

Non-destructive Method to Determine the Water Vapour Pressure in Vacuum Insulation Panels (VIP)

D. Kraus, D. Büttner, U. Heinemann, J. Fricke
Bavarian Centre for Applied Energy Research (ZAE Bayern)
Am Hubland, 97074 Würzburg, Germany
kraus@zae.uni-wuerzburg.de

1 Introduction

VIP with envelopes made of polymeric high barrier laminates and a pressed powder filling have been introduced into the building market in the recent years. In these applications, the high thermal resistance should be maintained for at least 20 to 50 years. Thus, tests have to be performed to assure the durability for this long period of time. For this type of VIP, degradation of the thermal performance with time is caused on the one hand by penetrating dry air and on the other hand by permeating water vapour. For pressed fumed silica boards, a relatively high gas pressure - typically in the order of 100 mbar - may be tolerated before thermal conductivity starts to increase significantly. Within the scope of durability tests, an increase in internal gas pressure can be detected much faster and more accurately than an increase in thermal conductivity. Thus, repeated measurements of the internal total gas pressure often performed by the foil lift-off method are the basis for calculations of the expected increase in thermal conductivity with time.

As for other polymeric laminates, the permeation rates of water vapour for high barrier laminates are several orders of magnitude larger than those for oxygen or nitrogen. Thus, for prognosis of the thermal behaviour, also the impact of the water content – both adsorbed by the filler material and as water vapour in the pores – and its variation with time have to be considered.

The difference in partial pressures inside and outside the panel is the impelling force for permeation. Since the partial pressures of dry gases (oxygen and nitrogen in the atmosphere) are much higher than the one of water vapour, the permeation of those gases is nearly constant for a long time. In contrast to dry gases the partial pressure of moisture is small at ambient temperature (e.g. 28 mbar at 23 °C). This leads to decreasing water permeation as the impelling force declines. Finally an equilibrium will be reached and the moisture permeation ceases.

Here, a non-destructive measurement procedure is presented to determine the contribution of water vapour to the total internal gas pressure. Our new technique is based on the foil lift-off method. In contrast to other methods with a single measurement per time step, a set of two measurements at different temperatures is performed. For a temperature independent sorption isotherm, the internal water vapour pressure (which is proportional to the saturated vapour pressure) is expected to vary exponentially with temperature whereas the pressure of the dry gases varies proportional to the absolute temperature according to the ideal gas law.

2 Method to determine the water vapour pressure

2.1 Description

The standard way to quantify the water content of a VIP leads to its destruction: First, the laminate has to be removed. Then, the mass of the core material must be determined two times – before and after water is expelled by heating. From the water mass in percent of the mass of the core material, the relative humidity and the partial pressure of water vapour can be calculated by making use of the sorption isotherm.

The novel technique presented here is based on the foil lift-off method shown in Figure 1. The panel is placed between two evacuable spaces. The upper and lower space will be simultaneously evacuated, avoiding net forces between upper and lower vacuum chamber. The pressure (p_1 ; see figure 1) and the distance to the surface of the panel are measured. As soon as the pressure p_1 falls below the internal pressure of the VIP (p_2 ; see figure 1), the envelope of the panel lifts off.

