces the reliability of the test. However, the rate of uncertainty regarding the ground heat loss is depending on the ground material. Often the ground consists of a large thermal mass which has a slow temperature variation. In that case the circumstances are quite stable which promotes the processes to be stable and constant (Bauwens & Roels, 2014).

Temperature differences
In order to get appropriate results *LEEDS Metropolitan University* (Johnston, et al., 2012) mentions the importance of having a sufficient temperature difference between the internal and the external temperature, which is described as 10 ℃. Therefore it is not preferable to perform the measurements during the summer. This recommendation promotes also the issue regarding the solar radiation’s influence on the indoor temperature. During the summer time the sun is as most prominent, and by avoiding measurements during the warmest months the influences of the solar radiation will be minimized.

Drying
During the measurement period of the *Co-heating test* the internal temperature is kept at an elevated temperature, which is most likely higher than the normal condition for the building. If the materials in the building contain moisture, there is a risk for the elevated temperature to dry out the materials. This means that extra energy is used to dry out the building in addition to heating the building, which results in a higher total energy use. Therefore, it is important that the building is sufficiently dried out before performing the *Co-heating test* (Johnston, et al., 2012).

Another consequence of drying is shrinkage of materials, which will affect the air tightness of the building and result in an increased air leakage. Due to this concern, it is preferable to perform an infiltration test both before and after the test in order to detect a possible increase in airflow. In that case, this can be taken into consideration in the data processing methods. (Butler & Dengel, 2013).

4.3 Adapted method

To be able to perform a practical measurement of the averaged heat transfer coefficient with regard to current limitations, the original *Co-heating test* is adapted to a method which is considered as feasible for the specific test objects and the current limitations of this research. However, it will still be possible to evaluate the original method due to high grade of consistency.

4.3.1 Performance of adapted method

The measurement period for the adapted test is different for the different test objects in this study, on account of accessibility limitations for the objects. The measurement time is between 5 to 7 days, which means that it is in the lowest acceptable time range according to the original test. When logging the temperature and the electrical energy use the data is collected every hour. However, when analysing the result it turned out that a shorter time between the logging intervals is more desirable in order to get more reliable results, for example logging every 15 min.

The result from the original *Co-heating test* is presented as the heat loss coefficient, *HLC [W/K]*. In Sweden it is common to use the average heat transfer coefficient in order to evaluate the performance of a building. Therefore, it was chosen to present the result from the adapted method as an average heat transfer coefficient, U_m $[W/m^2 \cdot K]$.

Figure 4.2 Windows covered by reflecting material.

For the test object that is subjected to solar radiation, the windows will be covered, according to experiments done in earlier research paper concerning the original *Co-heating test* (Butler & Dengel, 2013). Otherwise, the preparations before the measurements can start are consistent for the original and the adapted method.

4.3.2 Processing of data

In this study a slightly different approach for the data processing has been chosen in comparison to other publication done regarding the *Co-heating test.* As described in Chapter 4.3.1 the parameter of interest is the average heat transfer coefficient, U_m. In the following section the mind-set of the data processing for the adapted test will be described.

The logged values for the energy consumption as well as the temperatures for indoor and outdoor environments are plotted in graphs, dependent on time. In the beginning of the measurement periods there is an interval referred to as *Co-heating.* The data from the *Co-heating* interval is excluded in the graphs since this is not interesting for this study, as taking the period into account when performing the processing of data would lead to incorrect results.

The plotted graphs are then studied and interesting intervals are chosen for further studies. Intervals that are seen as more interesting are mainly where there are as stable temperatures as possible, both internal and external. A minimized spread of the temperature within the building is also important.

For the interval of interest, the values are used for further calculations of the heat loss coefficient.

The overall heat loss coefficient can be obtained by transforming the following energy equation, with respect to *HLC*:

$$\dot{Q} = HLC \times \Delta T \tag{6}$$

$$HLC = \frac{\dot{Q}}{\Delta T} \tag{7}$$

Where the parameters can be described as:

$\dot{Q}$	the transient power in $[W]$
HLC	the heat loss transfer coefficient in $[W/K]$
ΔT	is the temperature difference between indoor and outdoor in $[K]$

The energy consumption $\dot{Q}$ in the expression above is a parameter which includes the energy consumption for both the infiltration loss and the transmission loss. Thereby the parameter HLC for this equation does not express the transmission loss solely, it also includes the infiltration loss. In order to get the transmission heat loss coefficient K_{tr}, the transmission loss has to be separated from the infiltration loss. The following formula shows the relationship between the parameter:

$$\dot{Q} = \dot{Q}_{tr} + \dot{Q}_{inf} \tag{8}$$

$$HLC = K_{tr} + K_{inf} \tag{9}$$

Where the parameters can be described as:

$\dot{Q}_{tr}$	the transient power due to transmission in [*W*]
$\dot{Q}_{inf}$	the transient power due to infiltration in [*W*]
K_{tr}	the transmission heat loss coefficient in [*W/K*]
K_{inf}	the infiltration heat loss coefficient in [*W/K*]

Thus, equation (7) can be rewritten to:

$$K_{tr} = \frac{\dot{Q} - \dot{Q}_{inf}}{\Delta T} \tag{10}$$

To be able to solve $\dot{Q}_{inf}$ the following equation needs to be solved:

$$\dot{Q}_{inf} = \dot{n} \times \rho \times c_p \times \Delta T \tag{11}$$

Where the parameters can be described as:

$\dot{n}$	the airflow in [m^3/s]
ρ	the density of air in [kg/m^3]
c_p	the specific heat capacity of air in [$kJ/kg{\cdot}K$]

By performing a *Blower door test* in addition to the *Co-heating test*, a value for the air flow at 50 Pascal can be obtained, n_{50} in [m^3/s]. This value can be used to estimate the air flow n, in [m^3/s] by the following empirical relation according to SS-EN ISO 13789:2007 (Swedish Standards Institute, 2008):

$$n = \frac{n_{50}}{20} \tag{12}$$

To obtain U_m, the following relation is used:

$$K_{tr} = U_m \times A_{surf} \tag{13}$$

The parameters can be described as:

U_m	the average heat transfer coefficient in [$W/m^2{\cdot}K$]
A_{surf}	the enclosing area which in connected to the heated interior in [m^2]

Then equation (10) can be rewritten as:

$$U_m \times A_{surf} = \frac{\dot{Q} - \dot{Q}_{inf}}{\Delta T} \tag{14}$$

By the above relationships the average heat loss transfer coefficient can be obtained, by rewrite the equation with regard to U_m:

$$U_m = \frac{\dot{Q} - \dot{Q}_{inf}}{A_{surf} \times \Delta T} \tag{15}$$

This U_m is a transient value, meaning that it varies with time. For this study a stationary value is desirable. On account of that the chosen intervals are somewhat stable, steady state conditions are assumed for the periods. Thus, a stationary value can be obtained by averaging a transient interval.

4.3.3 Measurement equipment

Different kinds of appliances can be used for increasing the indoor temperature, according to the original test. For this study the elevated indoor temperature is achieved by using an external electric radiator. The radiator has floor consoles which enables the radiator to stand on its own for optimal placement. The emitted temperature is regulated by a thermostat which is said to have an accuracy of 0.2 ℃ (LVI Clever heating, n.d.). For the *Friggebod* the radiator is the only heating device, but for the *Community building* the radiator is just used in a part of the building while the rest of the house is heated by the existing heating system. The choice of only using the radiator in a part of the house for the community building is based on the large amount of equipment needed otherwise, and as it is known an existing heating system have not been used before for this application, therefore it was of interest to perform such a test as well.

Figure 4.3 Electrical radiator with thermostat.

To be able to circulate the air a fan may be used. The fan used in this research has the ability to operate in three different levels, for the first level the power consumption is 30 W and for the highest 50 W.

Figure 4.4 Fan and temperature loggers.

In order to measure the internal and external temperatures as well as the internal relative humidity, temperature loggers are used. For this research there are two different types of loggers available, the first kind has an accuracy of ± 0.21 ℃ for temperatures between 0 ℃ and 50 ℃, and the relative humidity level has an accuracy of ± 2.5 % between 10 % and 90 % RH (Onset, HOBO Data Loggers, 2013-2014). The other type of logger has an accuracy of ± 0.35 ℃ between 0 ℃ and 50 ℃, and the relative humidity level has an accuracy level of ± 2.5 % between 10 % RH and 90 % RH (HOBO, n.d.).

During the measurement period the energy consumption is measured and logged by the use of an energy/power measurement appliance. The applied device can measure the energy consumption with correctness of three decimals where the accuracy is 1 % (EMU Electronic Ltd, n.d.).

Figure 4.5 Energy logger measuring the energy consumption.

The information above indicates there is a certain known accuracy for the different devises. However, due to the human factor or manufacturing defects these accuracy levels may sometimes differ between the actual measurement error and the possible intended measurement error. Therefore, it is preferable to conduct a sensitivity analysis regarding the impact of the different parameters in order to understand the importance of measuring the actual accuracy for the different parameters.

An overview of devices used in this study can be found in the table below.

Table 4.1 Data for measurement equipment used in this study.

	Device	**Accuracy**	**Price per unit**
Electrical heating	LVI Kaba P, 230 V, 500 W	±0.2 ℃	1162 SEK[1]
Energy/power meter	EMU Check USB with data logger	1 %	3927 SEK[2]
Temperature loggers	HOBO Temperature/RH/Light	±0.35 ℃ between 0 ℃ and 50 ℃	1177 SEK[3]
		± 2.5 % from 10 % RH to 90 %	
	HOBO Temp/ RH 2.5 % Data logger	±0.21 ℃ between 0 ℃ and 50 ℃	1050 SEK[4]
		± 2.5 % from 10 % RH to 90 %	
Fan	Honeywell HT- 116E, 230 V, 50 W	–	349 SEK[5]

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[1] Accessed: 2015-05-26 16.10 Bygghemma

[2] Accessed: 2015-05-26 16.12 ELFA DISTRELEC

[3] Accessed: 2015-05-26 16.15 Onset HOBO dataloggers

[4] Accessed: 2015-05-25 16.30 Onset HOBO dataloggers

[5] Accessed: 2015-05-26 16.08 Clas Ohlson

5 Support Measurements

The *Co-heating test* provides the total heat loss of a building. If it is of interest to identify the transmission loss and the infiltration loss separately, support measurements may be necessary. To extract the infiltration loss from the transmission loss *Blower door test* is one of the methods that can be used. In addition, infrared thermography may be used as a qualitative study to detect thermal defects on the building envelope. For more information regarding the methodology and the execution of the *Blower door test*, reference is made to Chapter 5.1 and Appendix C. The infrared thermography is further explained in Chapter 5.2 and Appendix D.

5.1 Methodology of air tightness test

A *Blower door test* is a diagnostic tool that can be used to survey the air leakage in a building after it is constructed (The Energy Conservatory, 2012).

Figure 5.1 Blower door test equipment

5.1.1 Application

Mainly the *Blower door test* is used to examine the airtightness of a building. However, the test has also several other possible applications. To summarize the potential fields of use (The Energy Conservatory, 2012):

- Documenting the construction airtightness of a building
- Estimating natural infiltration rates in a building
- Measuring and documenting the effectiveness of air sealing activities.
- Measuring duct leakage in forced air distribution systems

5.1.2 General

When performing a *Blower door test* the building is pressurized and/or depressurised with the outdoor pressure as reference. To achieve the desired pressure difference a powerful fan is temporarily installed into an exterior doorway, sucking air in or out of the building. The fan is equipped with a door panel to seal the door opening, and a gauge to monitor the results. The pressure difference that occurs will cause movement between the indoor and outdoor air by forcing air through holes and cracks in the building envelope. The air tightness is then measured by measuring the airflow through the fan needed to maintain the desired pressure difference in the building. The tighter the building envelope is, the less air is needed to maintain the desired pressure difference. During the test the ventilation system shall be shut down and all ventilation openings shall be sealed (The Energy Conservatory, 2012).

Figure 5.2 Arrangement of measurement equipment for the Blower door test.

5.1.3 Data processing method

The software used to analyse the *Blower door test* is the *TECTITE Express 3.1*. This software can be used to calculate and display airtightness test results from manually collected *Blower door test* data. It can also be used to perform an automatic test in combination with a gauge (The Energy Conservatory, 2012). When performing an automatic test, the software controls the speed, prompts for choice of ring, records both the building pressure and the fan airflow, and finally calculates and stores the test results (The Energy Conservatory, 2012).

When starting an automatic test a test procedure needs to be chosen; *one-point test* or *multi-point test.* The *one-point test* is a quick and simple way to measure the airtightness and can even be done without using the provided software. When performing a *multi-point test*, the building will be tested over a range of pressures. For every pressure target the software takes a number of samples that will be averaged. By using multiple measurement points, some of the errors caused by fluctuating pressures and operator error can be averaged out over several measurements, which will increase the accuracy (The Energy Conservatory, 2012).

5.1.4 Reliability and challenges

Initially, it can be said that it is important to study the manual before performing the test, since there are many details that needs to be taken into consideration when performing the test.

One of the main challenges with the test is to prepare the building sufficiently before executing of the test. There might be a risk that openings that should be sealed have not been closed properly, or openings might even have been overlooked etc. Mounting of the *Blower door system* can also be challenging, for example it is important that there is no gap between the doorframe and the aluminium frame which can be difficult to achieve.

The reliability of the test is strongly influenced by the wind. If there is a calm wind during the measurement, it can usually be expected an uncertainty of ±15 %. In quite windy surroundings on the other hand, the uncertainty may reach ±40% (SINTEF Byggforsk, 2012).

5.2 Methodology of infrared thermography

The infrared thermography describes the surface temperature of a construction or construction part, and can be used to localize the critical parts of a building envelope. The thermography is not able to provide a quantitative analysis of the building performance. However, it might be very helpful to use the infrared camera to make a qualitative study of a building (SINTEF Byggforsk, 2012).

5.2.1 Application

In this study the infrared camera will primarily be used as an extra tool to localize possible weaknesses on the building envelope, such as heat loss, thermal bridges and air leakages. Another application possibility of the camera is to study technical installations in a building, such as chilled ceilings, floor heating and electrical installations (SINTEF Byggforsk, 2012).

5.2.2 General

A thermal camera captures the intensity of the radiation from the infrared part of the electromagnetic spectra. This is basically not visible in the human vision, but the thermal camera however amplifies the radiation and converts it into a visible image. The thermography can be used to investigate the building from both the inside and the outside (FLIR Systems AB, 2012).

The test can preferably be performed in combination with an airtightness since the airtightness test will amplify the air leakage through the building envelope. When depressurizing the building the cold air will flow through cracks in the building envelope and the temperature difference will then be clearly visible in the thermal image as a cold area, which makes it easier to localize (FLIR Systems AB, 2012).

5.2.3 Reliability and challenges

There are many factors that can be challenging when using a thermal camera and which might affect the resulting image. To be able to anticipate errors and interpret the results correctly it is important to know these factors and how to deal with them.

Emissivity
The thermal camera has an emissivity setting that needs to be adjusted according to the object of interest. This setting is very important to set correctly before capturing an image to achieve right temperature specification on the image. However, it is possible to change the emissivity afterwards by using the recommended software (FLIR Systems AB, 2012).

Reflection
Reflecting surfaces might provide a misleading result of the thermal image due to reflection of thermal radiation. Such reflections can for example be caused by reflection of a human body, a furnace, light bulbs etc. It is therefore important to choose the right camera angle, to avoid these kinds of problems (FLIR Systems AB, 2012).

Temperatures
It is most beneficial to use the infrared camera when the temperature difference between the outdoor and indoor air is as large as possible. A temperature difference of at least 10°C is preferred when investigating for deficient insulation (FLIR Systems AB, 2012). However, when localizing air leakages it is sufficient with a temperature difference of 5°C (SINTEF Byggforsk, 2012).

External influences
Sun, rain and wind are all external factors that will affect the surface temperature of a building. Depending on the thermal inertia of the material of a building, this might have a large influence on the resulting thermal image from an inspection (FLIR Systems AB, 2012).

Heating and ventilation systems
The surrounding indoor temperature will affect the interior surface temperature and influence the temperature pattern on a thermal image to a large extent. Instability of the indoor temperature is typically caused by heating systems that create temperature gradients, and cold air streaming from air conditioning systems (FLIR Systems AB, 2012).

Internal influences
It is important to move furniture away from the area that is to be thermographed in a sufficient time ahead, due to the insulating effect of the furniture. It is recommended to move all furniture from the exterior wall at least 6 hours before the thermographic imaging (FLIR Systems AB, 2012).

Construction materials

There is a large difference in thermal inertia between different materials, depending on the properties of the material. Concrete for example has a much better heat storage capacity than metal, resulting in a slower temperature change. It is therefore important to be aware of whether there has been any major change in the temperature indoors before the inspection, as this may affect the temperature reading (FLIR Systems AB, 2012).

Construction method

Something that may appear to be a mistake on a thermal image might just be caused by the construction method of the building. For example an outer wall with an air gap between the façade cladding and the rest of the construction. Here the stud system in the wall will be colder and therefore visible in a thermal image. This is a common effect and should not be considered as a defect (FLIR Systems AB, 2012).

6 Methodology of Theoretical Calculations

In this study a theoretical value of the average heat transfer coefficient, U_m, for the two test objects is compared with practical measured values.

In order to calculate U_m the thermal bridges have to be taken into account. There are different ways to handle the thermal bridges. One way is to increase the average *U*-value by 20 %, in order to take the thermal bridges into account. Another way is to calculate the thermal bridges one by one and then add the sum of them to U_m (Boverket, 2012). The heat flows for point-shaped thermal bridges are usually so small that they can be neglected in an U_m calculation. The reason for this is that the heat flow is rather small in relation to other heat losses through the building envelope, such as in the line-shape thermal bridges (Boverket, 2012).

6.1 Application and purpose

In this study a relative accurate value for the theoretical average heat loss transfer coefficient is desired since the calculated value will be compared to a practical measured value. Therefore the average heat loss transfer coefficient for the two test objects have to be calculated with care and awareness of the included parameters.

6.2 General

The thermal bridges are calculated according to *SS-EN ISO 10211:2007* (Swedish Standards Institute, 2008) and with help of a manual provided by *NCC*, developed internally for the company. The *U-values* for the different building parts are calculated according to SS-EN ISO 6946:2007 (Swedish Standards Institute, 2008) for the walls and the roof, and SS-EN ISO 13370:2007 (Swedish Standards Institute, 2008) for the floor.

6.3 Procedure

The average heat loss transfer coefficient, U_m, can be calculated as shown below.

$$U_m = \frac{\sum K_i + \sum \Psi_k \times l_k + \sum \chi_j}{A_{surf}} \tag{16}$$

Where the parameters can be explained as the following:

U_m	the average heat loss transfer in $[W/m^2K]$
K_i	the conductance for each building part in $[W/K]$
Ψ_k	the conductance for a line shaped thermal bridge in $[W/m{\cdot}K]$
l_k	the length of a line-shaped thermal bridge in $[m]$
χ_j	the conductance of a point-shaped thermal bridge in $[W/K]$
A_{surf}	the enclosing area connected to the heated interior in $[m^2]$

6.4 Software

The thermal bridges for the buildings are simulated in the software products *BLOCON Heat2* and *Comsol Multiphysics*. In these programs the thermal bridges are sketched one by one with relevant surface resistances and material properties.

The *U-values* for the different building parts as well as the final U_m-value for the *Friggebod* and the *Community building* are calculated by hand calculations in *MathWorks Matlab*.

6.5 Reliability and challenges with the test

A challenge with calculating the *U-values* and the thermal bridges theoretically is how to model them similar to the reality. The calculations and the different building component structures are based on the drawings. However, in reality the built construction may deviate from the drawings.

Another challenge is to localize all the thermal bridges to be able to include them in the calculation for the average heat loss transfer coefficient.

7 Case Study of Community Building

This case study is performed on a community building situated in *Kungsbacka*. The building has an area of approximately 200 m^2 divided on two floors. The house can be considered to have two main parts; an apartment and a community facility. The apartment is situated on the ground floor and consists of one room and bathroom. Hereinafter, the apartment excluding the bathroom is referred to as the *Guest room*, and the whole building is referred to as the *Community building.* A visualization of these definitions are shown in Figure 7.2

Figure 7.1 Community Building in Vallda Heberg where measurements are performed.

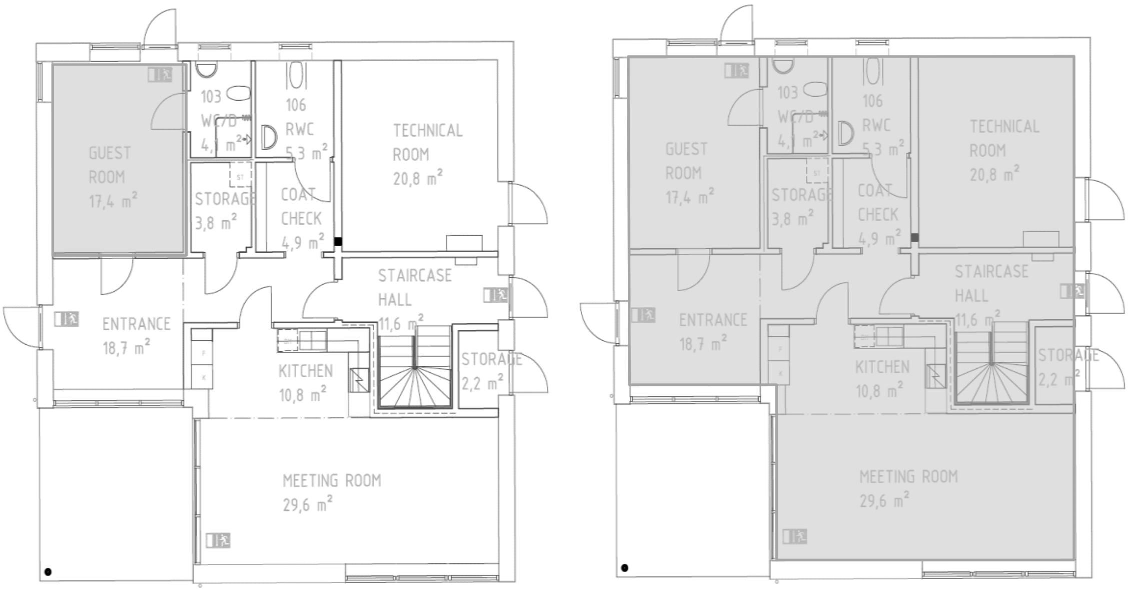

Figure 7.2 Definition of Guest room, and Community Building.

7.1 Background

The building is a community building and is as all other houses in the area, built after passive house technology and is conducted by *Eksta Bostads AB* and *NCC Construction Sweden.* The house is a rental facility for the residents in the neighbourhood (Eksta bostäder, n.d.).

The building was chosen for this study after a suggestion from *NCC. NCC* is well-familiar with this building since they have been responsible for both design and construction of this building.

The building is suitable for the test due to the possibility of renting the building for a longer period of time, which is necessary for performing this research. By renting a building it is possible to eliminate all internal loads which otherwise could have occurred if the measurement had been done in an inhabited dwelling. It is also possible to deactivate the ventilation in the building since human activities inside the building will not be present. Internal loads and activated ventilation would have disturbed the measurement results.

7.2 The passive house concept

As mentioned above, the *Community building* is constructed after Swedish passive house standard. What characterizes a passive house is high indoor comfort, low energy use, and reduced emissions of carbon dioxide (Sveriges centrum för nollenergihus, 2012).

The reason for calling it a *passive* house is due to the passive measures used for reducing the energy demand. The construction principles used for reducing the energy demands are listed below (Sveriges centrum för nollenergihus, 2012):

- Proper insulation
- Minimal air-leakages
- Minimal thermal bridges
- Well-insulated windows
- Proper orientation
- Proper shading
- Heat recovery unit

7.3 Construction

The external wall is built up from the outermost to the innermost layer; wooden façade cladding, insulating façade plate, cement bounded plate, composition of mineral wool and wooden studs, vapour barrier, composition again, and finally double gypsum boards. The wall is well insulated according to the passive house concept. Illustration of the wall is shown in Figure 7.3.

The roof of the house is divided into two parts. One side of the roof is covered by solar collectors and the other consists of a green roof. The structure of the roof is well insulated and containing a vapour barrier and wind protective layer. The construction is shown more in detail in Figure 7.3.

The floor is designed as a concrete floor on the ground with wooden flooring on the top. A thick layer of EPS is used as insulation. Detailed figure of the structure can be found in Figure 7.3.

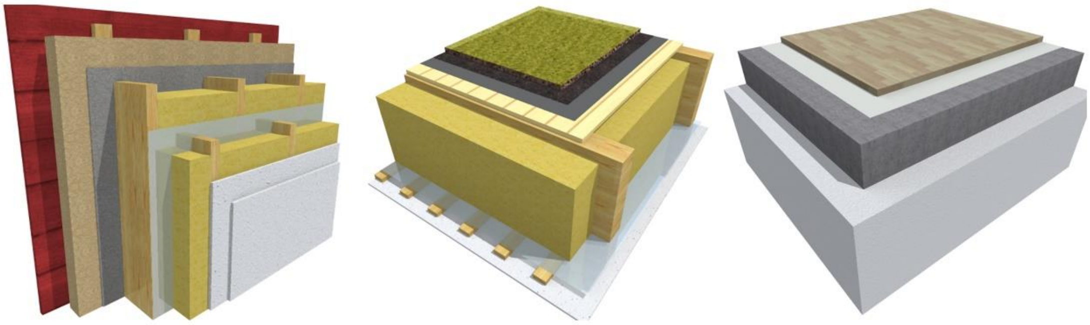

Figure 7.3 Detail of the wall, roof and floor, Community building.

The inner wall constructions differ depending on adjacent rooms. However, most of the walls are made of gypsum boards on wooden stud frames. Some walls are conducted with insulation due to fire classification and sound classification.

7.4 Co-heating test

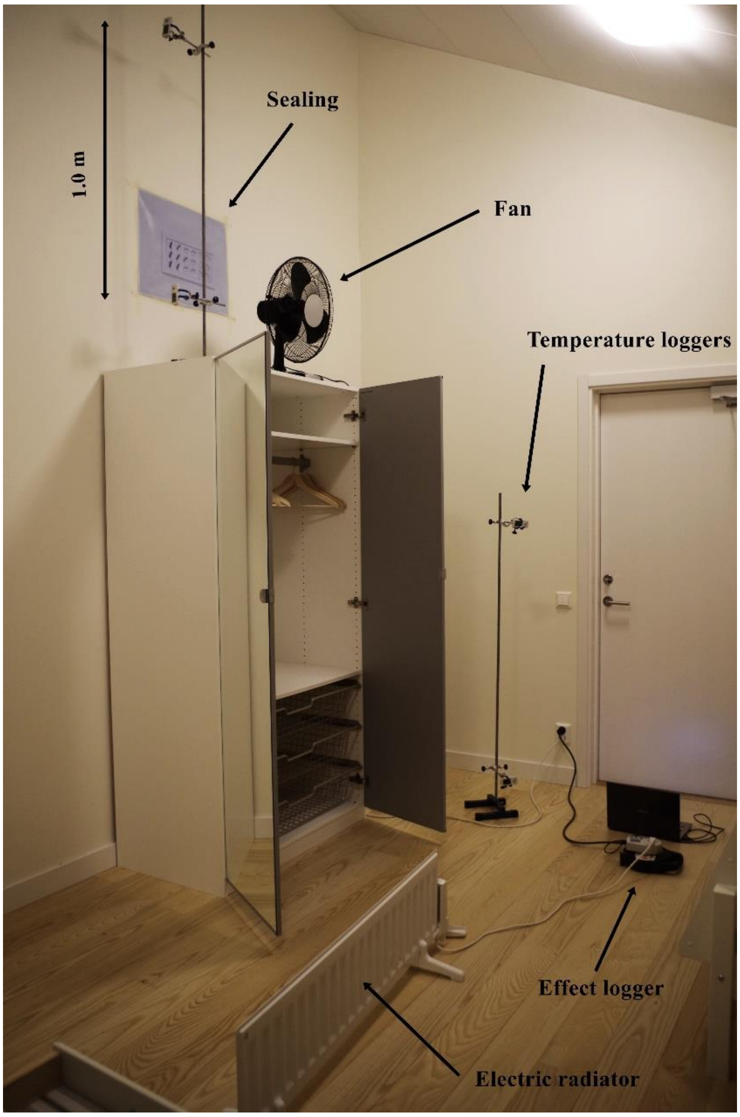

Figure 7.4 Measuring equipment for the Co-heating test, Community building.

The test object is large in scale and is larger than most normal family houses, which are the actual objects of interest for this test. After evaluating the required amount of equipment needed in order to conduct a standard *Co-heating test*, it was concluded that it would result in costs too high for the budget of this study. Therefore, it was decided to only perform the test on a part of the building; the *Guest room*. However, the community building is equipped with an existing energy/power measurement device that can be used to measure the total energy usage in the whole building. As it is known from earlier research papers, it has not been done any research regarding use of the existing heating system and monitoring device to perform a *Co-heating test*. It was therefore of interest to perform such a test in addition. If the existing heating system with an installed energy/power measurement device works just as well as using standalone electrical heaters the test would be both easier and cheaper to perform. Due to these considerations, two different kinds of tests were chosen to be carried out. The approaches are different but the purpose is the same.

For the *Community building* and the *Guest room* the test was conducted two times. This was done in order to get more test results and to reinforce a possible hypothesis. Test 1 lasted for approximately 5 days and test 2 for about 7 days.

Preparations

The preparations for the tests were done in accordance with the original *Co-heating test method*, which is more deeply described in Appendix B.

Briefly, the preparation that was made was to turn off the air communication with the outside. The ventilation system was deactivated and all the openings towards the outside were sealed by covering the vent openings by plastic sheets. The covering was done in order to minimise the ventilation losses, and to ensure that air could not leak through some of the unintended paths in the building. Flushing was done in the toilets, the showers and the sinks to ensure that they were filled with water. To make the air be spread freely and have access to every space, all cupboards and wardrobes doors were opened as well as all internal doors for all rooms. All internal gains were also turned off, such as fridge and freezer, this in order to minimise the internal heat sources. To minimise the influence of the solar radiation during the test all the windows were covered on the outside. For test 1 the windows were covered by foil and for test 2 the windows were covered by “potato chips bag” material.

Temperature sensors were distributed evenly in the building, mainly at a height of 1.5 meters above floor level, and typically in the centreline of a non-exterior wall. Rooms with a higher ceiling such as the 2nd floor and the kitchen were equipped with two levels of temperature loggers, this to be able to identify possible temperature gradients. This concerns the 2nd floor in test 1 and the kitchen one in test 2.

Since the measurements in the *Guest room* were done on a room level, a more accurate logging was desirable. Four temperature loggers were therefore placed at different levels in test 1, and at three different levels in test 2. The loggers where placed approximately in the middle of the room, mounted along a vertical line on tripods with equal distance between them, approximately 1m.

Execution of the test

The execution of the practical *Co-heating test* was done as mentioned earlier, by dividing the building into two parts, the *Guest room* and the *Community building*.

The *Guest room* was heated by an external radiator, which was connected to a power- and energy measurement appliance, provided with a data logger function for monitoring of the energy use during the measurement period. The existing radiator in the room was turned off during the measurements.

For the *Community building* the existing radiator system was used as heat source during the measurement periods. The power needed for the existing radiator in order to keep the elevated temperature, was registered as well by an existing logger in the building.

Many previous research papers state that it is beneficial to install fans in order to prevent stratification and to obtain a uniform temperature throughout the whole building. However, for the whole building it was chosen to not install fans, mainly due to economic reasons. For the test performed in the *Guest room* on the other hand, it was economically possible to install a fan since the smaller scale only required one. Because of the geometry of the *Guest room*; high ceiling with steep sloping, there is a risk of stratification and therefore it also seemed reasonable to install a fan.

During the measurements the energy consumption as well as the internal and external temperature were logged.

Additional investigations
The possibility to use a fan in the *Guest room* was utilized to investigate the influence of the fan during a test. The test was first started without the fan, then approximately halfway into the measurement period a fan was installed. For test 2, the fan was operating during the whole measurement period.

7.4.1 Theoretical result

For the *Community building*, the average U_m-value had already been calculated by *NCC*. However, the thermal bridges were taken into account by increasing the average U_m- value by 20 %. Due to this it was decided to calculate a more accurate theoretical value.

For a better overview of the thermal bridges calculated in *Comsol* and *Heat2*, reference is made to Appendix E and Appendix F. Appendix E for the *Community building and* Appendix F for the *Guest room.*

The following tables show the results of the theoretical calculations performed. Table 7.1 and Table 7.3 show the areas and the *U-values* for the different building components, for the *Community building* and the *Guest room*, respectively. Table 7.2 and Table 7.4 *shows* results in form of an average *U-value*, U_m, for the *Community building* and the *Guest room*, respectively. All calculations are done according to the *ISO International Standards*, as specified in Chapter 6.2.

The theoretical calculations are performed in *Matlab.* The scripts can be downloaded at the following website: www.byggnadsteknologi.se.

Community building

Table 7.1 Theoretical values for the Community building: Areas and U-values of the building components[1].

Building part	**Area [m^2]**	**U-value [W/m^2·K]**
Wall	161	0.10
Roof	152	0.11
Floor	137	0.08
Window	34	0.70
Door	7	0.65
Door with glass	4.9	0.80

Table 7.2 Theoretical values for the Community building: The average U-value, U_m[1].

Total transmission, ΣU·A [W/K]	75.85
Thermal bridges, ΣΨ·l [W/K]	20.15
Total area, A [m^2]	496
Average U-value, Um, [W/m^2·K]	**0.19**
BBR demand, Um, [W/m^2·K]	0.6[2]

Guest room

Table 7.3 Theoretical values for the Guest room: Areas and U-values of the building components[1].

Building part	**Area [m^2]**	**U-value [W/m^2·K]**
Wall	19.02	0.10
Roof	19.50	0.11
Floor	17.38	0.08
Window	3.17	0.70
Door with glass	2.13	0.80

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[1] *Matlab* script with calculations can be found at www.byggnadsteknologi.se

[2] Assuming the *Community building* to be considered as a facility, located in zone III, equipped with electrical heating system.

Table 7.4 Theoretical values for the Community building: The average U-value, U_m[1].

Total transmission, ΣU·A, [W/K]	10.56
Thermal bridges, ΣΨ·l, [W/K]	3.23
Total area, A, [m^2]	61.21
Average U-value, Um, [$W/m^2 \cdot K$]	**0.23**

It will not be correct to compare the *Guest room* with the demands stated in *BBR* since the given demands only apply for a whole buildings.

7.4.2 Practical result

In this chapter the results from the practical measurements will be presented. For each test performed, intervals of interest have been chosen for further study. The intervals of interest are periods where the conditions are as stable as possible, i.e. the outdoor and indoor temperatures as well as a minor spread of the indoor temperatures within the construction. The plotted data excludes the *Co-heating interval* in the graphs presented.

The plotted data from the measurements performed in the *Community building* can be found in Figure 7.5 for test 1 and Figure 7.7 for test 2. The intervals chosen for further evaluation are visualized in Figure 7.6 and Figure 7.8, for test 1 and 2, respectively. Furthermore, calculated results from the whole period and the chosen intervals can be found in Table 7.5 and Table 7.6, where the results are expressed as U_m and the deviation from the theoretical value.

The plotted data from the measurements performed in the *Guest room* can be found in Figure 7.9 for test 1 and Figure 7.11 for test 2. The intervals chosen for further evaluation are visualized in Figure 7.10 and Figure 7.12, for test 1 and 2, respectively. Furthermore, calculated results from the whole period and the chosen intervals can be found in Table 7.7 and Table 7.8, where the results are expressed as U_m and the deviation from the theoretical value. For test 2, corrected values with regard to heat loss to adjacent rooms are also presented.

Figures showing more detailed graphs connected to the chosen intervals can be seen in Appendix H for the *Community building* and Appendix I for the *Guest room*.

The practical calculations are performed in *Matlab*. The scripts can be downloaded at the following website: www.byggnadsteknologi.se.

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[1] *Matlab* script with calculations can be found at www.byggnadsteknologi.se

Community building, test 1

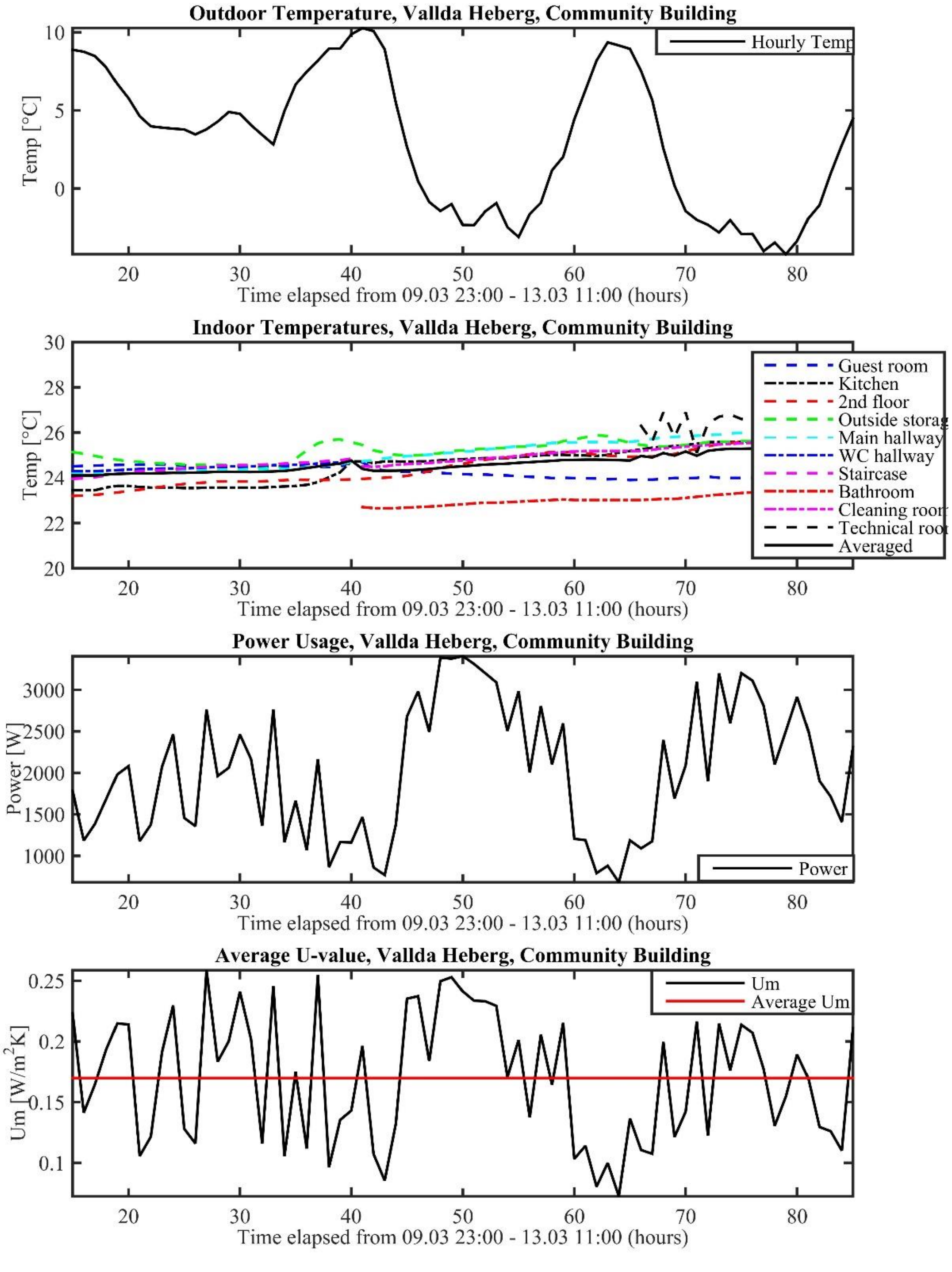


Figure 7.5 Measurement result of the whole logging interval for test 1, Community building.

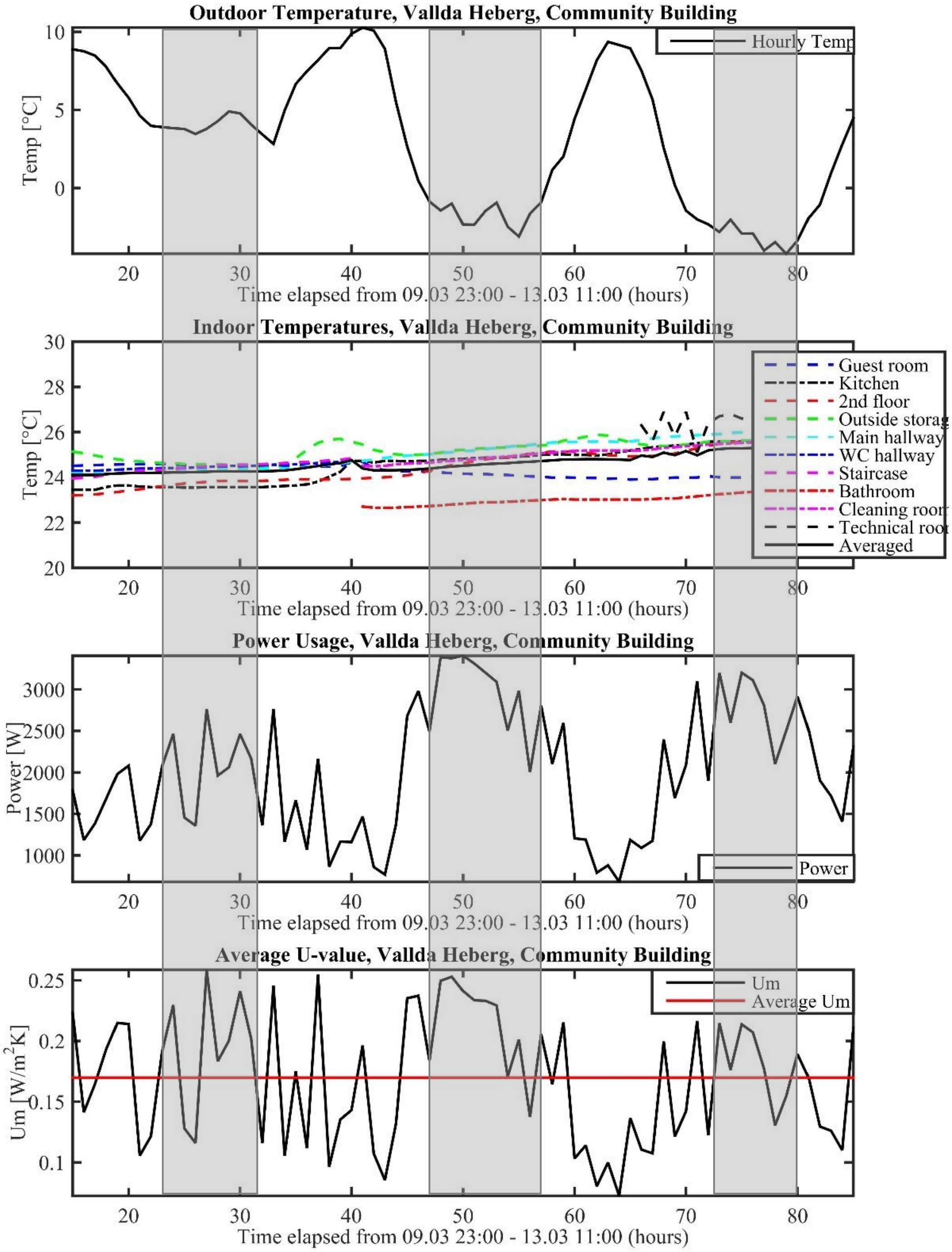


Figure 7.6 Chosen intervals for the Community building, test 1.

