Validation of the lift-off technique for measuring the internal pressure of fumed silica VIPs

Determination of boundary conditions for the lift-off measurements and processing of measurement raw data

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Disclaimer

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1 Definition of tasks

The Vacuum Insulation Panel Association VIPA authorized FIW München on behalf of its member companies to carry out a study concerning the measurement procedure for the determination of the internal pressure of a VIP via the foil lift-off technique. To receive comparable and reproducible results the investigations have to comprise investigations of the measurement principle as well as methods for data processing. As VIPs show a very individual behavior, a suitable measurement method is not easy to define.

For data processing measurement curves as displayed in Figure 1 are essential. Laser distance devices observe the movements of the foil surface while the decreasing internal pressure of the surrounding of the VIP (vacuum chamber) is also recorded. With properly set boundary conditions those clearly defined lift-off sections can be achieved.

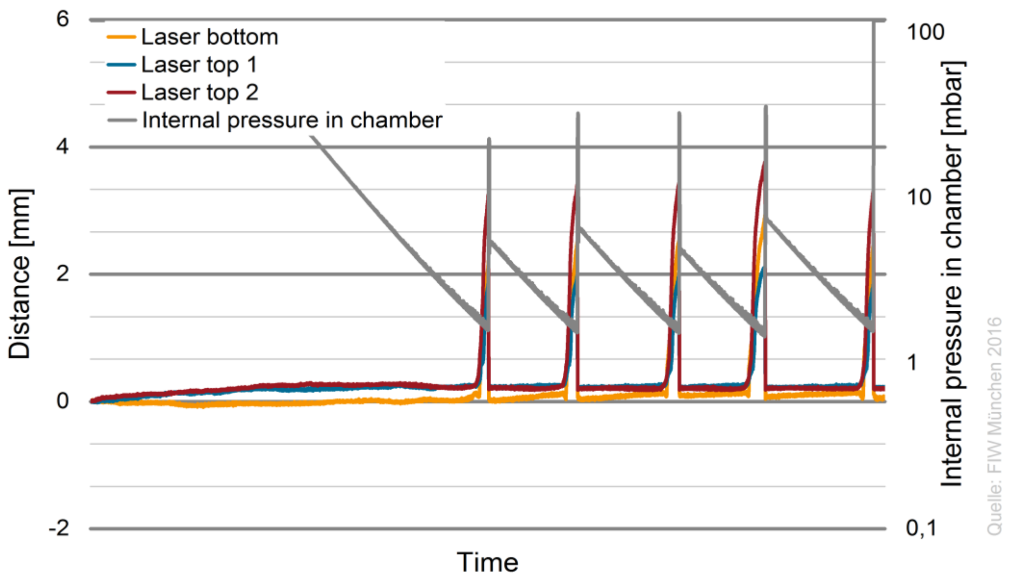


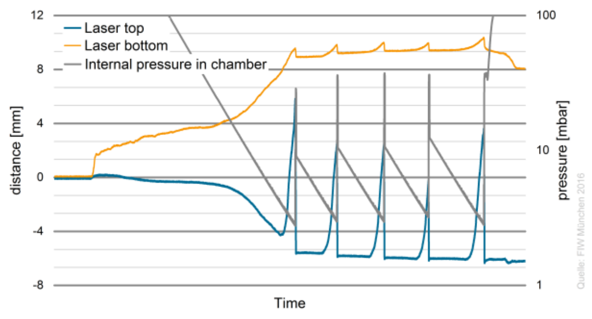
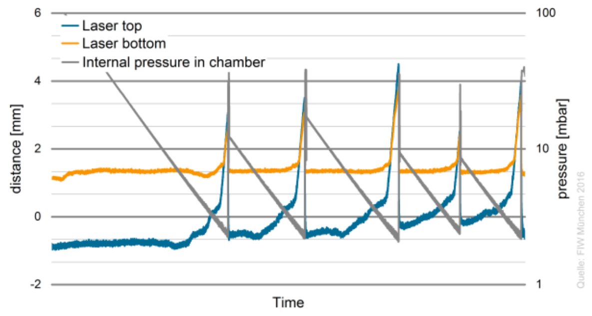
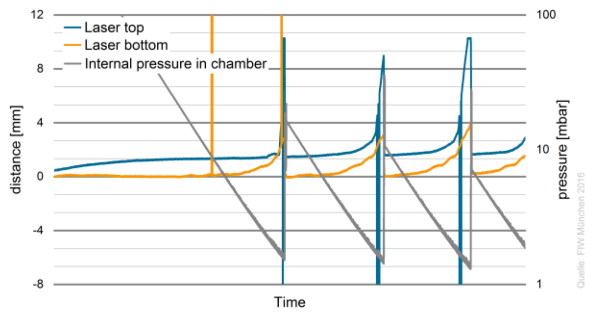
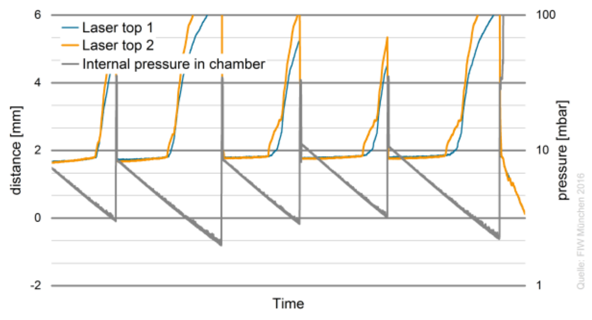
Figure 1: Sample measurement curve of the lift-off technique showing five lift-offs of the envelope foil in mm and the corresponding pressure inside the vacuum chamber in mbar as a function of time

