Vacuum Insulation Panels in Wood Frame Wall Constructions - Hot Box Measurements and Numerical Simulations

Thomas Haavi [a*], Bjørn Petter Jelle [b], Arild Gustavsen [c],
Steinar Grynning [d], Sivert Uvsløkk [e], Ruben Baetens [f] and Roland Caps [g]

[a] NTNU BHT and SINTEF, Phone + 98 23 0442, Fax +47 73 595045, thomas.haavi@sintef.no
[b] SINTEF and NTNU BAT, Phone +47 73 593377, Fax +47 73 593380, bjorn.petter.jelle@sintef.no
[c] NTNU BHT, Phone +47 73 595065, Fax +47 73 595045, arild.gustavsen@ntnu.no
[d] SINTEF, Phone +47 73 593375, Fax +47 73 593380, steinar.grynning@sintef.no
[e] SINTEF, Phone +47 73 593393, Fax +47 73 593380, sivert.uvslokk@sintef.no
[f] KUL and SINTEF, Phone +32 16 321348, Fax +32 16 321980, ruben.baetens@bwk.kuleuven.be
[g] VAQTEC, Phone +49 931 35 942 12, Fax +49 931 35 942 10, caps@va-q-tec.com

* Corresponding author

NTNU BHT   Department of Architectural Design, History and Technology, Norwegian University of
             Science and Technology (NTNU), NO-7491 Trondheim, Norway.

NTNU BAT   Department of Civil and Transport Engineering, Norwegian University of Science and
             Technology (NTNU), NO-7491 Trondheim, Norway.

SINTEF   Department of Materials and Structures, Trondheim, SINTEF Building and Infrastructure,
             NO-7465 Trondheim, Norway.

KUL   Laboratory of Building Physics - Department of Civil Engineering, Catholic University of
             Leuven (KUL), Kasteelpark Arenberg 40, B-3001 Heverlee, Belgium

VAQTEC   va-Q-tec AG, Karl-Ferdinand-Braun-Str. 7, D-97080 Würzburg, Germany

ABSTRACT

Energy use in buildings accounts for a significant part of the energy use and greenhouse gas emissions. New building regulations and new measures have been introduced to improve the energy efficiency of buildings. In these buildings the envelope constructions will have significant amounts of traditional thermal insulation, e.g. wall thicknesses up to about 400 mm are expected in passive houses. Such large thicknesses are not desirable due to several reasons, e.g. floor area considerations, efficient material use and need for new construction techniques.

Vacuum insulation panels (VIPs) are regarded as one of the most promising existing high performance thermal insulation solutions on the market today. Thermal performances 5 to 10 times better than traditional insulation materials (e.g. mineral wool) are achieved, resulting in substantial slimmer constructions. However, the robustness of building envelope systems applying VIPs has been questioned. In addition, thermal bridging due to the vacuum insulation panel envelope and load bearing elements of the walls may have a large effect on the overall thermal performance. Degradation of thermal performance of VIPs with time is also a crucial issue due to moisture and air diffusion through the panel envelope.

In this work the thermal performance and robustness of vacuum insulation panels in wood frame wall constructions were studied by hot box measurements and numerical simulations. The thermal performance of three different wall configurations was examined. VIPs were sandwiched between traditional insulation in walls where the load bearing elements were standard 36 mm thick wooden studs, I-profiled studs and U-profiled studs. The measured mean values of the thermal transmittance (U-value) were 0.09 W/(m^{2}K) with 36 mm wooden studs, 0.10 W/(m^{2}K) with U-profiled studs and 0.11 W/(m^{2}K) with I-profiled studs.

Keywords: Vacuum insulation panel, VIP, Wood frame wall, Hot box, Numerical simulation, Thermal performance, Building insulation, Thermal bridge, Thermal conductivity, Thermal transmittance, U-value, Thermal resistance.

1. INTRODUCTION

As energy requirements for buildings are tightened, the building envelopes applying traditional building insulation materials are getting thicker in order to have a sufficient high thermal resistance, i.e. a low thermal transmittance (U-value). Traditional building insulation materials like mineral wool, expanded or extruded polystyrene have thermal conductivity values typically between 33 to 40 mW/(mK). However, there exist other materials and solutions with lower thermal conductivities than these conventional building insulation materials. One of these solutions is the vacuum insulation panel (VIP), which exhibit conductivities as low as between 3.5 to 4 mW/(mK) in the pristine non-aged condition. The VIP solution consists of an open pore structure of fumed silica core with a metallized polymer laminate envelope acting as a moisture and air barrier around the core material. Depending on the properties of the laminate envelope, the thermal conductivity of VIP will increase during the years, e.g. up to 8 mW/(mK) after 25 years ageing. A perforated VIP, e.g. by a nail, will have a thermal conductivity of about 20 mW/(mK). It will be crucial to the thermal performance, to make the construction with VIPs in the building envelope as robust as possible.

Comprehensive work has already been carried out on investigations of the thermal properties, performance and service life of VIPs (Brunner et al. 2005). It should be noted that VIPs are rather complex products, where the panel core and laminate envelope have widely different thermal properties (Tenpierik et al. 2007). The work carried out on VIPs regarding their thermal performance includes numerical calculations (Schwab et al. 2005, Willems et al. 2005), analytical evaluations (Tenpierik and Cauberg 2007), laboratory measurements on a smaller scale (Wakili et al. 2004) and field studies of building projects (Platzer 2007). A recent extensive review on VIPs for building applications has been given by Baetens et al. (2010), also including material concepts beyond VIPs.