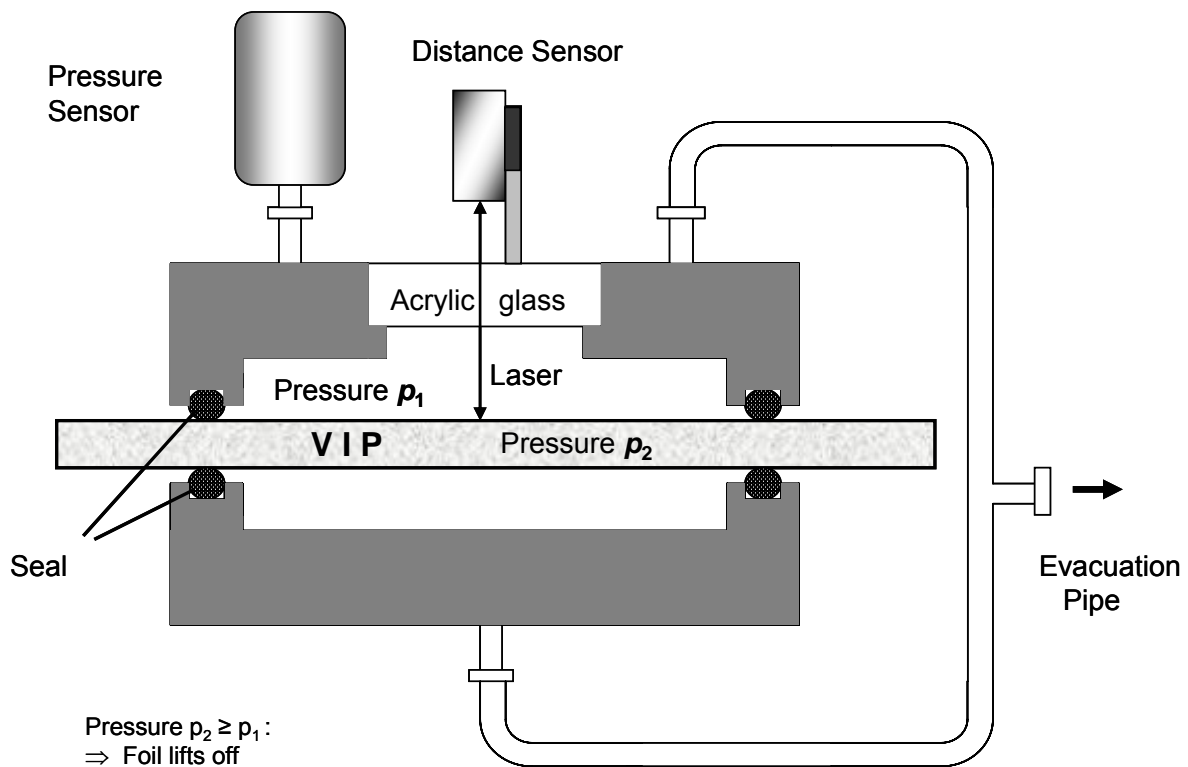


Figure 1: Principle of the foil lift-off method

The above procedure is performed at ambient temperature. When the measurement is repeated at a different temperature, the internal pressure for this specific temperature can be obtained.

Provided, that the sorption isotherm is independent of temperature, our method allows to derive to the internal water vapour pressure as the internal water content has not changed.

2.2 Theory

The pressure p_{dry} – as sum of the partial pressures of all dry gases - varies according to the ideal gas law:

$$p_{dry} \cdot V = N \cdot k \cdot T \quad \text{or} \quad p_{dry} \propto T \quad (1)$$

(N: number of atoms / molecules; k: *Boltzmann* constant = 1.38066×10^{-23} J/K).

Thus, p_{dry} is proportional to the absolute temperature T . On the other hand, the internal water vapour pressure varies exponentially with temperature:

$$p_{WV} \propto p_{WV, saturated} \propto \exp[f(\vartheta)] \quad (2)$$

(given that water vapour pressure is proportional to the saturated vapour pressure).

An approximation of the saturated vapour pressure depending on the temperature is given by the

Magnus equation:

$$p(\vartheta) = p(\vartheta = 0^\circ\text{C}) \cdot \exp\left[\frac{C_1 \cdot \vartheta}{C_1 + \vartheta}\right], \quad (3)$$

with $p(\vartheta = 0^\circ\text{C}) = 6.11$ mbar, $C_1 = 17.08$ and $C_2 = 234.18$ °C.

This equation has a high accuracy in the temperature range from 0 °C to 100 °C (< 0.22 %) [Wikipedia 2005]. Since the internal pressure is the sum of all partial pressures, the following equation gives the total pressure:

$$p(T) = a \cdot \frac{273.15^\circ\text{C} + \vartheta}{293.15^\circ\text{C}} + \varphi \cdot 6.11 \text{ mbar} \cdot \exp\left(\frac{C_1 \cdot \vartheta}{C_2 + \vartheta}\right), \quad (4)$$

whereas $a: p_{dry}(\vartheta = 20^\circ\text{C})$,

φ : relative humidity,

ϑ : temperature / °C and

T : absolute temperature / K.