1.1 Problem definition

The foil lift-off method is treated as the reference method to determine the internal pressure of VIPs. It is used for more than a decade now without any evidence or comparison to a direct measurement method. This means, it was never shown how close the lift-off pressure readings are to the actual internal pressure. Detailed information neither on how to conduct a measurement nor about processing gained data is available. According to FIW and Hanita experiences, there are several influencing factors on the result of the pressure measurement.

A large range of previously conducted measurements without taking care of the boundary conditions such as bearing show different typical effects as listed in Table 1. The tested panels were of different dimensions, manufacturers and stages of aging. The initial setup for mounting the laser devices and bearing of the panels comprised two linear bearings to place the panel on top.

Table 1: Factors affecting the measurement of the internal pressure without defined boundary conditions

No.	Sample diagram of typical effects	Description
1		Large distances of linear bearings lead to a deflection of the panel (horizontal parts of the blue line are not on the same level). The laser device at the bottom can hardly capture the lift-off because of the stretched foil (orange line).
2		Different form/ shape of the foil lift-off on the top and bottom side of the panel (blue vs. orange line)
3		Wrong measurement values due to movements of the foil and shifting of wrinkles in the orange curve
4		Despite nearly identical positioning of the laser devices „top 1“ and „top 2“ their lift-off looks differently. „Top 1“ shows a suddenly plopping foil, what can be seen in the earlier vertical rise of the orange curve.

In addition to the missing definition of boundary conditions a validation performed as a comparison of the readings of the measurement equipment may give important evidence about the accuracy of the applied method. Up to now there are no comparative measurements to confirm the assumed high accuracy of the method.

The applicability of a data processing algorithm is strongly dependent on the quality and quantity of the single measurement points. Due to individual characteristics of real measurement data, an influence of the individual method chosen for data evaluation and in some cases a user influence is likely to occur. Especially when the used tangents for the evaluation are fitted visually to the data the range of possible results is quite large. However, it is up to now not possible to conclude if the result of one evaluation method is more accurate as the true internal pressure is unknown.

1.2 Aim of the study

The mentioned influencing factors in Table 1 are meant to be eliminated by using an appropriate measurement setup and to obtain graphs like Figure 1. Observations showed, that the surface of the foil is only theoretically without movements when $p_{VIP} < p_C$. Relaxations, creeping or deflections of the core material with declining pressure of the surrounding space of a VIP as well as relocation of wrinkles caused by the production process are recorded by the laser-distance devices. Because of the diverse panel layouts, types of foil, stiffness of core materials and arrangement of welding seams, the requirements to a measurement setup are quite high. All misleading influencing factors should be suppressed and a newly developed internal pressure measurement setup should only measure the movement of the foil caused by pressure variation. For this purpose many tests have to be carried out to provide clarity on these influencing factors:

- Orientation of the specimens and measurement direction of the laser distance device (horizontal or vertical orientation of the specimen)
- Measurement direction from above or from underneath (gravitation effect on the foil)
- Number and technical characteristics of the laser devices
- Speed of evacuation process together with frequency of readings of the distance device
- Number of repetitions of the measurement (compensating expansion of the core and fleece of the VIP and solving adherence problems of the foil)
- Bearing distance for the VIP an possible restraints of the edges
- Positioning of laser(s) or suction bell
- Compensating deflection of the VIP
- Executing the measurement with decreasing or increasing external pressure
- Raw data assessment and derivation of the measurement result (algorithms for reliability and repeatability of results, as a basis for future automation of the measurement)

The development of adequate assessment steps for the determination of the internal pressure of a VIP from raw data generated by the foil lift-off in a vacuum chamber is a further important step. The generation of significant measurement data enables homogenous evaluation results without many variations.