The work presented here represents the second phase of an on-going experimental study of VIPs applied in the building envelope. The first phase explored the effect and importance of several ways of arranging different VIPs in various large scale structures (Grynning et al. 2009). The studies included hot box investigations of single and double layer configurations versus panel thicknesses, edge effects, effect of air gaps between the VIPs, staggering of VIPs, i.e. overlapping panels, and taped VIP joints. The second phase hot box measurements presented here, investigate the effect of applying different structural vertical timber frame stud profiles between the VIPs in order to minimize the heat loss through the building envelopes. Specifically, the thermal performance of standard wooden studs, I-profiled studs and U-profiled studs were examined with VIPs as the main thermal insulation between the vertical studs. These investigations are part of the large scale tests of VIPs to be studied within the research program *Robust Envelope Construction Details for Buildings of the 21st Century* (ROBUST), where on-going and future work will incorporate tests on VIPs in practical and useable configurations.

2. EXPERIMENTAL

2.1 Test materials

Vacuum Insulation Panels
The VIPs used in the hot box measurements are of the type va-Q-vip B delivered from the company va-Q-tec (va-Q-tec 2009a). The panels used are 40 mm thick, 600 mm wide and 1000 mm high (nominal dimensions). A 0.1 mm thick multilayer MF-2 type foil is used and the panels are in addition covered with a 0.3 mm thick fire retardant glass fibre material.

Studs

Standard 36 mm wooden studs, I-profiled studs and U-profiled studs were examined with VIPs combined with mineral wool as the thermal insulation between the vertical studs. These studs and the corresponding wall structures will be referred to as *36 mm stud*, *I-stud* and *U-stud* throughout this paper. The studs are shown in Figure 2-1. Description of the studs:

- **36mm stud:** Standard wooden stud with 36 mm thickness and originally 198 mm height. The height was reduced to 170 mm, the same as the I-stud and the U-stud.
- **I-stud:** I-profiled studs where the flange material was 47 mm x 47 mm wooden studs and the web material was 8 mm thick fibreboard. The web was glued to the flanges. The total height of the I-stud was 170 mm.
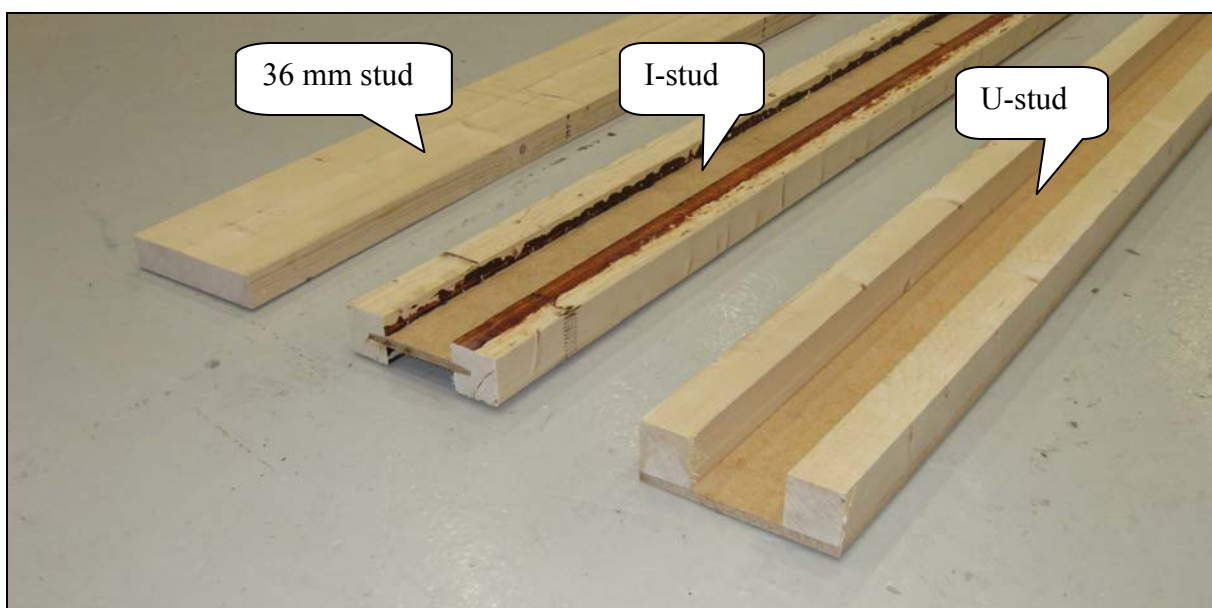- **U-stud:** U-profiled studs where the flange material was 45 mm x 45 mm wooden studs and the web material was 8 mm thick fibreboard. The web was nailed to the flanges. The total height of the U-stud was 170 mm.

Figure 2-1   The different studs used in the wood frame wall constructions.

Mineral Wool

Mineral wool with 25 mm and 70 mm thickness was used in the tested wall constructions, on both sides of the VIPs and in the I-stud and the U-stud (see Figure 2-2 to Figure 2-4).

Medium Density Fibreboard

Medium density fibreboard (MDF) with 6 mm thickness was used in the tested wall constructions, outside the insulation and the studs (see Figure 2-2 to Figure 2-4).