The relative humidity φ can be calculated by substituting a with φ determined at a different temperature:

$$\varphi = \frac{\frac{273.15^\circ\text{C} + \vartheta_1}{273.15^\circ\text{C} + \vartheta_2} \cdot p(T_2) - p(T_1)}{6.11 \text{ hPa} \cdot \left[\frac{273.15^\circ\text{C} + \vartheta_1}{273.15^\circ\text{C} + \vartheta_2} \cdot \exp\left(\frac{C_1 \cdot \vartheta_2}{C_2 + \vartheta_2}\right) - \exp\left(\frac{C_1 \cdot \vartheta_1}{C_2 + \vartheta_1}\right) \right]}. \quad (5)$$

From the definition of the relative humidity

$$p_{WV}(T) = \varphi \cdot p_{WV, \text{saturated}}(T) \quad (6)$$

the water vapour pressure $p_{WV}(T)$ in the VIP can be derived. Combining the result of equation (5) with equation (4) leads to the sum of partial pressures of the dry gases at room temperature (20 °C):

$$a = \frac{p(T) - \left[6.11 \text{ mbar} \cdot \varphi \cdot \exp\left(\frac{C_1 \cdot \vartheta}{C_2 + \vartheta}\right) \right]}{\frac{273.15 \text{ °C} + \vartheta}{293.15 \text{ °C}}} \text{ mbar} \quad (7)$$

In contrast to measuring the mass of water within the VIP by heating the core material, this method does not use the sorption isotherm.

2.3 Experimental results

First experimental test were accomplished with absolute pressure sensors built into the tested VIP. Thus, the resulting data of the measurement can be logged continuously. A disadvantage of the built-in instruments is a modification of the panels – the goal of the approach is to check industrial manufactured VIP - and thus, the possibility of a leakage as the sensor is connected with its power supply by wires or flanges which had to be inserted in the seal. Figure 2 shows a schematic drawing of the setup.

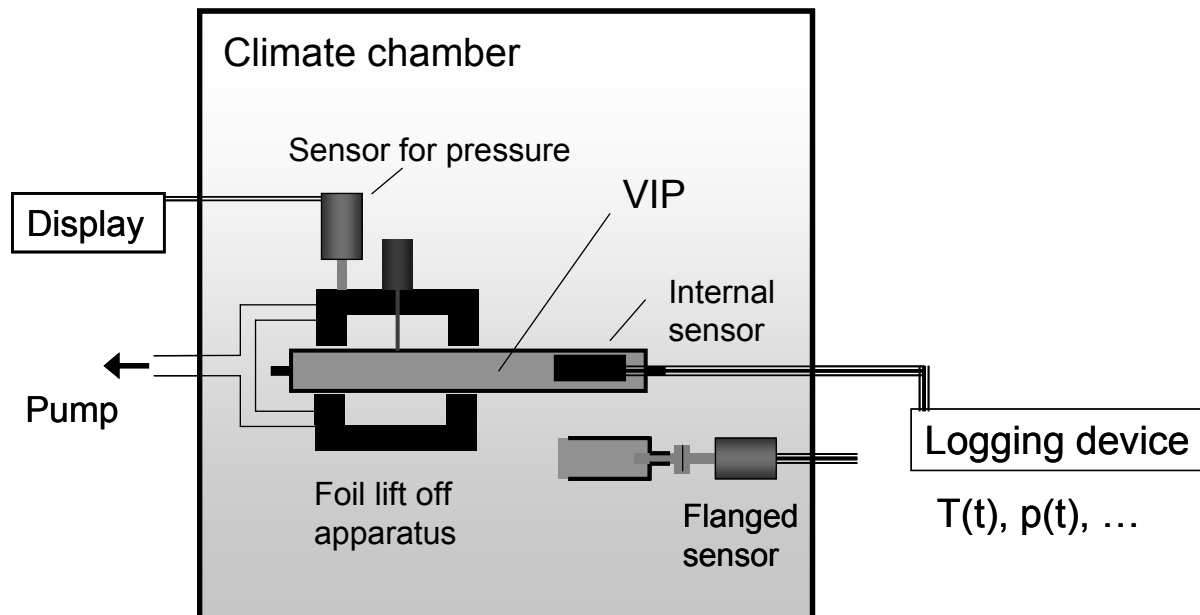


Figure 2: Schematic drawing of the method's setup. To assess the internal total pressure there is either a sensor sealed in the VIP or a sensor flanged on. Additionally the pressure can be measured by the foil lift-off method.

In this paper three differently prepared panels are discussed. The data of the VIP are shown in table 1. Up to now, only few data sets were measured with the foil lift-off method. Thus, the paper mainly discusses the logged data. The climatic conditions are given in table 2. Figure 3 shows the time course of the total internal pressure and the temperature in the climatic chamber of panel B.