To sum up, the purpose of this project is to:

- Validate the readings of the lift-off units against calibrated pressure gauges for the first time
- Fix the boundary conditions for the measurement
- Describe a reliable procedure for deriving pressure results from the obtained measurement raw data (assessment and algorithm)
- Cross-check the above mentioned results with other methods such as the suction bell
- Define the procedure for the standardization process

1.3 Benefits

Out of the mentioned research aims result the following benefits for VIPA members:

- Higher confidence for manufacturers for their Declaration of Performance (liability aspects)
- Better accuracy and more experience for the testing method
- Better known relation to real internal pressure (better knowledge on own products)
- Correct values for internal pressure (and pressure increase over time) are the basis for durability calculations on their products
- Pre-normative research: influence the standardization process
- Technical data about equipment and measurement value acquisition (know-how) on equipment and algorithms for automation)
- Basis for future development of internal pressure measurement techniques that could be applicable for fiber core panels as well

2 State of the Art

Several methods have been developed for the determination of the internal pressure. The foil lift-off technique is the most commonly used method or procedure to determine the internal pressure of VIPs during and after the production process. It is used in two versions for measuring the internal pressure of VIPs:

- The evacuation chamber method on a whole VIP (e.g. integrated in the Vacuum-Press)
- The suction bell method on a small section of a VIP envelope (e.g. for FPC after the production chain)

Both methods make use of one or more laser distance measuring devices that measure the distance to the surface of the foil while constantly evacuating the surrounding - the space under the suction bell for method 2 and the whole evacuation chamber for method 1. The level of vacuum for the pressure compensation method is shown to work in the range from 0.2 to about 100 mbar with membrane type pressure sensors with a measurement range from 0.01 to 110 mbar.

2.1 Vacuum chamber

The system measures internal pressure by using the envelope laminate as the measurement membrane. The specimen is placed in a vacuum chamber which is then evacuated. The system records automatically the decreasing pressure surrounding the panel and the displacement of the envelope when the external pressure surrounding the panel is getting close to or lower than the internal pressure of the panel. The pressure inside the vacuum chamber at which the envelope starts to move away from the core is considered to be equal to the internal pressure of the VIP. The proposed project is aimed to find the exact relation between the displacements of the different envelopes to the actual internal pressure of the panels.

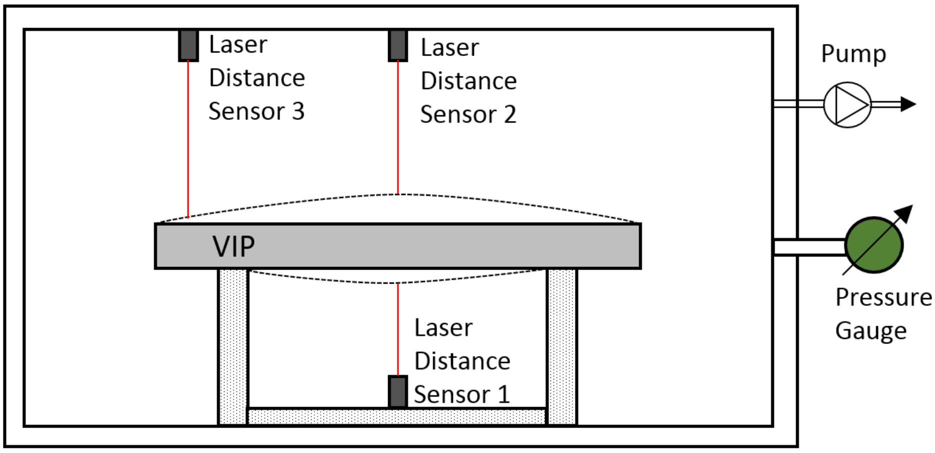


Figure 2: Principal sketch of the measuring device in a vacuum chamber

2.2 Suction Bell

The equipment consists of a top and bottom suction bell. In the top suction bell a laser distance meter is implemented. The bottom suction bell is integrated in a mobile table and has to prevent the specimen from destruction. The standard diameter of the measurement zone of the equipment is 250 mm. For attaching the gauge head to the surface of the vacuum insulation panel (VIP) and executing the measurement according to the pressure compensation method, two different vacuum pumps are installed and used. The first pump is used for tightly applying the gauge head to the VIP surface and evacuating the vacuum ring seal. Hereby possible existing leakages to the measurement area are mostly compensated. The second pump is used for creating the vacuum in the measurement zone (top and bottom suction bell).

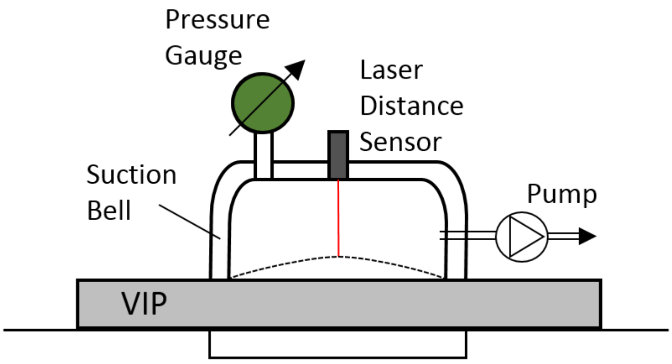


Figure 3: Principal sketch of the measuring devices of a suction bell

3 Approach and Methodology

As there are interdependencies between the measurement principle and the evaluation algorithm, correctly set boundary conditions are an important determining factor on the measurement of the internal pressure.