2.2   Test equipment

Measurements in the hot box have been carried out according to the governing standard, NS-EN ISO 8990:1997. The hot box at SINTEFs laboratory in Trondheim, Norway is a guarded hot box with a metering area of 2.45 m by 2.45 m. The U-values reported for the wall sections are however for the sizes reported in the figure texts for each wall section (Figure 2-2 to Figure 2-4). Measurements in the hot box were done for the following wood frame wall constructions with vacuum insulation panels:

1. Wall with 36 mm studs
2. Wall with I-studs
3. Wall with U-studs

The temperature was 0°C on the cold side, and 20°C on the hot side of the walls.

2.3 Wall with 36 mm studs

The wall consists of two 36 mm studs with insulation as shown in Figure 2-2. The sections with insulation have a nominal total thickness of 182 mm, and consist of the following layers: 6 mm MDF – 65 mm mineral wool – 40 mm VIP – 65 mm mineral wool – 6 mm MDF.
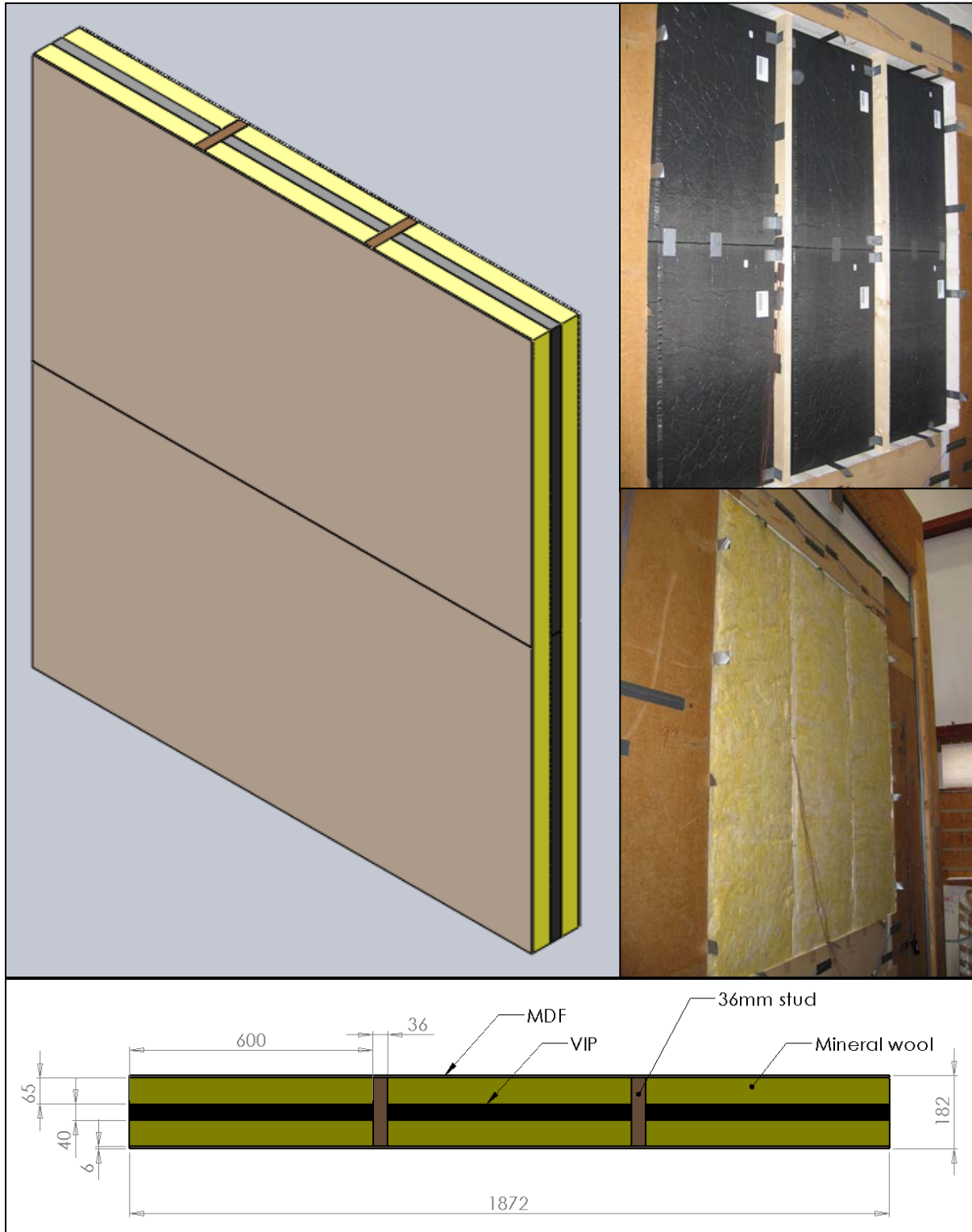

Figure 2-2 Wall with 36 mm studs. Nominal dim.: h = 2000 mm, w = 1872 mm, t = 182 mm.