Table 1: Compilation of the data of the three test panels

Panel	Sensors	Setup	Total pressure at room temperature	Comment
A	temperature, internal absolute pressure, wires through sealing	heated, evacuated, filled up with dry nitrogen.	≈ 150 mbar	
B	flanged absolute pressure	heated, evacuated, loaded with water.	≈ 40 mbar	
C	temperature, flanged absolute pressure	heated, evacuated.	1 - 2 mbar (at beginning)	leakage (0.19 mbar/h), nearly constant

Table 2: Climatic conditions

Step	1	2	3	4	5	6
Time / h	8	8	8	8	8	8
Temperature / °C	20	35	45	20	10	20

Steps 4 and 6 are for verification of the stability the total internal pressure. To determine the two variables (a and φ), only two pressure measurements at different temperatures are required. As more points were measured, the results could be confirmed by each other. Additionally, a non-linear parameter fit can be performed. In table 3 the results are listed. Due to the fact that the internal pressure increases about 0.19 mbar per hour, the measurement data for panel C were corrected. This leakage was assumed as being constant over time and was subtracted from the logged data. Thus, the results were more inaccurate.

In figure 3 the pressure of panel B versus time is shown. The first 8 hours are not plotted, since the logger had a malfunction. Obviously, the values of the pressure at the temperature points 35 °C and 45 °C has not reached it maximum value. Therefore, a second measurement cycle with a modified length of the time steps (each time step: 12 h) has been started.

Since the internal pressure of panel C reached values above the sensors detecting range, the VIP has to be evacuated again. Thus, the values of pressure (dry air at 20 °C) are not the same as before in cycle 1.

In Figure 4 the pressure of panel B in dependence of the time is plotted. Additional to the new measurements data, those data of the first measurement (figure 3) are depicted, too. Obviously, the length of each time step was not the problem. The distribution of content water was not homogeneous at the beginning of the measurement. Thus, it is not needed to increase the cycle time.

As the repeated measurements of the three prepared panels were finished, the core material of the VIP was heated and the internal water content was assessed in each instance. A comparison of these data with the calculated values is given in table 4. Therefore the sorption isotherm or an approximation [Schwab 2005] was needed, in contrast to this method. The results of the repeated cycle are shown in table 5.

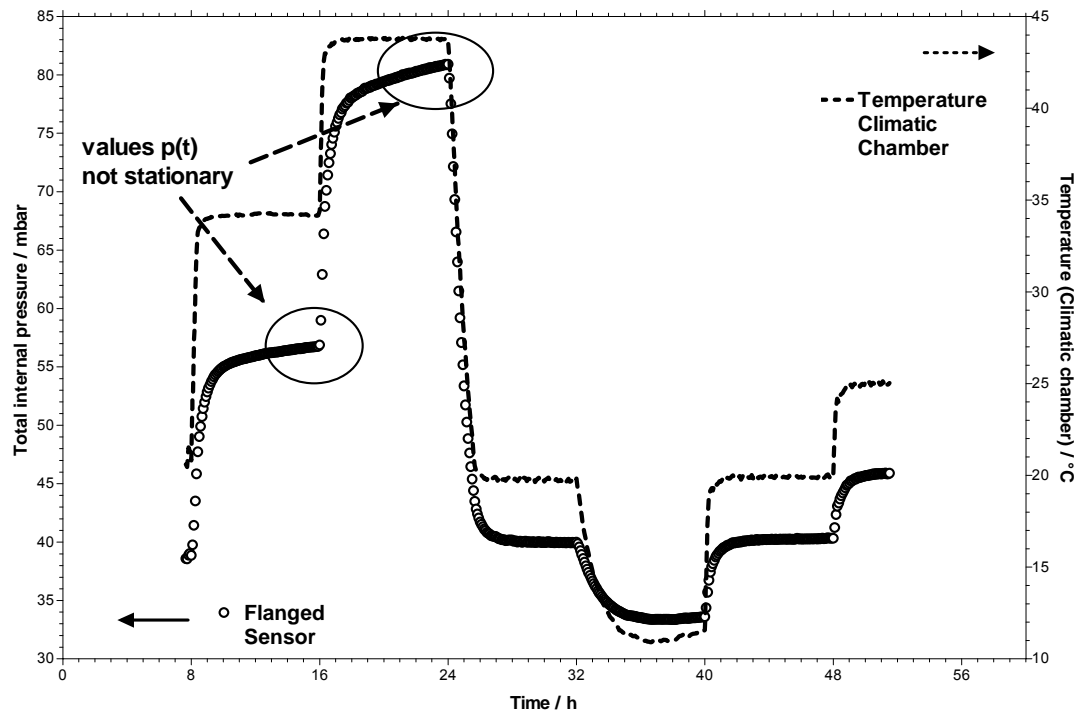


Figure 3: Pressure and temperature of Panel B as function of time. Left ordinate: total internal pressure (data points) of the VIP – measured with a flanged external sensor; Right ordinate: Temperature of the climatic chamber (dotted line).