Community building, test 2

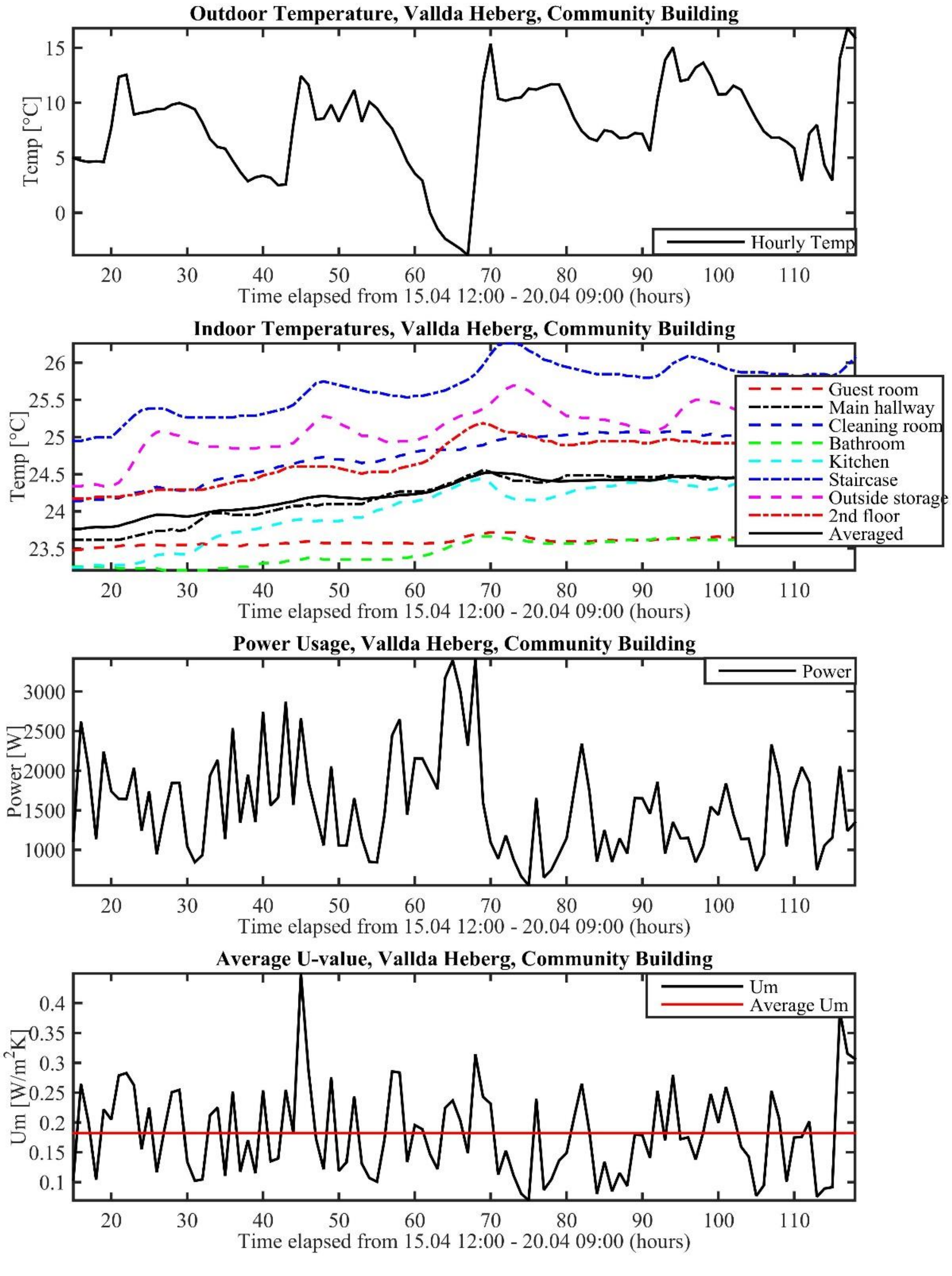


Figure 7.7 Measurement result of the whole logging interval for test 2, Community building.

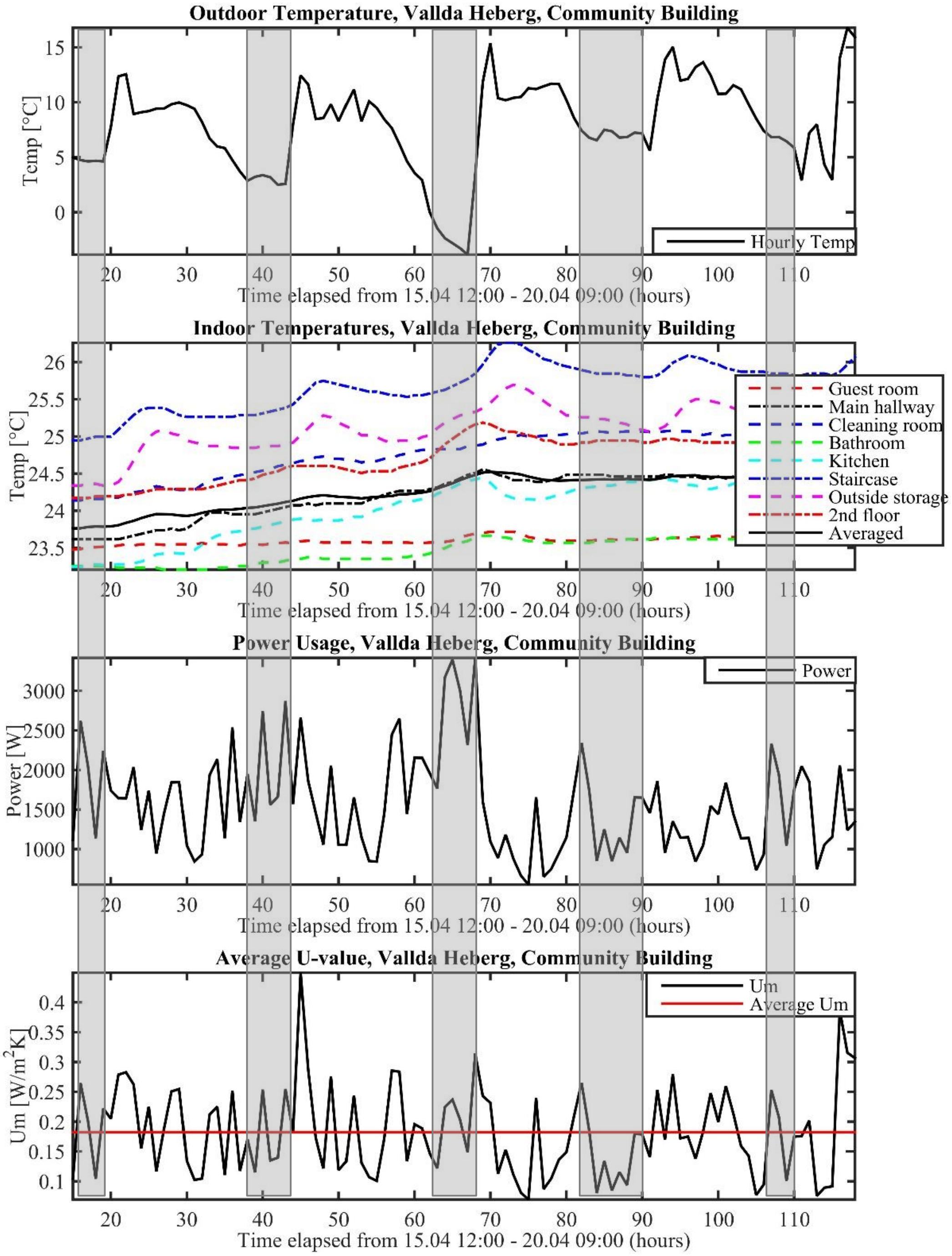


Figure 7.8 Chosen intervals for the Community building, test 2.

Guest room, test 1

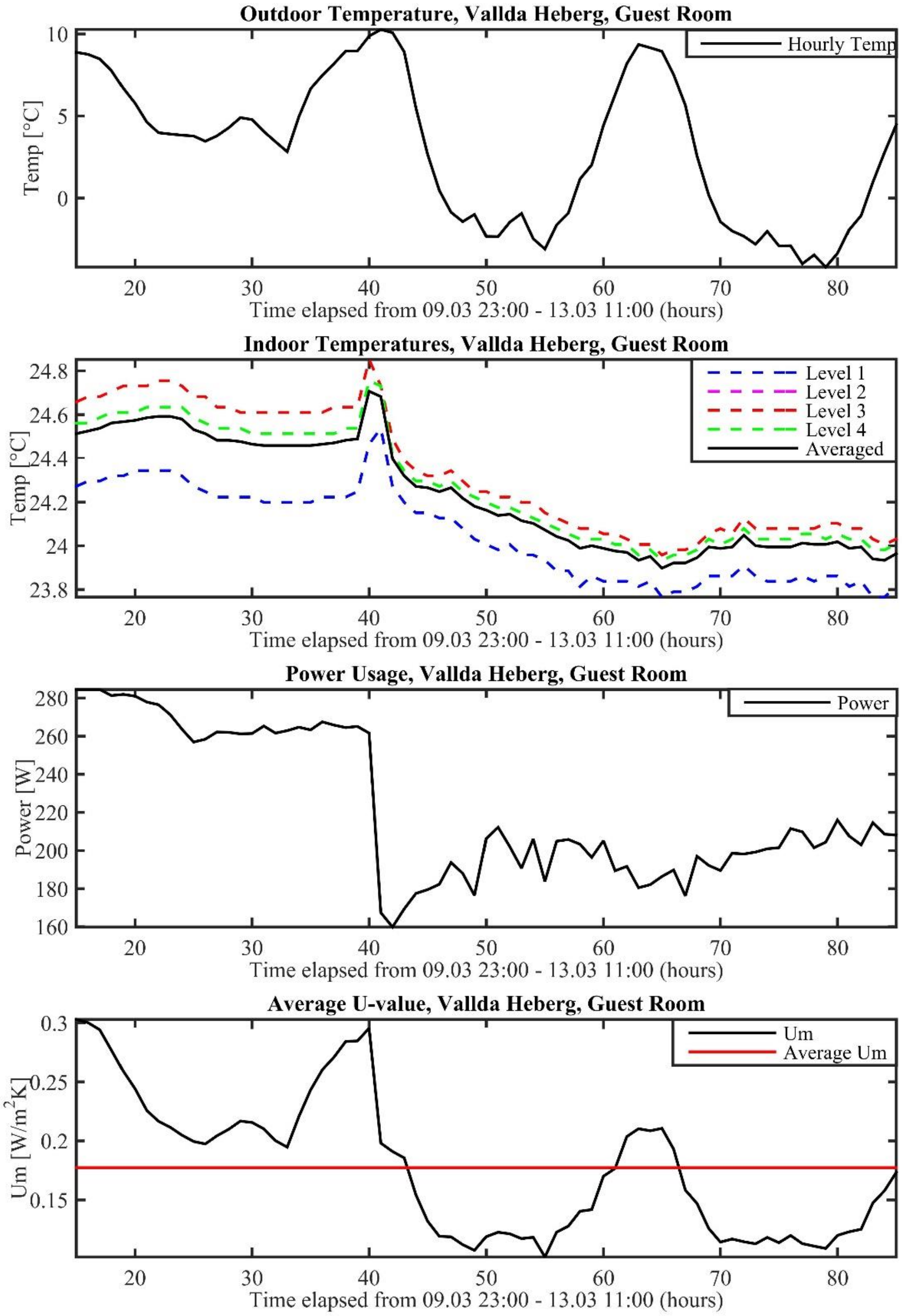


Figure 7.9 *Measurement result of the whole logging interval for test 1, Guest room.*

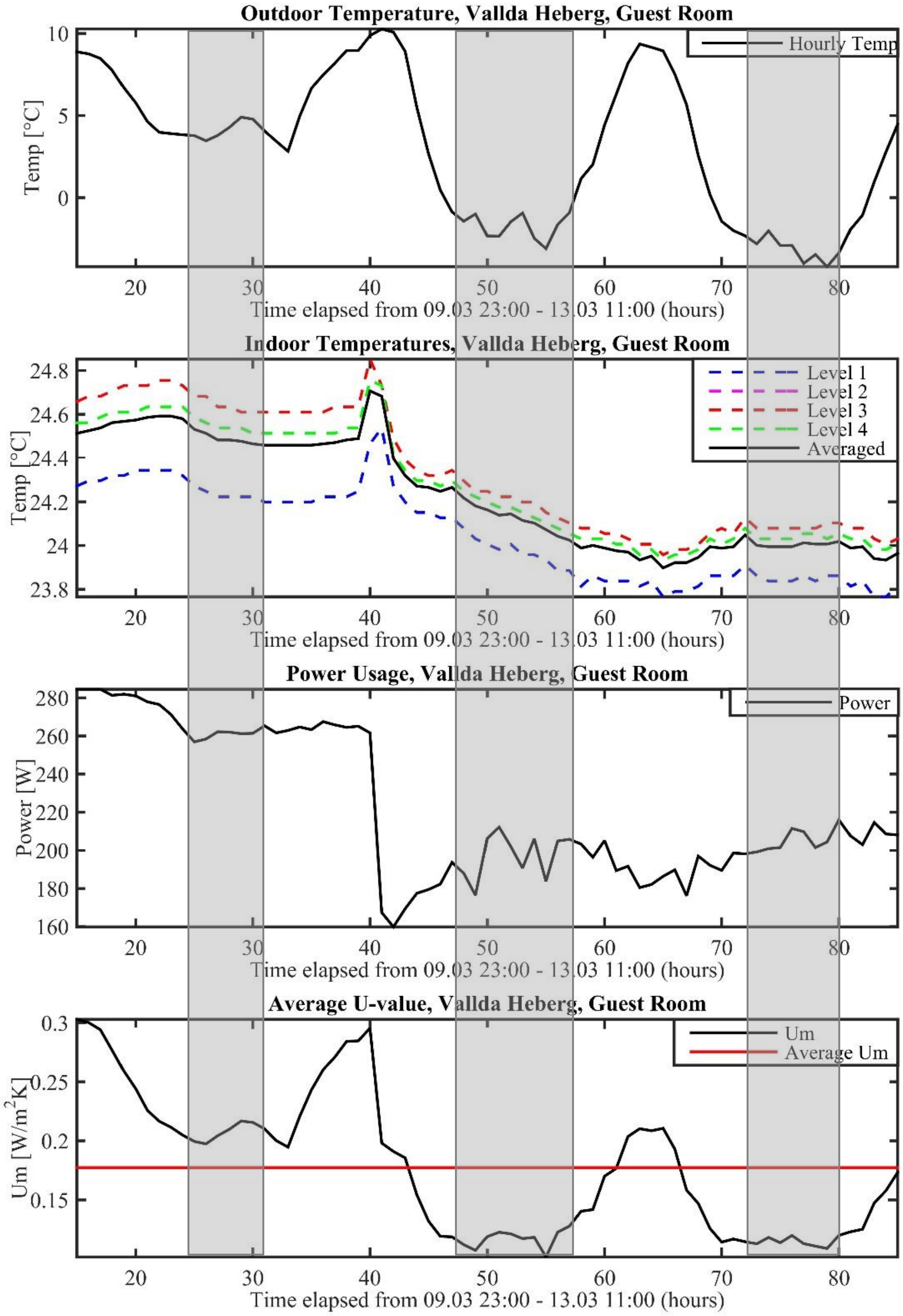
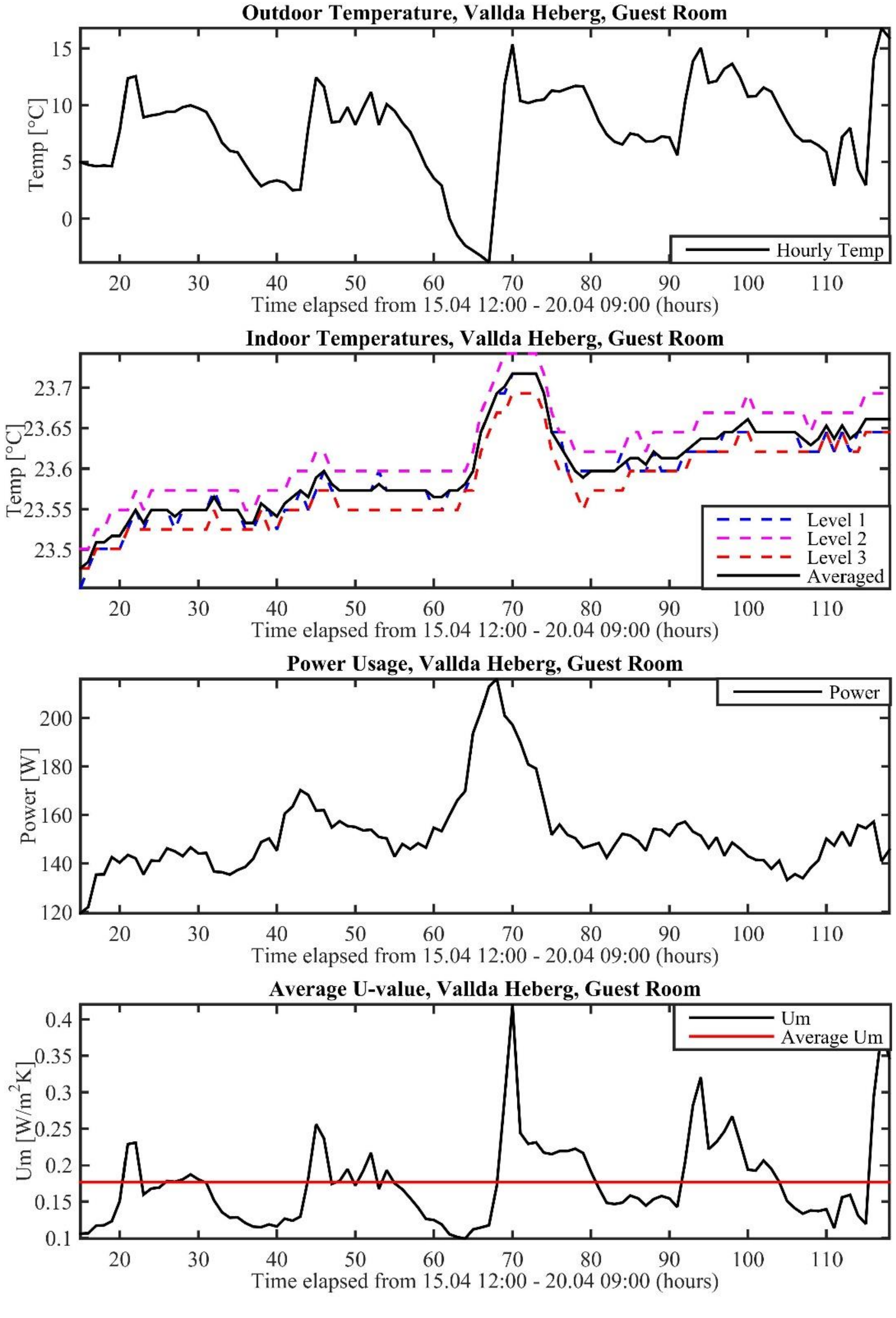


Figure 7.10 Chosen intervals for the Guest room, test 1.

Guest room, test 2



Outdoor Temperature, Vallda Heberg, Guest Room

Indoor Temperatures, Vallda Heberg, Guest Room

Power Usage, Vallda Heberg, Guest Room

Average U-value, Vallda Heberg, Guest Room

Figure 7.11 Measurement result of the whole logging interval for test 2, Guest room.

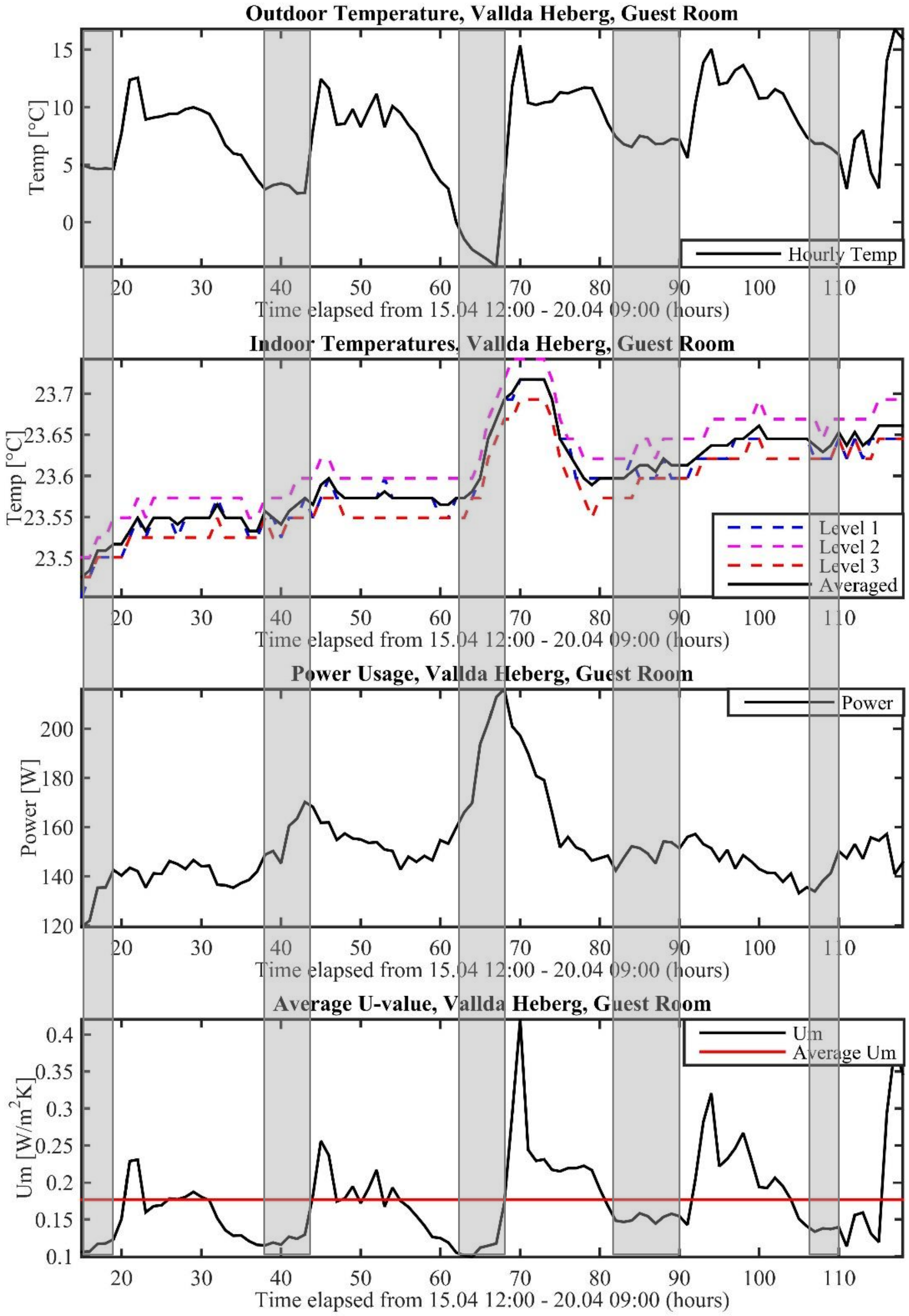


Figure 7.12 Chosen intervals for the Guest room, test 2.

Measured average heat loss transfer coefficient for chosen intervals

Table 7.5 Measured average heat transfer coefficient for chosen intervals, Community building test 1.

Interval	Period of Logging Community Building Test 1		U_m [W/m^2·K]	Deviation [%]
	Start	Stop		
Whole period	2015-03-10 23:00	2015-03-13 11:00	0.170	- 7.3
1	2015-03-10 23:00	2015-03-11 06:00	0.187	- 2.5
2	2015-03-11 22:00	2015-03-12 08:00	0.213	+ 10.7
3	2015-03-12 23:00	2015-03-13 07:00	0.176	- 8.2

Table 7.6 Measured average heat transfer coefficient for chosen intervals, Community building test 2.

Interval	Period of Logging Community Building Test 2		U_m [W/m^2·K]	Deviation [%]
	Start	Stop		
Whole period	2015-04-15 12:00	2015-04-20 09:00	0.182	- 5.4
1	2015-04-16 02:00	2015-04-16 07:00	0.198	+ 2.9
2	2015-04-17 02:00	2015-04-17 07:00	0.178	- 7.2
3	2015-04-18 02:00	2015-04-18 07:00	0.180	- 6.1
4	2015-04-18 22:00	2015-04-19 06:00	0.146	- 23.7
5	2015-04-19 22:00	2015-04-20 02:00	0.166	- 13.5

Table 7.7 *Measured average heat transfer coefficient for chosen intervals, Guest room test 1.*

Interval	**Period of Logging Guest Room Test 1**		**U_m [$W/m^2 \cdot K$]**	**Deviation [%]**
	Start	**Stop**		
Whole period	2015-03-10 23:00	2015-03-13 11:00	0.178	- 20.9
Period without fan	2015-03-10 10:00	2015-03-11 14:00	0.244	+ 8.6
Period with fan	2015-03-11 19:00	2015-03-13 12:00	0.141	- 37.3
1	2015-03-10 23:00	2015-03-11 06:00	0.207[1]	- 7.9
2	2015-03-11 22:00	2015-03-12 08:00	0.117[2]	- 47.9
3	2015-03-12 23:00	2015-03-13 07:00	0.115[3]	- 49.0

Table 7.8 *Measured and corrected measured average heat transfer coefficient for chosen intervals, Guest room test 2.*

Interval	**Period of Logging Guest room Test 2**		**U_m [$W/m^2 \cdot K$]**		**Deviation [%]**
	Start	**Stop**	**Measured**	**Corrected**	
Whole period	2015-04-15 12:00	2015-04-20 09:00	0.177	0.167	- 25.7
1	2015-04-16 02:00	2015-04-16 07:00	0.109	0.108	- 51.9
2	2015-04-17 02:00	2015-04-17 07:00	0.121	0.118	- 47.6
3	2015-04-18 02:00	2015-04-18 07:00	0.108	0.102	- 54.8
4	2015-04-18 22:00	2015-04-19 06:00	0.152	0.140	- 37.9
5	2015-04-19 22:00	2015-04-20 02:00	0.138	0.125	- 44.6

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[1] Interval without fan

[2] Interval with fan

[3] Interval with fan

7.4.3 Challenges and discussion

There have been both challenges and difficulties for the performed tests, which will be discussed below.

Heat loss to adjacent rooms

For both test 1 and test 2 it was found that it was relatively hard to get consistent indoor temperatures. This applies to the Guest room in relation to adjacent rooms, but it also applies to other rooms in the building in comparison with each other.

For the external radiator used in the *Guest room*, it turned out that the thermostat did not have the accuracy that was needed, which in turn resulted in a slightly temperature difference between the *Guest room* and the neighbouring rooms. An external temperature controller would have been useful to be able to regulate the temperature level thoroughly.

On account of the temperature difference between the *Guest room* and the neighbouring rooms, the measured power includes heat loss to the adjacent rooms. To manage this, the heat loss to the neighbouring rooms is calculated and extracted from the measured value in the best possible way. The heat loss to neighbouring rooms includes heat loss through the walls and the thermal bridges between the rooms. By extracting the heat loss to adjacent rooms, it can be assumed that there is no heat loss to the neighbouring rooms and the walls can be seen as adiabatic.

To derive a formula for the corrected U_m-value, formula (15) from Section 4.3.2 is used as a basis:

$$U_{m,meas} = \frac{\dot{Q}-\dot{Q}_{inf}}{A_{surf}\times\Delta T}$$

For this particular case, $\dot{Q}$ for the *Guest room* includes both heat loss through the external surfaces, and through internal surfaces towards adjacent rooms, in addition to the infiltration loss. As well as extracting the infiltration losses $\dot{Q}_{inf}$, the heat loss through the internal surfaces also needs to be extracted from $\dot{Q}$. Then the following equation is obtained:

$$U_{m,meas,corr} = \frac{\dot{Q}-\dot{Q}_{inf}-\dot{Q}_{tr,is}}{A_{surf}\times\Delta T} \qquad (17)$$

Where $\dot{Q}_{tr,is}$, the heat loss through internal surfaces, can be obtained by the following equation:

$$\dot{Q}_{tr,is} = \left(\sum K_{i,is} + \sum \Psi_{k,is} \times l_{k,is} + \sum \chi_{j,is}\right) \times \Delta T \qquad (18)$$

The $U_{m,meas,corr}$ will be used in further evaluation when comparing with the theoretical value.

In test 1 for the *Guest room* there only exists logged temperatures for the adjacent rooms in the second half of the measurement period, due to a human slip, which can be seen in Figure 7.5. This results in lack of information regarding heat loss to adjacent rooms for the whole period. On account of this a corrected value for the *Guest room* is only obtained for test 2. However, it is visible from the result in test 2 that the differences between the corrected and the measured value are relatively small. Based on the result from test 2 it is assumed that the uncorrected values from test 1 can be used in the evaluation process as well.

Existing radiator system

The existing radiators used for the test performed in the *Community Building* are attached to the external walls, mostly under windows. The placement of these radiators are not optimal since for the test, it is suggested to place the heating source in the middle of the room to be able to distribute the heat in the best way. This might have affected the circulation of the heat and thereby the result.

Solar radiation

When performing test 1 there was a period with a large amount of solar irradiation, and it was not possible to change the measurement period since the building needed to be booked in advance. Therefore, the radiation was tried to reduce by covering the windows, and the result showed that the influence of the sun were highly reduced and hardly noticed in the result. However, it was discovered after 1 ½ day that some parts of the aluminium foil had fallen off due to the wind. After this was detected, new foil was attached to the windows concerned. For these windows the new foil was attached to the inside of the windows, to make sure that they would not loosen again, due to probably high wind exposure at those locations. For the other windows the foil was left on the outside of the glass.

When performing test 2 there were both cloudy and sunny days. The windows were covered for this test as well, but the cover material used this time was of the same sort as for packaging of potato chips since it was easier to work with. However, this material turned out to transmit more solar radiation then the foil. This may be one of the reasons for the deviations in the internal air temperature throughout the house.

For the *Community building* some of the external doors were black. After the measurements it could be seen that in those directions where there were black doors and the solar radiation was strong, the indoor temperature was affected. Only one of the doors had sensors placed close enough to obtain measurements of its contribution. Any possible effect from the other doors was not logged but it could be felt when passing the area. It is probable that the doors transmitted more heat than the walls. This can be due to the higher *U-value* of the doors, but it is also likely that the black colour of the doors increased the irradiation. It is however assumed that this did not have any major impact on the measurements, but it would have been preferable to cover those doors in the same manners as the windows.

Seal around possible air leakage paths

Another challenge was to identify all possible air leakage paths and seal them properly. For both of the tests all vent openings were sealed but the connector sockets were left open due to time limitations and the probability of a minor impact.

Influence of the fan in the *G*uest Room

Before installation of the fan, it was possible to see a small spread in temperature between the measured levels in the *Guest room*. After installing a fan the temperature gradient decreased and a more uniform temperature was achieved in the room which is clearly visible in Figure 7.9.

In Figure 7.9 it can also be seen that the power usage has been reduced as a result of mixing the air. The counteraction of the stack effect has probably made it possible for the radiator to be utilized more efficiently than before.

Although the temperature and power usage behaved as anticipated, the practical U_m values obtained were rather unexpected. It turned out that U_m has become quite much lower than for the period without fan and the theoretical value, after the fan was installed. In test 2 the fan was in operation the whole period. The same can be observed here; the practical U_m is much lower than the theoretical U_m.

It is an interesting correlation between the intervals in test 1 and test 2, which were performed with a fan. The deviation from the theoretical value is large, however the deviation between them is not so large; they are actually quite close to each other. There is no doubt that something has happened after the fan was installed, but it is difficult to determine exactly what caused this behaviour.

One possible reason may be that the fan was too powerful compared to the size of the room, resulting in too high air speed which in turn caused convection in the room. Consequential, the radiator performs less and this may potentially decrease the practical U_m-value. This hypothesis may be strengthen by looking at the first interval in test 1 where no fan is installed, see Table 7.7. Here it can be seen that the result deviates from the theoretical value within a reliable range. However, since there is only one interval that can be connected to this theory there is lack of repeatability. Thus, more research needs to be performed in order to confirm this.

The internal surface resistance R_{si} may be another changed factor because of the fan convection. R_{si} is dependent on the wind speed nearby the wall surface; higher air speed results in lower resistance. Most probably would the fan have caused higher wind speed. With a known air speed nearby the wall when the fan was operating, it would have been possible to calculate a new R_{si} and thereby a new theoretical U_m-value to compare the practical with. However, a decreased R_{si} should actually have given an increased U_m, not a decreased as in this case. Besides, changing R_{si} seems to have a small impact on the final U_m value.

Another reason discussed was the released power from the fan itself. Initially this was neglected since it was assumed to be very low compared to the total power usage. However, in retrospect this was revaluated and included in the calculations. The power of the fan was measured to be 30W. This addition did actually have a perceptible effect on the result of the *Guest room,* however still not enough to explain the large gap.

The deviation from the theoretical value is difficult to determine and has need for further research, which will not be part of this study.

7.5 Air tightness test

The air tightness tests were performed for both the *Guest room* and for the *Community building*, separately. For both scenarios a pressurization test and a depressurization test were performed, which is a normal procedure. this to bring out an averaged value to use for the calculations.

Figure 7.13 Performance of Blower door test.

Preparations

Briefly, the preparation steps that were made was to turn off the ventilation system and seal all vent openings. Also all siphon taps was checked so that they were filled with water. For the *Guest room* the door towards the rest of the house as well as the door towards the restroom was sealed with tape around the doorframe, this to minimise air leakage from those places. For the whole-house measurements all internal doors throughout the whole house were opened including the door to the *Guest room*.

Execution of the test

The execution of the tests were also in accordance with the methodology for air tightness test, which can be read more about in Chapter *5*: *Methodology of Air tightness Method* and Appendix C.

7.5.1 Results

Table 7.9 and Table 7.10 show the results of the air tightness tests performed on the *Community building* and the *Guest room*, respectively.

The air tightness of a building can be expressed with several different units as shown in the tables below. Which one to be used depends on further application of the result. It may also depend on what the result is to be compared with, since units used in different standards may vary in different countries.

For further calculations it was of interest to obtain the value in [m^3/s]. For easiest possible conversion *v50* [*l/s*] has been chosen to proceed with. However, if the desire is to compare with the *BBR*, *q50* [$l/s{\cdot}m^2$] would be a more correct parameter (Boverket, 2014).

Table 7.9 Results from the air tightness test performed in the Community building.

	Parameter	**Depressurization**	**Pressurization**
Input data	Volume, [m^3]	630	
	Surface area, [m^2]	488	
	Floor area, [m^2]	204	
	Internal temperature, [°C]	23	
	External temperature, [°C]	6	
Results	v50, [l/s]	171	186
	n50, [1/h]	0.98	1.06
	w50, [$l/s{\cdot}m^2\ A_{temp}$]	0.84	0.91
	q50, [$l/s{\cdot}m^2\ A_{surf}$]	0.35	0.38
Averaged	$v50_{averaged}$, [l/s]	178.5	
	$w50_{averaged}$, [$l/s{\cdot}m^2\ A_{temp}$]	0.875	
	$q50_{averaged}$, [$l/s{\cdot}m^2\ A_{surf}$]	0.365	
BBR demand	q50, [$l/s{\cdot}m^2$]	The building envelope should be so tight that the demands for building-specific energy consumption and installed electrical power for heating is fulfilled[1]	
Passive house demand	w50, [$l/s{\cdot}m^2\ A_{temp}$]	0.50[2]	
	q50, [$l/s{\cdot}m^2\ A_{surf}$]	0.30	

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[1] Assuming the Community *building to be considered as a facility, located in zone III, equipped with other heating system* than electrical heating.

[2] For building with a shape factor over 1.7 (low buildings), may instead the leakage flow per heated area be maximum 0.5 l/s·m2 A_{temp} (Sveriges centrum för nollenergihus, 2012).

For more elaborated results of the air leakage tests, for both the depressurization and pressurization reference is made to Appendix K for the *Community building* and Appendix L for the *Guest room*. The building leakage curves generated from the Multi-Point test may also be found there.

Table 7.10 Results from the air tightness test performed in the Guest room.

	Parameter	**Depressurization**	**Pressurization**
Input data	Volume, [m^3]	630	
	Surface area, [m^2]	488	
	Floor area, [m^2]	204	
	Internal temperature, [°C]	23	
	External temperature, [°C]	6	
Results	v50, [l/s]	27	30
	n50, [1/h]	1.66	1.85
	w50, [$l/s \cdot m^2$ A_{temp}]	1.57	1.75
	q50, [$l/s \cdot m^2$ A_{surf}]	0.29	0.32
Averaged	v50 averaged, [l/s]	28.5	

7.5.2 Challenges and discussion

The challenge with this test and which often seems to be a problem, is to achieve adequate sealing, especially if the building is large of scale such as the *Community building*. It is therefore important to go through the building to check that all air leakage paths have been taken care of.

When performing the air tightness test in the *Guest room*, air leakages to neighbouring room might be a problem. Since the inner walls are assumed to be adiabatic in the theoretical calculations, the air leakage through the inner walls should actually not have been included in the practical calculations either. However, this air leakage is not possible to exclude from calculations, and will therefore be an uncertainty with the result.

The equipment used in these tests has been borrowed from *NCC*, where the equipment is calibrated regularly. This means that errors in the measurements due to lack of calibration can most probably be disregarded.

For both cases, the steel frame with the canvas was sealed towards the doorframe with the use of tape and sealing clay. This was done because there were leaks around the steel frame and the doorframe due to unevenness in the frame.

According to the measurements performed in this study, the studied building does not fulfil the requirements for air tightness for passive houses. After discussion with *NCC* it became clear that the *Community building* was actually the only building in the building project not to be certified after passive house standards. However, the *Community building* is anyway built by the same principles.

For both the *Community building* and the *Guest room* the depressurization test showed somewhat lower result than the pressurization test. The larger value for the pressurization test may be explained by the opening direction of doors and windows. If doors and windows have outswing opening directions, this will cause larger infiltration between frame and leaf during the pressurization test than the depressurisation test.

The measurements for the *Guest room* showed somewhat lower air leakage for both the pressurization and depressurization test, than the measurements done for the *Community building*. However, since the two different scenarios are not entirely comparable, this will not be further evaluated.

7.6 Infrared thermography

By studying the building with an infrared camera it was possible to detect temperature differences of the building construction surface. In that way possible air leakages, thermal bridges and other sources causing heat loss could be identified. The imaging was performed in conjunction with the air tightness test, so that the possible weaknesses would be easier to detect.

Thermal bridges will always be visible on a thermographic image since a thermal bridge always has a reduced indoor surface temperature. Thus, the investigation was then to see if the surface temperature was much lower than expected for a thermal bridge.

7.6.1 Results

Due to limited time, thermography was only performed on the Guest room instead of on the whole building. In the pictures taken no irregularities was found that could indicate possible weaknesses of the building envelope, therefore no pictures have been enclosed here. The picture may instead be found together with the inspection reports in Appendix N.

7.6.2 Challenges and discussion

It was difficult to set criteria for expected results and what to consider as abnormal since this requires more experience in interpreting result from infrared thermography.

8 Case Study of Friggebod

This construction has been temporarily situated in a large research- and experiment hall at *Chalmers University of Technology*. The *Friggebod* is approximately 10 m^2 and consists only of one room.

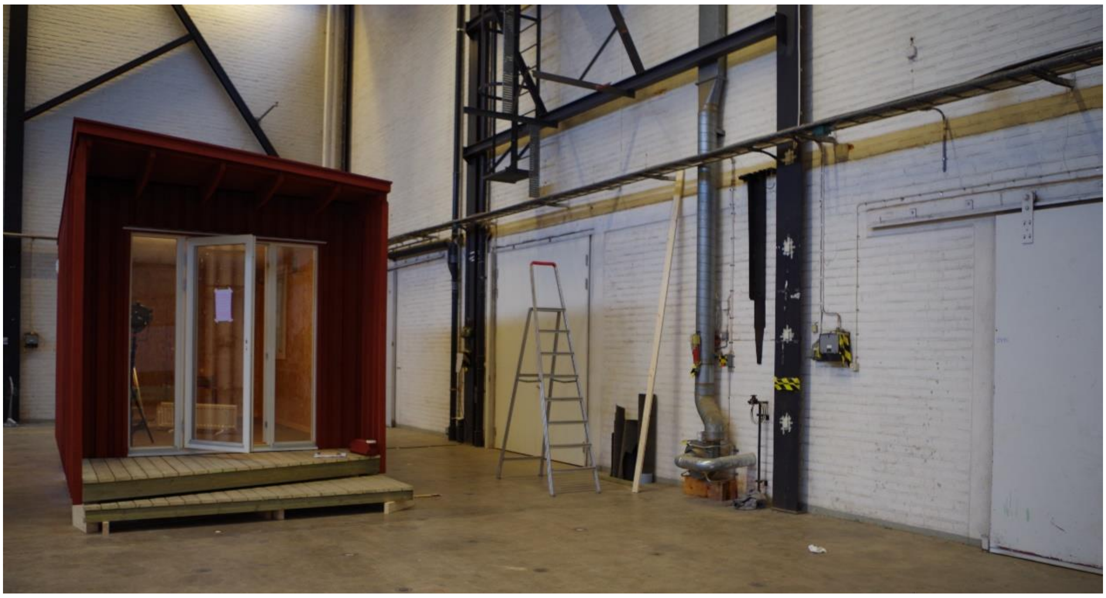

Figure 8.1 Friggebod where measurements are performed.

8.1 Background

This particular object was chosen for research due to its availability during the period of testing. During the springtime architecture students at *Chalmers University of Technology* are building a construction as a part of a course. After completion the building is sold and profits are given to charity. This year the building was a *Friggebod,* which can be translated from Swedish as: a simple single-storey structure.

This object is considered to be suitable for the research due to its size and its exterior conditions during the test period. The small size will eliminate many uncertainties that may occur in larger constructions, such as temperature gradients and number of construction failures. The fact that it is located in a hall excludes the influence of the solar radiation and the exterior temperature can more easily be kept stable.

8.2 Construction

The exterior wall is very simple and typically constructed with vertical wooden cladding as the outermost layer followed by a wind barrier, glass wool and wooden stud composition, and OSB as internal cladding. See Figure 8.2 for detailed illustration of the external wall.

The roof is a ventilated roof construction with a roofing felt as exterior cladding, followed by mineral wool and beam composition, wind barrier, and *tongue and groove* panels on the inside. The structure can be seen more in detail in Figure 8.2.