2.4 Wall with I-studs

The wall consists of two I-studs with insulation as shown in Figure 2-3. The sections with insulation have a nominal total thickness of 182mm, and consist of the following layers: 6 mm MDF – 65 mm mineral wool – 40 mm VIP – 65 mm mineral wool – 6 mm MDF. The volume between the web and the flanges of the I-stud is filled with mineral wool.
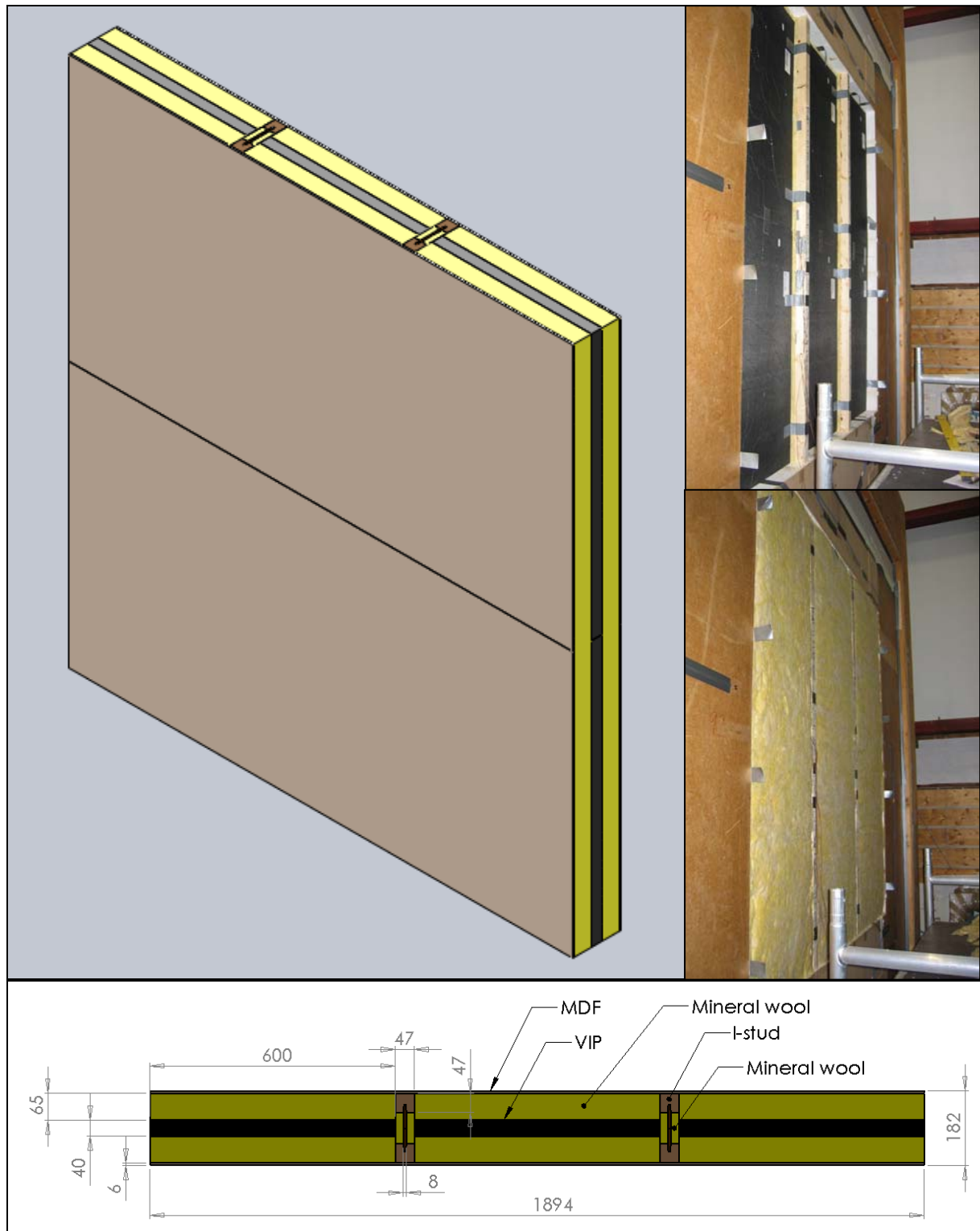

Figure 2-3   Wall with I-studs. Nominal dim.: h = 2000 mm, w = 1894 mm, t = 182 mm.