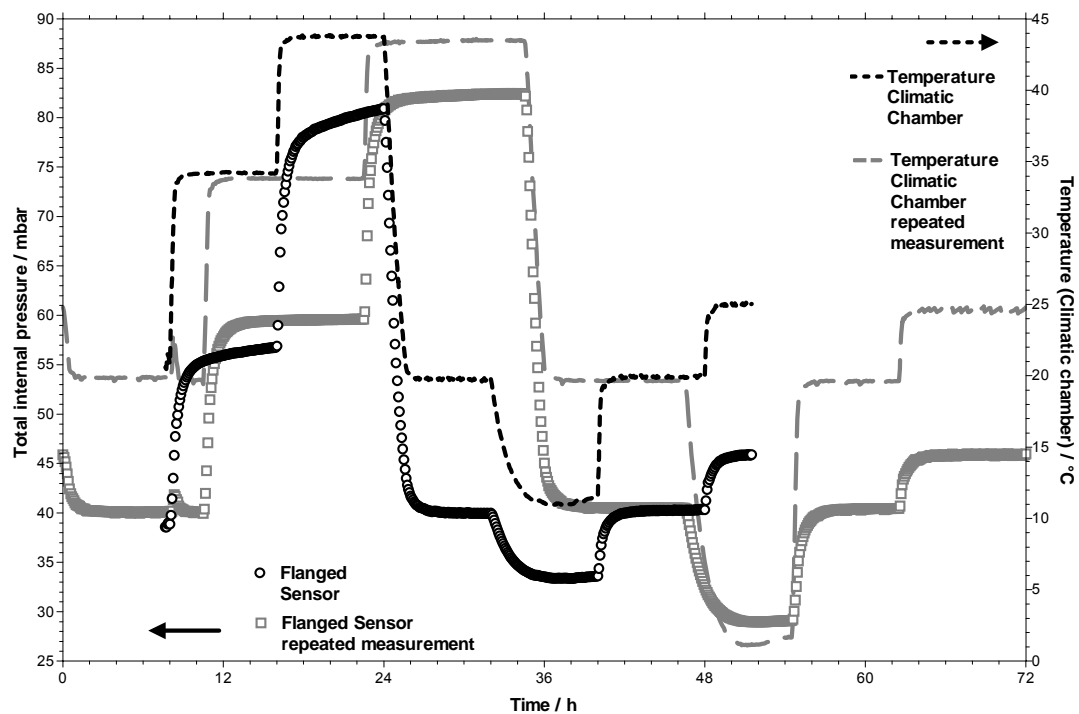


Figure 4: Pressure and temperature of Panel B as function of time. Left ordinate: total internal pressure (data points) of the VIP – measured with a flanged external sensor; Right ordinate: Temperature of the climatic chamber (dotted line). The black coloured lines are related to the first measurement cycle, the grey ones to the repeated one, respectively.

Table 3: Results of the measurements in the climatic chamber

Panel	Temperature ϑ_1 / °C	Temperature ϑ_1 / °C	Pressure (T_1) / mbar	Pressure (T_2) / mbar	Relative humidity φ / %	Pressure of Water Vapour (23 °C) / mbar	Pressure of dry air (20 °C) a / mbar
A	34.8	43.8	164.8	171.7	6.3 ± 0.2	1.79	153.51
A	19.9	34.2	156.5	164.8	2.3 ± 0.1	0.63	156.03
A	19.9	43.8	156.5	171.7	3.8 ± 0.1	1.06	155.68
B	19.7	34.2	40.0	56.6	49.2 ± 1.9	13.84	28.72
B	25.0	34.2	45.7	56.6	44.9 ± 2.0	12.63	30.93
C	20.3	35.1	1.27	2.50	3.7 ± 0.3	1.04	0.39
C	20.3	44.8	1.27	3.90	3.7 ± 0.2	1.03	0.40
C	35.1	44.8	2.50	3.90	3.6 ± 0.2	1.02	0.43