To perform the necessary test measurements an already existing simple setup works as reference method to notice any deteriorations or improvements from changes. Method M1 in Table 3 shows the principle scheme with the specification of the components in Table 2.

To reduce the gas pressure in the vicinity of the VIP, a cubic vacuum chamber is used. The continuous lowering of the gas pressure is realized with a dual stage rotary vane pump with an ultimate partial pressure of below 0.1 Pa and a maximum evacuation rate of 24 m^3/h. The water vapor tolerance of about 20 hPa is sufficient for a usual laboratory environment (20 °C / 60 % r. H.).

A precise gas pressure sensor is flanged to the vacuum chamber. It features a capacitive transmitter (ceramic design) with internal temperature compensation, a measurement range from $1 \cdot 10^{-2}$ hPa to 100 hPa, a resolution of 0.003 hPa and an accuracy of 0.2 % of the reading.

The movement of the envelope is detected with a laser triangulation displacement sensor. The working range is 50 mm. The sensor outputs with a resolution of 25 µm and a ± 0.2 % full scale (F.S.) linearity
Both sensors are read out with 16 bit analog-to-digital converters (ADCs) with an accuracy of ± 0.1 % of the reading.

Table 2: Measurement equipment used for the validation of the foil lift-off measurements and the development for data analysis

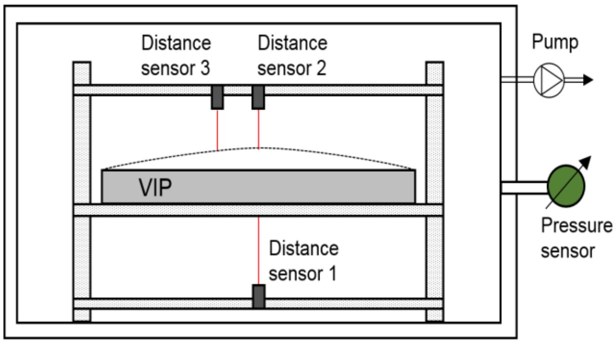
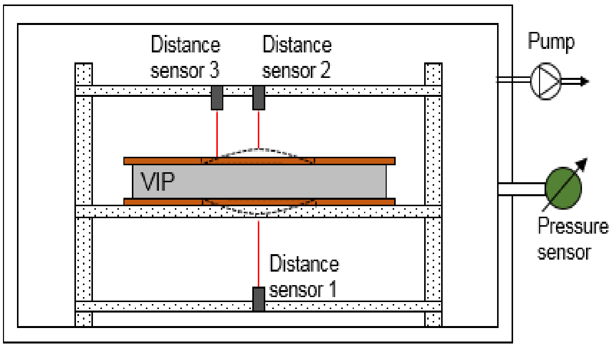
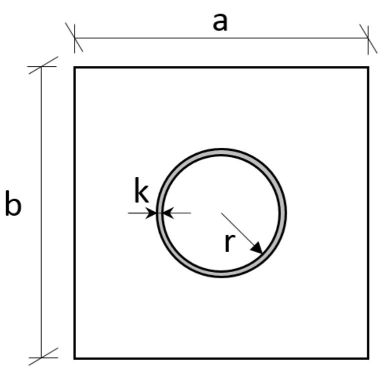
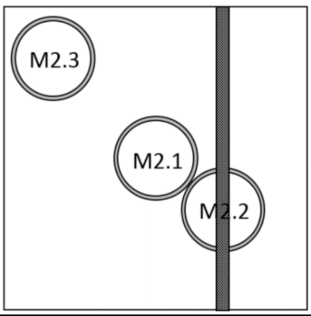
Vacuum chamber: Trinos Vacuum-Systems GmbH	
Type	Chamber for high vacuum, cubic
Dimensions	1000 x 1000 x 400 [mm]
Vacuum pump: Pfeiffer Vacuum Duo Line	
Pumping speed	400 l/min
Ultimate pressure	$4 * 10^{-4}$ mbar
Pressure gauge: Pfeiffer Vacuum transmitter CMR 362	
Measuring principle	Capacitive transmitter
Measurement range	0.01 – 110 mbar
Accuracy	0.2 % of measured value
Laser-Distance Sensor: Micro-Epsilon optoNCDT 1302-50	
Measuring principle	Laser triangulation displacement sensors
Measurement range	45 – 95 mm (50 mm)
Resolution	25 µm
Linearity	100 µm
Measuring rate	750 Hz