The floor is built as if the building was to be placed on a crawlspace with wind protective layer as the outermost layer towards the exterior climate, followed by the beam and mineral wool composition, and a massive wood layer as interior flooring. See Figure 8.2 for illustration.

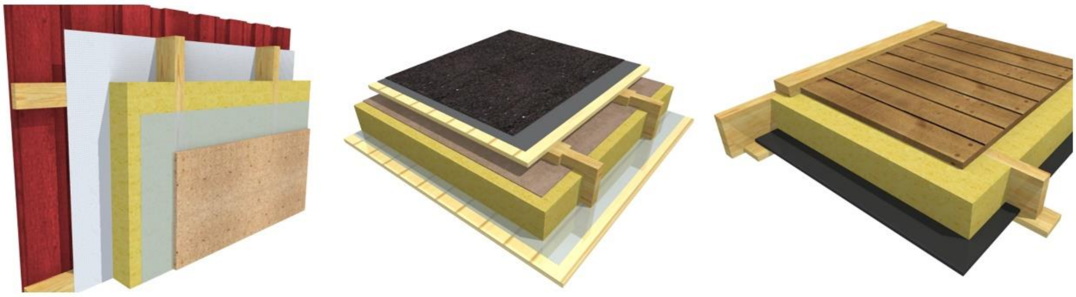

Figure 8.2 Detail of wall, roof and floor, Friggebod.

8.3 Co-heating test

The *Co-heating test* for this building was conducted according to the adapted *Co-heating test*, as explained in Section 4.3. The measuring time for this object was 7 days in total.

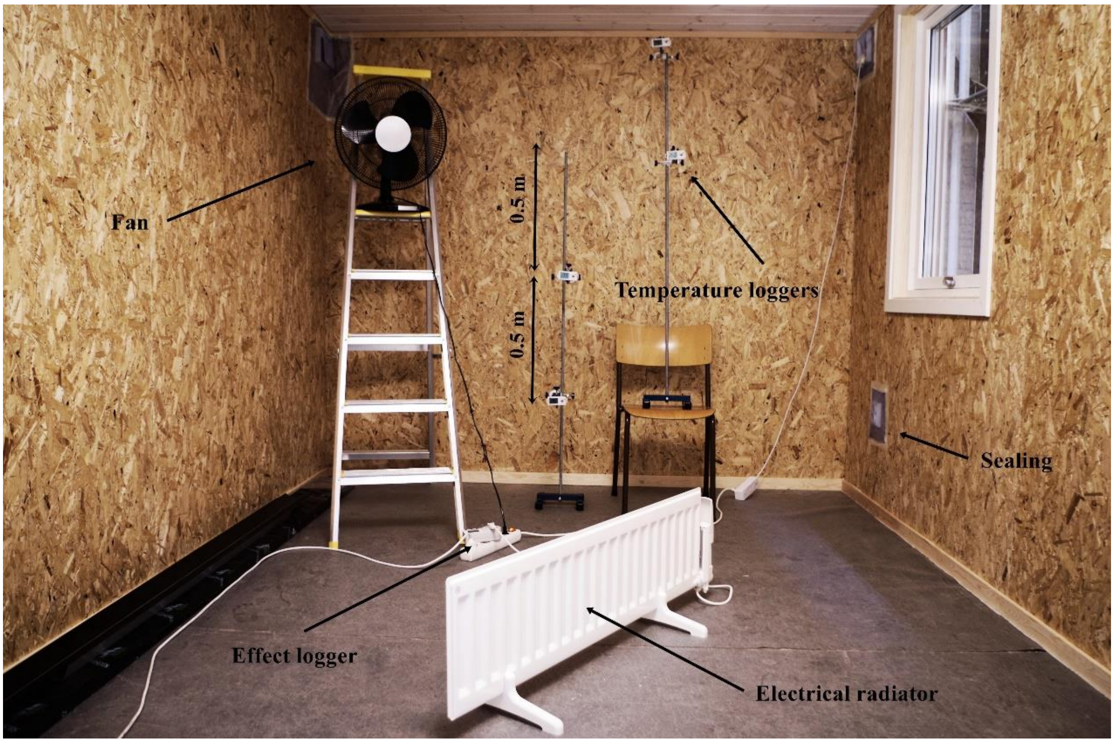

Figure 8.3 Measuring equipment for the Co-heating test, Friggebod.

Preparations
Before the test was initiated all ventilation openings were sealed to exclude influence from ventilation losses.

Then sensors for logging the temperature and relative humidity were placed both inside the building and outside, at different heights. Inside the object, 4 devices were placed on tripods with a vertical distance of 0.5 m between them. They were placed in a suitable location where the influence of direct heat from the radiator should be as low as possible. Outside the building 4 sensors were placed along a vertical line with approximately 0.8 m distance between them.

Since the construction was placed inside a hall, the solar radiation was not a problem, and it was therefore not necessary to cover any of the glass sections of the building.

Execution
The execution of the test was done by turning the thermostat on the radiator to 30 ℃. This higher temperature was chosen due to warmer external conditions on account of that the house was located inside a large hall where the temperature was around 17 ℃. The power/energy-meter and the temperature sensors were set to log every hour.

The radiator was placed in the middle of the room in order to spread the heat as good as possible. No fan was used since it was considered to be unnecessary as the relatively small size of the object enabled the heat to be spread by its own. The use of fan might have caused excessive forced convection due to the relatively small area in comparison to the air circulation provided by a fan. However, for the last 7 hours a fan was installed in the building, this in order to see the effect of an increased circulation of the air.

8.3.1 Theoretical result

The following tables show the results of the theoretical calculations performed. Table 8.1 shows the areas and U-values for the different building components, while Table 8.2 shows results in terms of an average *U-value*, U_m, for the whole building. All calculations are done according to the *ISO International Standards*, as specified in Chapter 6.2.

A better overview of the thermal bridges calculated in *Comsol* and *Heat2* can be found in Appendix G.

The theoretical calculations are performed in *Matlab*. The scripts can be downloaded at the following website: www.byggnadsteknologi.se.

Table 8.1 Theoretical value for the Friggebod: Areas and U-values of the building components[1].

Building Components	**Area [m^2]**	**U-value [$W/m^2 \cdot K$]**
Wall	24.176	0.374
Roof	9.890	0.257
Floor	9.865	0.242
Window	1.033	1.3
Window	2.006	1.4
Door	1.860	1.0

Table 8.2 Theoretical value for the Friggebod: The average U-value, Um[1].

Total transmission, $\Sigma U \cdot A$ [W/K]	19.979
Thermal bridges, $\Sigma \Psi \cdot l$ [W/K]	3.042
Total area, A [m^2]	48.831
Average U-value, Um [$W/m^2 \cdot K$]	**0.47**

8.3.2 Practical results

In this chapter the results from the practical measurements will be presented. For each test performed, intervals of interest have been chosen for further study. The intervals of interest are periods where the conditions are as stable as possible, i.e. the outdoor and indoor temperatures as well as a minor spread of the indoor temperatures within the construction. The plotted data excludes the *Co-heating interval* in the graphs presented.

The plotted data from the measurements performed in the *Friggebod* can be found in Figure 8.4. The intervals chosen for further evaluation are visualized in Figure 8.5. Furthermore, calculated results from the whole period and the chosen intervals can be found in Table 8.3, where the results are expressed as U_m and the deviation from the theoretical value.

Figures showing more detailed graphs connected to the chosen intervals can be seen in Appendix J.

The practical calculations are performed in *Matlab*. The scripts can be downloaded at the following website: www.byggnadsteknologi.se.

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[1] *Matlab* scripts with calculations can be found at www.byggnadsteknologi.se

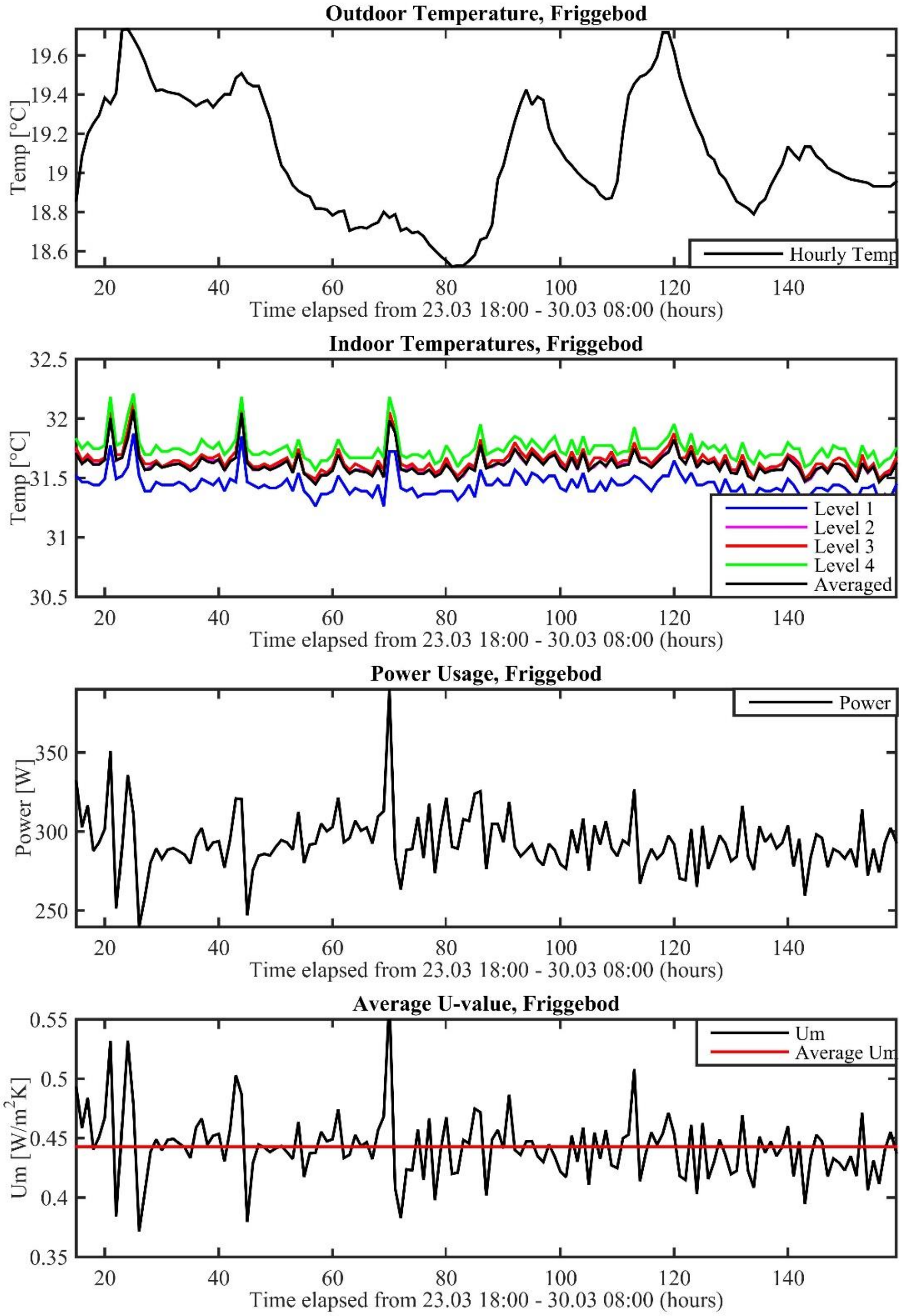

Figure 8.4 Measurement result of the whole logging interval, Friggebod.

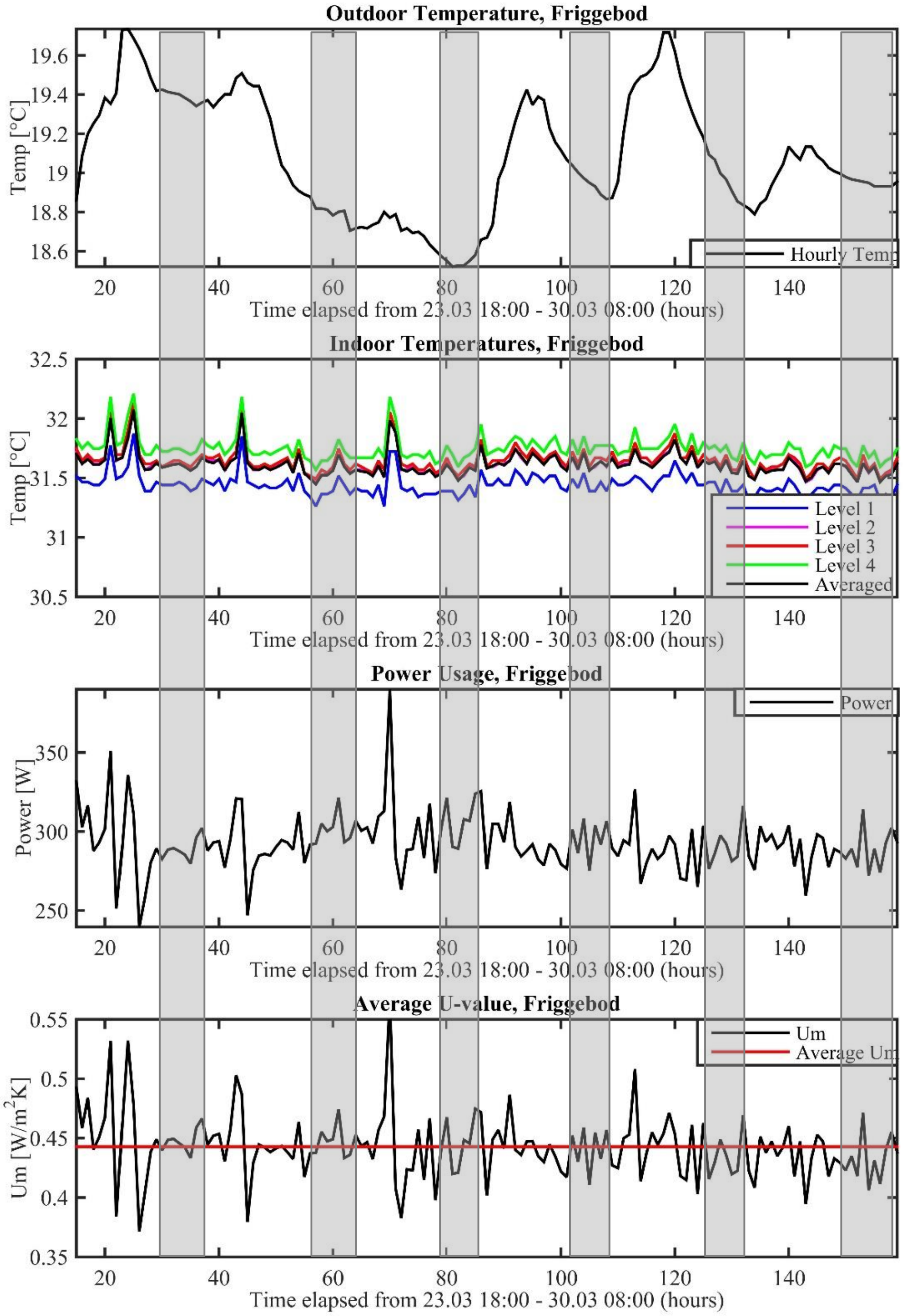

Figure 8.5 Chosen interval for the Friggebod.

Table 8.3 Measured average heat transfer coefficient for chosen intervals, Friggebod.

Interval	**Period of Logging Friggebod**		**Um [W/m^2·K]**	**Deviation [%]**
	Start	**Stop**		
Whole period	2015-03-24 09:00	2015-03-30 08:00	0.443	- 6.2
1	2015-03-24 23:00	2015-03-25 09:00	0.448	- 5.1
2	2015-03-26 02:00	2015-03-26 09:00	0.446	- 5.4
3	2015-03-27 01:00	2015-03-27 06:00	0.440	- 6.7
4	2015-03-27 23:00	2015-03-28 05:00	0.437	- 7.5
5	2015-03-28 23:00	2015-03-29 05:00	0.434	- 8.2
6	2015-03-29 23:00	2015-03-30 07:00	0.432	- 8.6

8.3.3 Challenges and discussion

Differences in the external temperature
Since the construction was placed in a large hall, the prevailing temperature conditions for the place were considered to be stable. On account of that the hall is accessible for other people, a number of unforeseen visits to the hall took place during the week. These visits created an air draught, which caused small deviations in the external temperature for the *Friggebod.* However, due to the very size of the hall the opening of entrances did not have any noticeable impact on the measurement results.

Installation of fan
The size of the construction is relativity small, therefore it was decided to conduct the major part of the test without a fan. Based on the result it could be seen that the temperature gradient was insignificant, and the decision of not using a fan seems reasonable. The air was able to circulate well even without a fan.

The results of installing a fan for the last hours of the test showed that the internal air temperature in the building did not have enough time to stabilize. The measurement period for when the fan was installed turned out to be too short in order to get reliable results. Therefore the time for which the fan was running is excluded in the graphs above illustrating the results.

Drying out
In Figure 8.6, the behaviour of the relative humidity during the measured period is shown. By investigating this figure it can be seen that the construction has been dried out during the execution of the test.

The building was finished just before our measurements started which also means that any possible built in moisture did not have time to dry out before the test started. Due to that the construction probably contained moisture and heating of the air lead to drying of the materials.

The drying process requires energy, this means that the measured energy consumption in the building during the *Co-heating test* includes in addition to transmission and infiltration losses, also energy used for drying. However, it is hard to see the progress of the drying process in the graph showing the power consumption and therefore the drying may not have that large impact on the energy consumption. Some of the prominent features in the curve of the relative humidity may be noticed in the power consumption graph. The increasing slope in the beginning of the relative humidity graph can be seen as a very unstable period in the power consumption graph. However, when the relative humidity stagnates the power usage consumption tends to become more stable as well. During the decreasing slope in the graph for the relative humidity the power consumption tends to vary constant. One additional thing that can be seen in the graphs, is that for the power usage graph there is a high peak and this can be seen in the relative humidity graph as well as a small dip, due to an increased drying.

When the radiator is started an elevation of the air temperature is initiated. The higher the air temperature, the more moisture the air will be able to contain. In the Co-heating phase in the beginning the air will gradually be able to contain more and more moisture, which explains the inclining slope in Figure 8.6. When the temperature has stabilized, the relative humidity will reach a stable condition as well. Then the constant heating of the air will cause drying of the construction, explaining the declining slope in the graph. However, the change in relative humidity and hence the energy used for drying is assumed to be low and is therefore neglected for this case.

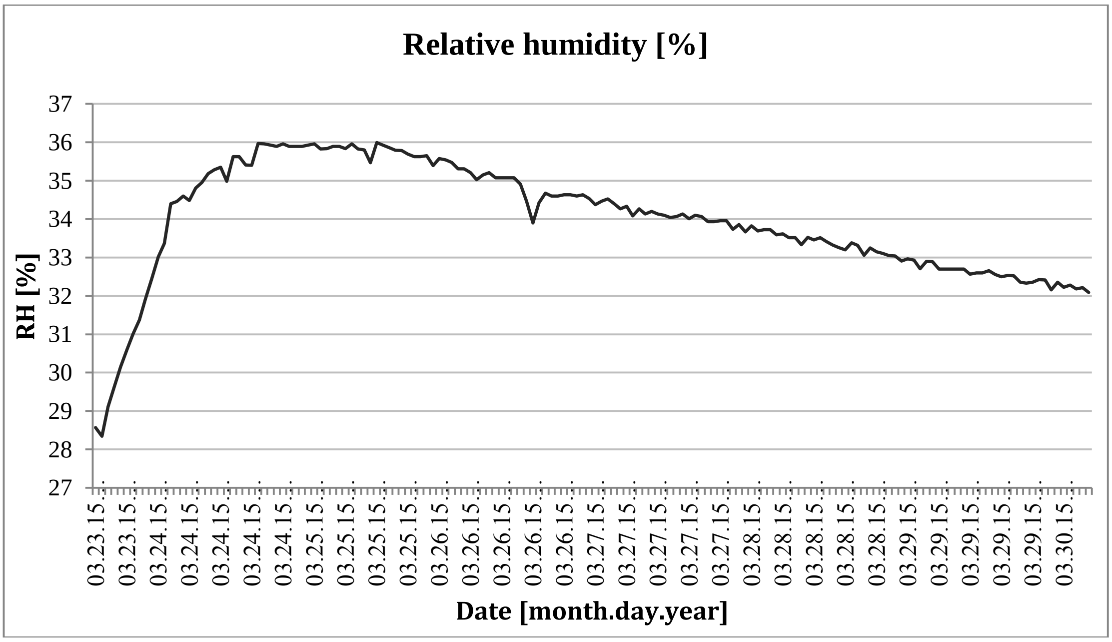

Figure 8.6 Relative humidity for the Friggebod.

The drying may also have caused shrinkage of the materials which can result in an increased air leakage. It is therefore recommended to perform an air infiltration test before and after the test to be able to detect a possible increase in air flow. However, for this case an infiltration test was only conducted before the *Co-heating* test, due to time limitations. This may have caused uncertainties in the results.

8.4 Air tightness test

Both a pressurization test and a depressurization test were performed on the *Friggebod,* so that an average value could be used in the calculations.

Figure 8.7 Performance of Blower door test.

Preparations
The preparations for the tests were done in accordance to the Air tightness method, which is described more in depth in Chapter *5.1*: *Methodology of air tightness test* and Appendix C.

For this specific case, openings, such as ventilation openings, electrical sockets, light switch and the electrical cabinet, where there was a high risk for leakage, were sealed.

Execution of the test
The execution of the tests was performed according to standard methods as further described in Chapter *5.1*: *Methodology of air tightness test.* The test was performed as a *Multi-Point test* according to the test standard *EN 13829.*

8.4.1 Results

The following table shows the results obtained from the *Blower door test* performed on the building in this case study.

Table 8.4 Results from the air tightness test performed in the Friggebod.

	Parameter	Depressurization	Pressurization
Input data	Volume, [m^3]	20	
	Surface area, [m^2]	50	
	Floor area, [m^2]	10	
	Internal temperature, [°C]	25	
	External temperature, [°C]	18	
Results	v50, [l/s]	26	33
	n50, [1/h]	4.64	5.98
	w50, [l/s·m^2 A_{temp}]	2.58	3.33
	q50, [l/s·m^2 A_{surf}]	0.52	0.67
Averaged	$v50_{averaged}$, [l/s]	29.5	
	$q50_{averaged}$, [l/s·m^2 A_{surf}]	0.59	
BBR demand	q50, [l/s·m^2 A_{surf}]	0.6[1]	

For more elaborated results of the air leakage tests, reference is made to Appendix M, where for example the building leakage curve generated from the *Multi-Point test* can be found.

8.4.2 Challenges and discussion

Challenges with the test were to seal properly around possible leakage paths. However, the number of possible leakage path were minor, therefore it was relative easy to maintain control over the possible leakages.

The equipment used for the air tightness test performed on the *Friggebod* belongs to *Chalmers University of Technology*. Unfortunately, the university has a lack of information regarding the last calibration of the equipment. Therefore it may be assumed that some uncertainties are caused by the equipment used.

The steel frame with the canvas needed to be sealed at the doorframe by using tape and sealing clay. This was done because there were gaps between the steel frame and the doorframe due to unevenness in the frame.

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[1] Assuming that the *Friggebod* is considered to be a facility, located in zone III, equipped with electrical heating.

The achieved results from the air leakage test fulfils the BBR requirements with small margins, but the results seem to be reasonable within these limits.

The difference between depressurization and pressurization was somewhat larger than expected, but not necessarily incorrect. This difference may, as described in Chapter 7.5.2, have been influenced by the opening direction of doors and windows. There is a larger infiltration between frame and leaf when performing a pressurization test compared with a depressurization test.

8.5 Infrared thermography

The thermography imaging was done to detect possible unintended weaknesses of the building envelope. The imaging was performed in conjunction with the air tightness test, so that the weaknesses would be easier to detect.

8.5.1 Results

Almost all photos seemed normal, with no noticeable deviations from what is to be expected. The exception was the photo shown below, which may indicate some irregularity in the connection between slab and wall. If it is of interest to see some of the pictures taken, inspection reports can be found in Appendix O.

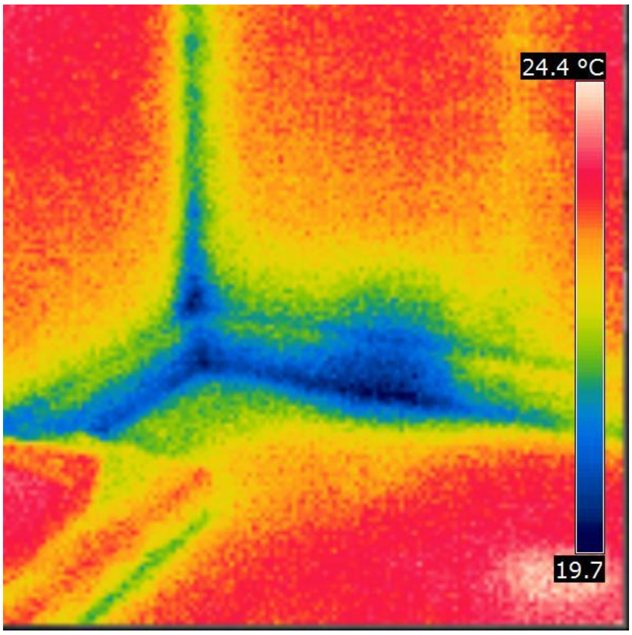

Figure 8.8 Thermographic image of corner detail, connection between two external walls and floor slab.

8.5.2 Challenges and discussion

The temperature difference between the exterior and interior environment was the biggest challenge when performing the thermography in this case study. The desired temperature difference for performing this kind of test is 10°C as discussed in Chapter 5.2.3. The actual temperature difference when performing the imaging was only 7°C, thus the desired temperature difference was not achieved. However, for localizing air leakages, it is sufficient with a temperature difference of 5°C, as also mentioned in Chapter 5.2.3. Therefore, the photos taken were used to evaluate possible air leakages only.

The majority of the pictures appeared normal, except the one shown in Figure 8.8. Here it is suspected that a construction defect might have caused some unintended air leakage, which may have influenced the result of the air tightness test.

9 Discussion and Recommendations

The purpose of this study was to examine the possibility to measure the as-built thermal performance of a building envelope by using the basis of the *Co-heating test* method. The three different points of views for the research have been the usability, the reliability and the future aspects of the test. In the following sections, challenges and outcomes related to the three aspects of the study will be discussed, as well as recommendations will be given based on the outcome of the research.

9.1 Usability

Required knowledge

An important characteristic when conducting the test is the understanding of the theory behind the test. Sufficient knowledge within the field of building physics is therefore essential to have in order to understand the physical processes behind the tests and to be able to process and interpret the measured data correctly.

Equipment

The equipment for the *Co-heating test* that is used for this study was rather easy to manage technically, and no specialist knowledge is needed in order to apply the devices. Since the equipment used in other researches regarding the Co-heating test is very similar to the equipment used in this study, it may be said that this tends to apply for *Co-heating tests* in general.

In order to get reliable results the measurement equipment has to be of good quality with small measurement uncertainties, therefore it might be worth to invest in equipment with higher quality to ensure a more reliable result.

Economical aspects

The required equipment is less expensive in comparison to other verification methods used for buildings. Therefore, it should not be unreasonable from an economic perspective to introduce this method as a standard method for verification of the heat loss of a building.

The amount of measurement equipment is depending on the size and complexity of the measurement object. Hence, the costs related to the execution of the test will depend on the object.

Support measurements

The *Co-heating test* provides the total heat loss of a building. If it is of interest to separate the transmission loss from the infiltration loss, as it was in this study, support measurements will be necessary. In this study it was done in order to obtain an average heat transfer coefficient, which was the desired parameter in this study, to be able to compare with the requirements from the Swedish building regulation. In other researches, it has also been recommended to perform similar support measurements.

By choosing to perform additional measurements, the expenses will increase. It will also require more knowledge regarding execution of support measurements. However, if a building is to be verified according to a regulation it is most likely that measurements such as a *Blower door test* will be performed anyway.

9.2 Reliability

Preferable conditions

By performing this study knowledge has been gained about preferable and undesirable conditions during the test. Many of the findings regarding the optimal weather conditions correspond to the recommendations that earlier research regarding the original *Co-heating test* has stated.

The time of the year when the tests were conducted do not seem to have been ideal. The tests were performed in the months March and April when the external weather conditions were not optimal. But since the study was allocated to the period between January and June, and since the investigated premises were not available prior to that time, this was the only option.

To eliminate the uncertainties regarding the external weather conditions as much as possible, it might be beneficial to perform the measurements during periods with low wind influence and overcast weather. However, this might be challenging since the period of measurement extends over several days and the weather behaviour is not always easy to predict. It has also been learned that it is desirable for the measurements to achieve a large temperature difference between the inside and outside air and a minimal influence from the solar- and sky radiation. These are conditions that earlier research has indicated as well. Therefore, it seems that the measurements are best performed during the cold months, preferable with overcast weather, which in Sweden most probably is between October and February.

The most suitable time for performing the test connected to the life time of a building, can be challenging to decide. The test have shown that it must be conducted when no people are present in order to not affect the measurements. Therefore the test seems to best be performed directly after finished constructed, before people have moved in. However, to carry out the measurements during this period is not entirely optimal. Firstly, the sale and occupancy of the house will be delayed. Secondly, if performing the test direct after the house is finished constructed, the building will still contain built in moisture and additional energy needs to be used to dry out the building. Lastly, the time for the house to reach a steady state condition will be increased, since the thermal pillow under the house needs time to stabilize and also for the house itself to adapt to a new temperature.

Reasonableness of the results

For larger buildings such as the *Community building* it is shown that a major challenge is to maintain a stable temperature within the building, and keep the temperature diversifications between the rooms at a minimum, especially since no fans are used in this study. However, for measurement intervals of the *Community building* where the external and internal temperature conditions are fulfilled, it seems possible to obtain reasonable results without too large deviations from the theoretical calculated values.

When performing the test on room scale such as the *Guest room*, the results indicated that the test method may not be suitable for this application. The deviation between the measured practical value and the calculated theoretical value may be considered to be somewhat large, and the gap is difficult to identify. It is hard to say what caused these deviations; it may have been the heat loss to adjacent rooms or an excessive convection due to the fan. However, more research has to be done in order to confirm this.

It is probably better to conduct the test on a whole building instead of only a part, due to a measurement on a whole building scale enables a larger test area. If measurements are performed only on a part of a building, a construction defect or a design weakness may be too prominent which can lead to misleading results. If conducting the test on a whole building a possible deviation or defect in the construction is probably smoothed out and the risk for misleading results are smaller.

For a smaller construction consisting of only a single room, placed in a location with controlled external conditions, such as the *Friggebod*, the results appear to be rather reliable. The small volume makes it possible to achieve a quite stable and uniform interior temperature during the whole period of measurement. In combination with likewise a stable exterior temperature during the measurement, it is possible to utilize intervals from the complete logging period. This indicates that the method is a test that works rather well if the ambient conditions during the test is favourable.

The conditions for the test performed in the *Friggebod* are not consistent with the reality, as the actual external weather conditions are not stable. However, the result strengthens the hypothesis that reasonable results can be achieved if stable temperature conditions, together with minimal influence from other external weather parameters are achieved.

Uncertainties

The overall uncertainty of the *Co-heating method* is a combination of several different factors. Nevertheless, it is not always easy to ascertain the extent to which these will influence the result.

Equipment is one of the parameters that may lead to uncertainties of the results. Measurement instruments such as the thermostats on radiators, temperature loggers and energy/power loggers can cause deviations due to the tolerances of the instrument. These kinds of uncertainties related to the measurement instruments can rather easily be identified since information regarding tolerances of the instruments may be provided by the manufacturer. However, even though the manufacturer gives information about the measurement uncertainties there can still be deviations from those values due to manufacturing defects. It might also be a risk that the instruments are inadequately calibrated.

When performing tests it is also important to have a sufficient amount of equipment in order to get reliable results. This became a problem when performing the test in the *Community building*. Shortage in temperature loggers made it impossible to monitor the temperature in all rooms as initially desired. It is highly likely that the missing information would have influenced the result since the other temperatures logged indicated a spread in the indoor temperature, but to what extent is difficult to ascertain. However, it has probably not led to any major deviation.

Another influencing parameter is the simplification of the heat balance equation used to calculate the average heat transfer coefficient. Different assumptions are hidden in the simplifications, and will cause uncertainties in the final result. The majority of the external weather parameters, such as the sun radiation, sky radiation and the wind have been neglected in the formula since they were considered to have minor influence on the result. Since these uncertainties may be difficult to quantify, it might be important to counteract them as much as possible in the measurements and the data processing.

Due to these uncertainties and the difficulties by accounting them, it is problematic to determine a value for the overall accuracy or level of uncertainty.

9.3 Future outlook

Further research
There are still many uncertainties and challenges with the test which needs to be further analysed to be able to be dealt with. For further research of the *Co-heating test* the findings in this study can be useful to take into consideration.

For this study, it was proposed to implement a parameter study to be able to identify some of the uncertainties influencing the results. Unfortunately, due to time limitations it was no possible to carry out this analysis. A parameter analysis is therefore recommended for further study of the method, in order to be aware of which parameters that have large influence on the measurements and the results.

Repeatability is also important to achieve in order to strengthen the future prospects and further development of the test.

Standardization of the method
According to this study it is possible to see a potential for this method in the future. However, the current status of the test indicates that the method is not yet fully developed to be used as a standard method in the building industry.

9.4 Additional evaluations

Usage of existing heating system
If the building has installed electricity meters, the existing heating system can preferably be used, according to this study. This is beneficial since less equipment is needed and thereby the expenses with performing the test can be reduced.

Usage of fan
It have been learned during the tests in this study that the use of fans, in order to circulate the air, is a process that is rather sensitive. When fans are needed, it seems important that the created convection is not too large, since this tends to disturb the measurement results. The need of fans has to be evaluated for each individual case, depending on the size and geometry of the test objects.

Data processing method

In this study a different approach regarding the treatment of data is used in comparison to other studies, as it is known to date. In this section the mind-set of the data processing is discussed.

When choosing the right intervals from the measurement to be evaluated there are many parameters to consider and it is impossible to come up with a determination that will apply for all tests. All tests need to be evaluated separately dependent on the building type and the thermal conditions. The desire for the data processing method used in this study is to achieve intervals with reasonable stable conditions for the external and internal temperatures. In that way, it is possible to assume the interval to be in a steady-state condition, and the conducted heat is then time-independent providing a stationary average heat transfer coefficient. The study has also shown that in addition to a stable indoor temperature it seems important that the temperatures in the various rooms within the building do not deviate too widely in order to get results which are reliable.

The interesting intervals for the test objects used in this study seemed to be during the night periods when no solar radiation is present. For the night periods the data from the most stable hours have been chosen to be further analysed. Due to this, the length of the intervals varies between 4h to 11h. On account of that, some of the chosen measurement periods are relatively short and consists of few measurement points, due to 1h logging interval. Therefore it may have been more appropriate to measure the logging intervals more frequently than 1h, this to get more measurement data and by that more reliable results.

The logging periods for the original *Co-heating* test is said to preferable be performed for a period of 1- 3 weeks. However, this seems to be dependent on the conditions when performing the test. If the test is conducted during the cold months, then there might already be a sufficient temperature difference between the indoor and outdoor temperature and no elevation of the indoor temperature is necessary. The building may already be in steady state condition, and in case of that, the time for the measurements can most probably be shortened. Based on that, the time for performing the test may deviate on account of the prevailing conditions.

The thermal mass says something about how fast a building is able to respond to internal and external temperature fluctuations, and is very important to consider when choosing measurement intervals to use for data processing. For a heavyweight building, the night periods are probably not a good choice for choosing measurement intervals. This because the stored energy that is released during nights will probably affect the required energy needed to maintain the desired internal temperature. Instead a stable daytime interval seems more preferable. On the other hand that might be challenging especially in sunny conditions. The constructions that have been investigated in this study are common Swedish timber frame constructions, and may be categorized as lightweight construction. For these kinds of constructions the night periods tend to be the best choice regarding influence from the thermal mass, since lightweight construction does not have the same ability to store energy as a heavy built building. Irradiation on the external walls will likely enter the building during the day, and the radiation from the external environment will affect the internal temperature.

10 Conclusion

This study has investigated the usability, the reliability and the future outlook of the *Co-heating method*. In order to accomplish this, both theoretical approaches and practical methods were applied. Two different test objects were investigated.

This study shows that the method is in general rather easy to perform and not so practically challenging to install. The required equipment is simple and relative inexpensive to provide. However, knowledge within the field of building physics is essential to have as a basis when conducting the test.

The desire for the data processing method used in this study seems to be to achieve intervals with reasonable stable conditions for the external and internal temperatures. In that way, it is possible to assume the interval to be in a steady-state condition, thus a stationary average heat transfer coefficient can be estimated. In order to achieve as stable conditions as possible, it is desirable with a large temperature difference between the inside and outside air, and minimal influence from the solar- and sky radiation. This is conditions that earlier research has indicated as well. Therefore, it seems that the measurements are best performed during the cold months, preferable with overcast weather.

The measurements in this study indicates that the *Co-heating test* tends to give rather good results under beneficial conditions. The study indicates that the test is more suitable to perform on an entire building instead of only a part of a building. However, more research has to be done in order to confirm this, since the results may be affected by the chosen methodology in this study.

The conditions for the test performed in the *Friggebod* are not consistent with reality, as the actual external weather conditions are not stable. However, the result strengthens the hypothesis that reasonable results can be achieved if stable temperature conditions, together with minimal influence from other external weather parameters are achieved.

This study confirms that there are still many uncertainties associated with this test that needs to be identified. By making use of the knowledge that is achieved in this study and performing further research within the subject, the test method can be strengthen. Having that said, it is possible to see a bright potential for this test.

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12 Appendices

Appendix A Research Papers - Development of the Co-heating Test

Between 1970-1980

- *Electric Co-heating: A Method for Evaluating Sesonal Heatng Efficiencies and Heat Loss Rates in Dwellings* (Sonderegger & Modera, 1979)
- *Low Cost Performance of Passive Solar Buildings* (Palmiter, et al., 1979)

Between 1980 - 1990

- *Linford Low Energy Houses* (Everett, et al., 1985)
- PRISM: An Introduction (Fels, 1986)
- *Short-Term Energy Monitoring (STEM), Application of the PSTAR method to a Residence in Fredricksburg Virginia* (Subbarao, et al., 1988)
- *The Thermal Envelope Perspective – Past, present and future* (Howard & Saunders, 1989)

Between 1990 - 2000

- *Development of a Method for the Measurement of Specific Heat Loss in Occupied Detached Houses* (Lundin, et al., 2004)
- *Electric Coheating as a Means to Test Duct Efficeiency: Review and Analysis of the Literature* (Andrews, 1995)

Between 2000 - 2010

- *Inverse Modeling Toolkit: Numerical Algorithms* (Kissock, et al., 2003)
- *Development and Validation of a method aimed at Estimating Building Performance Parameters* (Lundin, et al., 2004)
- *Evaluating the Impact of an Enchanced Energy Performance Standard on Load-bearing Masonry Domestic Construction* (Wingfield, et al., 2006)
- *Measuring Residential Duct Efficiency With the Short-term Coheat Test Methodology* (Francisco, et al., 2006)
- *Thermal Performance of a Passive House: Measurements and Simulation* (Manioglu, et al., 2007)
- *Evidence for Heat Losses via Party Wall Cavities in Masonry Construction* (Lowe, et al., 2007)

Between 2010 - 2015

- *Whole House Heat Loss Test Method (Coheating)* (Wingfield, et al., 2010)
- *Low Carbon Housing – Lessons from Elm Three Mews* (Bell, et al., 2010)
- *Using Simulated Co-heating Tests to Understand Weather Driven Sources of Unceratinty Within the Coheating Test Method* (Stamp, et al., 2011)
- *Comparing Primary and Secondary Terms Analysis and Re-normalisation (Pstar) Test and Co-heating results* (Palmer, et al., 2011)
- *Reliability of Co-heating Measurements* (Bauwens, et al., 2012)
- *Quick Measurements of Energy Efficiency of Buildings* (Mangematin, et al., 2012)
- *Whole House Heat Loss Test Method (Coheating)* (Johnston, et al., 2012)
- *Review of Co-heating Test Methodologies* (Butler & Dengel, 2013)
- *Co-heating Test: A- state-of-the-art and Application Challenges* (Bauwens & Roels, 2014)
- *Adding Value and Meaning to Coheating Tests* (Stafford, et al., 2014)

Appendix B How to Perform the Original Co-heating Test

The heat loss factor that can be gained by this test is a combination of the transmission losses and the ventilation losses. In order to separate these parameters additional practical measurements have to be done. *Blower door test* or *Tracer gas test* are methods that can be used for detaching the ventilation losses from the transmission losses (Bauwens & Roels, 2014).

Internal heat gains

Before the *Co-heating test* can start some preparations have to be made. All internal gains shall be turned off or removed, this to be able to reduce the effects of unwanted internal gains. To prevent disturbances and internal loads from people inside the building, the house shall be unoccupied during the whole period of measurements (Johnston, et al., 2012).

Air leakage

Reduction of influences of external air movements is required and in order to accomplish this all openings connected to the building envelope shall be closed. This means that all doors, windows and ventilators shall be sealed as well as trickle vents and acoustic vents. Air leakage can also find its way through flues and drainage traps. To avoid this, there shall be water in the drainage traps, and the flues shall be closed throughout the test. During the test all internal doors shall be opened and if there are any storage cupboards, also those shall be opened to ensure uniform conditions throughout the whole building (Johnston, et al., 2012).

Figure B.1 Preparations for the Co-heating test.

Divide into zones

Inside the investigated building it might be needed to divide rooms and floors into different zones (Butler & Dengel, 2013). If a floor or some rooms have an increased glazing or is exposed to an increased level of solar radiation these shall be divided into separate zones. If this is not the case, it is common to have the rooms on one floor in the same zone. Depending on how many zones the dwelling is divided into, the placement of the different appliances are different. Even if the dwelling is divided into zones, the house shall still have the same measuring conditions everywhere, uniformity is desirable.

Heating and measuring electrical energy

The performance of the test can be explained as homogeneously heating the interior of a building and meanwhile measure the energy consumption as well as the interior and exterior climate conditions (Johnston, et al., 2012).

During the test the electrical energy use that is needed for keeping the elevated temperature shall be measured. The indoor air temperature shall be increased to typically 25 °C and the heating shall be done by using electrical heaters. To ensure that the heat is spread equally throughout the house fans may be needed. The increased temperature shall be kept constant throughout the whole period of measurements, which usually lasts for 1-3 weeks after the building has been saturated by heat. Throughout the entire period of measurements the electrical energy use needed to maintain the increased temperature level shall be monitored. The data from the measured parameters shall be collected 24 hours a day and the data shall be collected in a suitable interval, for example every 10 minutes (Johnston, et al., 2012).

Figure B.2 Measurement of energy use and indoor temperature.

Measure thermal conditions

The indoor air temperature and the external weather conditions shall be measured during the period. Also the outdoor air temperature and the solar radiation as well as the wind direction and its speed shall be measured (Bauwens & Roels, 2014). Preferably the indoor relative humidity shall be measured as well. This to gain information about whether the heat only has been used for elevating the internal temperature, or if the heat has also been used for drying out the building (Johnston, et al., 2012).