2.5 Wall with U-studs

The wall consists of two U-studs with insulation as shown in Figure 2-4. The sections with insulation have a nominal total thickness of 182mm, and consist of the following layers:
6 mm MDF – 65 mm mineral wool – 40 mm VIP – 65 mm mineral wool – 6 mm MDF
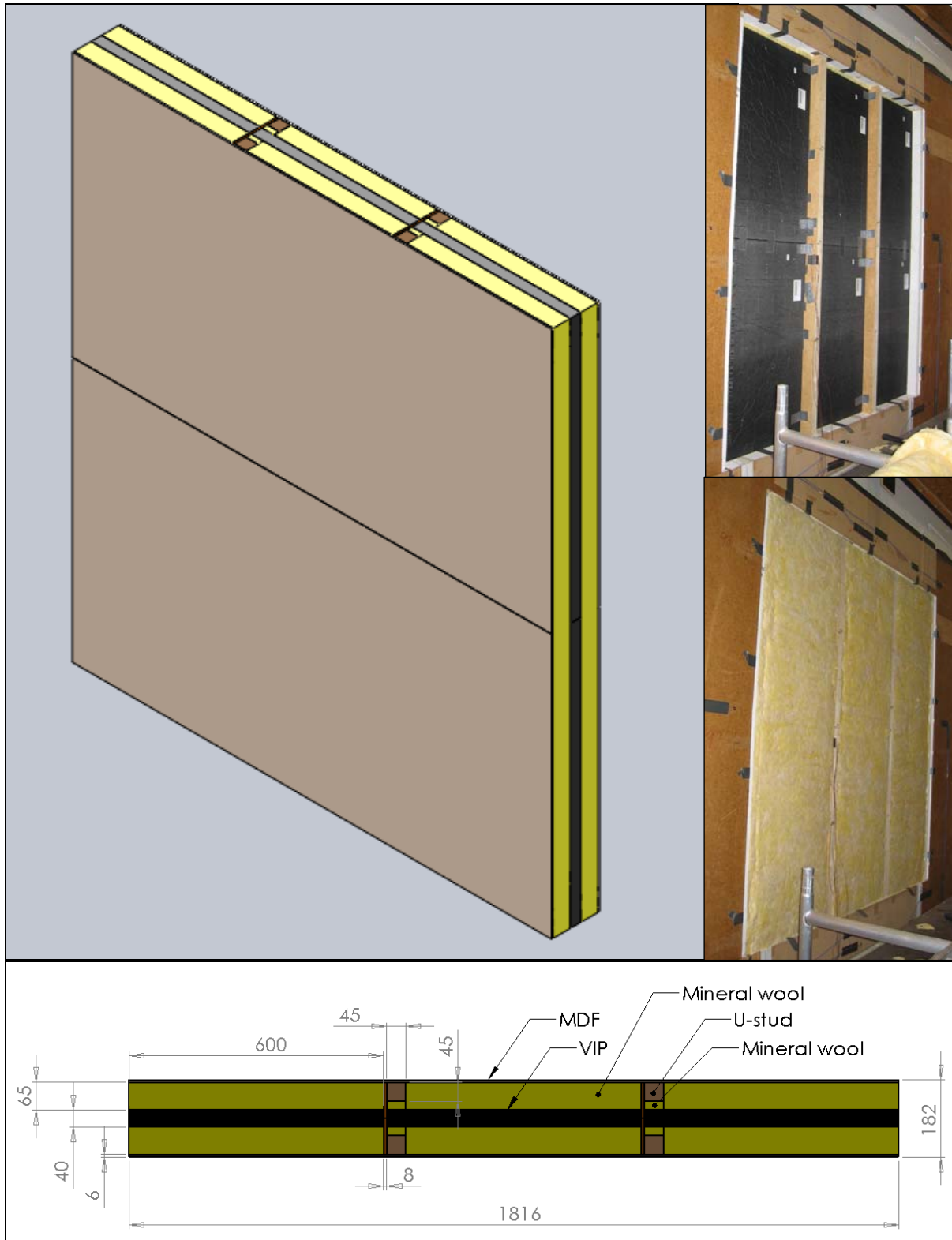The volume between the flanges of the U-stud and the VIP is filled with mineral wool.

Figure 2-4   Wall with U-studs. Nominal dim.: h = 2000 mm, w = 1816 mm, t = 182 mm.

2.6 Instrumentation

In addition to the general instrumentation in the hot box, the wall constructions were instrumented with 40 thermocouples and 2 heat flow meters as shown in Figure 2-5. There were 14 thermocouples on each side of the wall, and 6 thermocouples on the web of each stud. The heat flow meters were located on the hot side of the wall, close to the centre of the VIPs between the studs (approximately 100 mm to the left of the centre to avoid interference with the thermocouples). The two heat flow meters, referred to as TNO PU 43T.0024 and TNO PU 43T.0025, have been calibrated in a heat flow meter apparatus.

Figure 2-5   Placement of thermocouples and heat flow meters on wall and studs.
Upper left: Hot side, Upper right: Cold side.
Lower left: 36 mm stud, Lower middle: I-stud, Lower right: U-stud.

3. NUMERICAL SIMULATIONS

U-values have been calculated using the two dimensional, finite element program THERM Version 5.2 (Finlayson et al. 1998). The wall constructions which were tested in the hot box were modelled as shown in Figure 3-1, using the dimensions and thermal conductivities summarised in Table 3-1.

Nominal dimensions as shown in Figure 2-2 to Figure 2-4 have in general been used, except for the VIP panels. The measured average thickness of the VIP panels were 38.0 mm, i.e. 5 % less than the nominal dimension of 40 mm. The thickness of the mineral wool was increased accordingly to 66 mm.

The total thermal resistance of two VIP panels were measured in a heat flow meter apparatus according to the governing standard (NS-EN 12667 2001). The results from these measurements were used together with the values for VIP foil conductivity λ_{foil} = 0.54 W/(mK) (Tenpierik and Cauberg 2007) and VIP fire protective glass fibre λ_{gf} = 0.31 W/(mK) (va-Q-tec 2009b) to calculate an average VIP core conductivity λ_{core} = 0.00426 W/(mK).

It is common to measure the thermal conductivity through the thickness of fibreboard plates, but the thermal conductivity in the longitudinal direction is not well known. The thermal resistance in the longitudinal direction, i.e. the direction of the heat flow through the I-stud and the U-stud, was therefore measured in a heat flow meter apparatus according to the governing standard (NS-EN 12667 2001). The corresponding thermal conductivity $\lambda_{fb\parallel}$ = 0.38 W/(mK) were used in the numerical simulations.

The thermal conductivity of the 36 mm studs were calculated on basis of measured density and moisture content (Grynning and Uvsløkk 2008), which gave $\lambda_{w\,36mm}$ = 0.10 W/(mK). This thermal conductivity was used for the 36 mm studs, but also for the wooden flanges in the I-studs and U-studs although their density was not measured.

Typical thermal conductivity for wood $\lambda_{w\,typ}$ = 0.13 W/(mK) from NS-EN ISO 10456 (2007) is considerably higher. The U-values of the wall structures were also calculated with this thermal conductivity for comparison.