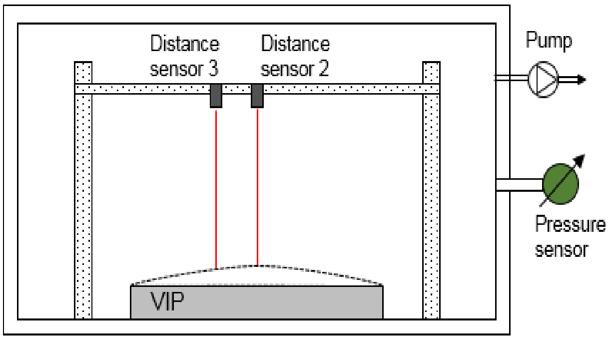
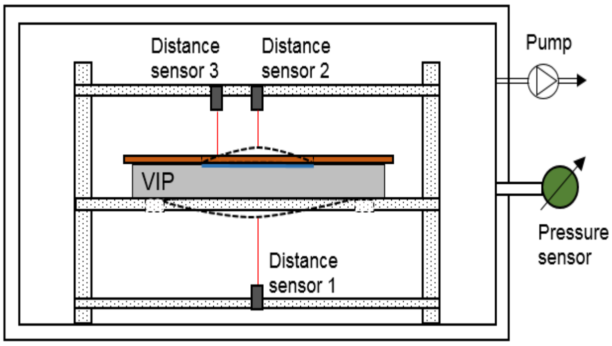
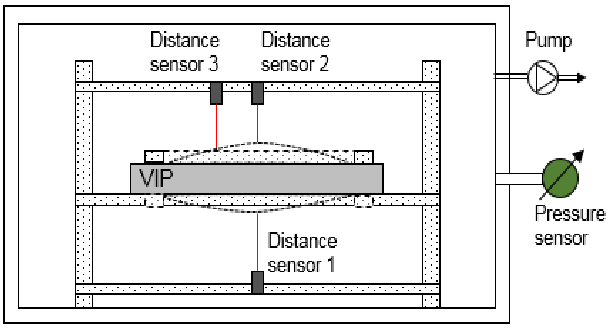
3.1 Investigation of boundary conditions

To check on the relevant influencing factors and develop a concept for correct and reliable measurement results many variations in the setup have to be tried out. The tested methods concerning the following boundary conditions are shown in Table 3:

- Examination of the influence of the type of the bearing (free bearing, restrained panel etc.)
- Definition of the bearings and the bearing distance where the VIP is placed on
- Direction for the distance detection device – measurement with a laser from underneath or from above the specimen
- Measurement from both directions and correction for the deflection of the panel
- Number of lasers and selection of the correct measurement spots on the specimen
- Number of repetitions for each measurement
- Evacuation speed [mbar/sec]
- Pressure limits to prevent damage to the panels
- Pressure increase in between the measurement repetitions – to which level the pressure in the chamber needs to be increased to have independent results for the repetitions
- Height of the lift-off that is necessary to detect the pressure accurately

Table 3: Methods to develop boundary conditions for the foil lift-off method

Method	Setup	Description
M 1		<u>Linear Bearing:</u> The panels are not mounted to the two linear bearings made of aluminum profiles. The width of one profile is 2 cm, the distance of the two bearings is 25 cm. <u>Positioning of laser devices:</u> 1: from the bottom, located in center 2: from the top, located in center 3: from the top, located to observe edge zones
M 2	  	<u>Measuring template:</u> Restriction of the measurement area on both sides with a template made of acrylic glass having a circular cutting in the center. Stable bearing due to added load to the panels and prevention of deflections. Identical cutting in both templates. <u>Specification of the template (2x):</u> Diameter cutout: 20 cm (r = 10 cm) Thickness of acrylic plate: 15 mm Dimensions (a x b):500 x 500 mm Important: rounded edges to avoid destruction of the foil! For better adaption of the template to the surface of the foil a ring seal is inserted into the milled edge (k = 8 x 8 mm) along the circular cutout (grey area). <u>Selection of ring seals:</u> 8 x 10 mm and 8 x 12 mm (meaning 2 or 4 mm of hangover) <u>Positioning of laser devices:</u> 1: center of circle from bottom 2: center of circle from top <u>Positioning of template:</u> To gather information about the influence of welding seams: M 2.1: center of circle = Center of panel M 2.2: seam through measurement area (if available) M 2.3: eccentric measurement area