Analyse the data

By measuring the electrical energy use for retaining the elevated indoor temperature the building's heat loss can be determined by interpretation and analysis of the gathered data (Bauwens & Roels, 2014).

Equipment for indoor measurements

The increase of the internal temperature shall be done with an electric heater. Appliances that are common to use are convector heaters or fan heaters. Since the internal room temperature shall be kept at a constant level it has to be possible to control the temperature from the heaters which can be done by a room thermostat or a digital temperature controller. Circulation fans are also common to use, to be able to circulate the air and to prevent from stratification. The amount of heaters and fans that is needed is depending on the design and layout of the building. The equipment shall be able to accomplish the elevated temperature of 25 ℃ in the whole building. In case of a large amount of windows facing towards south, overheating shall be prevented by fans. The electric energy use shall be measured for all the equipment that is used in the building. Electrical devices that is not a part of the measurement equipment in the dwelling shall be turned off, but if something additional has to be running, the energy use of that appliance shall be measured. The internal data that needs to be measured is the temperature, the air humidity and the electrical energy used. To be able to monitor this it is preferable to have a data logger which can collect the electrical energy use and temperature sensors which have a built- in logging function (Johnston, et al., 2012).

The electric heaters shall be located so that the out coming heat can be spread freely in the room, it shall not be directed towards a wall or any close obstacles. If there are a lot of small room inside the house, many heaters may be required. For a case with two floors or a high level to the ceiling, an increased number of fan heaters can be needed as well (Johnston, et al., 2012).

Adjacent buildings or apartments

If the dwelling that is to be tested is located adjacent to another building, apartment or similar this has to be taken into account. The adjacent construction will affect the measurements of the investigated building. To reduce the impact of the neighbouring construction a possible solution is to heat up not only the test object but also the adjacent building. If the possibility to heat up the neighbouring building is reduced, a solution in order to be aware of the heat fluxes through the party wall is to mount heat flux plates on the separating wall (Johnston, et al., 2012).

Measure outdoor conditions

In order to get reliable and suitable data it is important to measure the external weather conditions carefully. Some parameters are essential and some are only seen as desirable to have information about. The solar irradiance is a parameter that is essential to monitor to be able to correct the measurements for the solar heat gains to the building. The solar irradiance is not taken into account in the calculations, but by measuring, it is possible to leave out the data for the days when the sun have been strong. The outdoor air temperature is also a significant parameter to measure. Information about the wind is counted as desirable to receive information about. The placing of the measuring equipment is important to be located at an area where the external disturbances are minimized.

The sensor that registers the air temperature shall preferably be placed in a radiant shield to prevent influences by the direct sun. Nor shall it be attached to a dark surface which becomes very warm if the sun is shining on it. It is preferable to place the sensor on the north side of the building if the sensor is attached to the wall, in order to minimize heat transfer from a warm wall. The irradiance measurement appliance shall be placed at a location where the disturbances are minimized. The appliance shall be located at an area where there is no shading or building reflections.

The wind is useful to have information about, on account of that the wind and its speed affects the ventilation heat loss due to the convective heat losses. The effect of the wind is depending on the airtightness of the building fabric. A windy weather condition can for a longer period of time increase the heat loss coefficient considerably. A possibility in order to reduce the need of this measurement is to perform the measurements during low wind- weather. Another possibility is to leave out the measured data for the days when the wind has been strong (Butler & Dengel, 2013).

Appendix C How to Perform an Air Tightness Test

In order to perform the test, a decision regarding if it shall be conducted as a multi-point test or a one- point test have to be decided. A one point test only measures at a single point. If this test is chosen no computer is needed in order to analyse the data. With the multipoint test the building is tested for a range of pressures, from 60 Pa to 15 Pa, usually with 8 different pressures. Two different types of tests are possible to perform; pressurization and depressurization of the house. Often both of them are performed and then a mean value of the two results is calculated. But for some circumstances either pressurization or depressurization are more preferable. A pressurization test is mostly used when a fireplace is present. This is on account of that smoke and pollutants has to be prevented from being pulled into the building (The Energy Conservatory, 2012).

Figure C.1 Mounted Blower door test equipment

C.1 Equipment for the Test

There are several manufacturers on the market today that offers so-called *Blower Door systems*, which includes all necessary equipment needed to perform a *Blower door test*. The *Blower Door system* that this manual covers is the *Minneapolis BlowerDoor measurement system model 3,* which is manufactured by *The Energy Conservatory* (The Energy Conservatory, 2012). The equipment that comes with the system is shown in the picture below.

When the fan is operating, air is pulled into the inlet side and out through the outlet side of the fan. The fan is equipped with flow rings that are used to control the flow rate. The rings are attached to the inlet of the fan. Chosen size of the ring depends on the airflow needed i.e. how airtight the building is (The Energy Conservatory, 2012).

The test instrument enclosed with *model 3* is the *DG-700 Digital Pressure Gauge*. This controller monitors the building pressure and the fan pressure signals during a *Blower door test*. The DG-700 can be used to control the *Blower door* fan automatically by using either TECTITE software or the built-in cruise control that allows controlling the *Blower door* fan without a software (The Energy Conservatory, 2012).

The fan speed controller is used to control the speed of the *Blower door* fan. This can be done manually by just adjusting the knob, or it can be done automatically by using the *DG-700* (The Energy Conservatory, 2012).

Figure C.2 DG-700 Digital Pressure Gauge and adjustable aluminium frame with nylon panel.

To seal the door opening where the fan is placed, an adjustable aluminium frame with a nylon panel is used. The aluminium frame can be resized and adjusted to fit any typical size of a residential door opening (The Energy Conservatory, 2012).

C.2 Execution of the test

Mounting of the frame
Mount the frame in the door opening in an approximate size. Thereafter mount the nylon panel on the frame and put back the aluminium frame in the door opening, and tighten up the frame (The Energy Conservatory, 2012).

Placement of the fan
Place the fan in the opening of the nylon panel. A green plastic hose used for measuring the air pressure outdoor, shall be drawn out in the whole in the right corner of the panel. It shall be placed in such way that the wind will be influencing as less as possible. This will increase the accuracy of the measurement. .

For fan model 3, depressurization is conducted when the side with the rings is be directed into the room and the exhaust side is directed facing the outside. For pressurization the fan shall be directed in the opposite direction; the side with the rings shall be facing the exterior and the exhaust side of the fan shall be directed towards the relevant room. (The Energy Conservatory, 2012).

Figure C.3 Adjust the frame, mount the nylon panel on the frame, and put the frame back in the door opening and tighten up the frame.

Mount the gauge

The other end of the green tubing shall be connected to the green marked valve on the gauge and the red tubing to the red marked valve. The other end of the red tubing shall be attached to the fan, if using ring D or E than the end which goes to the fan shall be connected to the vent on ring D instead. If pressurization is conducted also a transparent tubing shall be connected to the outside and the other end to the gauge (The Energy Conservatory, 2012).

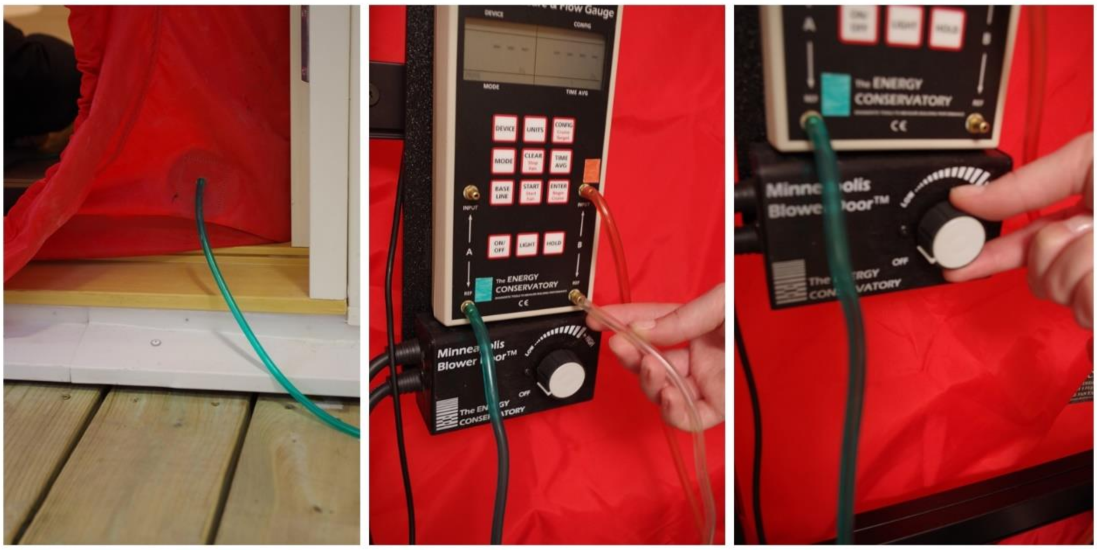


Figure C.4 Green tubing drown out the whole in the right corner of panel, other end connected to the valve on the gauge marked green. Red tubing on the gauge market red. If pressurization conducted, transparent tubing connected to the gauge also. Test-drive the fan to see if the frame is mounted correctly.

Figure C.5 Other end of red tubing connected to the fan. If using ring D or E, other end of tubing connected to vent on ring D.

Trial of the fan
Before starting the actual test it might be useful to test drive the fan to see if the frame is mounted correctly. Test the fan at maximal under pressure and control for unintended air leakages (SINTEF Byggforsk, 2012).

Connection to a computer with a relevant data program
If connection to a data program shall be used, instructions on the screen will be visible. These can preferably be followed in order to proceed with the test (The Energy Conservatory, 2012).

Measure the baseline building pressure
When performing the baseline the ring without any opening shall be mounted to the fan alternatively the covering for the fan (The Energy Conservatory, 2012).

Start the test and adjust to a suitable ring size
Depending on the size and the degree of airtightness of the room, different ring sizes is required (The Energy Conservatory, 2012).

Decide the pressurization and measure the pressure difference
By starting the fan and adjust the ring size the air flow can be decided (The Energy Conservatory, 2012).

Collect data
If using the computer program the data will automatically be performed, otherwise the data has to be manually read of the display (The Energy Conservatory, 2012).

Appendix D How to Perform an Infrared Thermographic Test

Define the task
Initially, begin with deciding the purpose of the test. What should the thermal imaging contribute with (FLIR Systems AB, 2012)?

Investigate temperature difference
The temperature difference between the outside and inside shall be investigated. To get reliable results there have to be a sufficient temperature difference between the inside and the outside (FLIR Systems AB, 2012).

Thermographic inspection from outside
Start with investigating the building from the outside. Here insulation defects and thermal bridges may easily be localized (FLIR Systems AB, 2012).

Thermographic inspection from inside
This step requires some thorough preparation to achieve the best reliable result. Furniture needs to be moved from the wall and curtains needs to be taken down sufficient time in advance of the inspection, since these might have an insulating effect (FLIR Systems AB, 2012).

When the preparation is done the imaging can start. It is important to have control over where the images have been taken. This can easily be done by marking with an arrow on the floor and in a floor plan to show exactly from which angle the thermal image has been taken (FLIR Systems AB, 2012).

Combine with an airtightness test
By performing an airtightness test in combination with thermographic imaging, it will be much easier to localize the path of the air infiltration since the airtightness test will amplify the air leakage through the building envelope. The thermal imaging should be performed when depressurizing the building. Due to the negative pressure indoor, cold air will flow in through cracks in the building envelope and cool down the surrounding areas of the cracks. The temperature difference will then be clearly visible in the thermal image as a cold area, which makes it easier to localize (FLIR Systems AB, 2012).

Equipment
An infrared camera is needed to perform this test. Optional a *Blower Door system*.

Analysis and report
When the thermal imaging is done, the pictures should be analysed and a report should be developed for easier presentation of the inspection. A software may become handy to interpret the result, to create a report of the inspection, or if the picture needs to be edited in afterwards. In this report, the software *FLIR QuickReport* is used (FLIR Systems AB, 2012).

Appendix E Thermal Bridges, Community Building

Components/Details	Length [m]	Ψ [W/m·K]	ΣΨ*l [W/K]
External wall/Slab on ground	40.191	0.1703	6.845
External wall/External wall, external corner	17.327	0.0222	0.385
External wall/External wall, internal corner	4.351	0.0268	0.117
External wall/Window, horizontal	42.365	0.0563	2.385
External wall/Window, vertical	32.280	0.0494	1.595
Door/Slab on ground	9.120	0.2872	2.619
External wall/Door	26.590	0.0556	1.478
External wall/Slab	17.245	0.0613	1.057
External wall/Pitched roof	24.602	0.0552	1.358
Pitched roof/Flat roof	9.148	0.0596	0.545
Parapet/roof	27.064	0.0400	1.083
Pitched roof/Pitched roof	10.000	0.0679	0.679
Total			**20.145**

Calculated according to *SS-EN ISO 10211:2007* (Swedish Standards Institute, 2008) in *BLOCON Heat2.*

Appendix F Thermal Bridges, Guest Room in Community Building

F.1 For heat loss through external surfaces (adiabatic interior walls)

Components/Details	Length [m]	Ψ [W/m·K]	ΣΨ*l [W/K]
External wall/Slab on ground	8.402	0.1703	1.431
External wall/Pitched roof	4.750	0.0552	0.262
Parapet/Roof	4.108	0.0400	0.164
External wall/External wall, external corner	2.486	0.0222	0.055
External wall/Window, horizontal	4.840	0.0563	0.272
External wall/Window, vertical	5.240	0.0494	0.259
External wall/Door	5.230	0.0556	0.291
Slab on ground/Door	1.010	0.2872	0.290
Internal wall, Guest room/hallway / External wall	2.486	0.0127	0.032
Internal wall, Guest room/bathroom / External wall	2.684	0.0182	0.049
Internal wall, Guest room/2nd floor / External wall	1.324	0.0203	0.027
Internal wall, Guest room/2nd floor / Roof	4.750	0.0088	0.042
Internal wall, Guest room/hallway / Roof	4.108	0.0126	0.052
Total			**3.226**

Calculated according to *SS-EN ISO 10211:2007* (Swedish Standards Institute, 2008) in *BLOCON Heat2.*

F.2 For heat loss through internal surfaces

Components/Details	**Length [m]**	**Ψ [W/m·K]**	**ΣΨ*l [W/K]**
Internal wall, Guest room/hallway / External wall	2.486	0.0597	0.149
Internal wall, Guest room/bathroom / External wall	2.684	0.0278	0.075
Internal wall, Guest room/2nd floor / External wall	1.324	0.0448	0.059
Internal wall, Guest room/2nd floor / Roof	4.750	0.0532	0.253
Internal wall, Guest room/hallway / Roof	4.108	0.0280	0.115
Internal wall, Guest room/hallway / Slab on ground	3.660	0.4515	1.652
Internal wall, Guest room/cleaning room / Slab on ground	2.229	0.4049	0.903
Internal wall, Guest room/bathroom Slab on ground	2.382	0.3877	0.924
Internal wall, Guest room/hallway/cleaning room, external corner	2.684	0.0031	0.008
Internal wall, Guest room/hallway/2ndfloor, external corner	1.324	0.0031	0.004
Internal wall guestroom/cleaning room/bathroom	Simplification: Have chosen to neglect these two thermal bridges due to negligible temperature difference between the rooms (hallway, 2nd floor, cleaning room and bathroom)		
Internal wall, Guest room/slab 2nd floor			
Total			**4.141**

Calculated according to *SS-EN ISO 10211:2007* (Swedish Standards Institute, 2008) in *BLOCON Heat2.*

Appendix G Thermal Bridges, Friggebod

Components/Details	**Length [m]**	**Ψ [W/mK]**	**ΣΨ*l [W/K]**
External wall/Slab 1	3.153	0.0590	0.186
External wall/Slab 2	7.848	0.0717	0.563
External wall/Roof 1	7.848	0.0667	0.523
External wall/Roof 2	5.028	0.0530	0.266
External wall / External wall	9.032	0.0751	0.678
External wall, window	11.030	0.0749	0.826
Total			**3.042**

Calculated according to *SS-EN ISO 10211:2007* (Swedish Standards Institute, 2008) in *Comsol Multiphysics*

Appendix H Measurement Result with Chosen Intervals, Community Building

H.1 Test 1

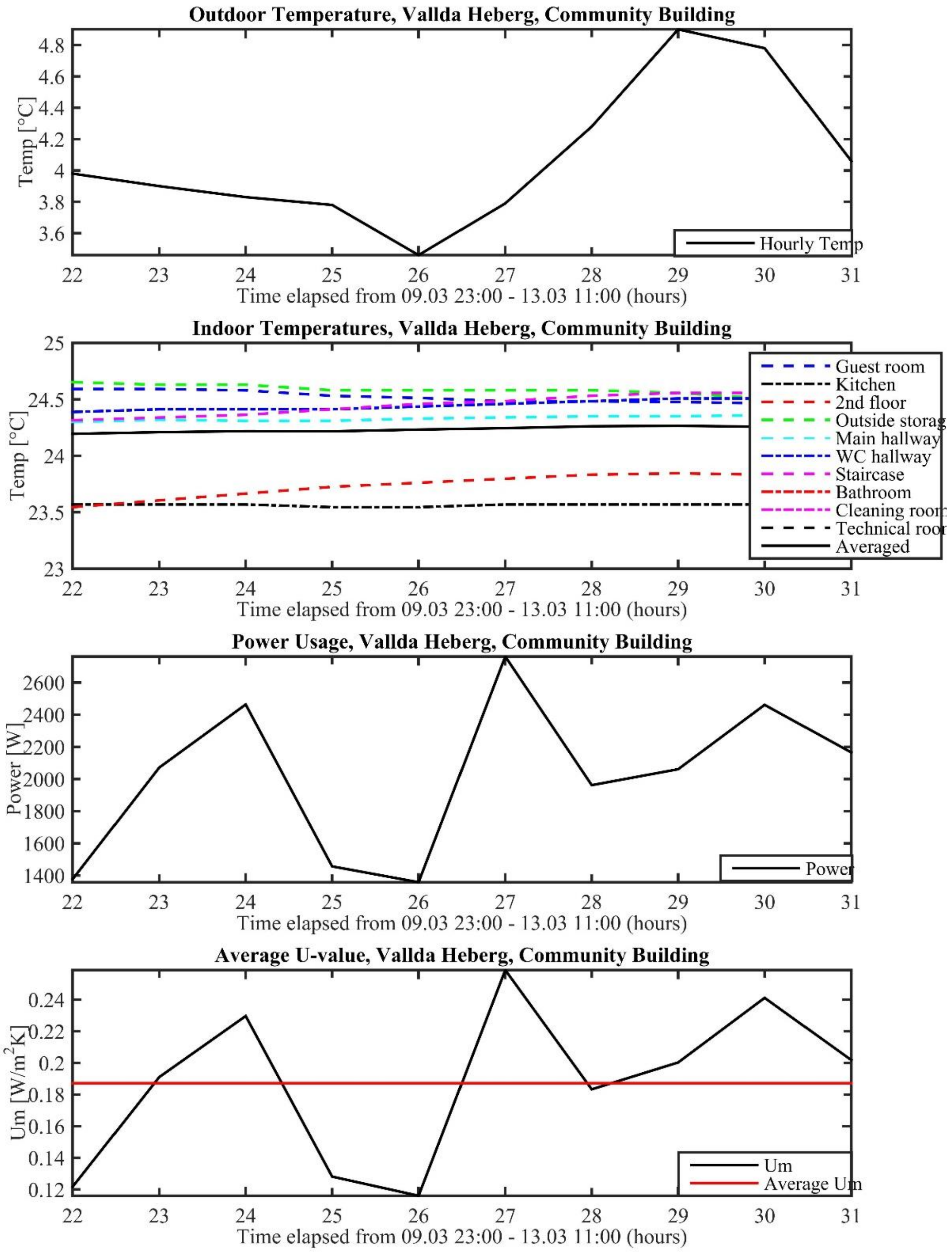


Figure H.1 Measurement result of interval 1; 2015-03-10 23.00 – 2015-03-11 06.00, for Community building test 1

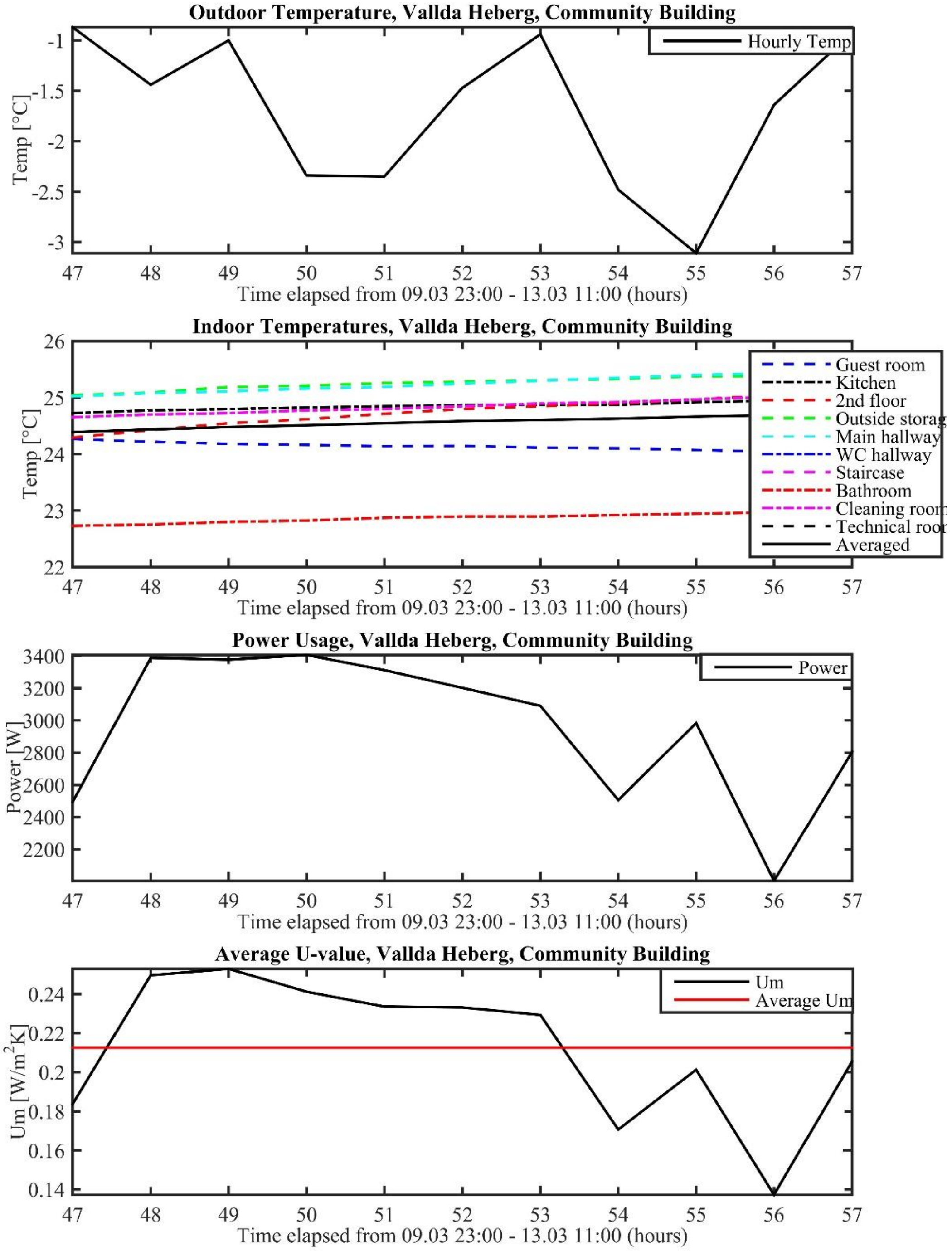
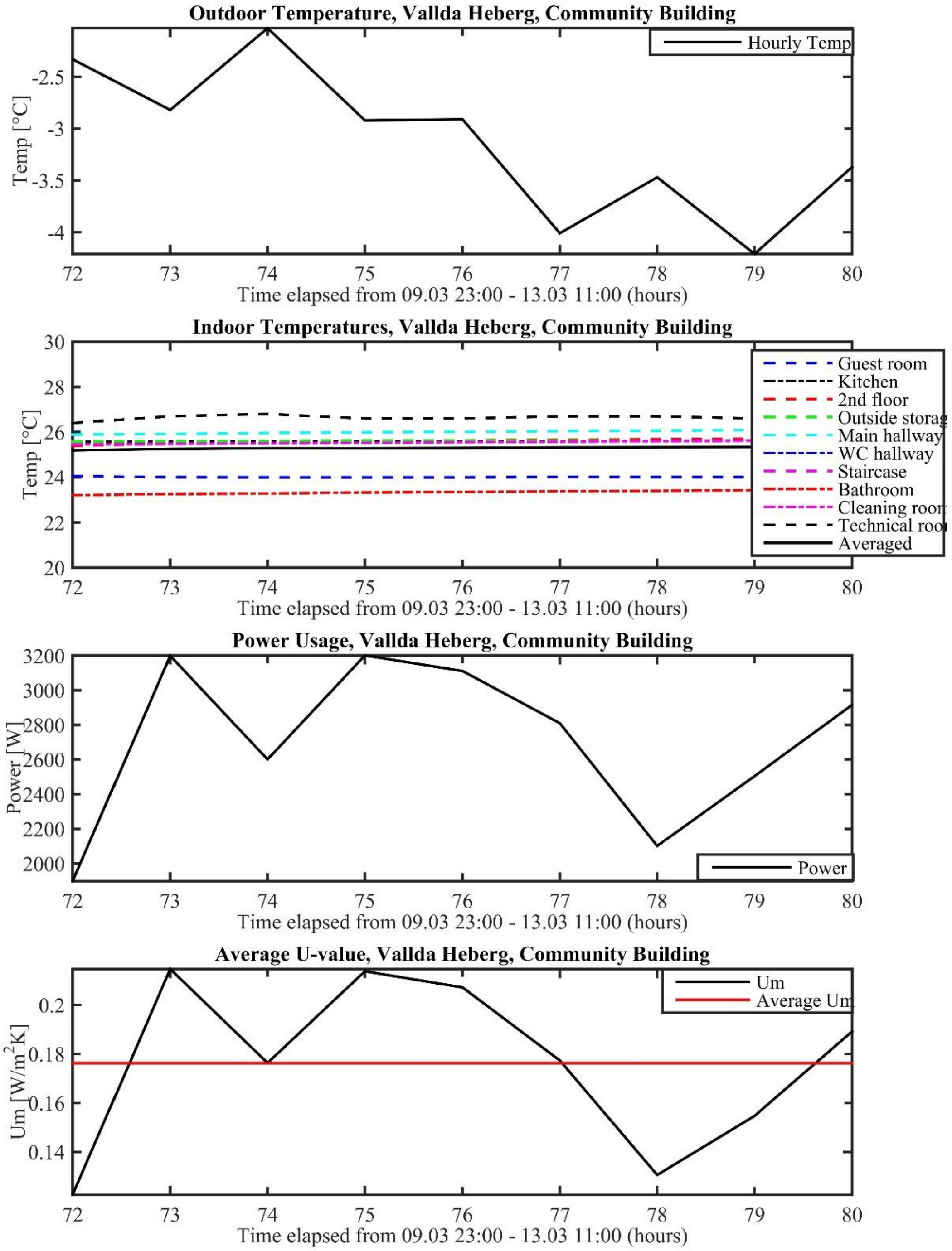


Figure H.2 Measurement result of interval 2; 2015-03-11 22.00 – 2015-03-12 08.00, for Community building test 1


Outdoor Temperature, Vallda Heberg, Community Building

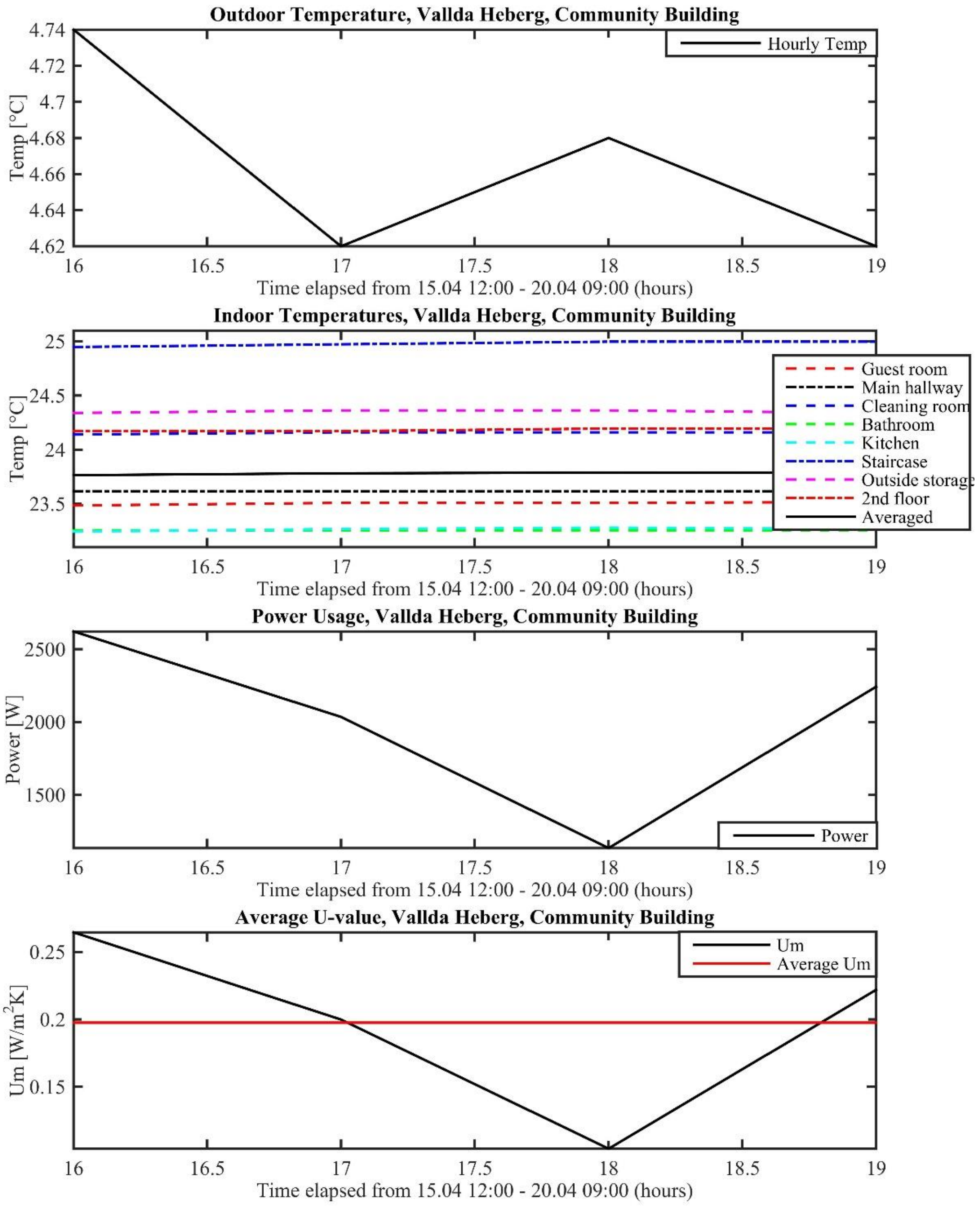
Indoor Temperatures, Vallda Heberg, Community Building

Power Usage, Vallda Heberg, Community Building

Average U-value, Vallda Heberg, Community Building

Figure H.3 Measurement result of interval 3; 2015-03-12 23.00 – 2015-03-12 07.00, for Community building test 1

H.2 Test 2



Outdoor Temperature, Vallda Heberg, Community Building

Indoor Temperatures, Vallda Heberg, Community Building

Power Usage, Vallda Heberg, Community Building

Average U-value, Vallda Heberg, Community Building

Figure H.4 Measurement result of interval 1; 2015-04-16 02.00 – 2015-04-16 07.00, for Community building test 2.

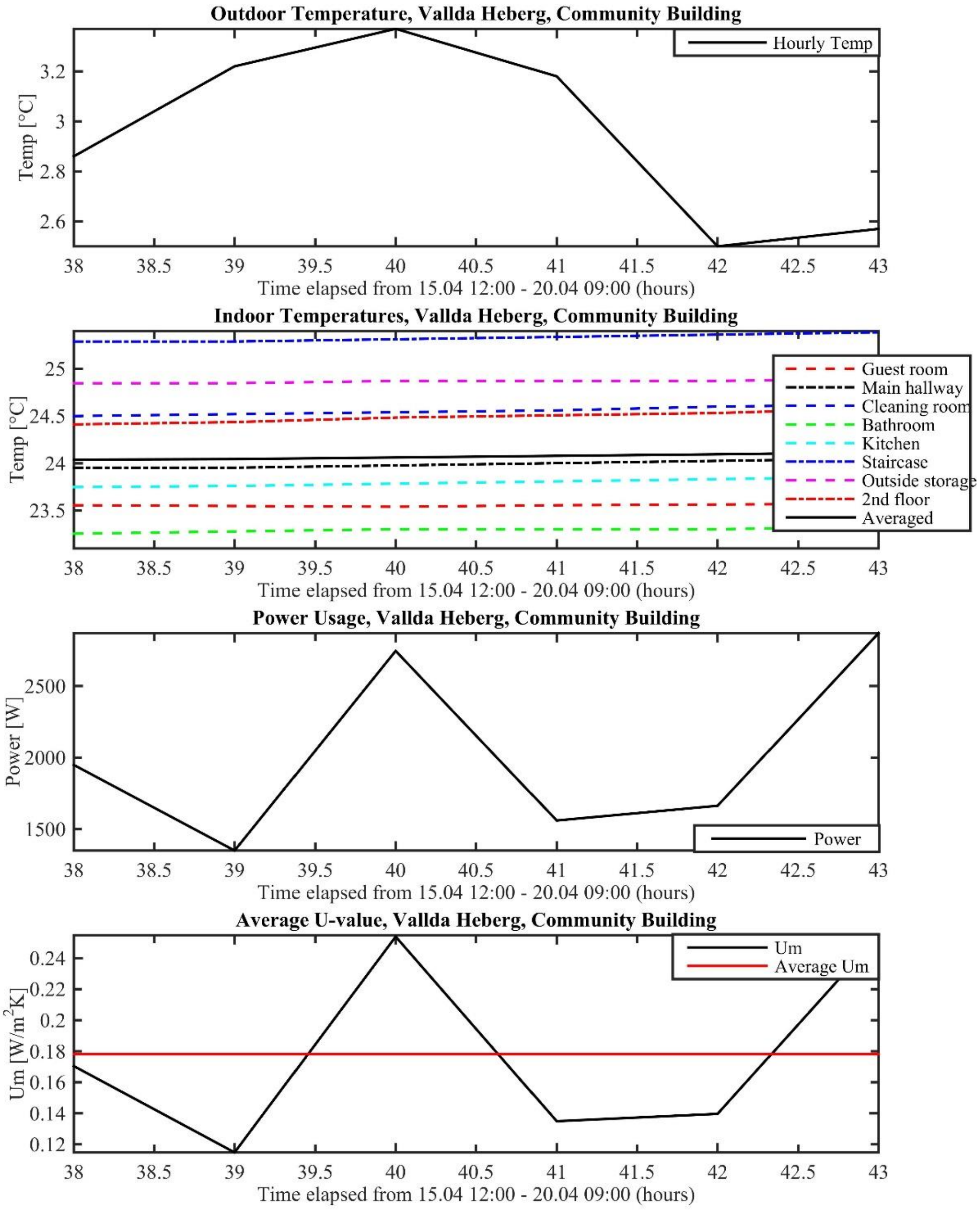


Figure H.5 Measurement result of interval 2; 2015-04-17 22.00 – 2015-04-17 07.00, for Community building test 2

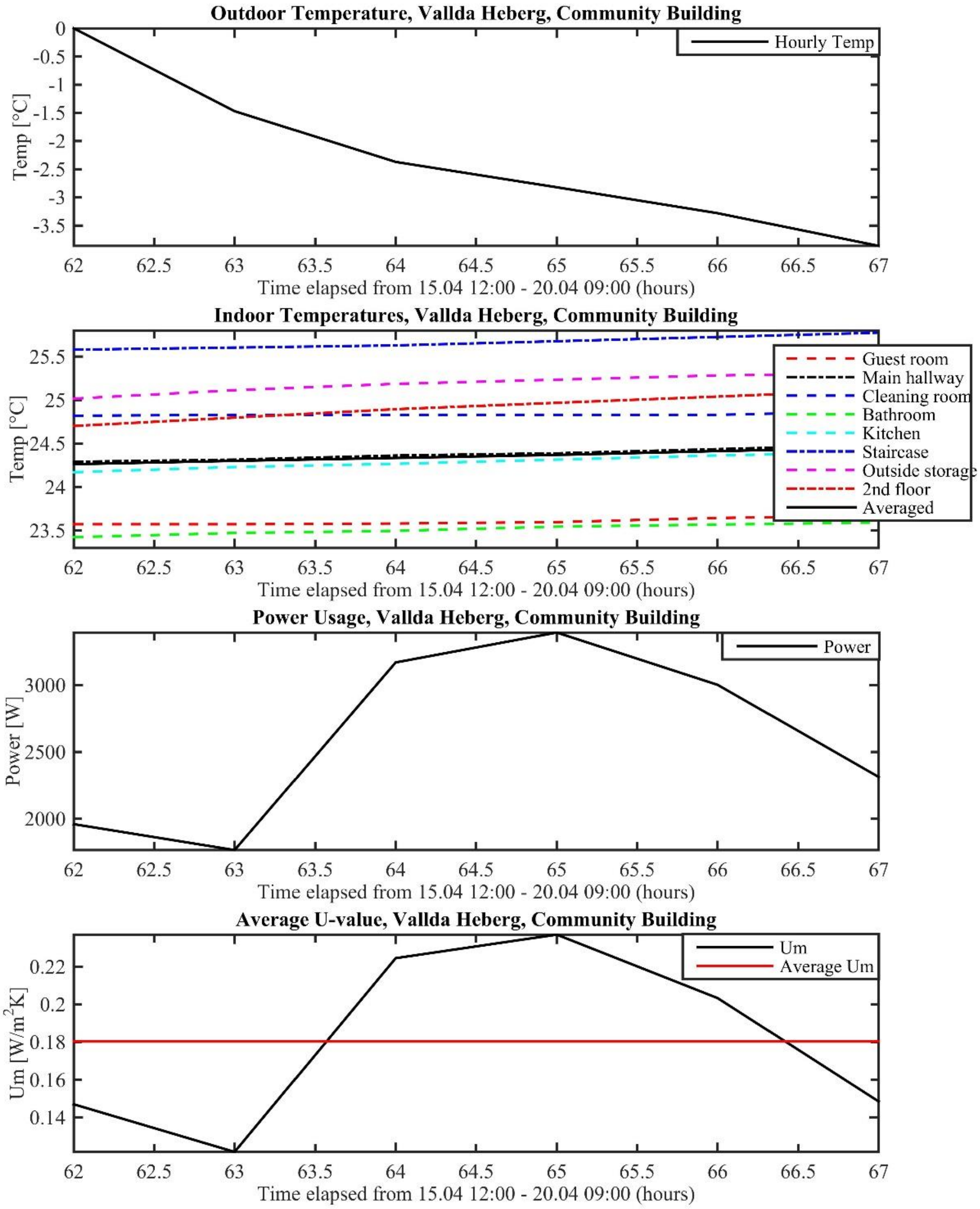


Figure H.6 Measurement result of interval 3; 2015-04-18 02.00 – 2015-04-18 07.00, for Community building test 2.

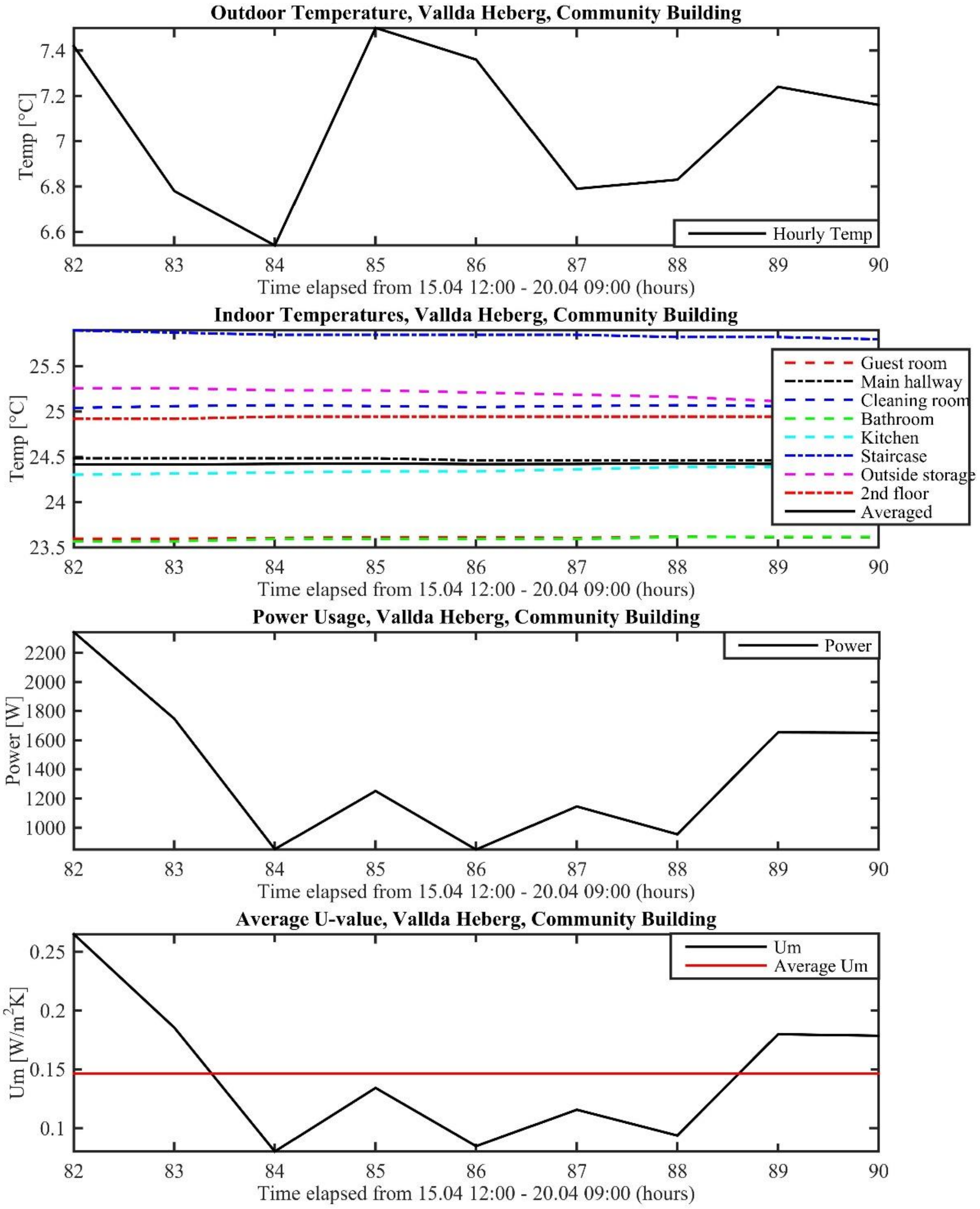


Figure H.7 Measurement result of interval 4; 2015-04-18 22.00 – 2015-04-19 06.00, for Community building test 2.