Table 3-1   Thermal conductivities and dimensions used in numerical simulations

Item	Thermal conductivity [W/mK]	Thickness [mm]	Reference/Comment
VIP core	0.0043	37.2	Thermal conductivity based on measurement of 2 VIP panels
VIP multilayer MF-2 type foil	0.54	0.1	Tenpierik and Cauberg (2007)
VIP fire retardant glass fibre material	0.31	0.3	va-Q-tec (2009b)
36 mm wood stud	0.10 (0.13)	36	Thermal conductivity of 0.10 W/(mK) is calculated from measured density and moisture content in 36 mm studs. The value in parenthesis (0.13 W/(mK)) is typical value for wood (NS-EN ISO 10456 2007)
Wooden flange in I-stud and U-stud	0.10 (0.13)	See Figure 2-3 and Figure 2-4	
Fibreboard in web of I-stud and U-stud	0.38	8	Thermal conductivity from measurement
Mineral wool	0.037	66	Glava (2008)
MDF	0.18	6	NS-EN ISO 10456 (2007)

Figure 3-1   Numerical simulation models with temperature isotherms.

4. RESULTS AND DISCUSSION

The results from the testing in the hot box are summarised in Table 4-1 and Table 4-2. The presented results are the mean, maximum and minimum value of the thermal transmittance (U-value) during the time interval where the results were extracted.

The results in Table 4-1, shows the average U-value for the different wall constructions with studs. The hot box results indicate that the wall with 36 mm studs has the lowest U-value, and that the wall with I-studs has the highest U-value. This correlates with the results from the numerical simulations, shown in Table 4-3. The results of the numerical simulations where the thermal conductivity of wood is increased from 0.10 W/(mK) to 0.13 W/(mK) is shown in parenthesis in Table 4-3.

The results in Table 4-2, shows the U-value which is measured with the heat flow meters (HFM), i.e. close to the centre of the VIPs, excluding the effect of the studs. The measured U-value at the centre of the VIPs is almost the same for all three wall constructions. This is expected, since this area should not be influenced by the studs.

A comparison of the hot box measurements and the numerical analyses are shown in Table 4-3, Table 4-4, Figure 4-1 and Figure 4-2. It can be seen that the measurements and simulations have quite good correlation. All the results are within 6.2% deviation, except the wall with 36 mm studs, where the results from the numerical simulations are 11.6 % higher.

It should be noted that all the U-values are very low. This means that the measured U-values are more sensitive to variations in the assembly of the full-scale wall constructions and possible air leakages.

The low U-values also imply that the numerical simulations are more sensitive to the accuracy of the dimensions and thermal conductivities used as input. Relatively small variations in the thermal conductivity and the thickness of the VIP panels, as well as variations in the thermal conductivities of the studs, have significant impact on the average U-value of the wall. This is illustrated by the results shown in parenthesis in Table 4-3, where the thermal conductivity of the wood is increased from 0.10 W/(mK) to 0.13 W/(mK). The deviation from the Hot Box measurements is then increasing, e.g. from 11.6 % to 17.9 % for the wall with 36 mm studs.

The thermal conductivity $\lambda_{w\ 36mm} = 0.10$ W/(mK), which were used in the numerical simulations, is calculated on basis of measured density and moisture content of the 36 mm studs (Grynning and Uvsløkk 2008). This value is considered to be more accurate than the standardised value for wood $\lambda_{w\ typ} = 0.13$ W/(mK) (NS-EN ISO 10456 2007), but a direct measurement of the thermal conductivity would be preferable.

The accuracy of the numerical simulations were significantly improved by measurements of the thickness and thermal resistance of VIP panels, as well as the thermal resistance of the fibreboard in the web of the I-studs and U-studs. Measurements of the thermal resistance of the 36 mm studs, as well as the mineral wool and the MDF, are assumed to further improve the accuracy of the numerical simulations.

Table 4-1   U-value measured in hot box. Average for wall with studs.

	Mean U-value	Maximum U-value *)	Minimum U-value *)
	[W/(m²K)]	[W/(m²K)]	[W/(m²K)]
36 mm stud	0.094	0.096	0.092
I-stud	0.108	0.109	0.107
U-stud	0.103	0.105	0.101

*) Maximum/minimum U-value for the time interval where the results were extracted.

Table 4-2   U-value measured by HFM in hot box. Wall at the centre of the VIPs.

	Mean U-value	Maximum U-value *)	Minimum U-value *)
	[W/(m²K)]	[W/(m²K)]	[W/(m²K)]
36 mm stud	0.082	0.083	0.082
I-stud	0.084	0.084	0.084
U-stud	0.083	0.084	0.082

*) Maximum/minimum U-value for the time interval where the results were extracted.

Table 4-3   Comparison of measurements and numerical analyses - Wall with studs. The effect of increasing the thermal conductivity of wood from 0.10 W/(mK) to 0.13 W/(mK) is shown in parenthesis.

	Hot Box	Numerical	Difference
	[W/(m²K)]	[W/(m²K)]	[%]
36 mm stud	0.094	0.105 (0.111)	11.6 (17.9)
I-stud	0.108	0.110 (0.112)	1.5 (3.7)
U-stud	0.103	0.108 (0.109)	5.0 (6.2)

Table 4-4   Comparison of measurements and numerical analyses – Wall at the centre of the VIPs.