M 3		<u>Flat bearing on the bottom of the chamber:</u> Without any bearing construction. Foil lift-off measurement only from the top possible. <u>Positioning of laser devices:</u> 2: from the top, located in center 3: from the top, located to observe edge zones
M 4		<u>Combination of bearing possibilities:</u> Square-shaped bearing according to M5 on the bottom. Measurement template according to M2 with an insert of a knitted nylon fabric on top. An adhesive tape on the nylon in the area of the laser beam ensures proper recording of the lift-off. <u>Positioning of laser devices:</u> 1: from the bottom, at center of square 2: from top, at center of circle 3: from top, at edge of circle
M 5		<u>Square-shaped restriction of the measurement area:</u> bearing of the panel in between two quadratic aluminum profiles, inner length of edge: 25 cm. <u>Positioning of laser devices:</u> 1: from the bottom, at center of square 2: from the top, at center of square 3: from the top, at edge area of square <u>M 5+:</u> inside the square profiles a knitted nylon fabric from nylon tights is inserted. The lift-off of the foil is recorded through this fabric.

3.2 Validation of the lift-off technique

The validation is conducted via simultaneously measuring the internal pressure of a VIP, the displacement of the envelope foil and the pressure inside the vacuum chamber. By doing so, the exact relation between these three measured parameters can be found. In future tests it will help to determine the internal pressure inside the VIPs from the measurements of the pressure inside the evacuated chamber and the displacement of the envelope.

This important validation procedure can be done by connecting a pressure gauge to the VIP envelope. A leak-tight connector invented by Avery Dennison Hanita enables the connection to the inside of the panel. The result of such procedure will be a correlation relation between the actual internal pressure and the displacement of the envelope when the lift-off procedure is carried out.

The picture below (Figure 4) presents the configuration of the applied specimen with the leak-tight connector. A special specimen consisting of a combination of two core materials inside one envelope bag has to be prepared. The base plate of the connector sits on a suitable connector support material (see front in photo). This support material also has to be evacuable as the connector´s inner outlet is at its bottom and it is placed into a prefabricated deepening of the material. The other half of the VIP contains a standard fumed silica VIP core material. By means of the feedthrough, the connector enables the evacuation of the entire internal volume of the panel and also the internal pressure can be measured very accurately.

The complete unit is placed inside the vacuum chamber and the displacement of the envelope is then detected on the flat silica core side, applying the defined boundary conditions. The vacuum unit needs to be modified to install the required setup and connect the specimen to the vacuum pump as well. The scheme of the setup is shown in Figure 5 where the part left of the 3-way ball valve is the standard foil lift-off technique combination. The components branching off from the top of the ball valve serve as connection to the inside of the specimen.

Figure 4: Specimen with the leak-tight connector and a connector support inside one half and a standard fumed silica core inside the other part of the panel

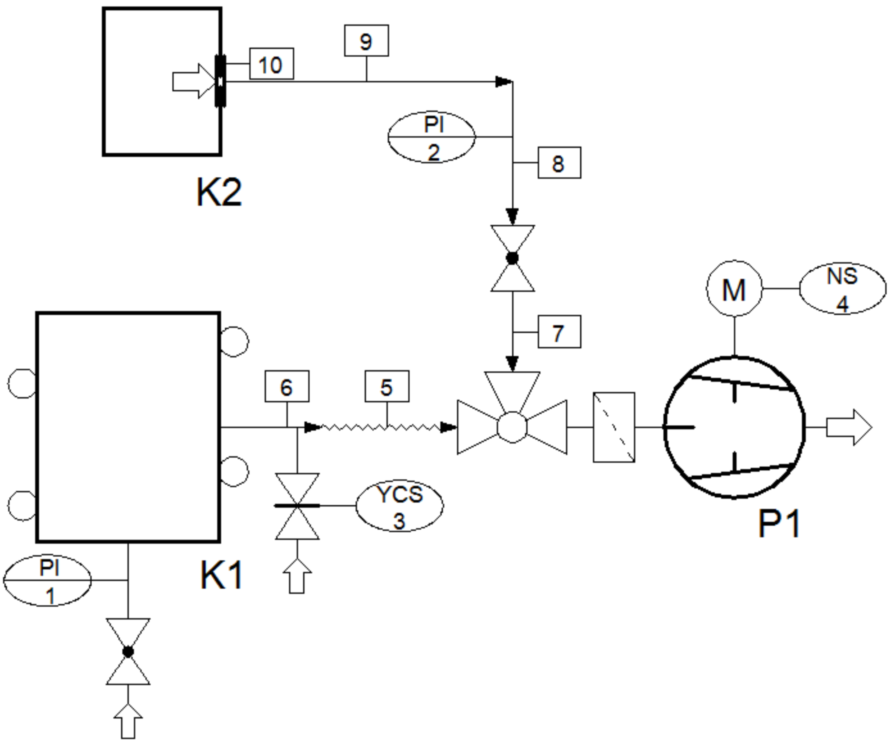


Figure 5: Scheme of the setup for conducting tests for the validation of the lift-off technique