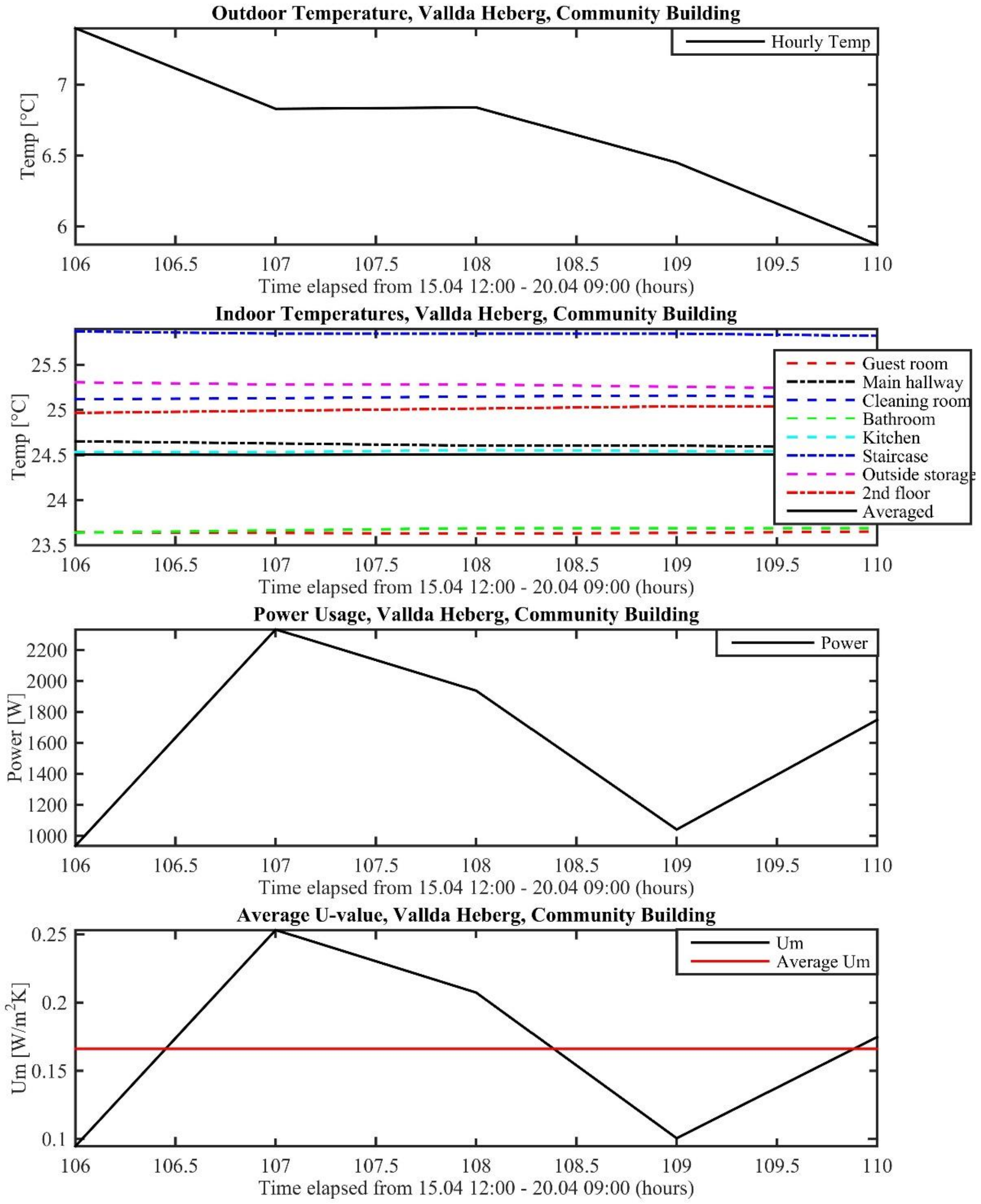


Figure H.8 Measurement result of interval 5; 2015-04-19 22.00 – 2015-04-20 02.00, for Community building test 2.

Appendix I Measurement Result with Chosen Interval, Guest Room

I.1 Test 1

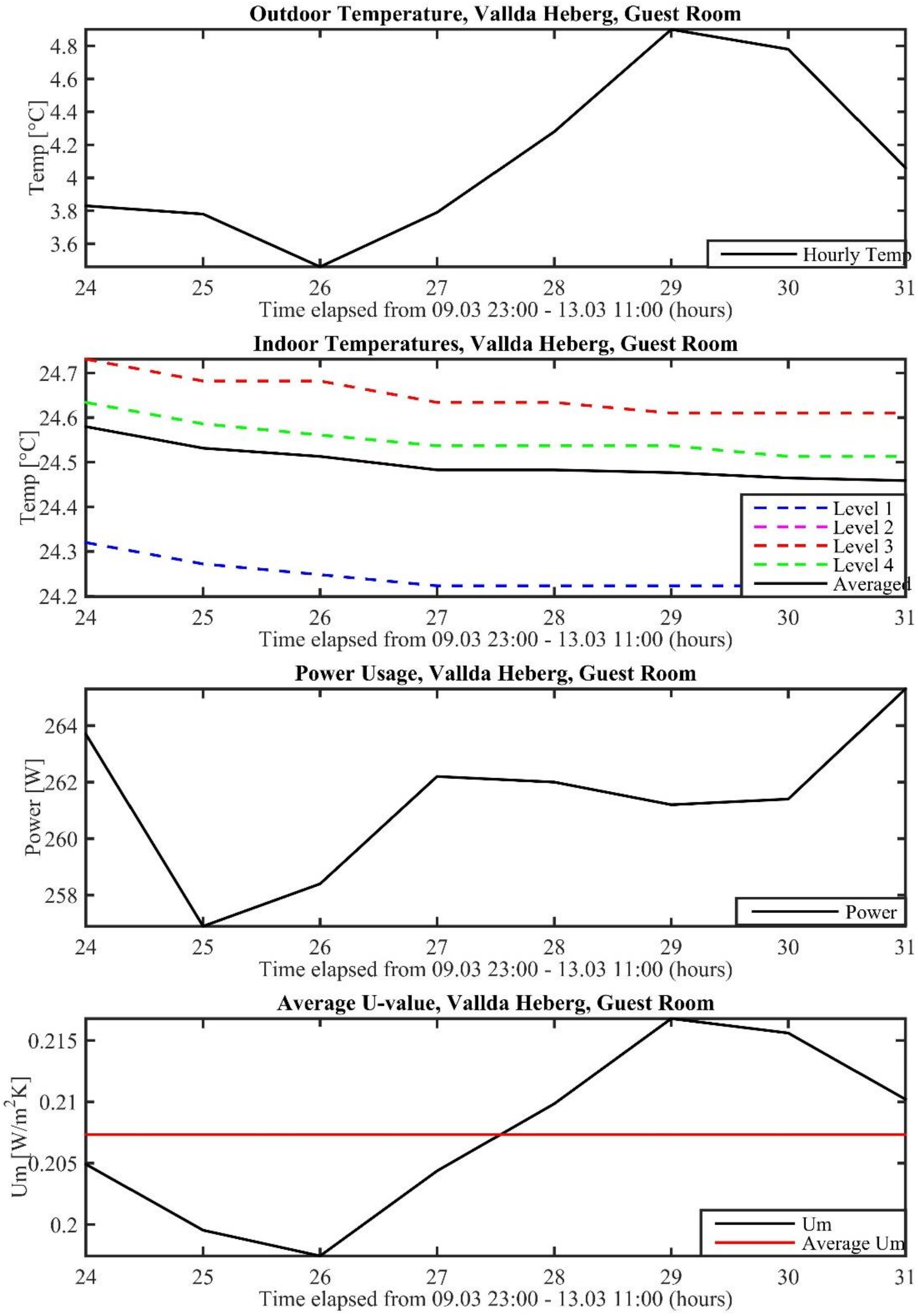


Figure I.1 Measurement result of interval 1; 2015-03-10 23.00 – 2015-03-11 06.00, for Guest room test 1.

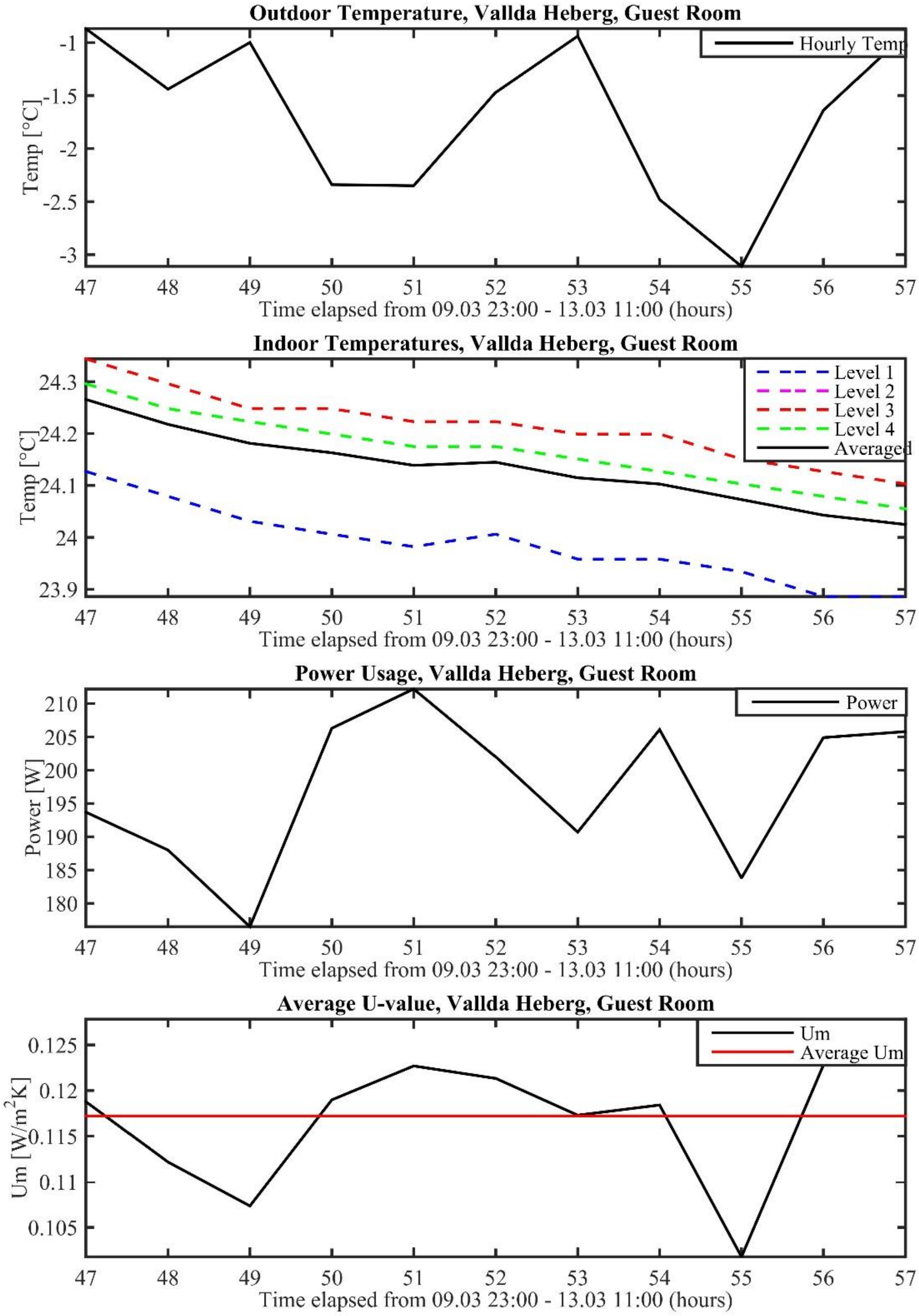


Figure I.2 Measurement result of interval 2; 2015-03-11 22.00 – 2015-03-12 08.00, for Guest room test 1.

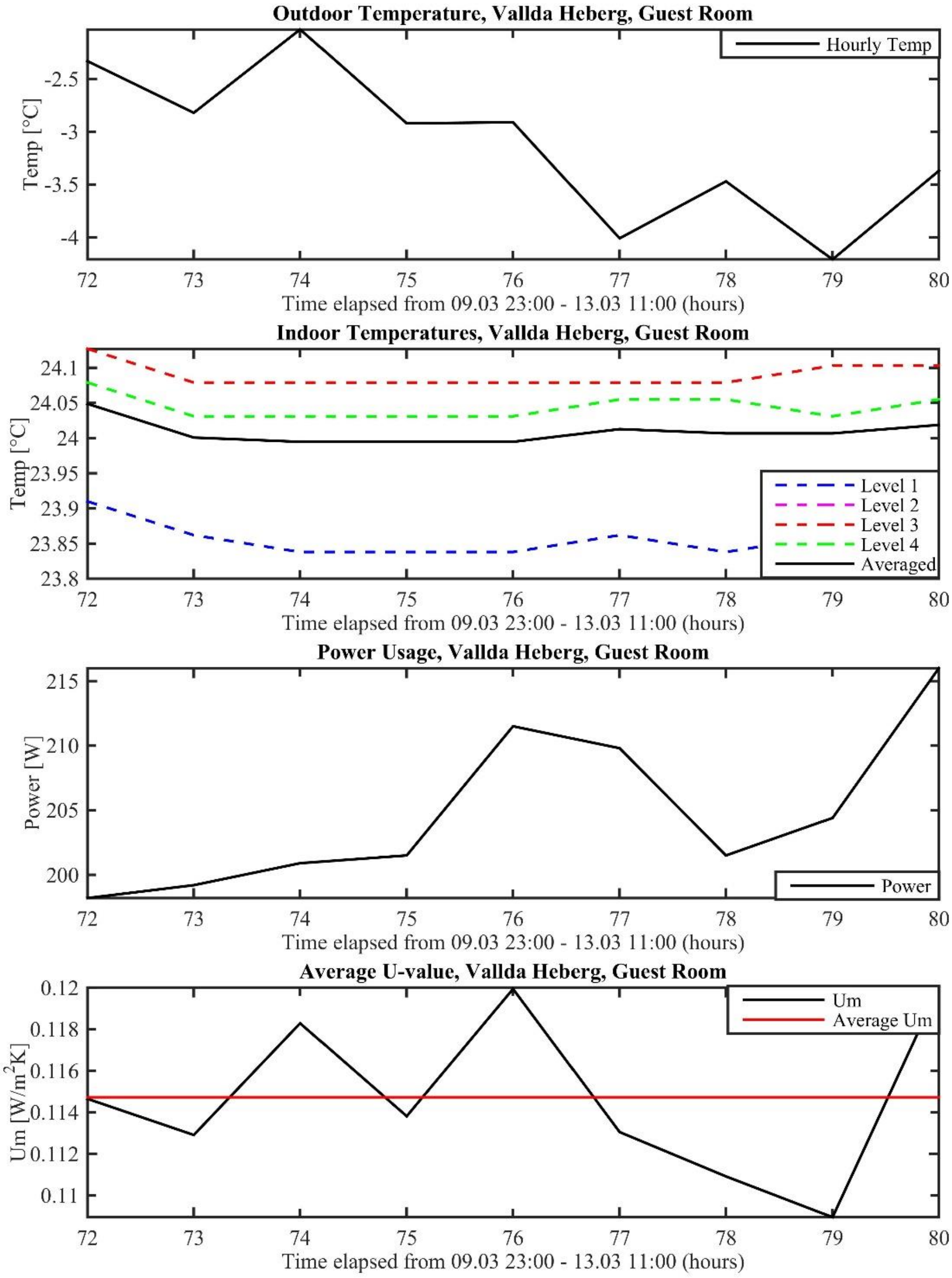


Figure I.3 Measurement result of interval 3; 2015-03-12 23.00 – 2015-03-13 07.00, for Guest room test 1.

I.2 Test 2

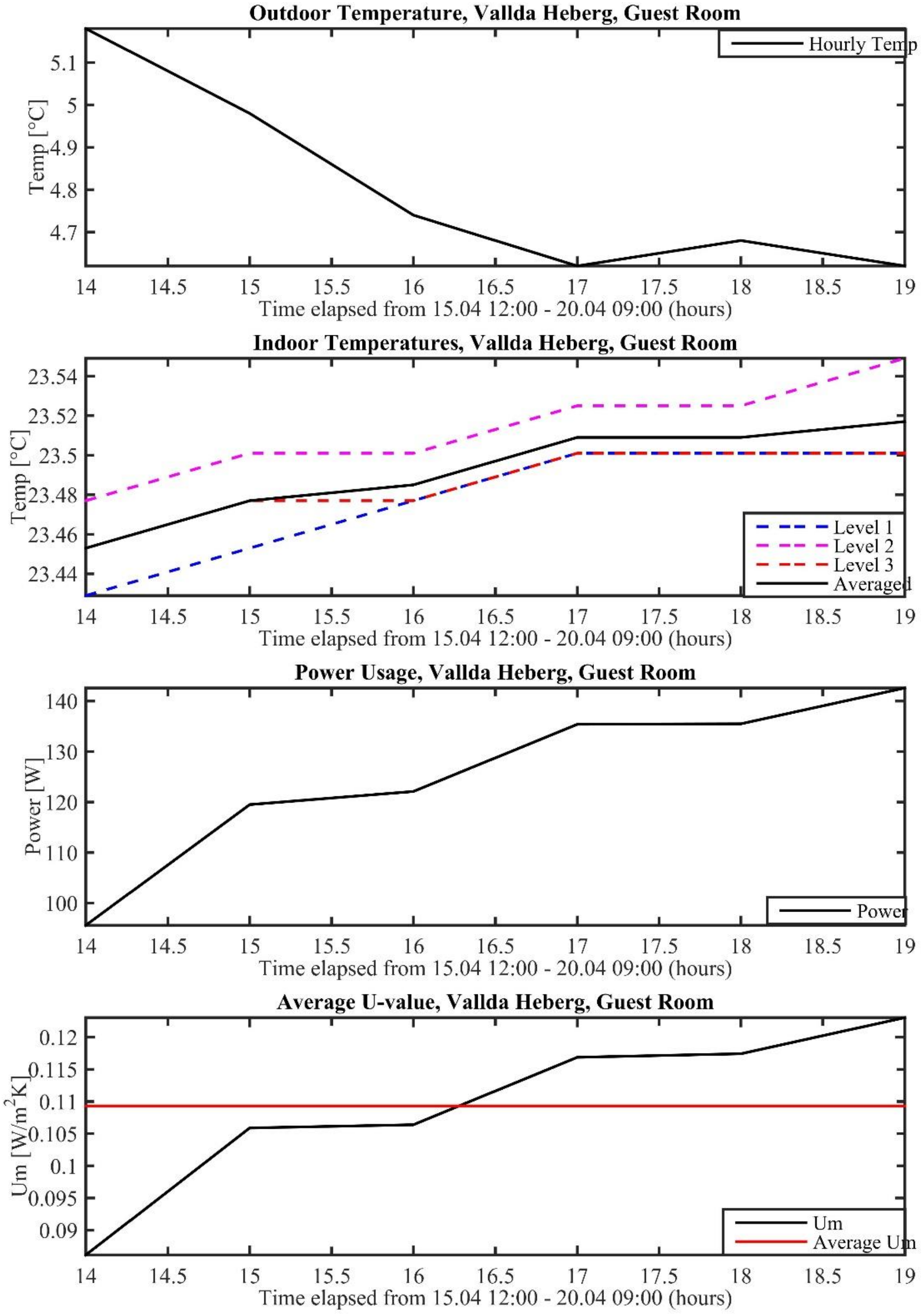


Figure I.4 Measurement result of interval 1; 2015-04-16 02.00 – 2015-04-16 07.00, for Guest room test 2.

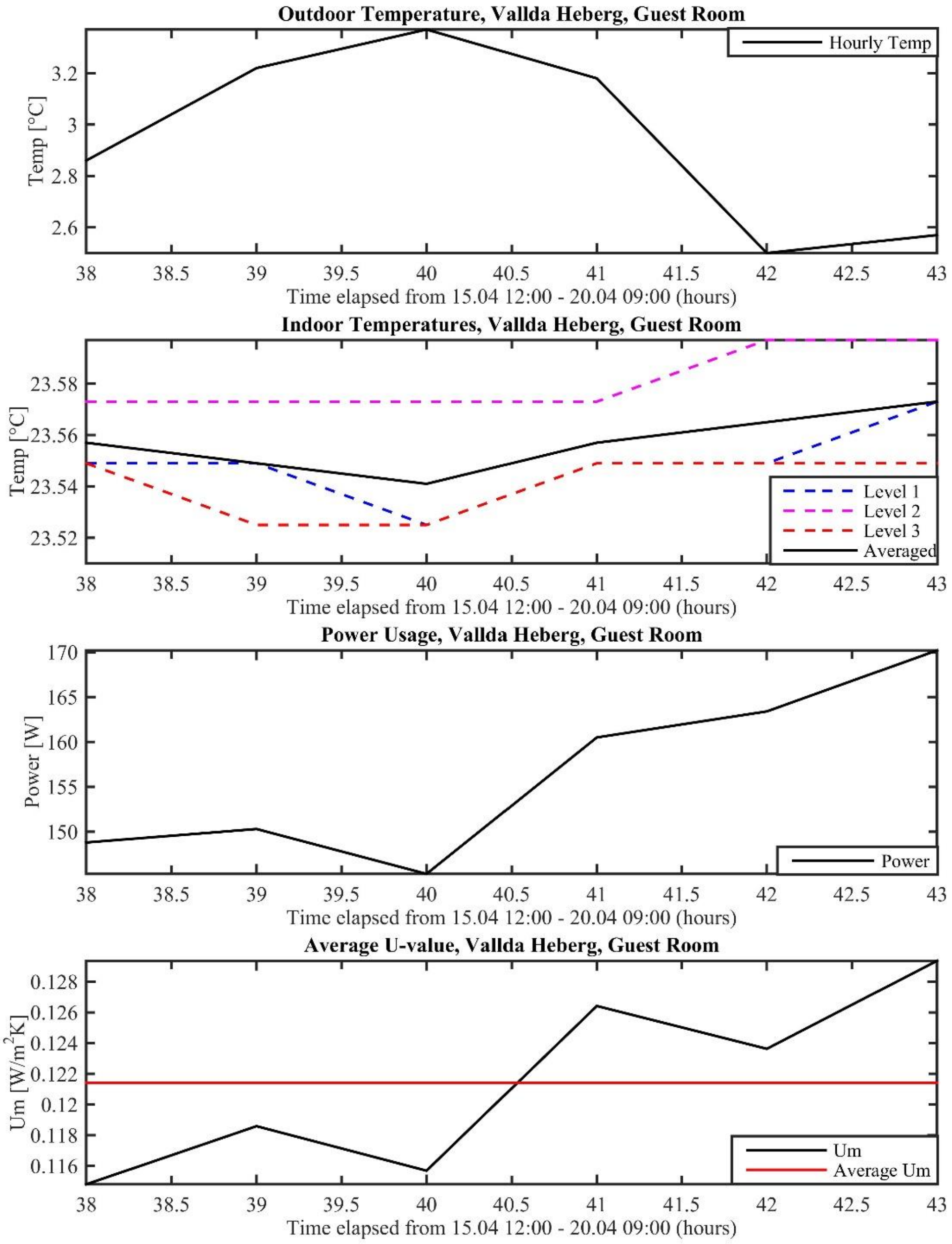


Figure I.5 Measurement result of interval 2; 2015-04-17 02.00 – 2015-04-17 07.00, for Guest room test 2.

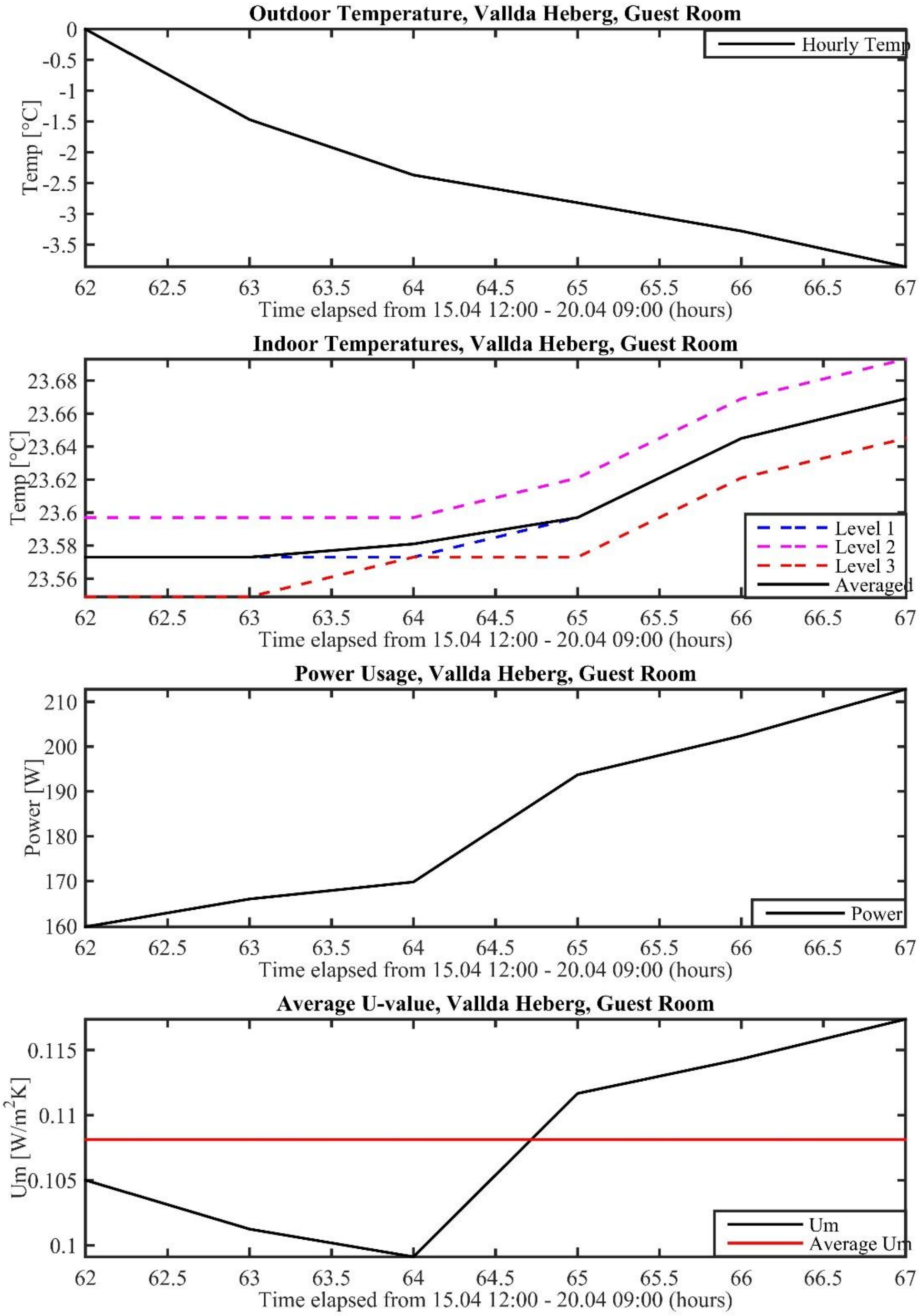


Figure I.6 *Measurement result of interval 3 2015-04-18 02.00 – 2015-04-18 07.00, for Guest room test 2.*

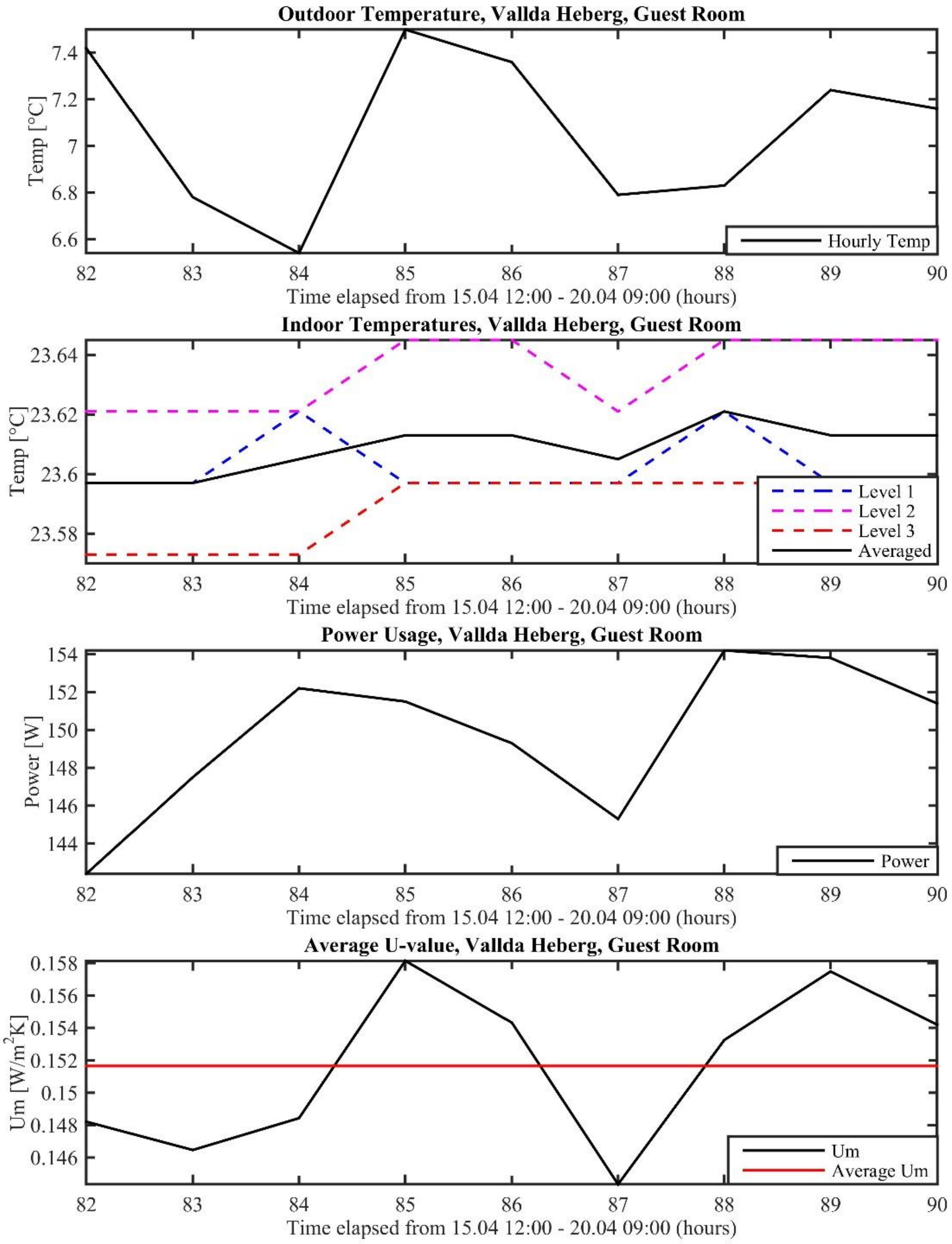


Figure I.7 Measurement result of interval 4; 2015-04-18 02.00 – 2015-04-18 07.00, for Guest room test 2.

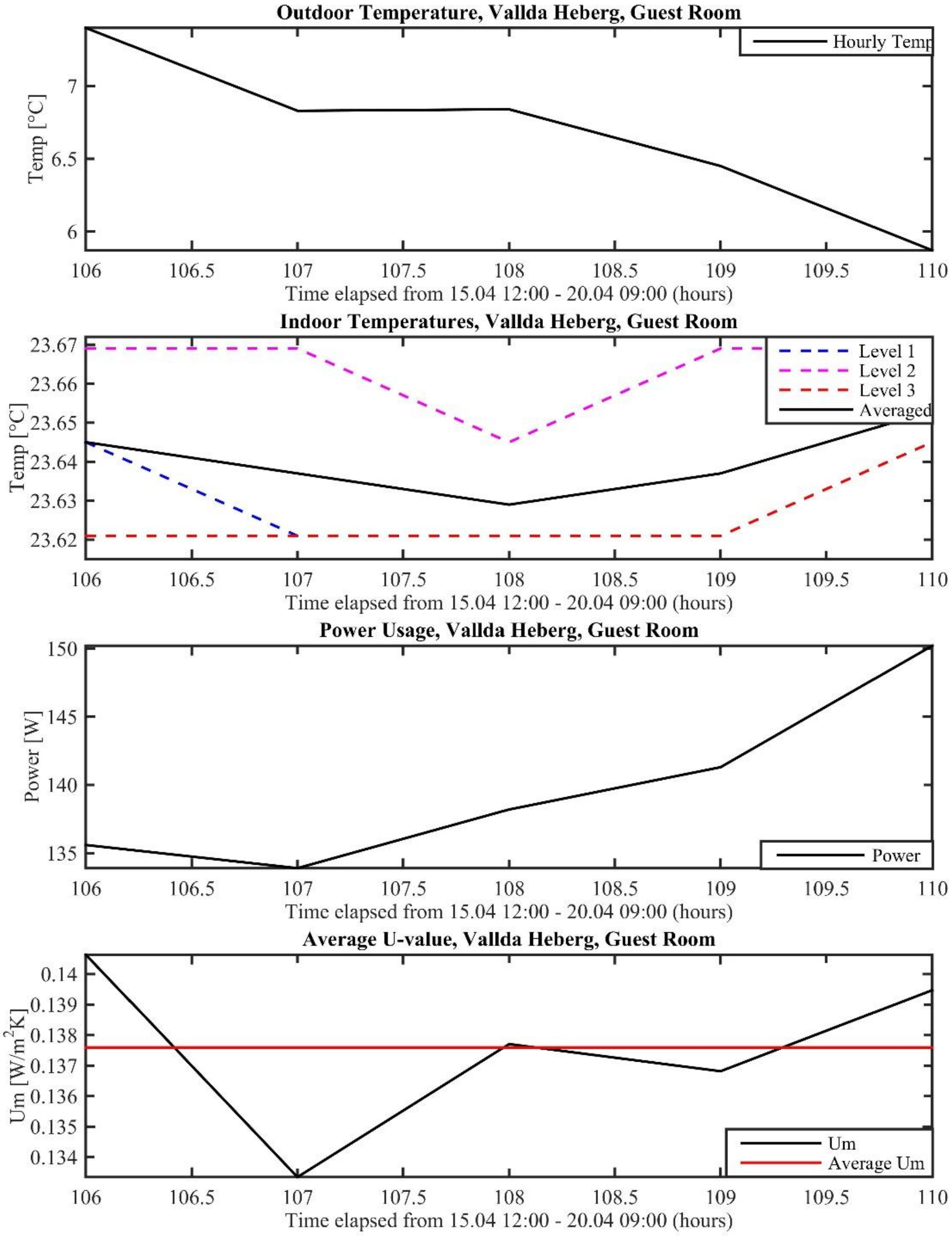


Figure I.8 Measurement result of interval 5; 2015-04-18 22.00 – 2015-04-19 06.00, for Guest room test 2.

Appendix J Measurement Result with Chosen Intervals, Friggebod

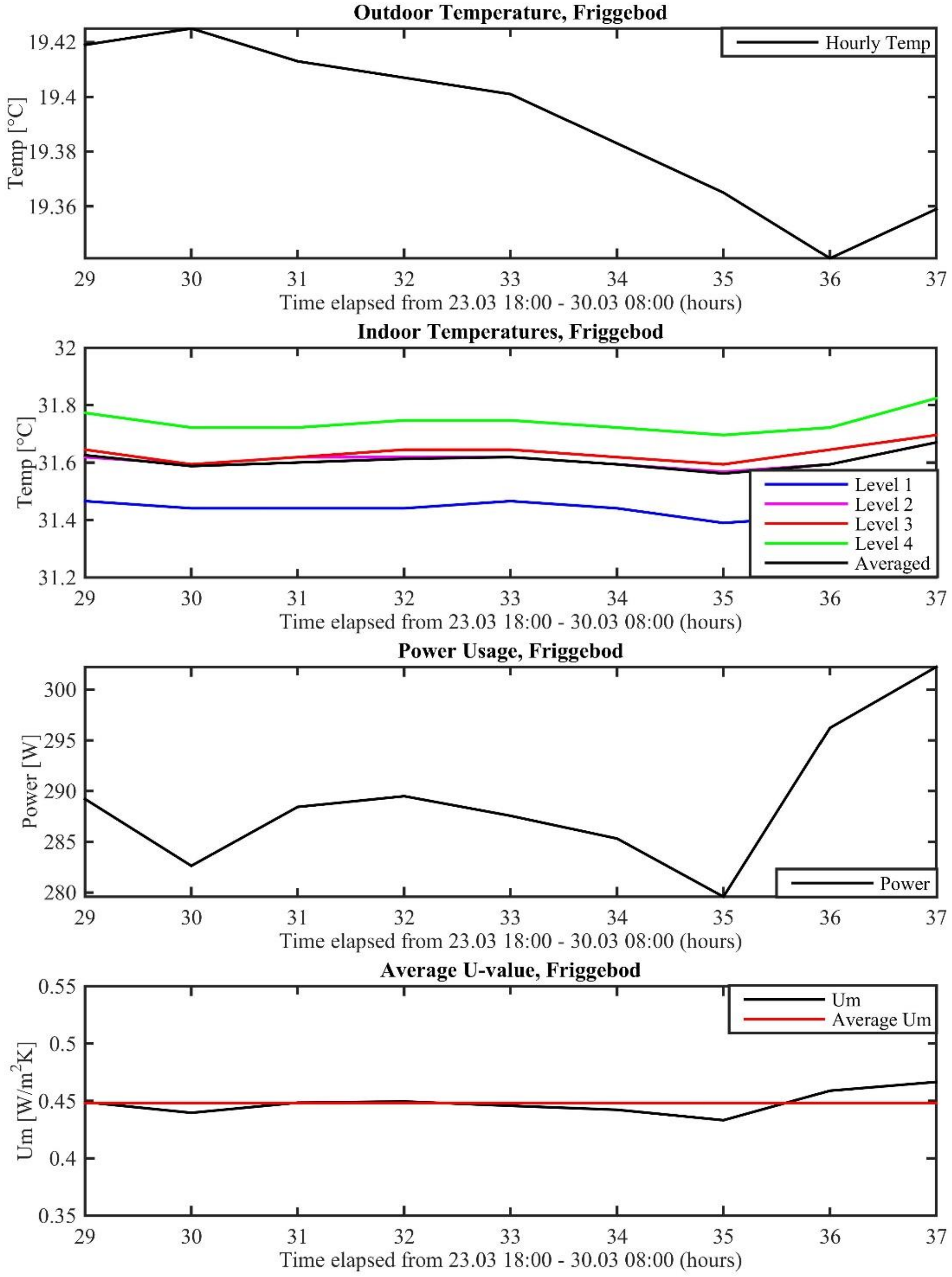


Figure J.1 Measurement result of interval 1; 2015-03 24 23:00 - 2015-03-25 07:00, for Friggebod.

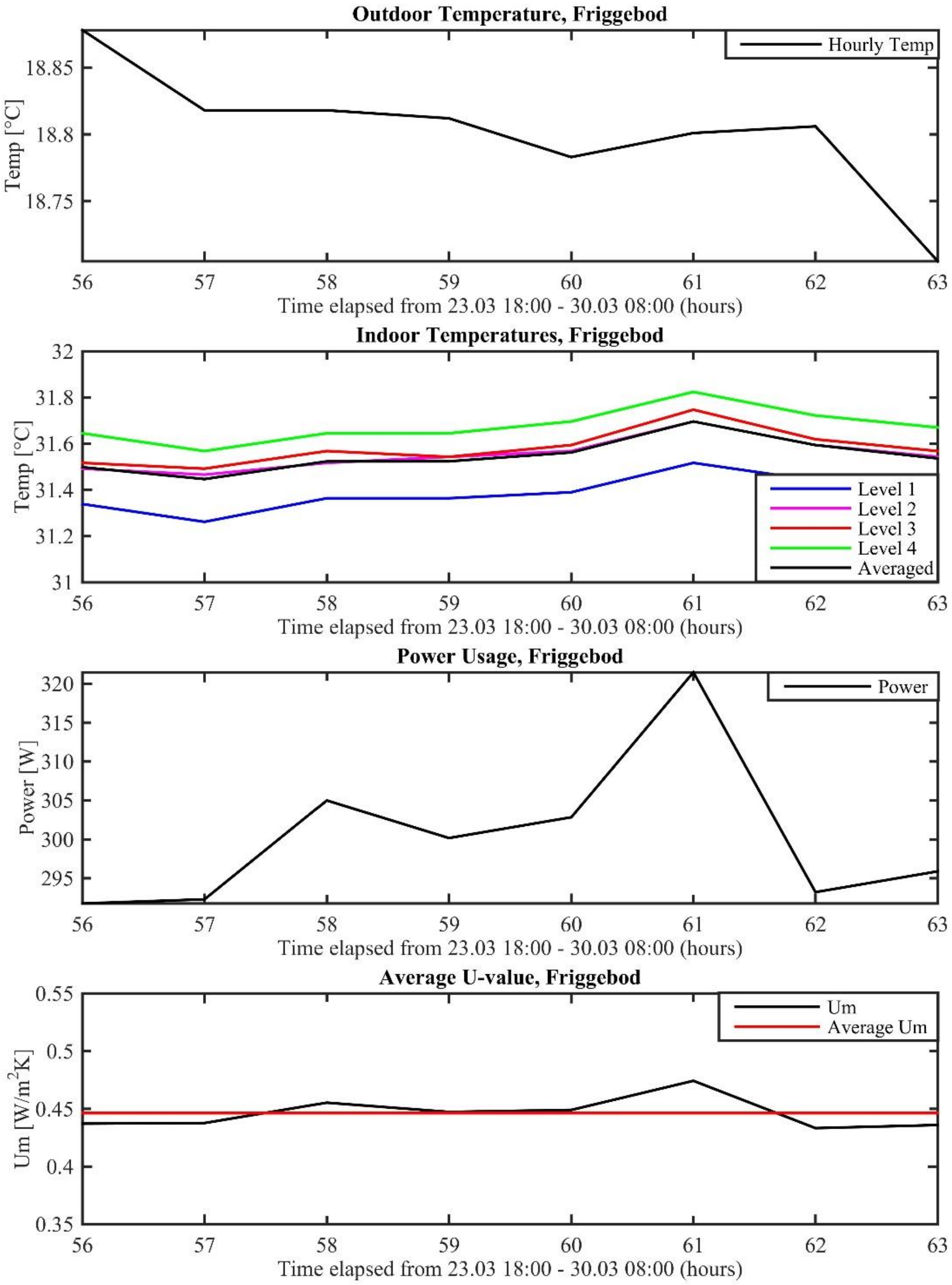


Figure J.2 Measurement result of interval 2; 2015-03-26 02:00 - 2015-03-27 09:00, for Friggebod.