Table 4: Relative humidity of the Panels

Panel	Mass before heating / g	Mass after heating / g	Mass of content water / g	Intent Water / m-%	Relative humidity φ (<i>calc.</i>) / %	Relative humidity φ (<i>determ.</i>) / %	
						Cy1	Cy2
A	348.10	347.50	0.56	0.17 ± 0.03	2.0 ± 0.5	2.3 ... 6.4	1.0 ... 3.6
B	340.02	330.60	9.62	2.85 ± 0.05	47 ± 7	44.9 ... 49.2	59.7 ... 62.2
C	343.51	342.89	0.58	0.18 ± 0.03	2.1 ± 0.5	3.6 ... 3.7	1.7 ... 3.6

Table 5: Results of the repeated measurements in the climatic chamber

Panel	Temperature ϑ_1 / °C	Temperature ϑ_1 / °C	Pressure (T_1) / mbar	Pressure (T_2) / mbar	Relative humidity φ / %	Pressure of Water Vapour (23 °C) / mbar	Pressure of dry air (20 °C) a / mbar
A	20.5	34.2	157.0	164.6	1.0 ± 0.1	0.27	156.50
A	20.5	44.0	157.0	171.4	2.8 ± 0.1	0.80	156.05
A	1.0	20.5	146.0	157.0	3.6 ± 0.6	1.01	155.87
A	1.0	34.4	146.0	164.6	1.7 ± 0.2	0.49	156.00
A	1.0	44.0	146.0	171.4	3.0 ± 0.2	0.84	155.91
B	33.8	43.5	59.6	82.4	60.8 ± 2.6	17.12	26.32
B	19.8	33.8	40.0	59.6	62.2 ± 2.7	17.51	25.62
B	1.0	19.8	28.9	40.5	59.7 ± 7.5	16.80	26.71
B	1.0	43.5	28.9	82.4	60.4 ± 3.3	17.01	26.66
B	19.8	43.5	40.0	82.4	61.5 ± 1.9	17.30	25.80
C	34.4	44.2	6.2	7.6	3.6 ± 2.4	1.00	4.01
C	19.9	44.2	5.38	7.6	2.7 ± 2.4	0.76	4.76
C	19.9	34.4	5.38	6.15	1.7 ± 2.4	0.47	4.99

2.4 Accuracy of the results

A closing estimation of possible sources of error hasn't finished yet. To determine the accuracy of the approach following errors are assumed:

- External pressure Sensor (panel C; 0 to 12 mbar): ≤ 0.2 mbar,
- External pressure Sensor (panel A; 0 to 120 mbar): ≤ 0.6 mbar,
- Internal pressure Sensor (panel B; 0 to 200 mbar): ≤ 3.2 mbar (max. error in the compensation temperature range) and
- Temperature sensors: ≤ 0.7 K.

The rules for error propagation were applied, whereas the accuracy of the logger, and of Magnus equation (3) [± 0.2 %] was neglected. The errors of the data of panel C do not disregard the increased inaccuracy due to the leakage (in table 3 and table 5: grey).

3 Conclusions and outlook

A novel approach to determine the water vapour pressure is presented. The first results are encouraging. Unfortunately, up to now there were not enough values measured by the foil lift-off method. As a new transportable foil lift-off apparatus will be made available soon, several new tests and comparison between that method and additional pressure sensors will be performed. Generally, measuring the internal pressure with the foil lift-off method is leading to comparable results, since the pressure values data have the same order of errors as those discussed in this paper.

Our approach comprises an innovative procedure to determine the water vapour pressure in the panel. In contrast to this method, standard measurements needed the sorption isotherm to quantify the water content and led to the destruction of the VIP.

4 Acknowledgment

The project „Energieoptimiertes Bauen, Teilkonzept 1: Aufbau einer Koordinationsstelle für die nationalen Tätigkeiten zum ECBCS-Annex 39 „High Performance Thermal Insulations for Buildings“ (HiPTI) der Internationalen Energieagentur (IEA) und Qualitätskontrolle von Vakuumisulations-paneelen [0327321E]“ is funded by the BMWa (German Federal Ministry of Economics and Labour) in Berlin.

5 References

[Wikipedia 2005] www.wikipedia.org

[Schwab 2005] **Permeation of different gases through foils used as envelopes for vacuum insulation panels.** H. Schwab, U. Heinemann, A. Beck, H.-P. Ebert and J. Fricke, Journal of Thermal Env. & Bldg. Sci., Vol. 28, No. 4 (April 2005).