In addition to the measurements inside a vacuum chamber, the behavior of the pressure inside a panel is observed during a measurement with a suction bell. Therefore the leak-tight connector is only connected to a pressure gauge and a shut-off valve. All other components for the measurement are installed at the suction bell. Six common VIPs with the following dimensions are also measured for comparison reasons by both lift-off techniques:

- 1 panel of 300 x 300 x 10 mm
- 1 panel of 300 x 300 x 30 mm
- 2 panels from different manufacturers of 500 x 600 x 10 mm
- 2 panels from different manufacturers of 500 x 600 x 30 mm

3.3 Development of algorithms for data analysis

For the further processing of the distance measurement results into the internal pressure results a basic algorithm for data analysis is developed. The tangent method and the triangle method are used to validate the application of different algorithms. For data evaluation, the distance of the movement of the foil is plotted as a function of the pressure of the vacuum chamber as shown during a lift- off in Figure 6. Before and after every lift-off a linear behavior is assumed. The lift-off of the foil then is not a sharp kink in the measuring data but describes a continuous curve which ends in a linear behavior until the chamber is ventilated to start the proceeding lift-off. The short-duration chamber ventilations allow the foil to get in proper contact to the core material again. Two different methods were applied to evaluate the raw data which are described in the following paragraphs. Separate analysis of parts of the measurement data each containing a lift-off sequence between the short-duration ventilations of the vacuum chamber is conducted for both methods. The data was determined with the measurement equipment listed in Table 2.

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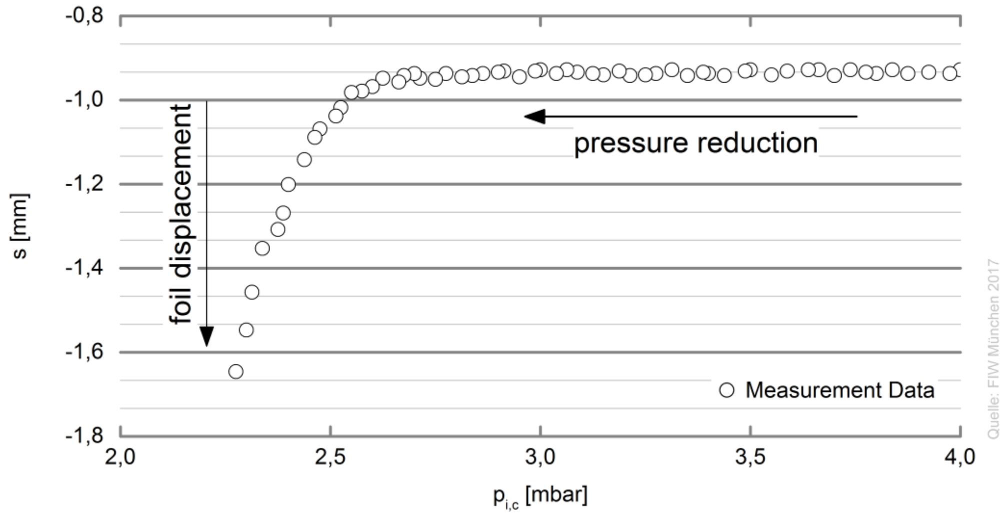


Figure 6: Exemplary measurement data s($p_{i,c}$) determined on a VIP with 15 mm thickness, sample rate 1 Hz

A sensitivity analysis of the tangent method and triangle method to typical test data patterns is conducted to find out more about interdependencies between the type of data pattern and evaluation method. Most common patterns are straight flanks and a sharp kink, a curved transition zone, a reciprocal behavior before the lift-off or a high spreading of the measurement points. For all cases a comparison of the results for different q-values for the tangent method and the result of the triangle method will has been done.

Tangent Method

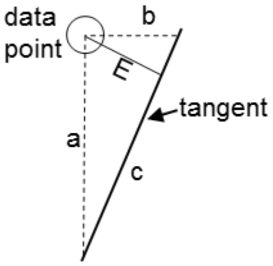
The basic principle of the tangent method is finding the point of intersection between the two tangents of the linear parts of the measurement curve. This point defines the internal pressure at the point of time when the lift-off took place. To find the linear sectors of the two tangent lines, a linear regression analysis of the measurement data starting with two data points (values of pressure and displacement) and increasing the included data point by point is conducted. This is done from the beginning of the chosen sequence onwards for tangent A and from the end of the sequence backwards for tangent B.