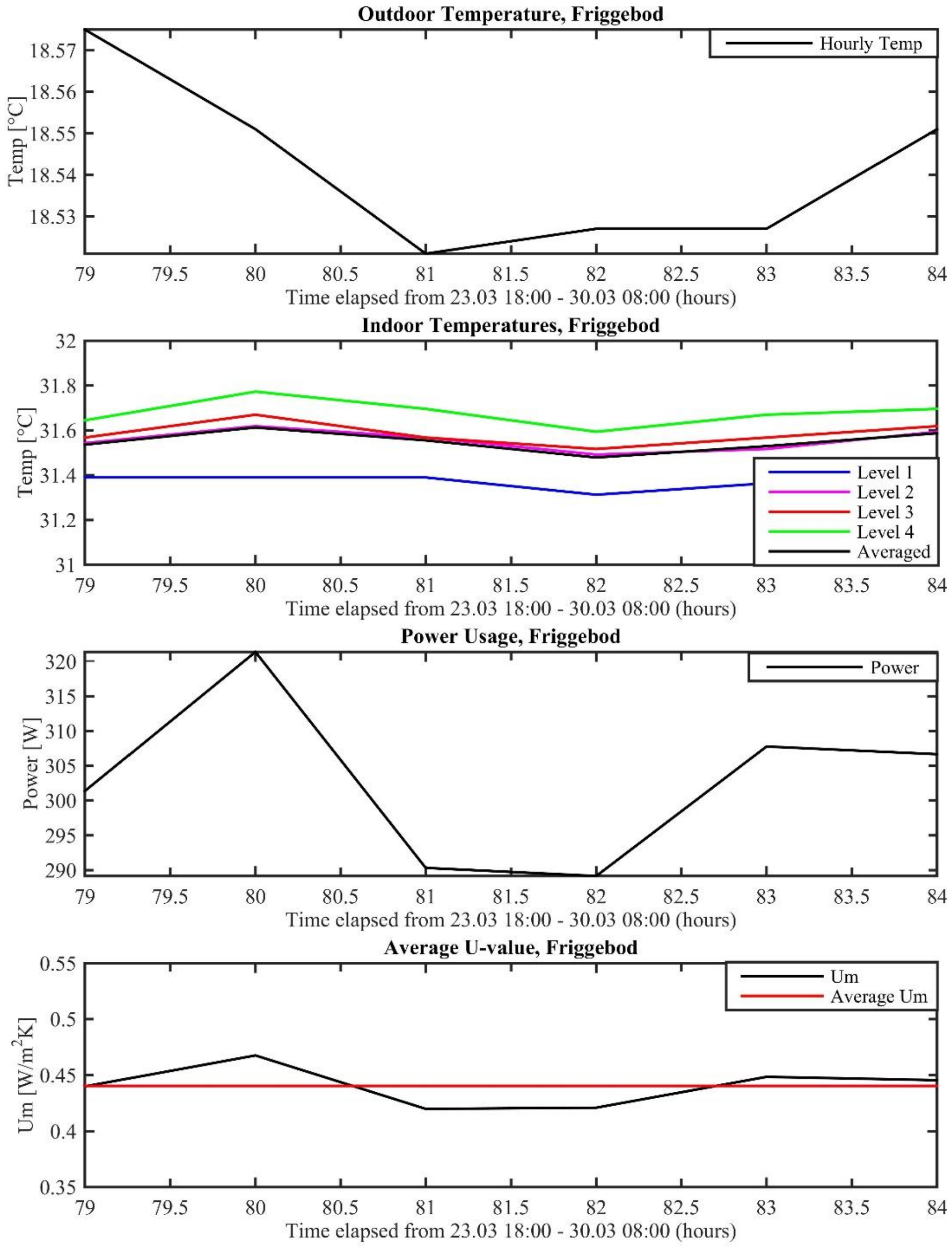


Figure J.3 Measurement result of interval 3; 2015-03-27 01:00 - 2015-03-28 06:00, for Friggebod.

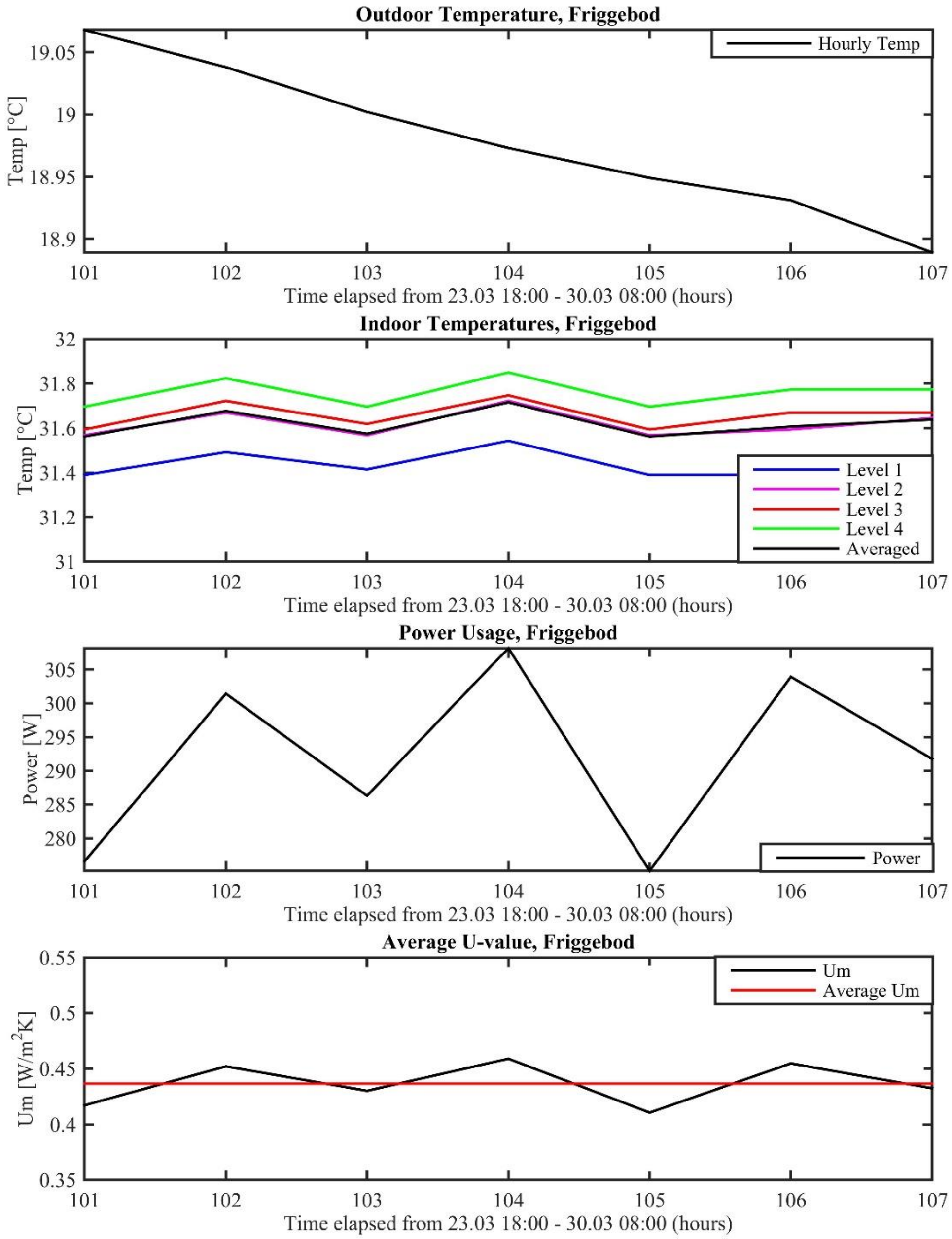


Figure J.4 Measurement result of interval 4; 2015-03-27 23:00 - 2015-03-28 05:00, for Friggebod.

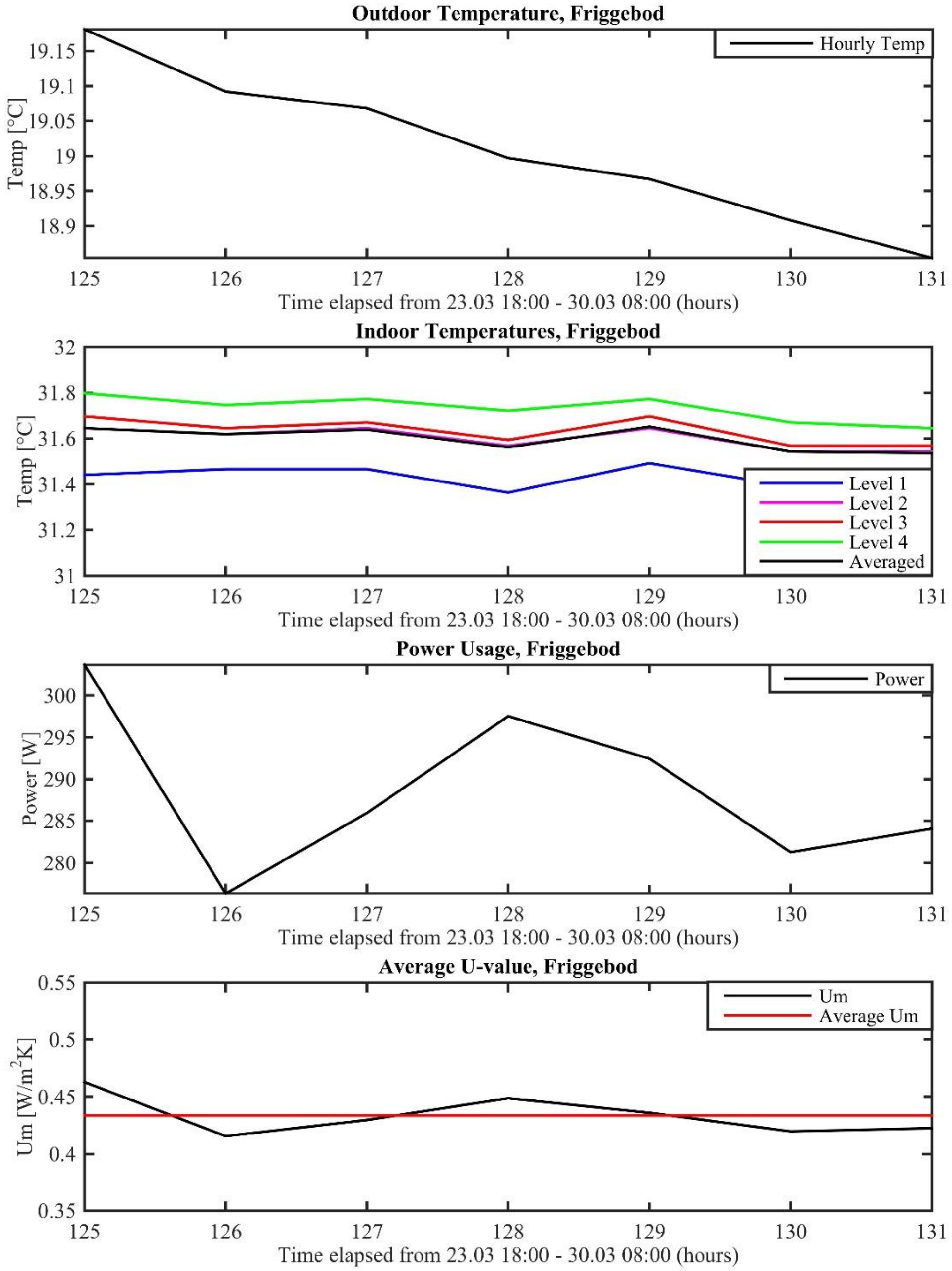


Figure J.5 *Measurement result of interval 5; 2015-03-28 23:00 - 2015-03-29 05:00, for Friggebod.*

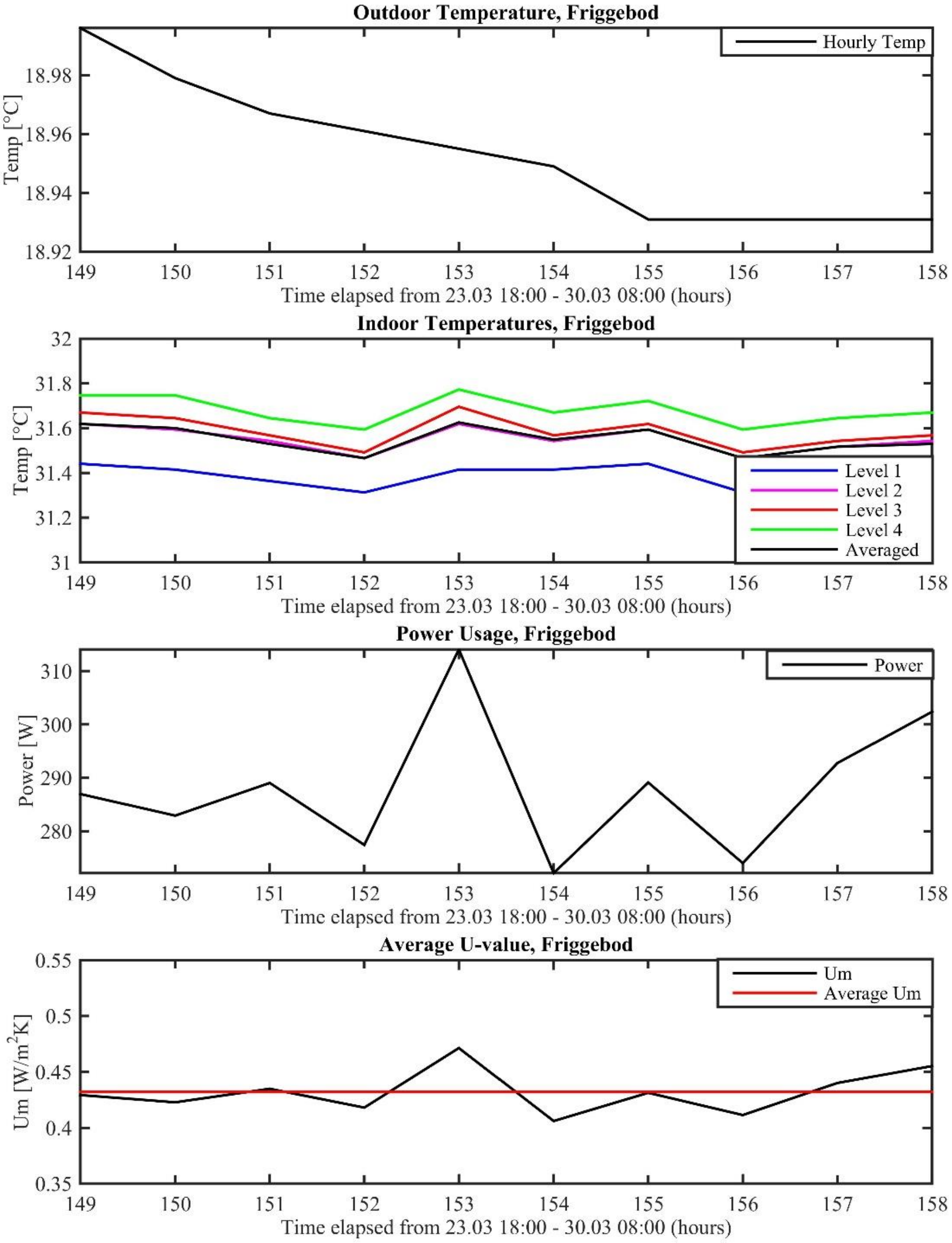
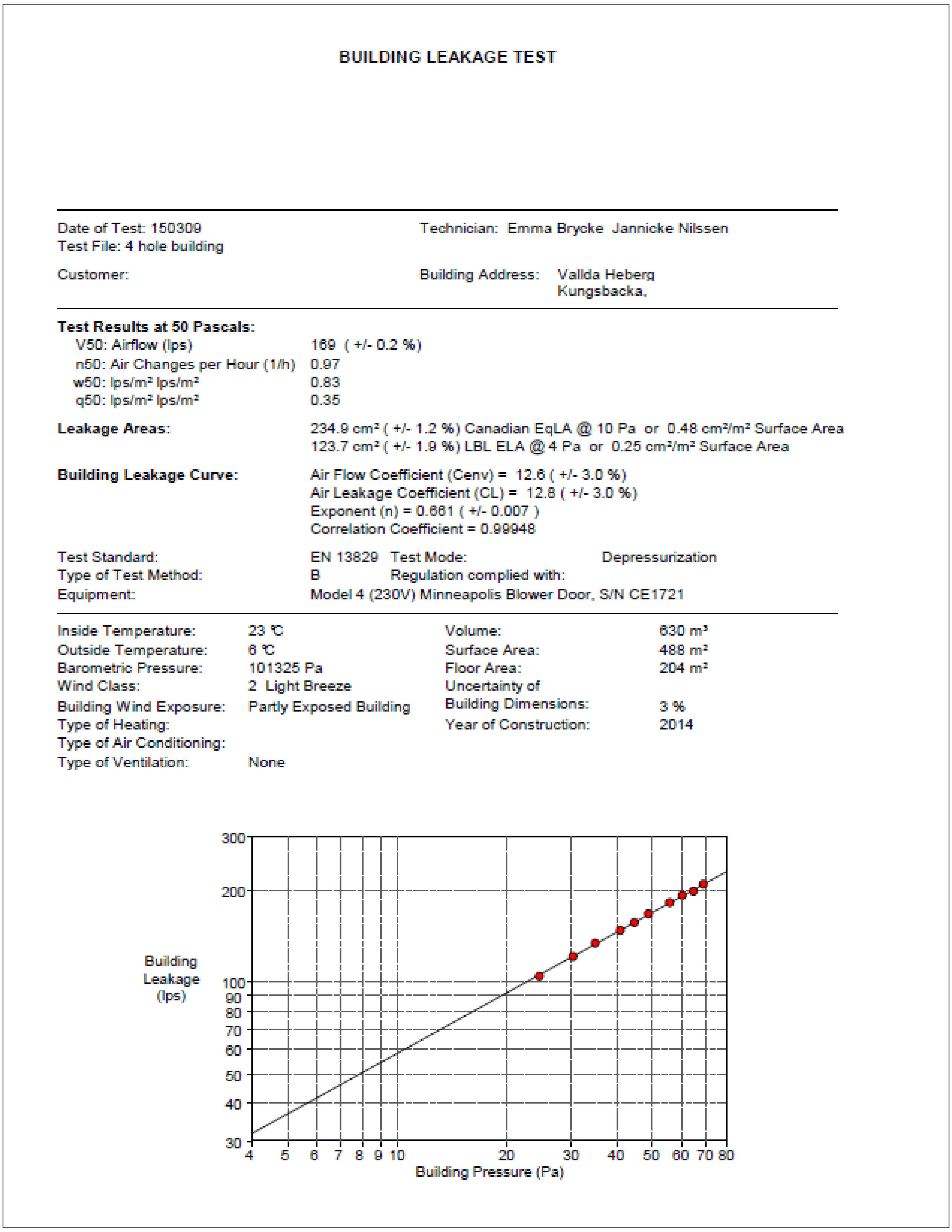


Figure J.6 Measurement result of interval 6; 2015-03-29 23:00 - 2015-03-30 07:00, for Friggebod.

Appendix K Building Leakage Test, Community Building

K.1 Depressurization



BUILDING LEAKAGE TEST

Date of Test: 150309
Test File: 4 hole building

Technician: Emma Brycke Jannicke Nilssen

Customer:

Building Address: Vallda Heberg
Kungsbacka,

Test Results at 50 Pascals:

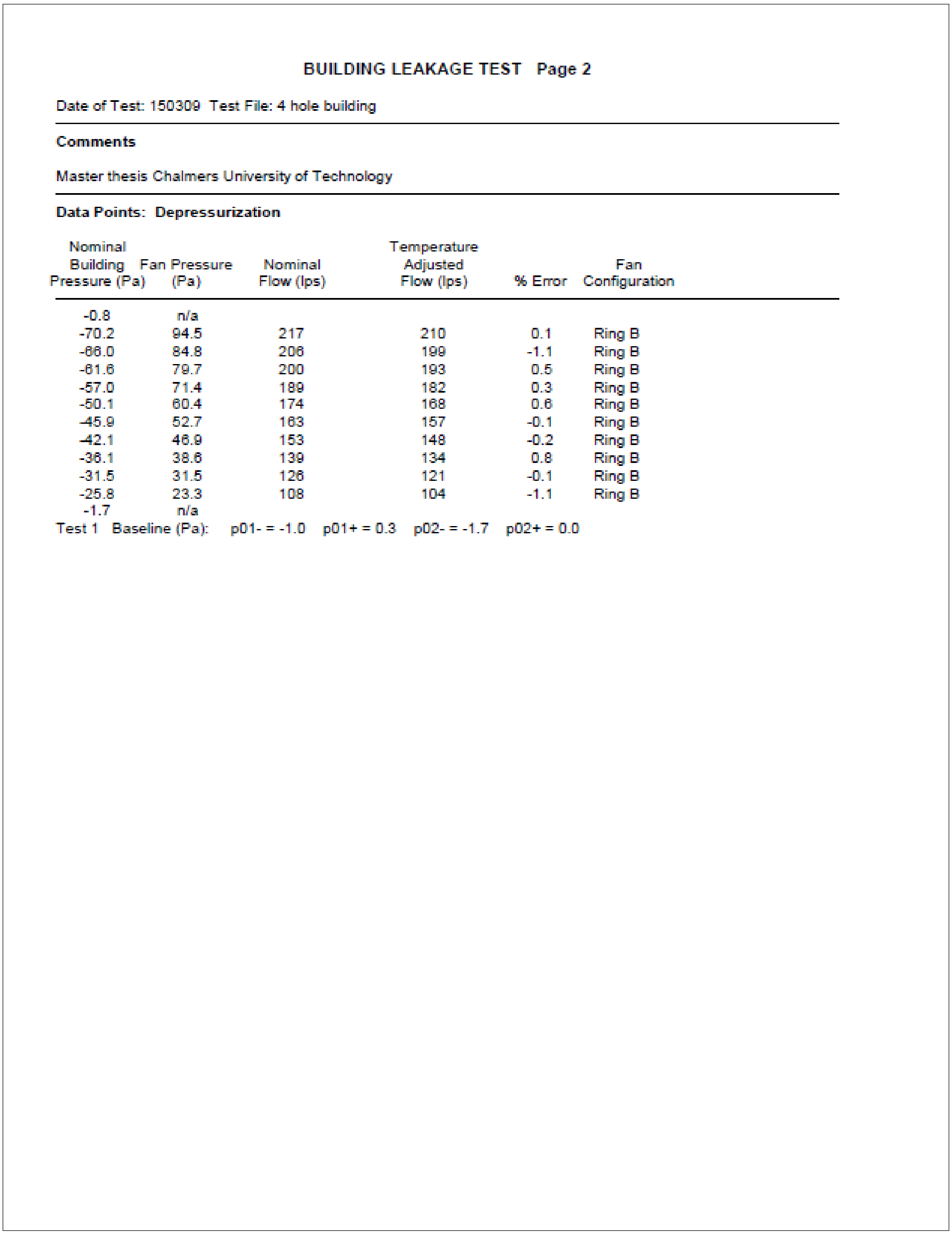
V50: Airflow (lps)	169 (+/- 0.2 %)
n50: Air Changes per Hour (1/h)	0.97
w50: lps/m² lps/m²	0.83
q50: lps/m² lps/m²	0.35

Leakage Areas: 234.9 cm² (+/- 1.2 %) Canadian EqLA @ 10 Pa or 0.48 cm²/m² Surface Area
123.7 cm² (+/- 1.9 %) LBL ELA @ 4 Pa or 0.25 cm²/m² Surface Area

Building Leakage Curve: Air Flow Coefficient (Cenv) = 12.6 (+/- 3.0 %)
Air Leakage Coefficient (CL) = 12.8 (+/- 3.0 %)
Exponent (n) = 0.661 (+/- 0.007)
Correlation Coefficient = 0.99948

Test Standard: EN 13829 Test Mode: Depressurization
Type of Test Method: B Regulation complied with:
Equipment: Model 4 (230V) Minneapolis Blower Door, S/N CE1721

Inside Temperature:	23 °C	Volume:	630 m³
Outside Temperature:	6 °C	Surface Area:	488 m²
Barometric Pressure:	101325 Pa	Floor Area:	204 m²
Wind Class:	2 Light Breeze	Uncertainty of Building Dimensions:	3 %
Building Wind Exposure:	Partly Exposed Building	Year of Construction:	2014
Type of Heating:			
Type of Air Conditioning:			
Type of Ventilation:	None		



BUILDING LEAKAGE TEST Page 2

Date of Test: 150309 Test File: 4 hole building

Comments

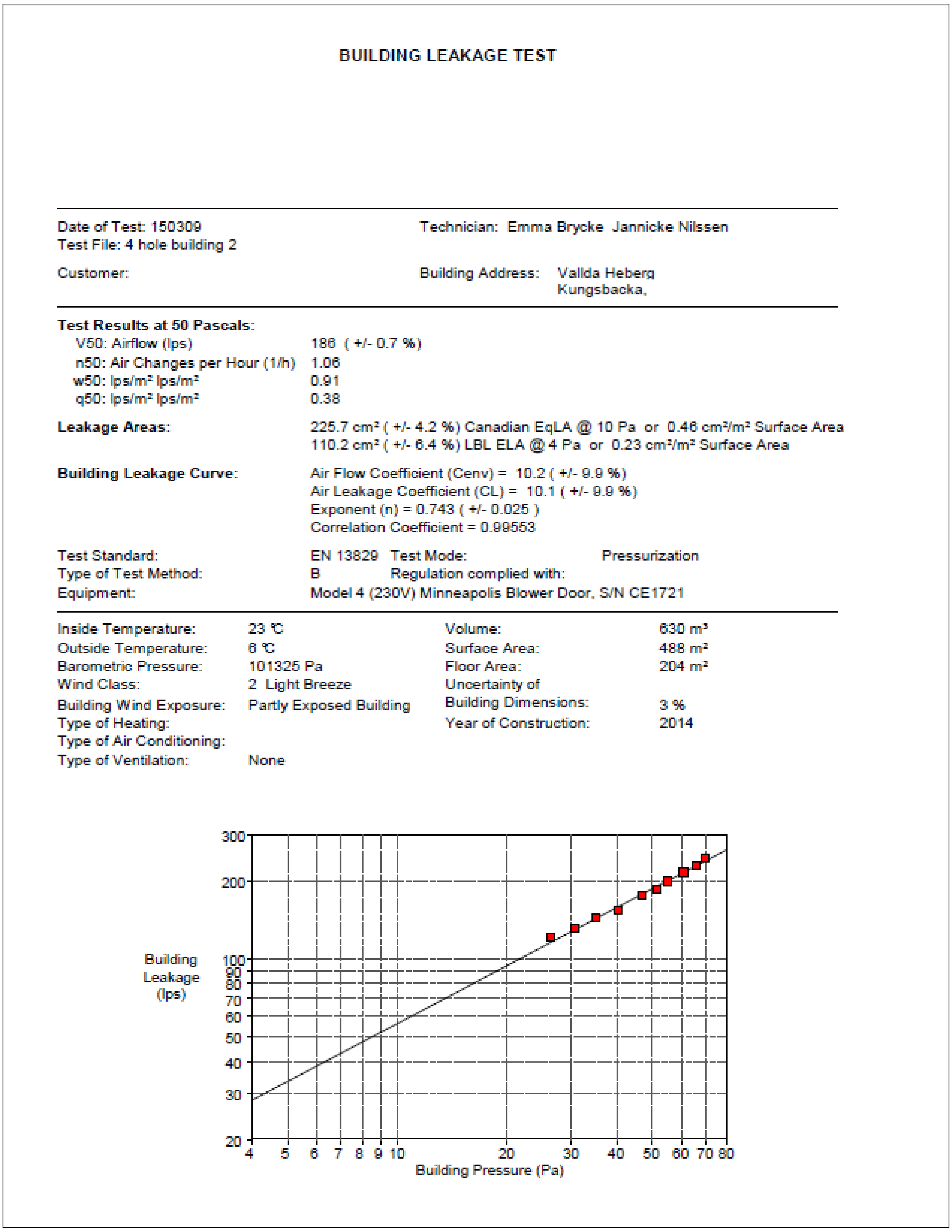
Master thesis Chalmers University of Technology

Data Points: Depressurization

Nominal Building Pressure (Pa)	Fan Pressure (Pa)	Nominal Flow (lps)	Temperature Adjusted Flow (lps)	% Error	Fan Configuration
-0.8	n/a				
-70.2	94.5	217	210	0.1	Ring B
-66.0	84.8	206	199	-1.1	Ring B
-61.6	79.7	200	193	0.5	Ring B
-57.0	71.4	189	182	0.3	Ring B
-50.1	60.4	174	168	0.6	Ring B
-45.9	52.7	163	157	-0.1	Ring B
-42.1	46.9	153	148	-0.2	Ring B
-36.1	38.6	139	134	0.8	Ring B
-31.5	31.5	126	121	-0.1	Ring B
-25.8	23.3	108	104	-1.1	Ring B
-1.7	n/a				

Test 1 Baseline (Pa): p01- = -1.0 p01+ = 0.3 p02- = -1.7 p02+ = 0.0

K.2 Pressurization



BUILDING LEAKAGE TEST

Date of Test: 150309
Test File: 4 hole building 2

Technician: Emma Brycke Jannicke Nilssen

Customer:

Building Address: Vallda Heberg
Kungsbacka,

Test Results at 50 Pascals:

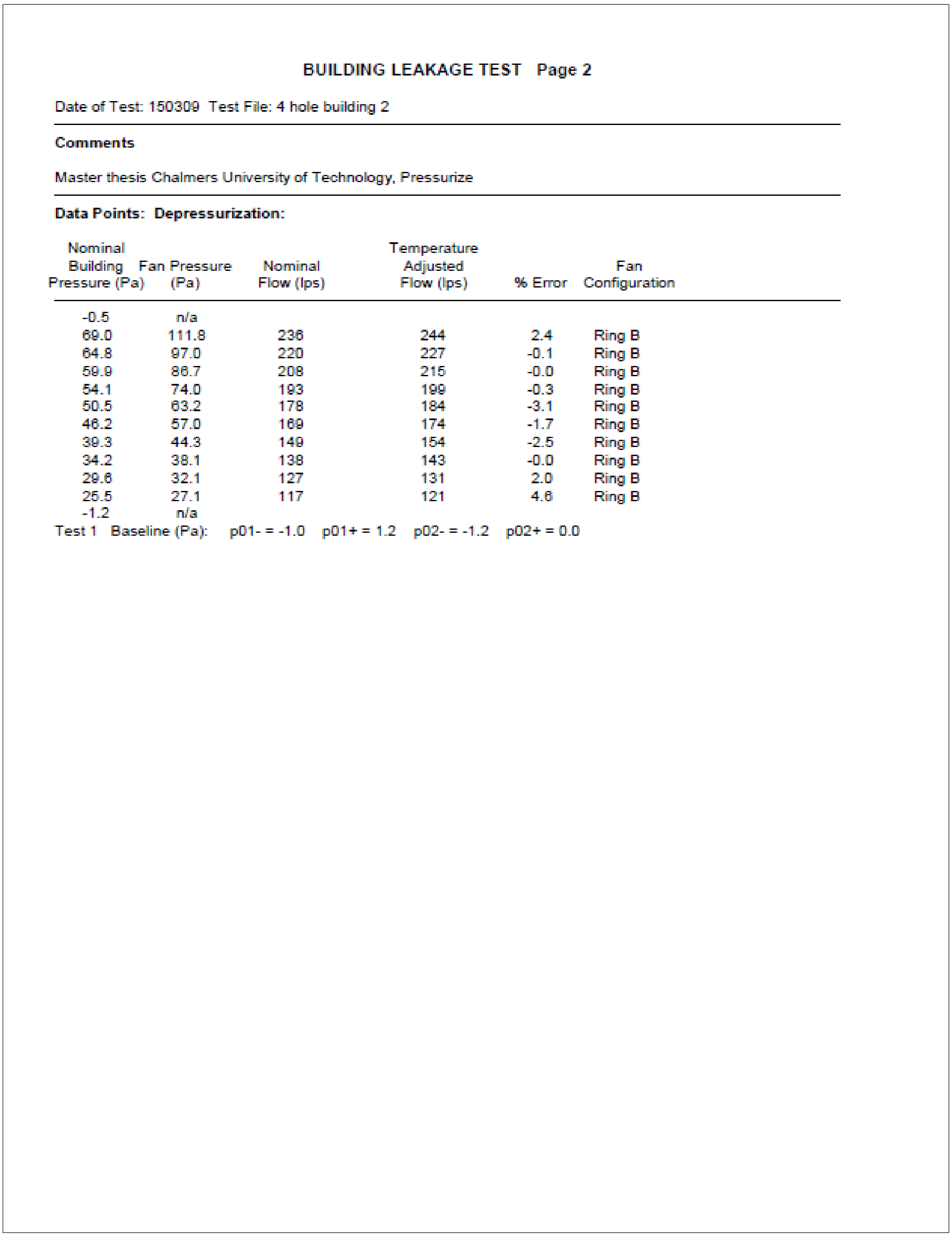
V50: Airflow (lps)	186 (+/- 0.7 %)
n50: Air Changes per Hour (1/h)	1.06
w50: lps/m² lps/m²	0.91
q50: lps/m² lps/m²	0.38

Leakage Areas:
225.7 cm² (+/- 4.2 %) Canadian EqLA @ 10 Pa or 0.46 cm²/m² Surface Area
110.2 cm² (+/- 6.4 %) LBL ELA @ 4 Pa or 0.23 cm²/m² Surface Area

Building Leakage Curve:
Air Flow Coefficient (Cenv) = 10.2 (+/- 9.9 %)
Air Leakage Coefficient (CL) = 10.1 (+/- 9.9 %)
Exponent (n) = 0.743 (+/- 0.025)
Correlation Coefficient = 0.99553

Test Standard: EN 13829 Test Mode: Pressurization
Type of Test Method: B Regulation complied with:
Equipment: Model 4 (230V) Minneapolis Blower Door, S/N CE1721

Inside Temperature:	23 °C	Volume:	630 m³
Outside Temperature:	6 °C	Surface Area:	488 m²
Barometric Pressure:	101325 Pa	Floor Area:	204 m²
Wind Class:	2 Light Breeze	Uncertainty of Building Dimensions:	3 %
Building Wind Exposure:	Partly Exposed Building	Year of Construction:	2014
Type of Heating:			
Type of Air Conditioning:			
Type of Ventilation:	None		



BUILDING LEAKAGE TEST Page 2

Date of Test: 150309 Test File: 4 hole building 2

Comments

Master thesis Chalmers University of Technology, Pressurize

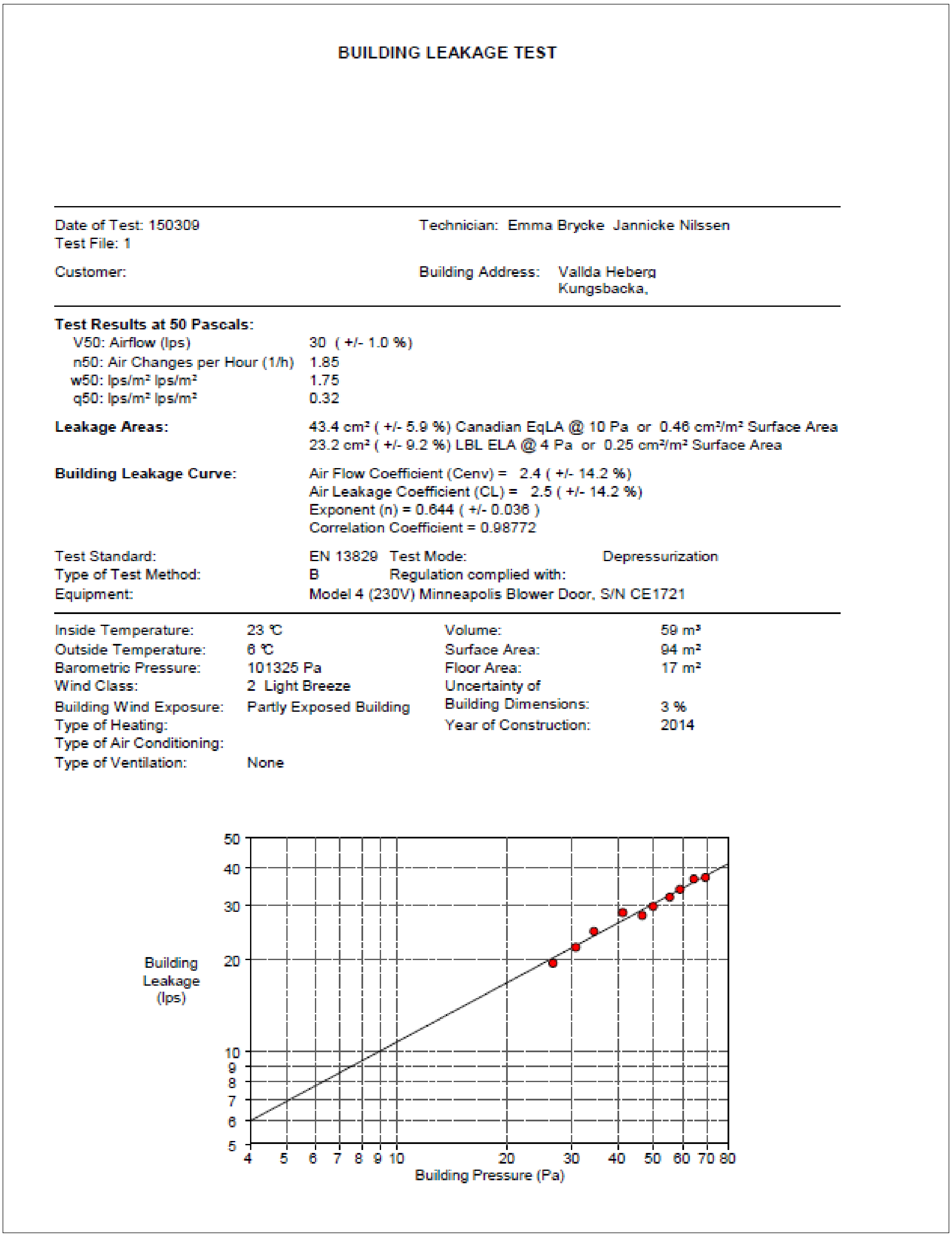
Data Points: Depressurization:

Nominal Building Pressure (Pa)	Fan Pressure (Pa)	Nominal Flow (lps)	Temperature Adjusted Flow (lps)	% Error	Fan Configuration
-0.5	n/a				
69.0	111.8	236	244	2.4	Ring B
64.8	97.0	220	227	-0.1	Ring B
59.9	86.7	208	215	-0.0	Ring B
54.1	74.0	193	199	-0.3	Ring B
50.5	63.2	178	184	-3.1	Ring B
46.2	57.0	169	174	-1.7	Ring B
39.3	44.3	149	154	-2.5	Ring B
34.2	38.1	138	143	-0.0	Ring B
29.6	32.1	127	131	2.0	Ring B
25.5	27.1	117	121	4.6	Ring B
-1.2	n/a				

Test 1 Baseline (Pa): p01- = -1.0 p01+ = 1.2 p02- = -1.2 p02+ = 0.0

Appendix L Building Leakage test, Guest Room

L.1 Depressurization



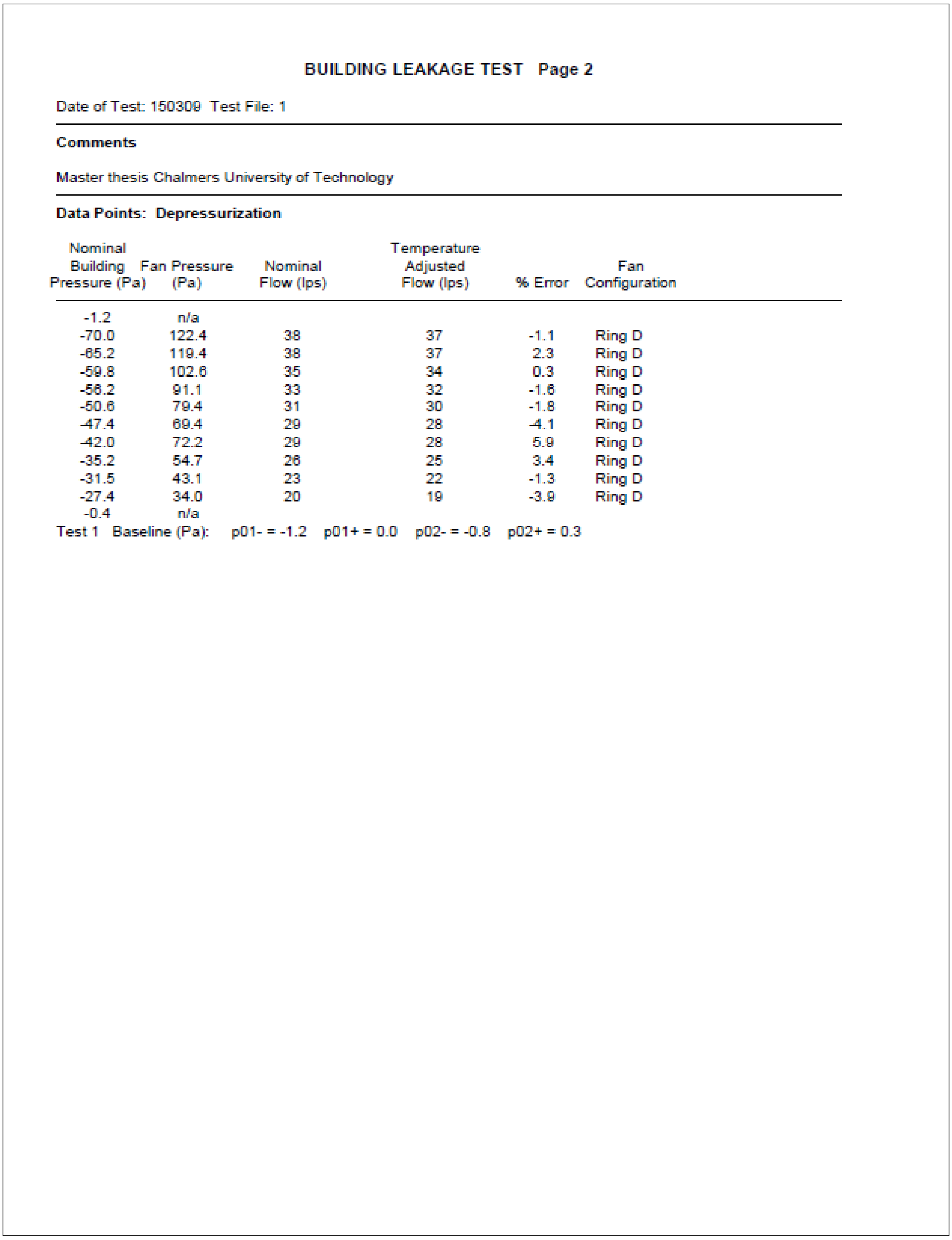
BUILDING LEAKAGE TEST

Date of Test: 150309		Technician:	Emma Brycke Jannicke Nilssen
Test File: 1			
Customer:		Building Address:	Vallda Heberg Kungsbacka,

Test Results at 50 Pascals:

V50: Airflow (lps)	30 (+/- 1.0 %)
n50: Air Changes per Hour (1/h)	1.85
w50: lps/m² lps/m²	1.75
q50: lps/m² lps/m²	0.32
Leakage Areas:	43.4 cm² (+/- 5.9 %) Canadian EqLA @ 10 Pa or 0.46 cm²/m² Surface Area 23.2 cm² (+/- 9.2 %) LBL ELA @ 4 Pa or 0.25 cm²/m² Surface Area
Building Leakage Curve:	Air Flow Coefficient (Cenv) = 2.4 (+/- 14.2 %) Air Leakage Coefficient (CL) = 2.5 (+/- 14.2 %) Exponent (n) = 0.644 (+/- 0.036) Correlation Coefficient = 0.98772
Test Standard:	EN 13829 Test Mode: Depressurization
Type of Test Method:	B Regulation complied with:
Equipment:	Model 4 (230V) Minneapolis Blower Door, S/N CE1721

Inside Temperature:	23 ℃	Volume:	59 m³
Outside Temperature:	6 ℃	Surface Area:	94 m²
Barometric Pressure:	101325 Pa	Floor Area:	17 m²
Wind Class:	2 Light Breeze	Uncertainty of Building Dimensions:	3 %
Building Wind Exposure:	Partly Exposed Building		
Type of Heating:		Year of Construction:	2014
Type of Air Conditioning:			
Type of Ventilation:	None		



BUILDING LEAKAGE TEST Page 2

Date of Test: 150309 Test File: 1

Comments

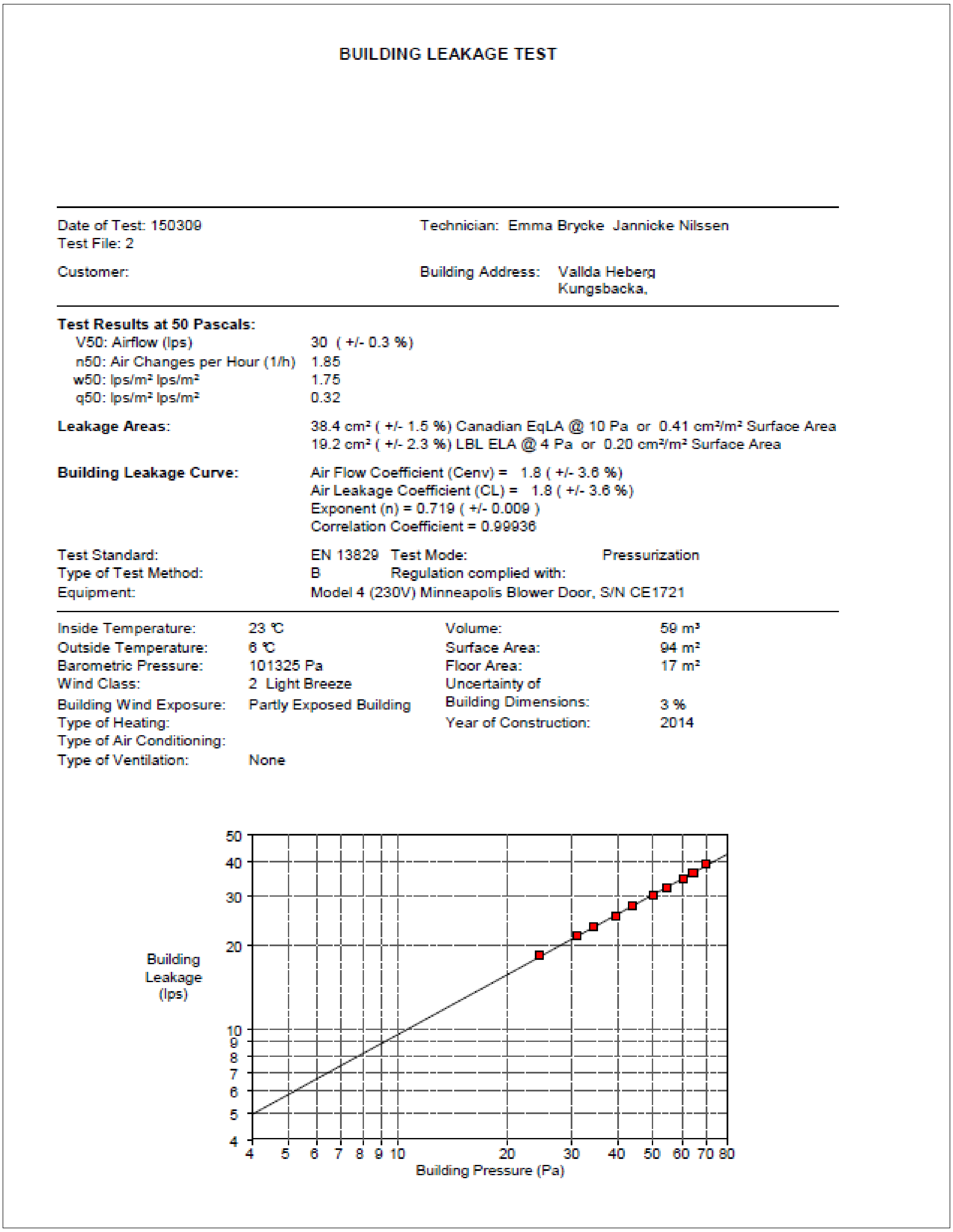
Master thesis Chalmers University of Technology

Data Points: Depressurization

Nominal Building Pressure (Pa)	Fan Pressure (Pa)	Nominal Flow (lps)	Temperature Adjusted Flow (lps)	% Error	Fan Configuration
-1.2	n/a				
-70.0	122.4	38	37	-1.1	Ring D
-65.2	119.4	38	37	2.3	Ring D
-59.8	102.6	35	34	0.3	Ring D
-56.2	91.1	33	32	-1.6	Ring D
-50.6	79.4	31	30	-1.8	Ring D
-47.4	69.4	29	28	-4.1	Ring D
-42.0	72.2	29	28	5.9	Ring D
-35.2	54.7	26	25	3.4	Ring D
-31.5	43.1	23	22	-1.3	Ring D
-27.4	34.0	20	19	-3.9	Ring D
-0.4	n/a				

Test 1 Baseline (Pa): p01- = -1.2 p01+ = 0.0 p02- = -0.8 p02+ = 0.3

L.2 Pressurization



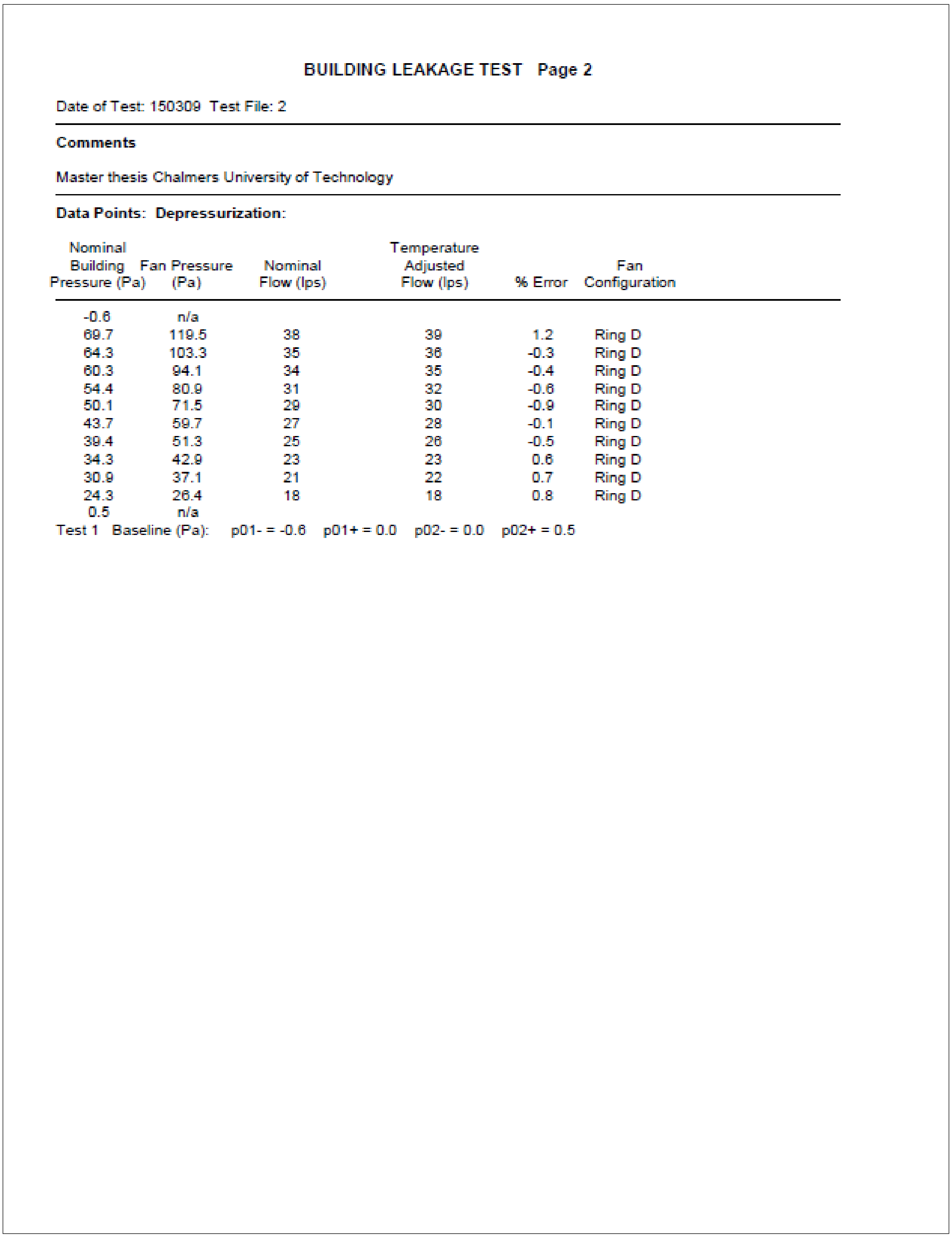
BUILDING LEAKAGE TEST

Date of Test: 150309		Technician:	Emma Brycke Jannicke Nilssen
Test File: 2			
Customer:		Building Address:	Vallda Heberg Kungsbacka,

Test Results at 50 Pascals:

V50: Airflow (lps)	30 (+/- 0.3 %)
n50: Air Changes per Hour (1/h)	1.85
w50: lps/m² lps/m²	1.75
q50: lps/m² lps/m²	0.32
Leakage Areas:	38.4 cm² (+/- 1.5 %) Canadian EqLA @ 10 Pa or 0.41 cm²/m² Surface Area 19.2 cm² (+/- 2.3 %) LBL ELA @ 4 Pa or 0.20 cm²/m² Surface Area
Building Leakage Curve:	Air Flow Coefficient (Cenv) = 1.8 (+/- 3.6 %) Air Leakage Coefficient (CL) = 1.8 (+/- 3.6 %) Exponent (n) = 0.719 (+/- 0.009) Correlation Coefficient = 0.99936
Test Standard:	EN 13829 Test Mode: Pressurization
Type of Test Method:	B Regulation complied with:
Equipment:	Model 4 (230V) Minneapolis Blower Door, S/N CE1721

Inside Temperature:	23 ℃	Volume:	59 m³
Outside Temperature:	6 ℃	Surface Area:	94 m²
Barometric Pressure:	101325 Pa	Floor Area:	17 m²
Wind Class:	2 Light Breeze	Uncertainty of	
Building Wind Exposure:	Partly Exposed Building	Building Dimensions:	3 %
Type of Heating:		Year of Construction:	2014
Type of Air Conditioning:			
Type of Ventilation:	None		



BUILDING LEAKAGE TEST Page 2

Date of Test: 150309 Test File: 2

Comments

Master thesis Chalmers University of Technology

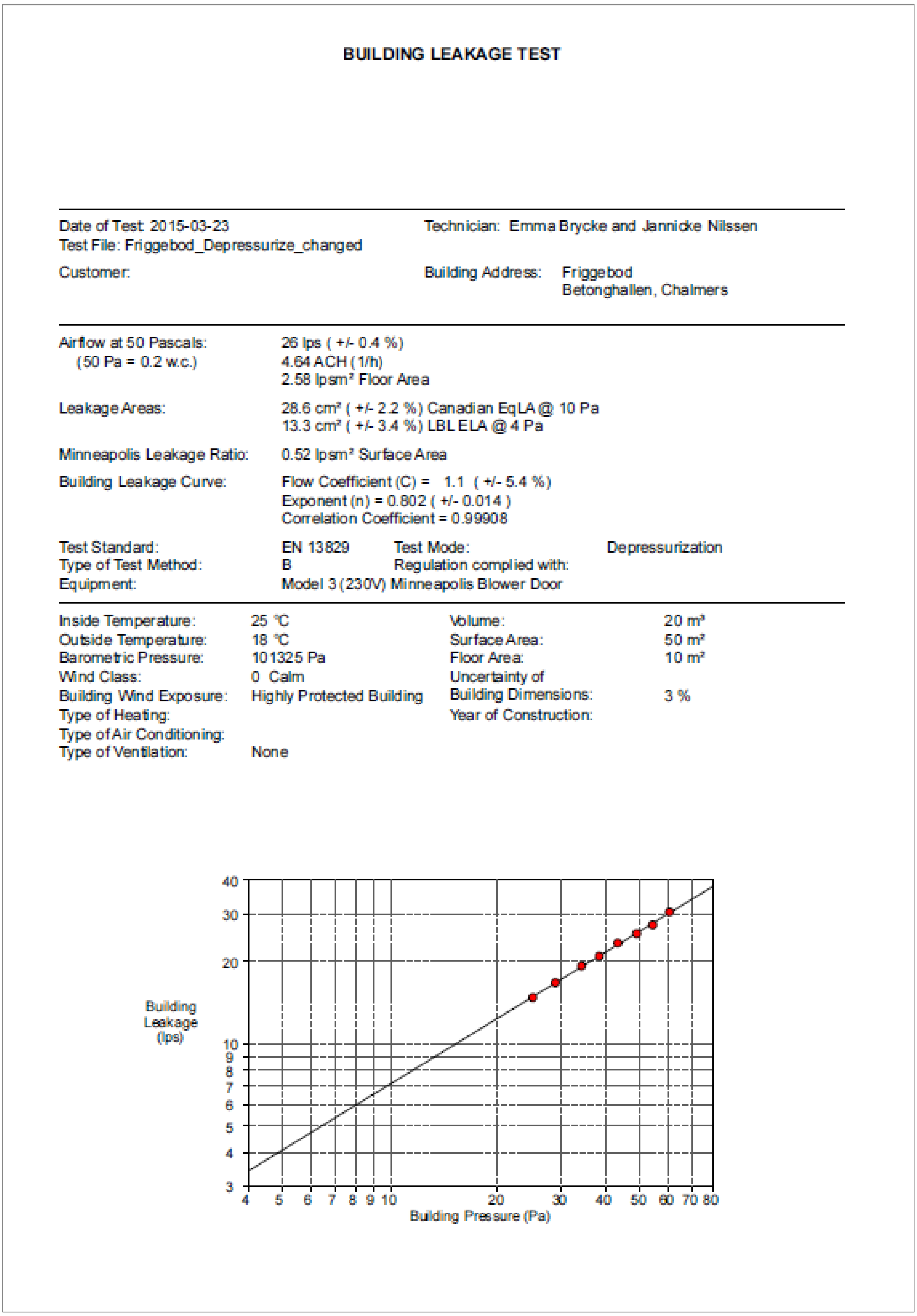
Data Points: Depressurization:

Nominal Building Pressure (Pa)	Fan Pressure (Pa)	Nominal Flow (lps)	Temperature Adjusted Flow (lps)	% Error	Fan Configuration
-0.6	n/a				
69.7	119.5	38	39	1.2	Ring D
64.3	103.3	35	36	-0.3	Ring D
60.3	94.1	34	35	-0.4	Ring D
54.4	80.9	31	32	-0.6	Ring D
50.1	71.5	29	30	-0.9	Ring D
43.7	59.7	27	28	-0.1	Ring D
39.4	51.3	25	26	-0.5	Ring D
34.3	42.9	23	23	0.6	Ring D
30.9	37.1	21	22	0.7	Ring D
24.3	26.4	18	18	0.8	Ring D
0.5	n/a				

Test 1 Baseline (Pa): p01- = -0.6 p01+ = 0.0 p02- = 0.0 p02+ = 0.5

Appendix M   Building Leakage Test, Friggebod

M.1   Depressurization



BUILDING LEAKAGE TEST

Date of Test: 2015-03-23
Test File: Friggebod_Depressurize_changed
Technician: Emma Brycke and Jannicke Nilssen
Customer:
Building Address: Friggebod
Betonghallen, Chalmers

Airflow at 50 Pascals: 26 lps (+/- 0.4 %)
(50 Pa = 0.2 w.c.) 4.64 ACH (1/h)
2.58 lpsm² Floor Area

Leakage Areas: 28.6 cm² (+/- 2.2 %) Canadian EqLA @ 10 Pa
13.3 cm² (+/- 3.4 %) LBL ELA @ 4 Pa

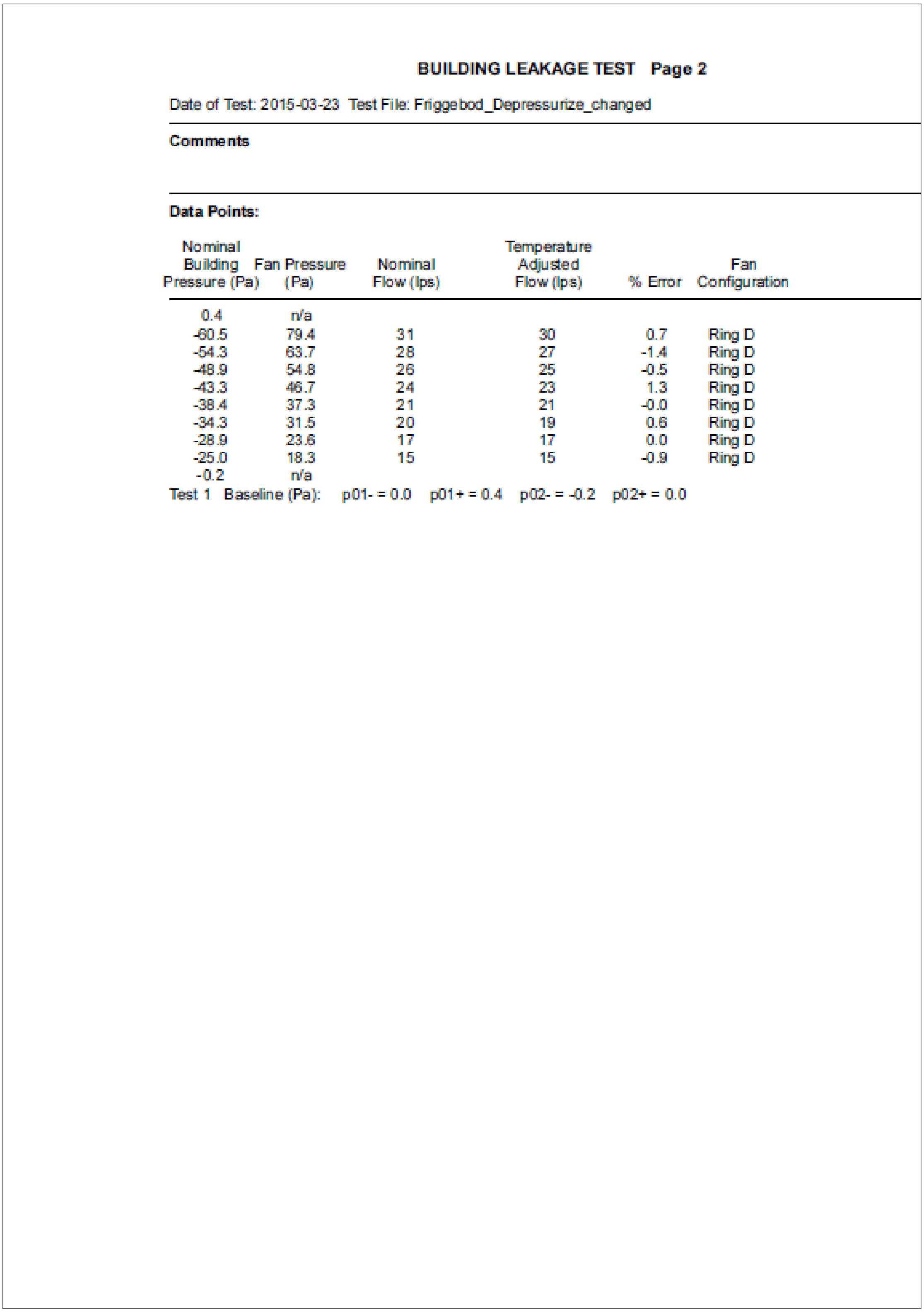
Minneapolis Leakage Ratio: 0.52 lpsm² Surface Area

Building Leakage Curve: Flow Coefficient (C) = 1.1 (+/- 5.4 %)
Exponent (n) = 0.802 (+/- 0.014)
Correlation Coefficient = 0.99908

Test Standard: EN 13829
Test Mode: Depressurization
Type of Test Method: B
Regulation complied with:
Equipment: Model 3 (230V) Minneapolis Blower Door

Inside Temperature: 25 °C
Outside Temperature: 18 °C
Barometric Pressure: 101325 Pa
Wind Class: 0 Calm
Building Wind Exposure: Highly Protected Building
Type of Heating:
Type of Air Conditioning:
Type of Ventilation: None

Volume: 20 m³
Surface Area: 50 m²
Floor Area: 10 m²
Uncertainty of Building Dimensions: 3 %
Year of Construction:



BUILDING LEAKAGE TEST Page 2

Date of Test: 2015-03-23 Test File: Friggebod_Depressurize_changed

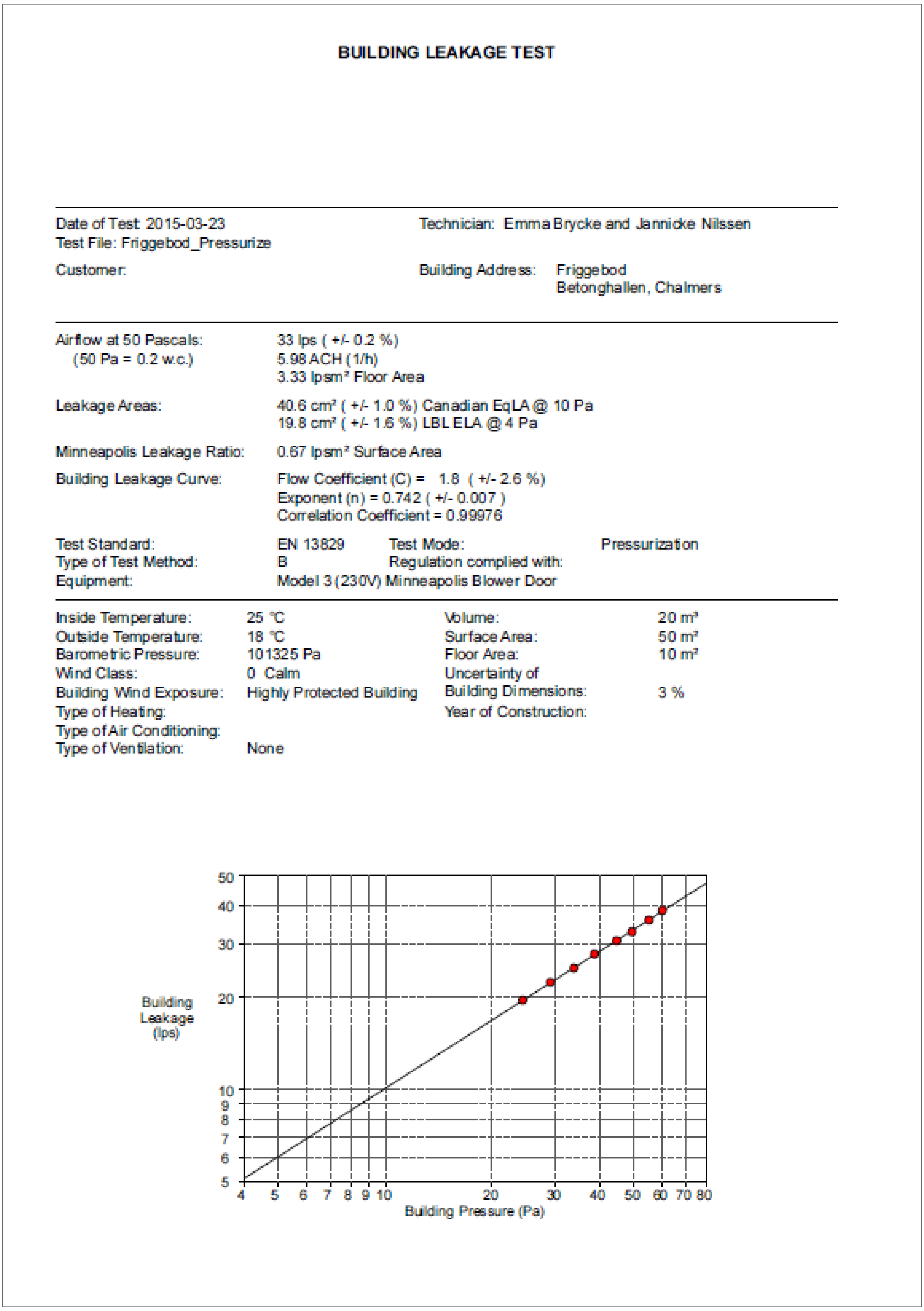
Comments

Data Points:

Nominal Building Pressure (Pa)	Fan Pressure (Pa)	Nominal Flow (lps)	Temperature Adjusted Flow (lps)	% Error	Fan Configuration
0.4	n/a				
-60.5	79.4	31	30	0.7	Ring D
-54.3	63.7	28	27	-1.4	Ring D
-48.9	54.8	26	25	-0.5	Ring D
-43.3	46.7	24	23	1.3	Ring D
-38.4	37.3	21	21	-0.0	Ring D
-34.3	31.5	20	19	0.6	Ring D
-28.9	23.6	17	17	0.0	Ring D
-25.0	18.3	15	15	-0.9	Ring D
-0.2	n/a				

Test 1 Baseline (Pa): p01- = 0.0 p01+ = 0.4 p02- = -0.2 p02+ = 0.0

M.2 Pressurization



BUILDING LEAKAGE TEST

Date of Test: 2015-03-23
Test File: Friggebod_Pressurize
Customer:

Technician: Emma Brycke and Jannicke Nilssen
Building Address: Friggebod
Betonghallen, Chalmers

Airflow at 50 Pascals: 33 lps (+/- 0.2 %)
(50 Pa = 0.2 w.c.) 5.98 ACH (1/h)
3.33 lpsm² Floor Area

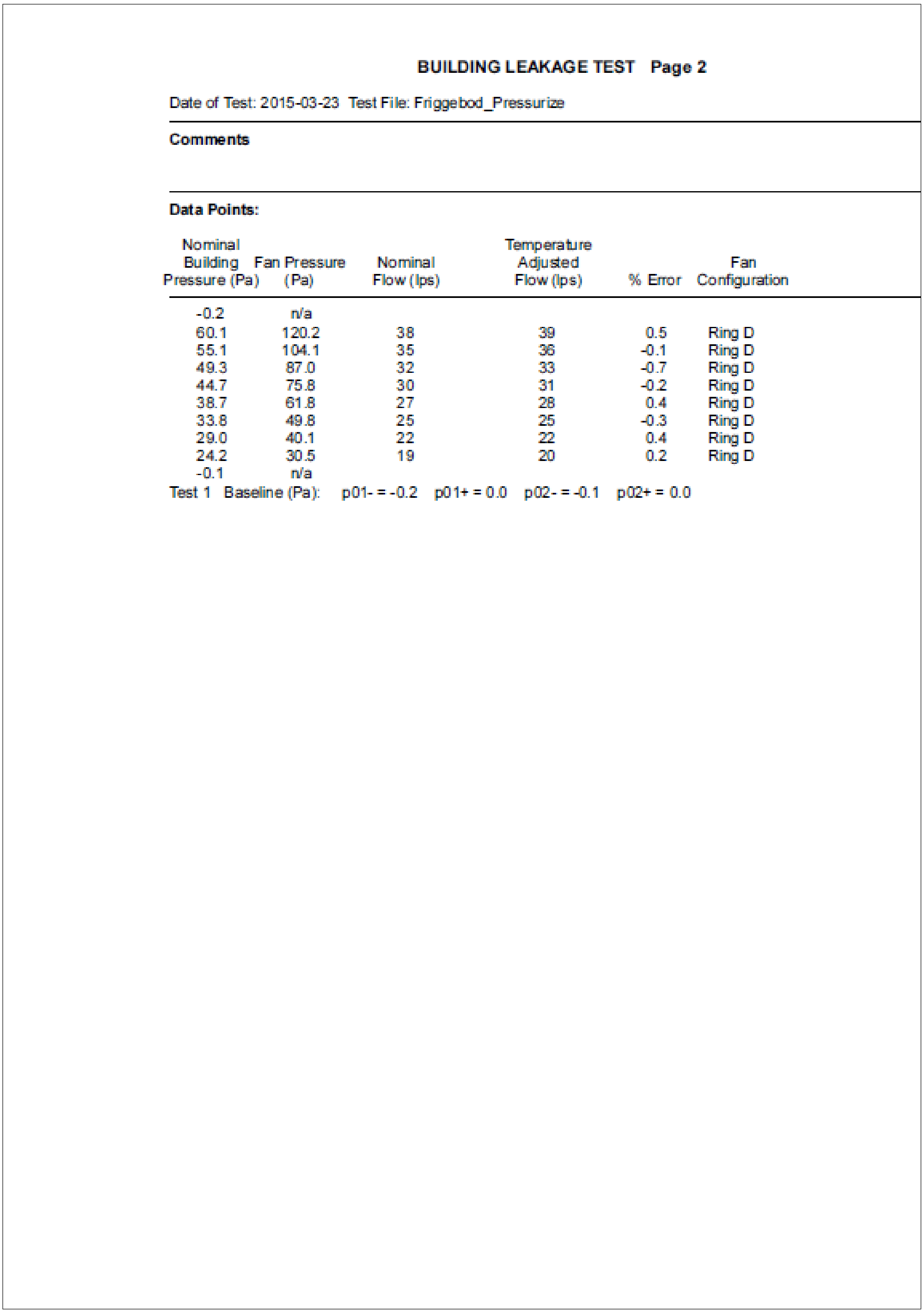
Leakage Areas: 40.6 cm² (+/- 1.0 %) Canadian EqLA @ 10 Pa
19.8 cm² (+/- 1.6 %) LBL ELA @ 4 Pa

Minneapolis Leakage Ratio: 0.67 lpsm² Surface Area

Building Leakage Curve: Flow Coefficient (C) = 1.8 (+/- 2.6 %)
Exponent (n) = 0.742 (+/- 0.007)
Correlation Coefficient = 0.99976

Test Standard: EN 13829 Test Mode: Pressurization
Type of Test Method: B Regulation complied with:
Equipment: Model 3 (230V) Minneapolis Blower Door

Inside Temperature:	25 °C	Volume:	20 m³
Outside Temperature:	18 °C	Surface Area:	50 m²
Barometric Pressure:	101325 Pa	Floor Area:	10 m²
Wind Class:	0 Calm	Uncertainty of	
Building Wind Exposure:	Highly Protected Building	Building Dimensions:	3 %
Type of Heating:		Year of Construction:	
Type of Air Conditioning:			
Type of Ventilation:	None		



BUILDING LEAKAGE TEST Page 2

Date of Test: 2015-03-23 Test File: Friggebod_Pressurize

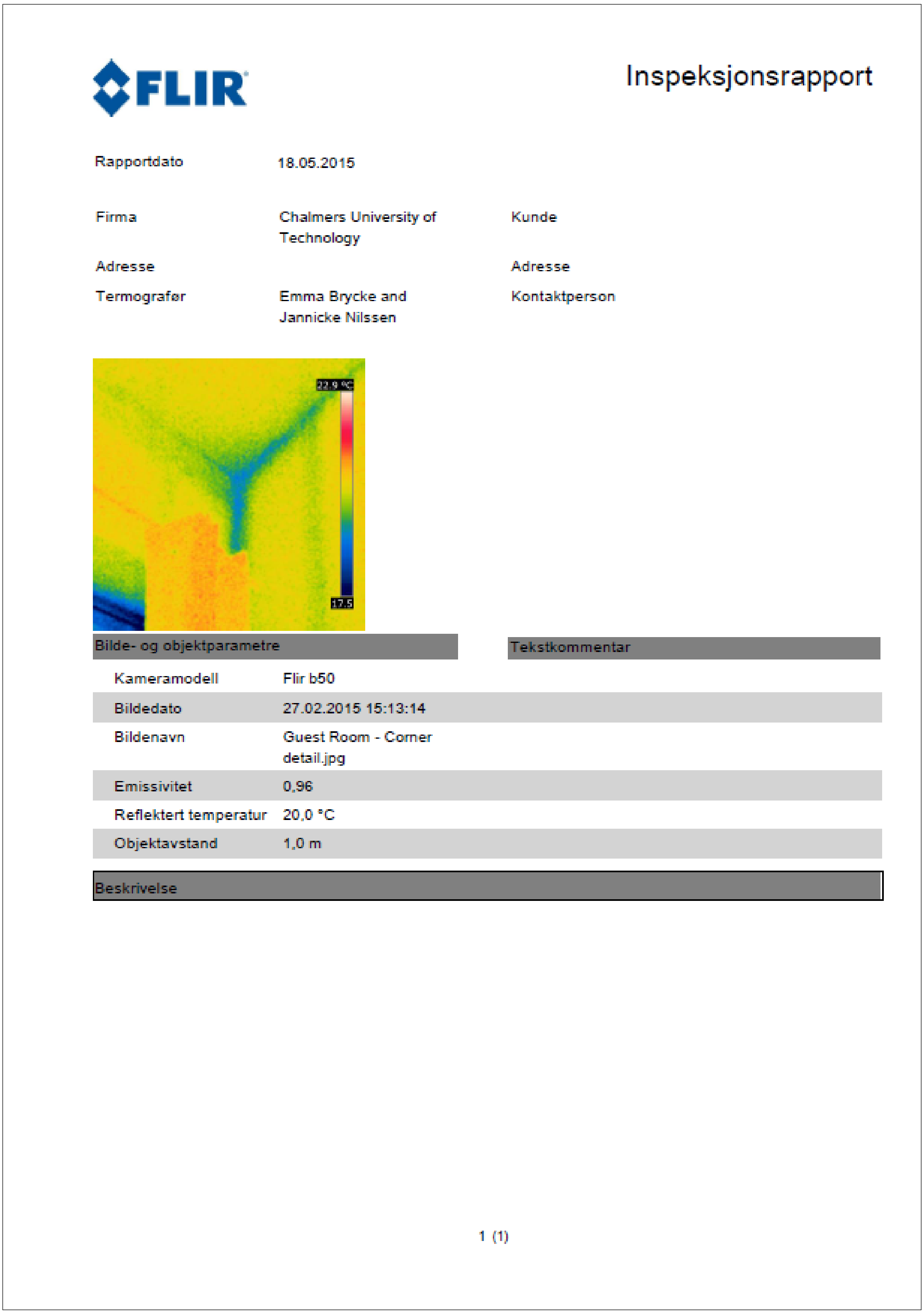
Comments

Data Points:

Nominal Building Pressure (Pa)	Fan Pressure (Pa)	Nominal Flow (lps)	Temperature Adjusted Flow (lps)	% Error	Fan Configuration
-0.2	n/a				
60.1	120.2	38	39	0.5	Ring D
55.1	104.1	35	36	-0.1	Ring D
49.3	87.0	32	33	-0.7	Ring D
44.7	75.8	30	31	-0.2	Ring D
38.7	61.8	27	28	0.4	Ring D
33.8	49.8	25	25	-0.3	Ring D
29.0	40.1	22	22	0.4	Ring D
24.2	30.5	19	20	0.2	Ring D
-0.1	n/a				

Test 1 Baseline (Pa): p01- = -0.2 p01+ = 0.0 p02- = -0.1 p02+ = 0.0

Appendix N Inspection Reports, Thermography, Guest Room



FLIR

Inspeksjonsrapport

Rapportdato	18.05.2015		
Firma	Chalmers University of Technology	Kunde	
Adresse		Adresse	
Termografør	Emma Brycke and Jannicke Nilssen	Kontaktperson	

Bilde- og objektparametre

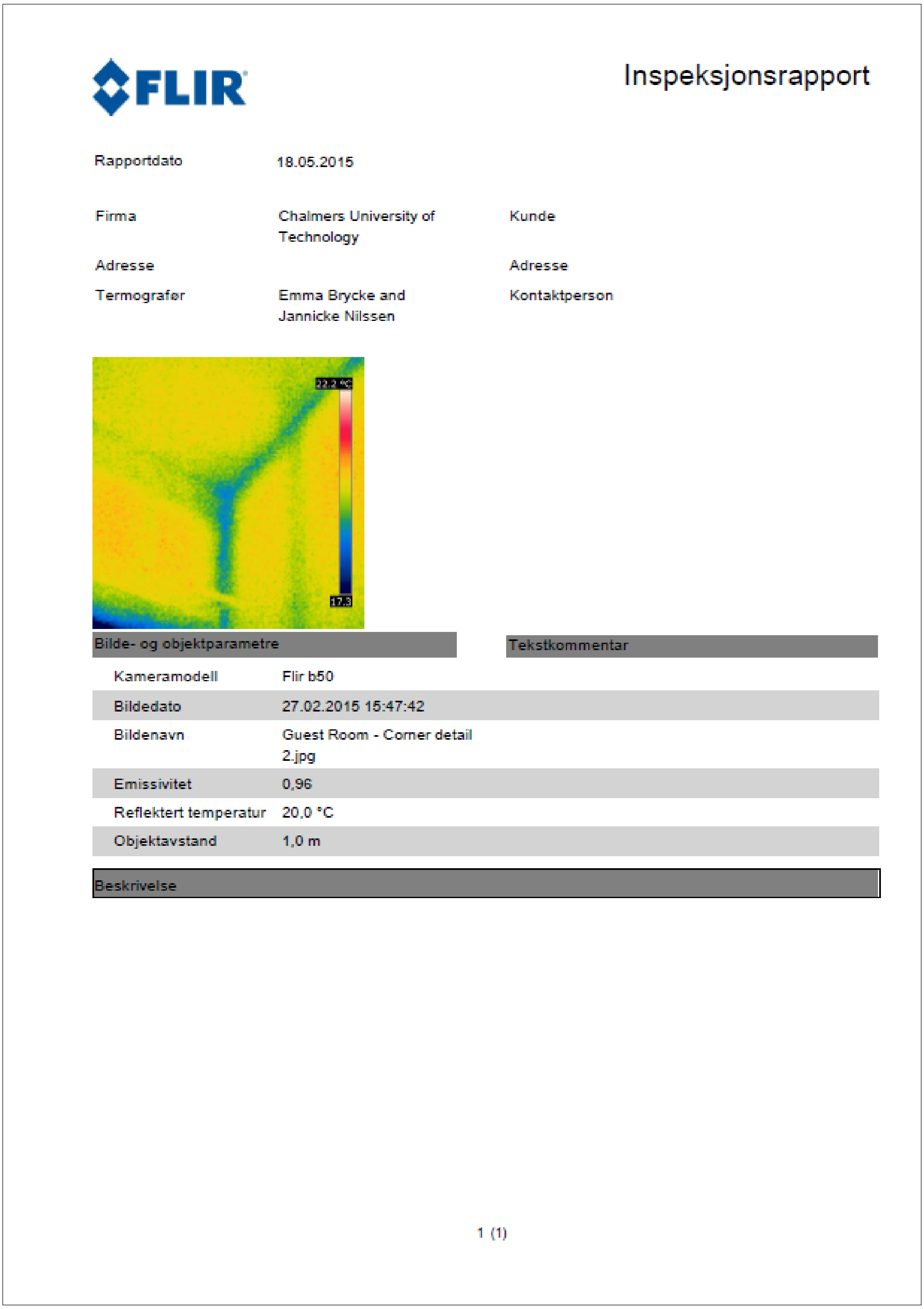
Kameramodell	Flir b50
Bildedato	27.02.2015 15:13:14
Bildenavn	Guest Room - Corner detail.jpg
Emissivitet	0,96
Reflektert temperatur	20,0 °C
Objektavstand	1,0 m

Tekstkommentar

Beskrivelse

1 (1)

Figure N.1 Corner Detail – Roof/Wall nr. 1.



Inspeksjonsrapport

Rapportdato	18.05.2015		
Firma	Chalmers University of Technology	Kunde	
Adresse		Adresse	
Termografør	Emma Brycke and Jannicke Nilssen	Kontaktperson	

Bilde- og objektparametre

Tekstkommentar

Kameramodell	Flir b50
Bildedato	27.02.2015 15:47:42
Bildenavn	Guest Room - Corner detail 2.jpg
Emissivitet	0,96
Reflektert temperatur	20,0 °C
Objektavstand	1,0 m

Beskrivelse

1 (1)

Figure N.2 Corner Detail –Roof/Wall nr. 2.