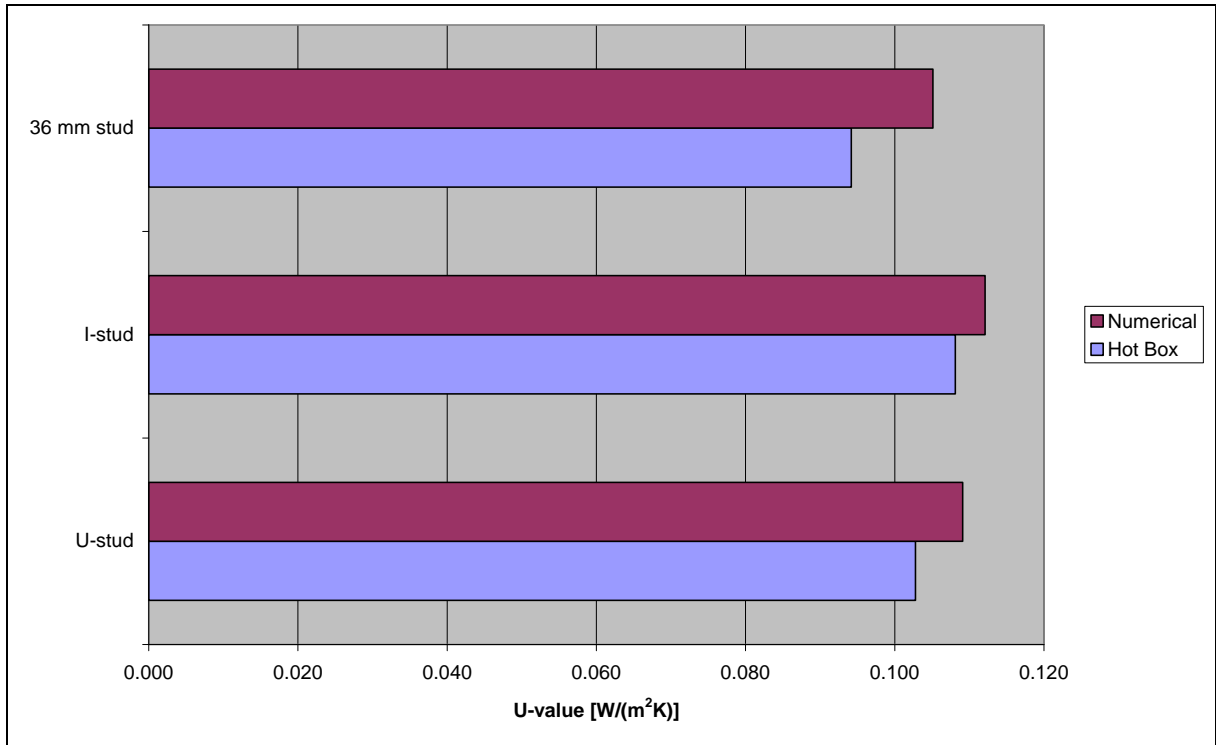|	Hot Box	Numerical	Difference
	[W/(m²K)]	[W/(m²K)]	[%]
36 mm stud	0.082	0.080	-3.2
I-stud	0.084	0.080	-4.9
U-stud	0.083	0.080	-4.0

Figure 4-1   Comparison of results – Wall with studs (Table 4-3). Numerical analyses with thermal conductivity of 0.10 W/(mK) for wood is shown.
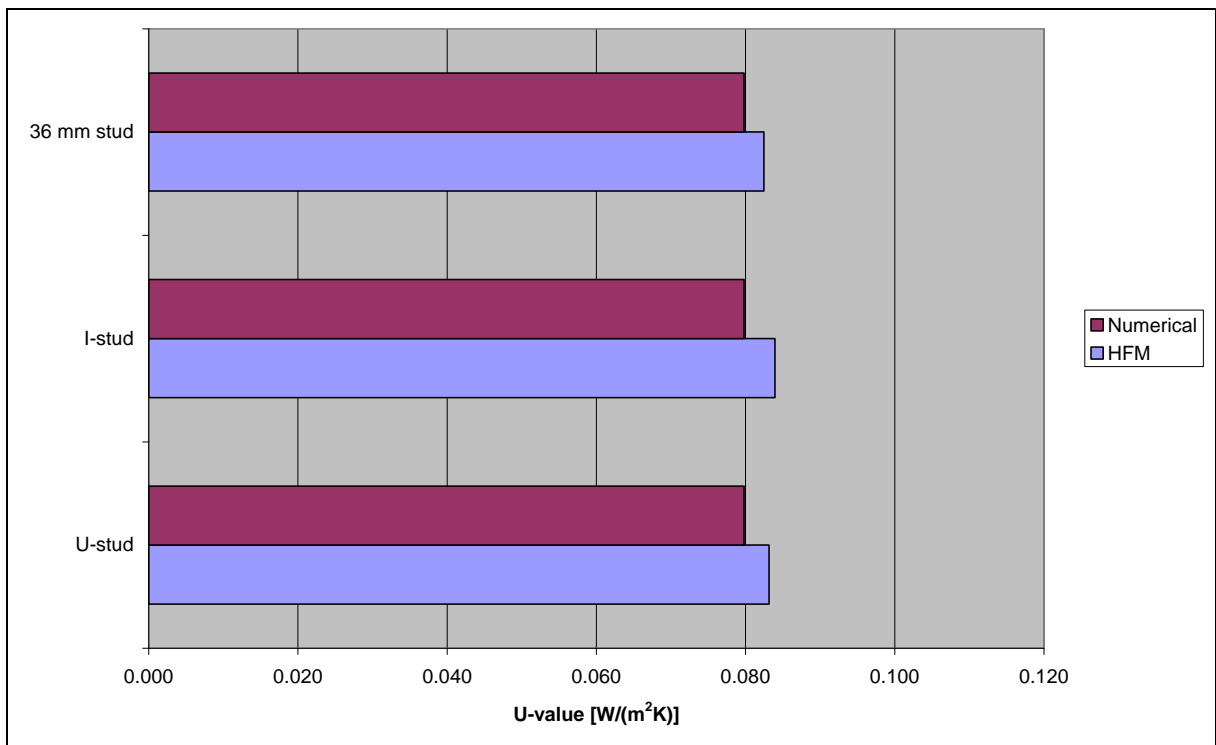

Figure 4-2   Comparison of results – Wall at the centre of the VIPs (Table 4-4).

5. CONCLUSIONS

The hot box testing and numerical analyses of different wood frame wall constructions with Vacuum Insulation Panels gave the following thermal transmittance (U-value):

	Hot Box [W/(m^{2}K)]	Numerical [W/(m^{2}K)]	Difference [%]
Wall with 36 mm stud	0.094	0.105	11.6
Wall with I-studs	0.108	0.110	1.5
Wall with U-studs	0.103	0.108	5.0

The wall sections had a somewhat low fraction of timber frame members and the results are not necessarily representative for normal walls. However, the comparison of the three wall structures have shown that with such low U-values, the numerical simulations are more sensitive to the accuracy of the dimensions and thermal conductivities used as input.

The accuracy of the numerical simulations were significantly improved by measurements of the thickness and thermal resistance of VIP panels, as well as the thermal resistance of the fibreboard in the web of the I-studs and U-studs.

Measurements of the thermal resistance of the 36 mm studs, as well as the mineral wool and the MDF, are assumed to further improve the accuracy of the numerical simulations.

ACKNOWLEDGEMENTS

REFERENCES

R. Baetens, B. P. Jelle, J. V. Thue, M. J. Tenpierik, S. Grynning, S. Uvsløkk and A. Gustavsen, "Vacuum Insulation Panels for Building Applications: A Review and Beyond", *Energy and Buildings*, **42**, 147-172, 2010.

S. Brunner, H. Cauberg, M. Erb, U. Heinemann, E. Kücükpinar-Niarchos, K. Kumaran, Ph. Mukhopadhyaya, K. Noller, D. Quénard, H. Sallée, H. Schwab, H. Simmler, C. Stramm and M. J. Tenpierik, "Vacuum insulation panels. Study on VIP-components and panels for service life prediction in building applications (Subtask A)", Final report for the *IEA/ECBCS Annex 39 HiPTI-project* (High Performance Thermal Insulation for buildings and building systems), 2005.

E. Finlayson, R. Mitchell, D. Arasteh, C. Huizenga and D. Curcija; "THERM 2.0: Program Description, A PC Program for Analyzing the Two-Dimensional Heat Transfer Through Building Products", (THERM Version 5.2); Lawrence Berkeley National Laboratory; June 1998.

Glava, Product data, Glava rull A37, Blad 330, Oslo Norway, Glava A/S, April 2008.

S. Grynning and S. Uvsløkk; "Varmekonduktivitet for furu og gran"; *Tre & Profil*, **5**, 44-45, 2008.

S. Grynning, B. P. Jelle, S. Uvsløkk, R. Baetens, V. Meløysund, T. Haavi and A. Gustavsen, "Comparison of Laboratory Investigations and Numerical Simulations of Vacuum Insulation Panels in Various Wall Structure Arrangements", in *Proceedings of the 9th International Vacuum Insulation Symposium (IVIS 2009)*, London, England, 17-18 September, 2009.

NS-EN ISO 8990:1997; "Thermal insulation Determination of steady-state thermal transmission properties Calibrated and guarded hot box", 1997.

NS-EN ISO 10456:2007; "Building materials and products, Hygrothermal properties – Tabulated design values and procedures for determining declared and design thermal values", 2007.

NS-EN 12667:2001; "Thermal performance of building materials and products Determination of thermal resistance by means of guarded hot plate and heat flow meter methods products of high and medium thermal resistance", 2001.

W. Platzer, "Optimisation and testing of a VIP exterior thermal insulation composite system (ETICS)", *Proceedings of the 8th International Vacuum Insulation Symposium,* Würzburg, September 18-19, 2007.

H. Schwab, C. Stark, J. Wachtel, H. P. Ebert and J. Fricke, "Thermal bridges in vacuum-insulated building facades", *Journal of Thermal Envelope and Building Science*, **28**, 345-355, 2005.

M. Tenpierik and H. Cauberg; "Analytical models for calculating thermal bridge effects caused by thin high barrier envelopes around vacuum insulation panels", *Journal of Building Physics*, **30**, 185-215, 2007.

M. J. Tenpierik, J. J. M. Cauberg and T. I. Thorsell, "Integrating vacuum insulation panels in building constructions: An integral perspective", *Construction Innovation*, **7**, 38-53, 2007.

va-Q-tec; Product information, Vacuum Insulation Panel (va-Q-vip B), Würzburg Germany, va-Q-tec GmbH, http://www.va-q-tec.com, 2009(a).

va-Q-tec and ZAE Bayern, Unpublished results (2007) according to method described at http://www.zae-bayern.de/files/thermoscan.pdf, information received from va-Q-tec (Roland Caps) in communication with SINTEF, 2009(b).

K. G. Wakili, R. Bundi and B. Binder, "Effective thermal conductivity of vacuum insulation panels", *Building Research & Information*, **32:4**, 293-299, 2004.

W. M. Willems, K. Schild and G. Hellinger; "Numerical investigation on thermal bridge effects in vacuum insulating elements", *Proceedings of the 7th International Vacuum Insulation Symposium*, pp. 5-14, 2005, EMPA, Dübendorf, September 28-29, 2005.