FLIR

Inspeksjonsrapport

Rapportdato	18.05.2015		
Firma	Chalmers University of Technology	Kunde	
Adresse		Adresse	
Termografør	Emma Brycke and Jannicke Nilssen	Kontaktperson	

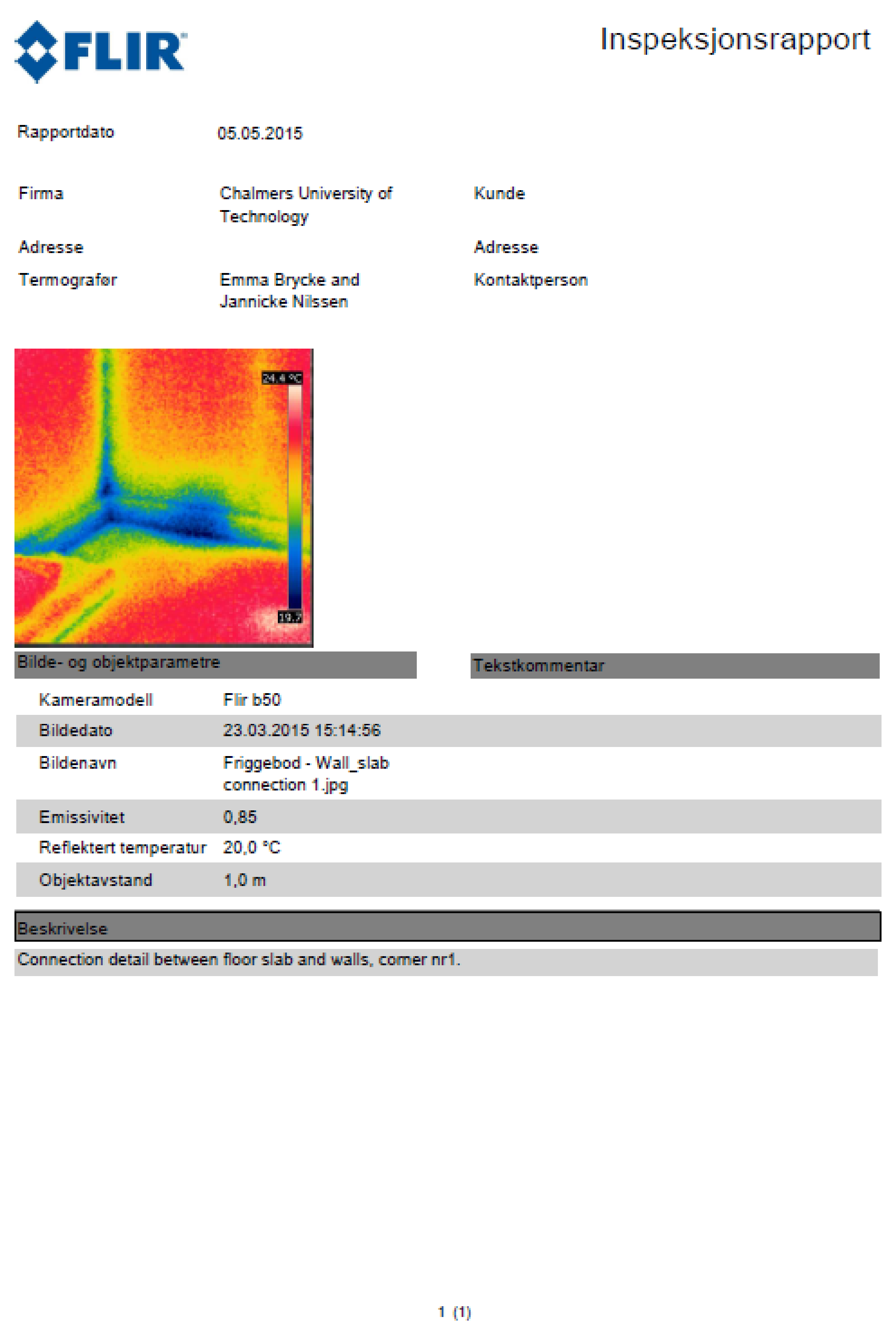
Bilde- og objektparametre		Tekstkommentar
Kameramodell	Flir b50	
Bildedato	27.02.2015 15:48:02	
Bildenavn	Guest Room - Window detail.jpg	
Emissivitet	0,96	
Reflektert temperatur	20,0 °C	
Objektavstand	1,0 m	

Beskrivelse

1 (1)

Figure N.3 Corner Detail – Window Corner.

Appendix O Inspection Reports, Thermography Friggebod



Inspeksjonsrapport

Rapportdato	05.05.2015		
Firma	Chalmers University of Technology	Kunde	
Adresse		Adresse	
Termografør	Emma Brycke and Jannicke Nilssen	Kontaktperson	

Bilde- og objektparametre

Kameramodell	Flir b50
Bildedato	23.03.2015 15:14:56
Bildenavn	Friggebod - Wall_slab connection 1.jpg
Emissivitet	0,85
Reflektert temperatur	20,0 °C
Objektavstand	1,0 m

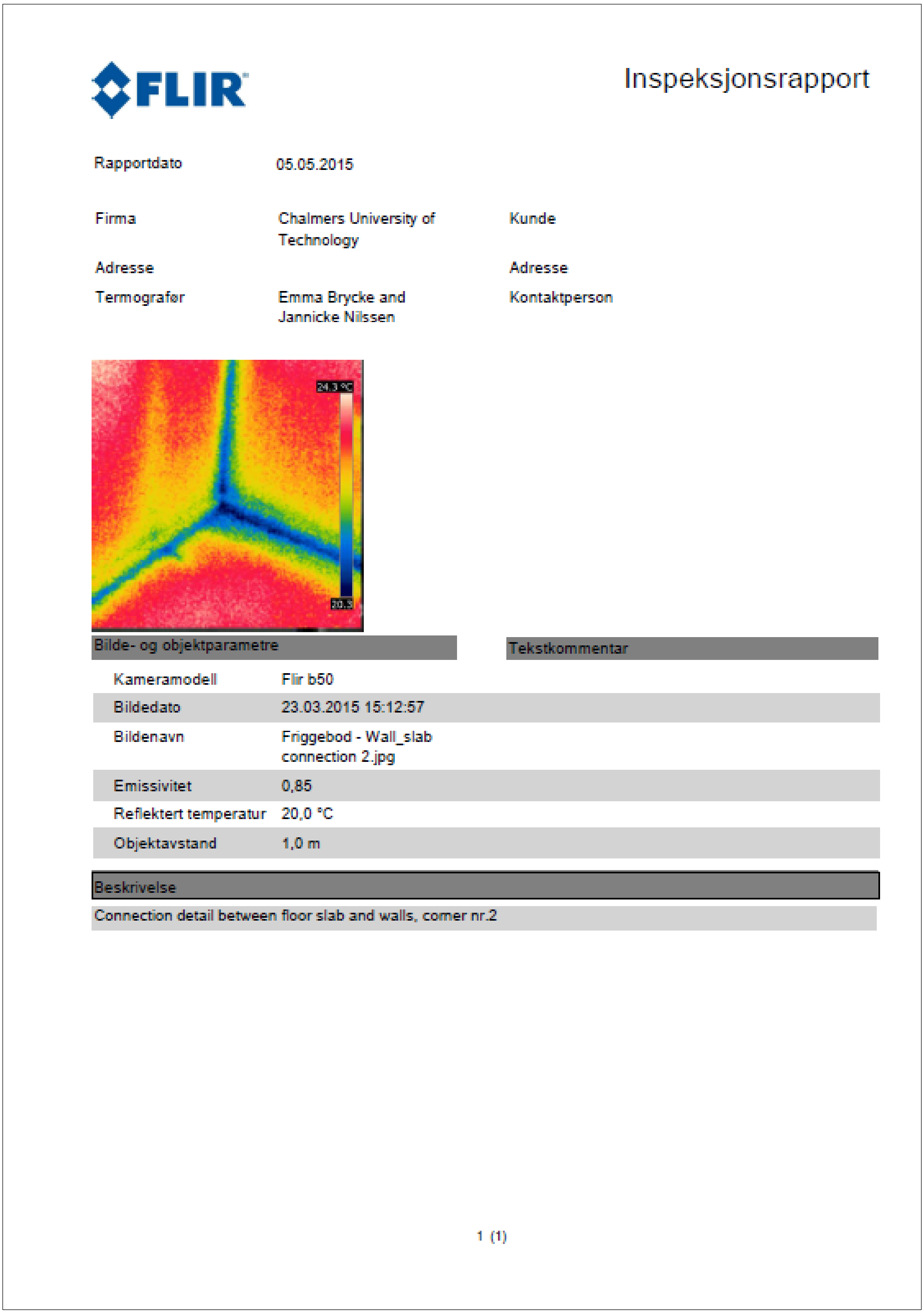
Tekstkommentar

Beskrivelse

Connection detail between floor slab and walls, corner nr1.

1 (1)

Figure O.1 Corner detail – Floor Slab/Walls nr. 1.



FLIR

Inspeksjonsrapport

Rapportdato	05.05.2015		
Firma	Chalmers University of Technology	Kunde	
Adresse		Adresse	
Termografør	Emma Brycke and Jannicke Nilssen	Kontaktperson	

Bilde- og objektparametre

Tekstkommentar

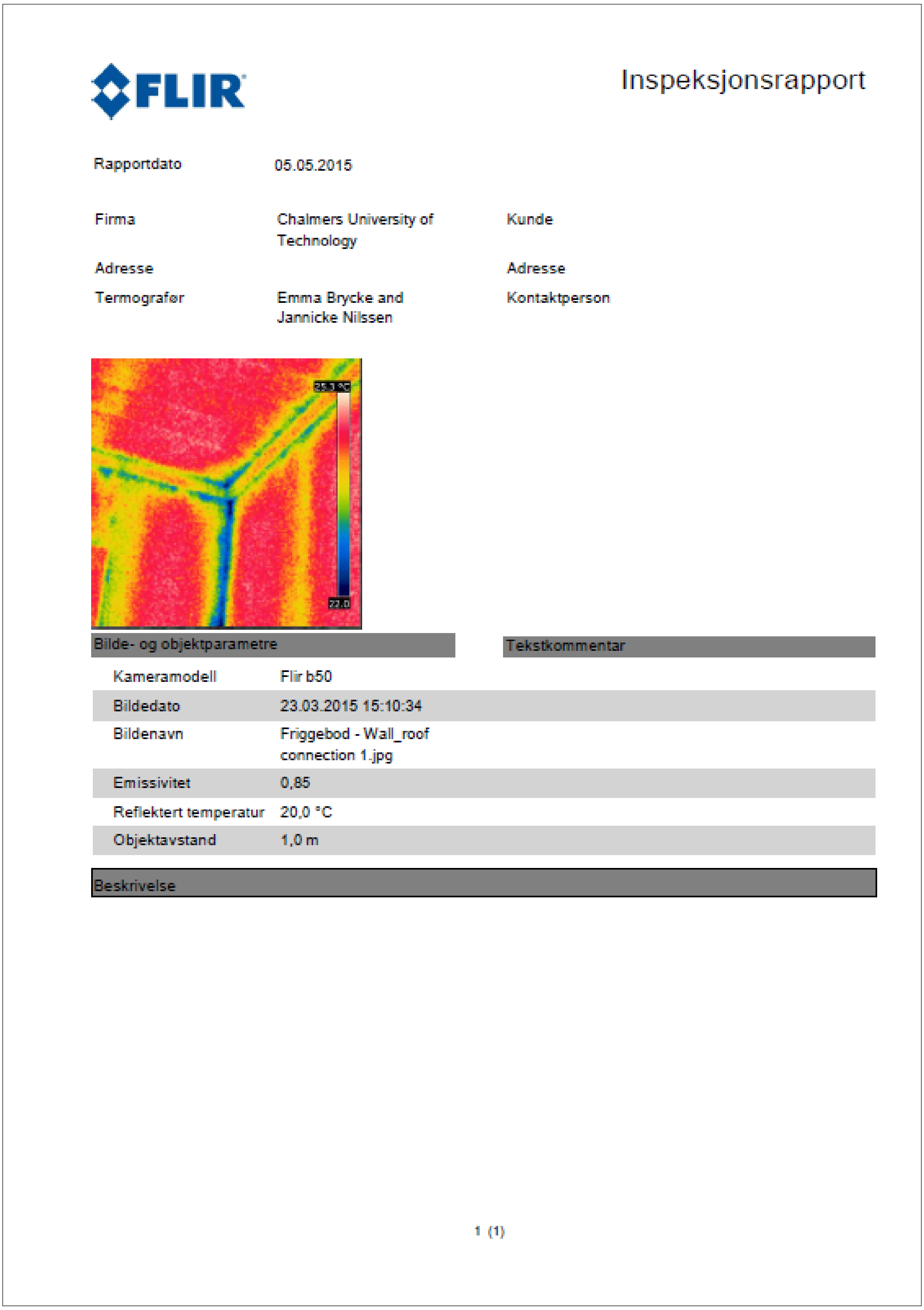
Kameramodell	Flir b50
Bildedato	23.03.2015 15:12:57
Bildenavn	Friggebod - Wall_slab connection 2.jpg
Emissivitet	0,85
Reflektert temperatur	20,0 °C
Objektavstand	1,0 m

Beskrivelse

Connection detail between floor slab and walls, corner nr.2

1 (1)

Figure O.2 Corner Detail – Floor Slab/Wall nr. 2



Inspeksjonsrapport

Rapportdato	05.05.2015		
Firma	Chalmers University of Technology	Kunde	
Adresse		Adresse	
Termografør	Emma Brycke and Jannicke Nilssen	Kontaktperson	

Bilde- og objektparametre

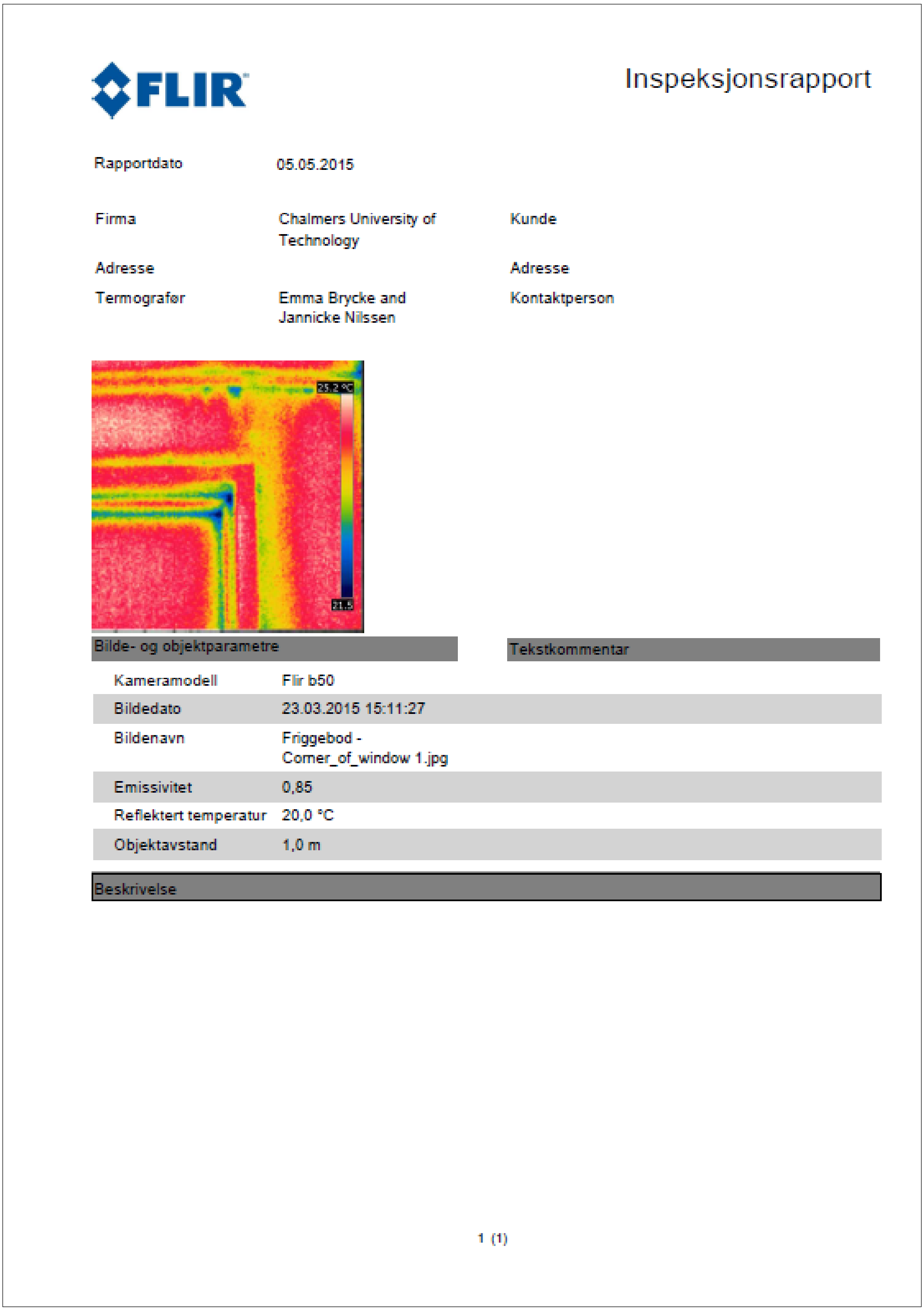
Tekstkommentar

Kameramodell	Flir b50
Bildedato	23.03.2015 15:10:34
Bildenavn	Friggebod - Wall_roof connection 1.jpg
Emissivitet	0,85
Reflektert temperatur	20,0 °C
Objektavstand	1,0 m

Beskrivelse

1 (1)

Figure O.3 Corner Detail – Roof/Walls



FLIR

Inspeksjonsrapport

Rapportdato	05.05.2015		
Firma	Chalmers University of Technology	Kunde	
Adresse		Adresse	
Termografør	Emma Brycke and Jannicke Nilssen	Kontaktperson	

Bilde- og objektparametre

Tekstkommentar

Kameramodell	Flir b50
Bildedato	23.03.2015 15:11:27
Bildenavn	Friggebod - Corner_of_window 1.jpg
Emissivitet	0,85
Reflektert temperatur	20,0 °C
Objektavstand	1,0 m

Beskrivelse

1 (1)

Figure O.4 Corner Detail – Window Corner

Appendix P Construction Drawings, Community Building

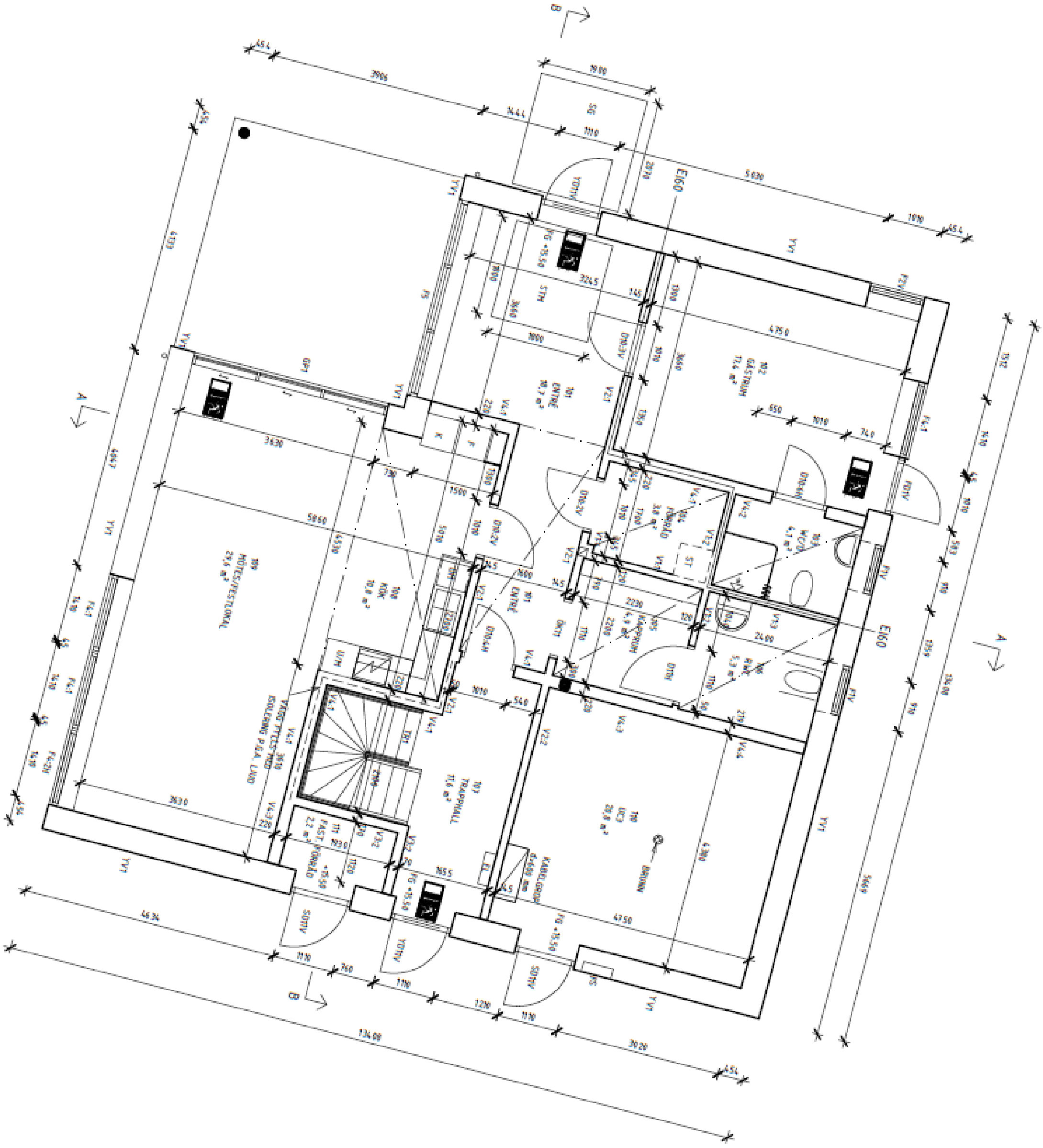


Figure P.1 Plan drawing, 1st floor in Community building (Architect: Håkan Markgren)..

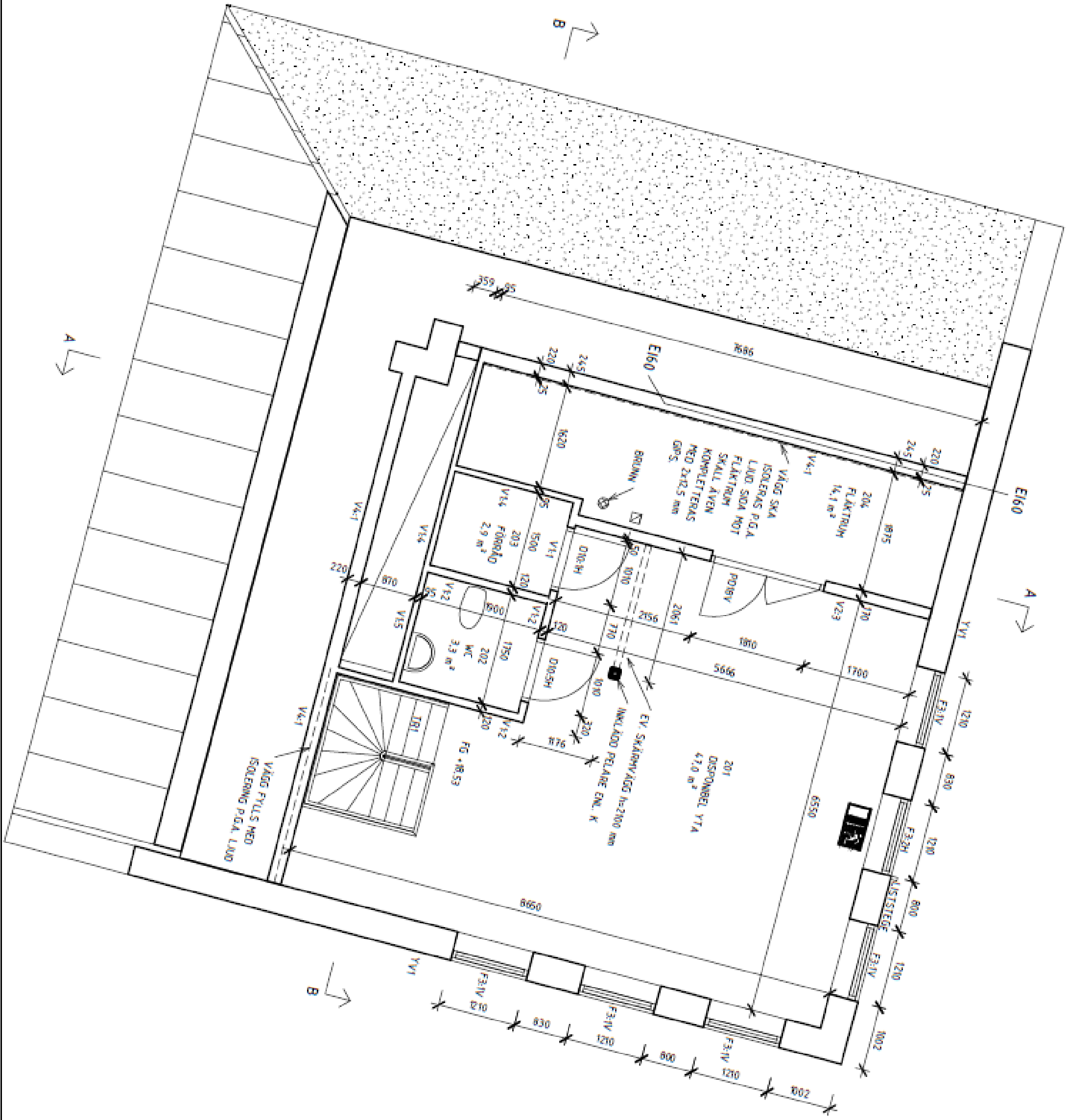


Figure P.2 *Plan drawing, 2nd floor in Community building (Architect: Håkan Markgren)..*

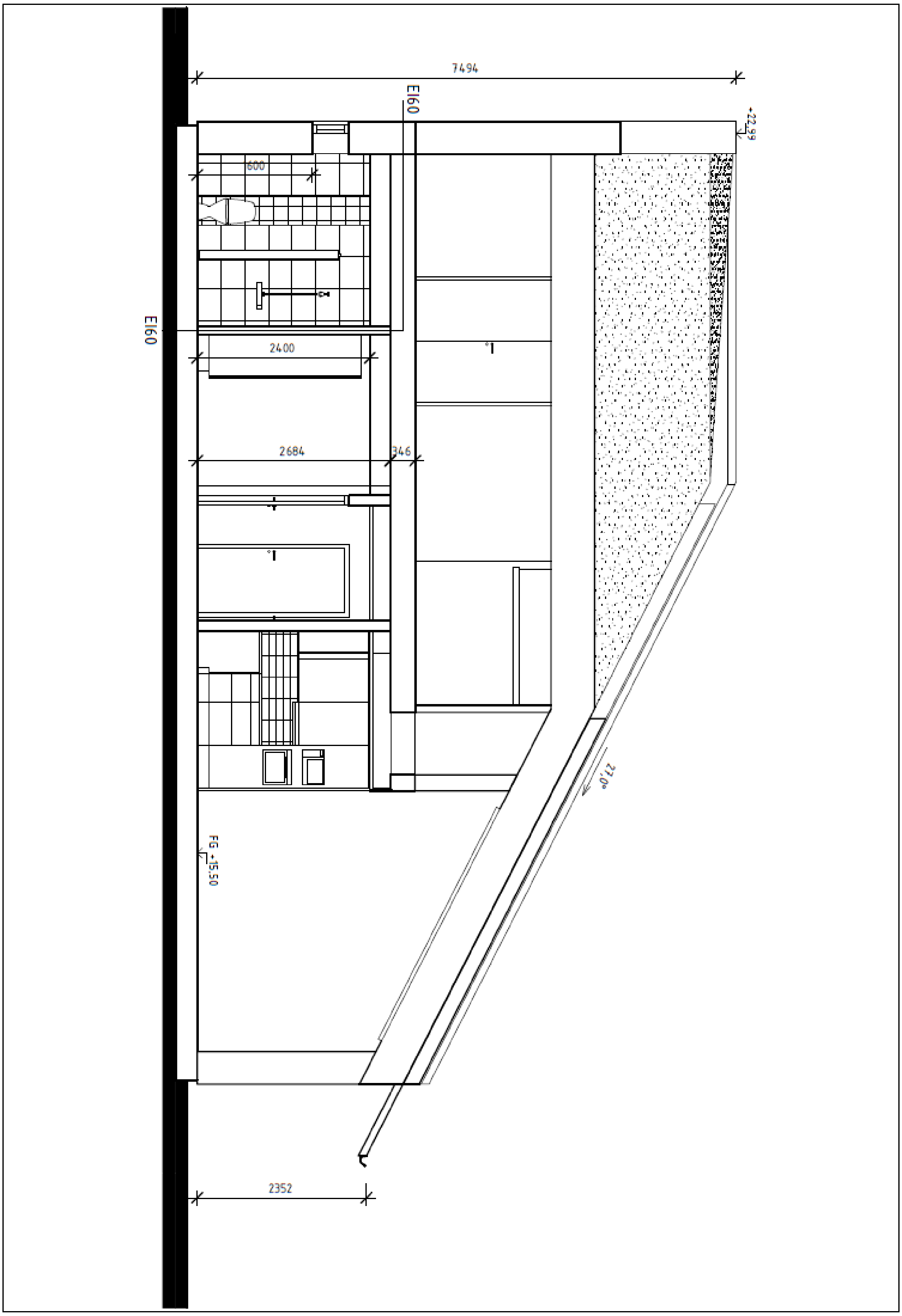


Figure P.3 Section B-B, Community building (Architect: Håkan Markgren)..

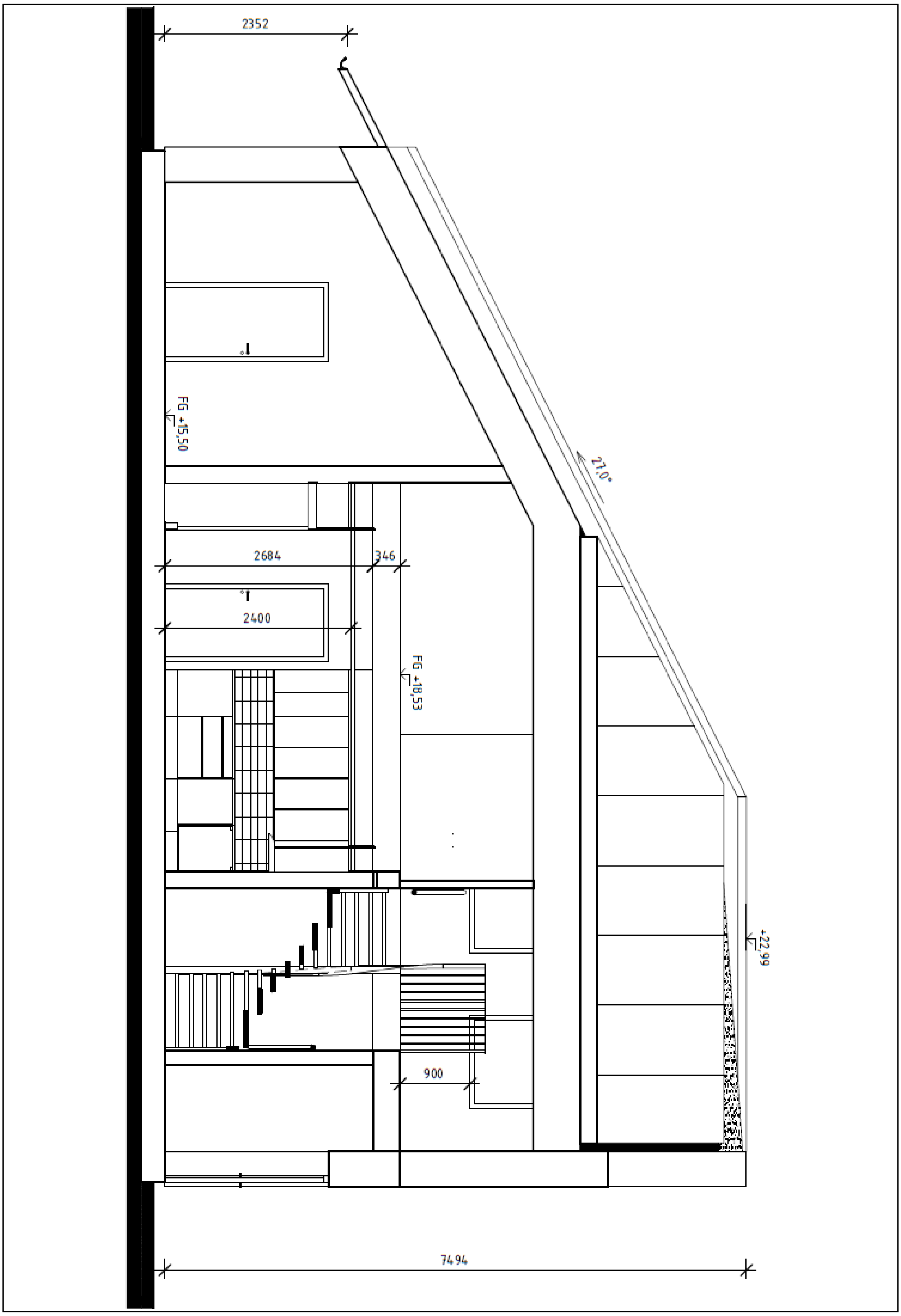


Figure P.4 Section A-A, Community building (Architect: Håkan Markgren).

Appendix Q Construction Drawings, Friggebod

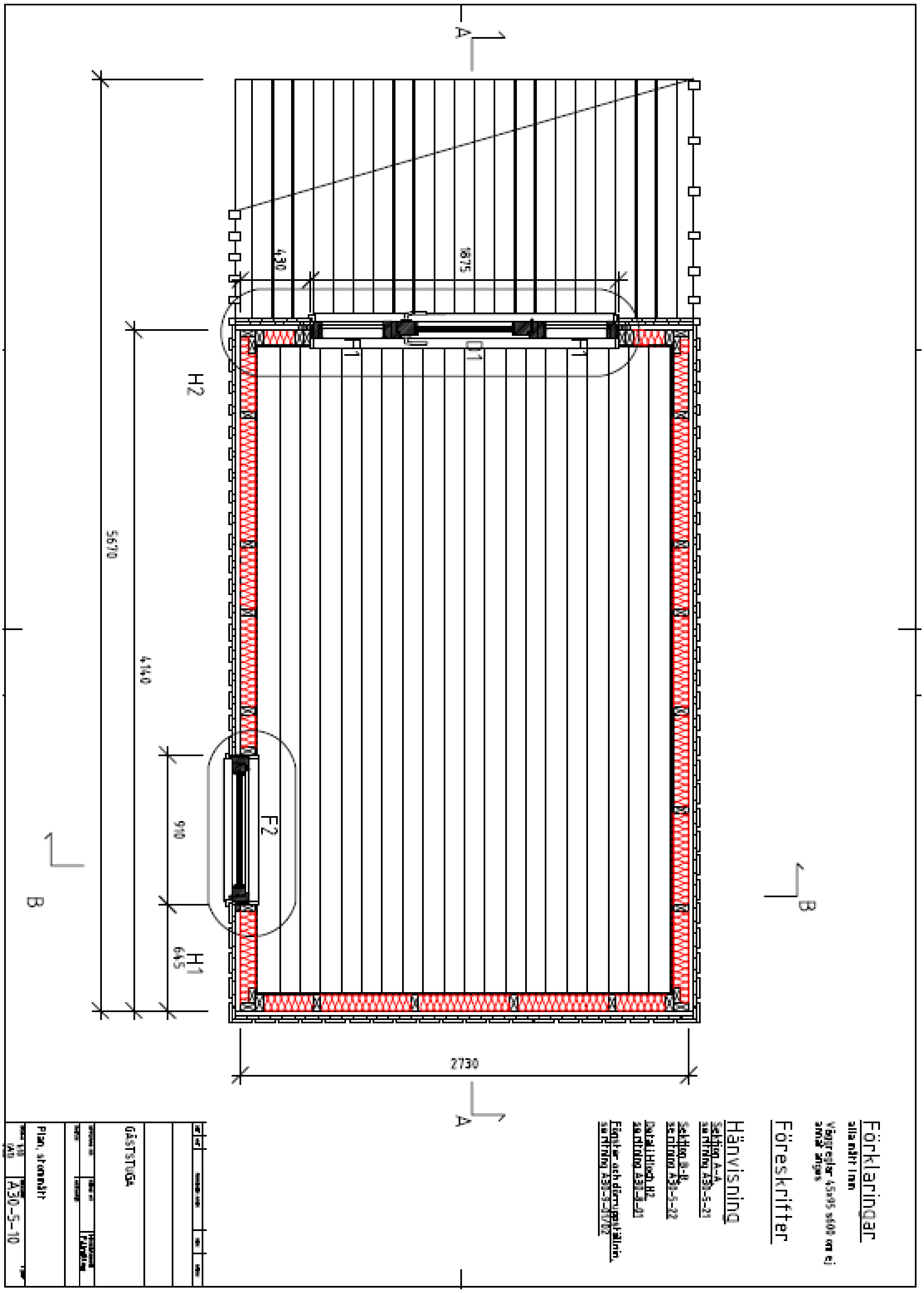


Figure Q.1 Plan drawing, Friggebod (Architect: Andrea Brandén)

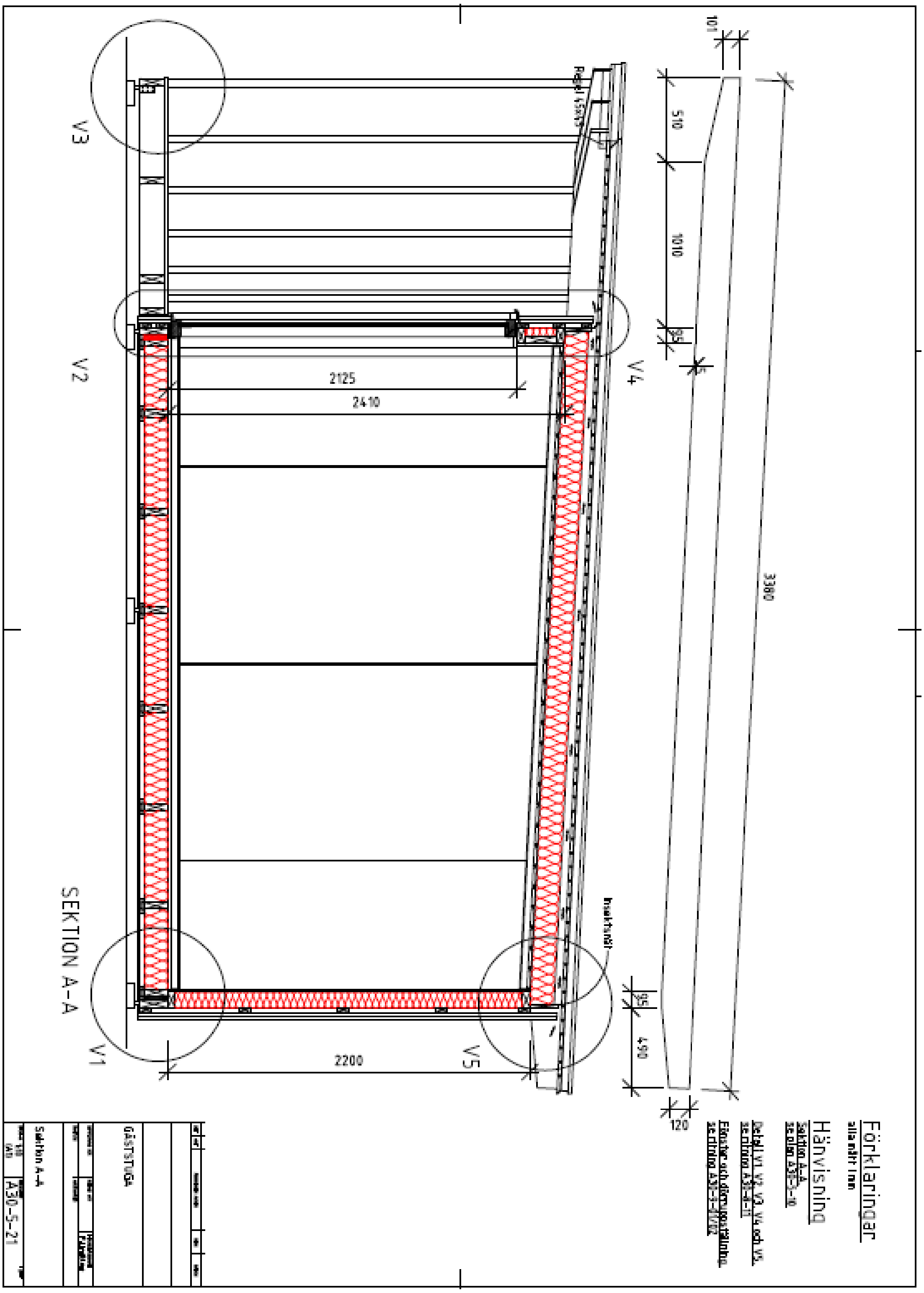


Figure Q.2 Section A-A, Friggebod (Architect: Andrea Brandén).

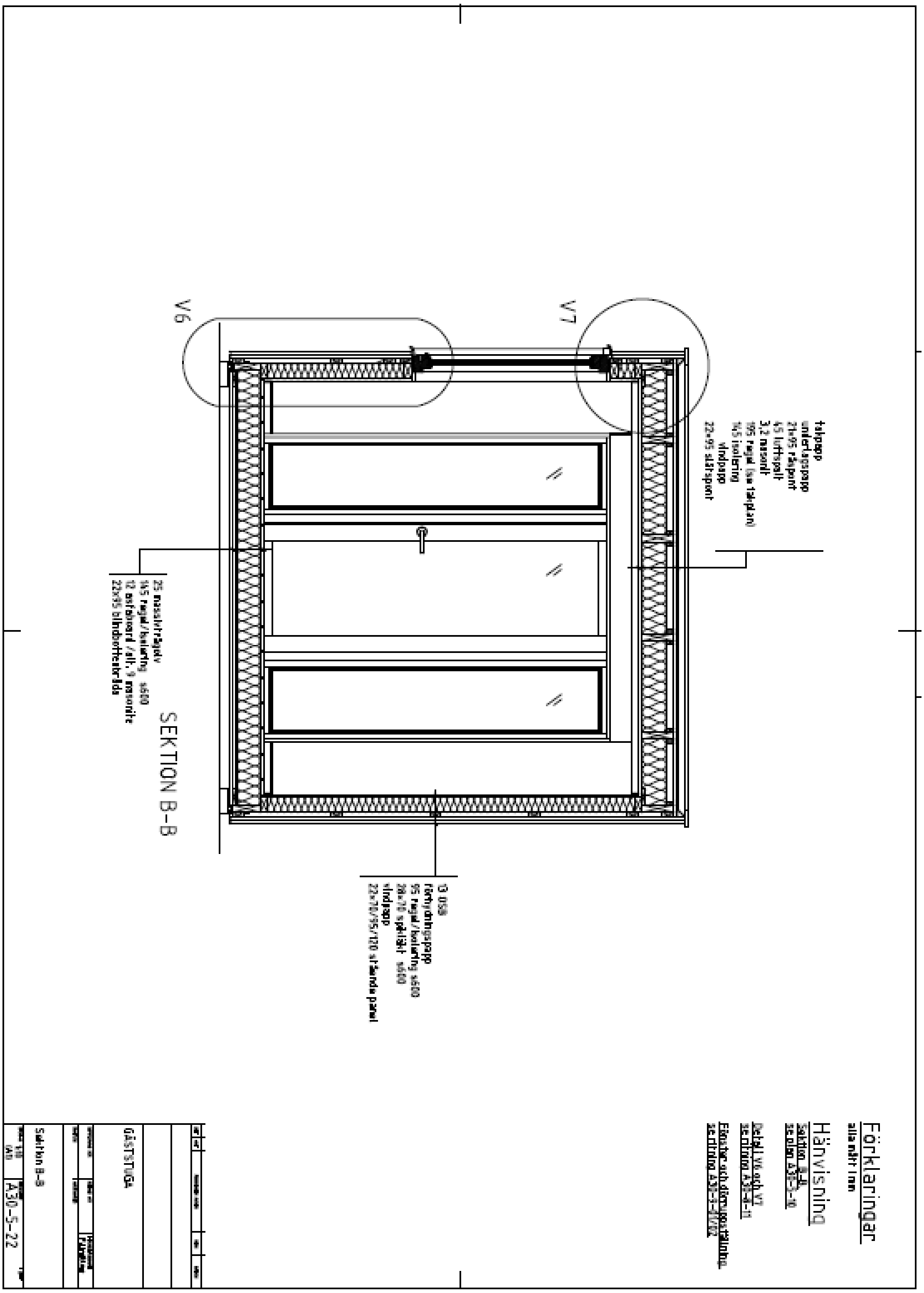


Figure Q.3 Section B-B, Friggebod (Architect: Andrea Brandén).