With each increment of the number of data point in the regression, the sum of error squares (SSE) divided by the number of data points is calculated (Q-values) (2).

$$Q = (\frac{SSE}{n^2}) \quad (1)$$

SSE: sum of squared errors of regression
n: number of data points included in the regression

The steeper the slope of the left flank of the measurement data pattern (see Figure 6) occurs, the bigger the residuals in the direction of the ordinate become. To homogenize the calculation of the Q-values for tangent A and tangent B the squared residuals for both tangents are calculated according to equation (2).



$$SSE = E^2 = (\frac{a \cdot b}{c})^2 \quad (2)$$

The Q-values for each tangent are then divided by the maximum single Q-value found, to obtain a relative quality criterion q for each regression (equation (3)).

$$q = \frac{Q}{Q_{max}} = \left(\frac{SSE}{n^2}\right) \cdot \frac{n_{max}^2}{\max(SSE)} \quad (3)$$

n_{max}: number of data points, where the maximum SSE is found

Because of the characteristics of the tangents regression data with a very high and a very low gradient respectively compared to the SSE of the measurement data, the coefficient of determination R^2 is not suitable for this application. The assessment of the regression using the q-value is superior to R^2-methods.

For the tangents, the regression including the largest number of data points and a q-value below a certain threshold is selected. The abscissa value of the intersection of the tangents gives the result of internal pressure of the VIP.

Figure 7 shows exemplary results of this analysis for different threshold levels of q. The ticked data points show the parts of the measurement data included in the particular linear regression.

Alternatively, the tangent for all measurement sequences of a test run can be selected by fitting a common threshold value q to a minimum variance of the results with the additional constraint, that for all measurement sequences an intersection i.e. 2 tangents are found.

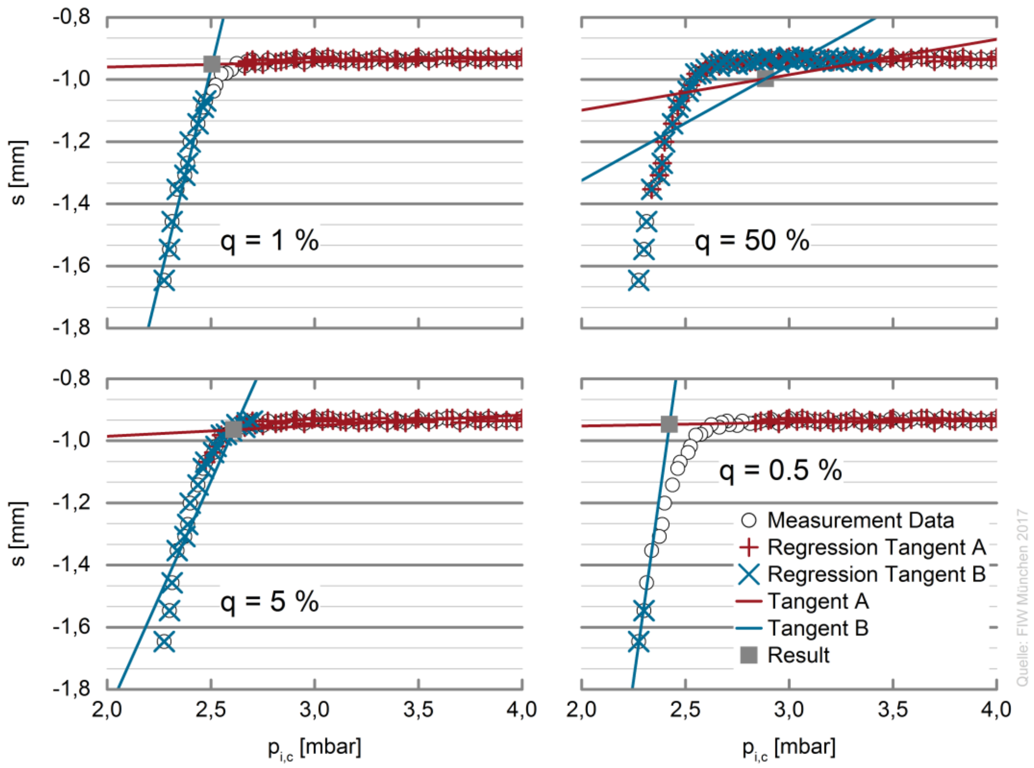


Figure 7: Utilization of the tangent method on exemplary real measurement data; results of analysis with different thresholds of q

Triangle Method

An alternative method developed by FIW is the triangle method. It is also based on the analysis of each lift-off sequence. A polyline consisting of all measurement points can be closed easily to a shape that can be basically described as a triangle with a rounded tip representing the bent transition zone. Therefore, the first and the last measurement point have to be connected.

The tip of the triangle is a certain measurement point inside the bent transition zone. The first and the last measurement point of the data that is chosen for evaluation defines a straight line. In the next step for all other measurement points, the distance between these measurement points and the straight line is calculated. This can be done by dropping a perpendicular from the measurement point on the straight line and calculating the distance between the dropped perpendicular foot on the straight line and the measurement point. The tip of the triangle is the measurement point with the greatest distance from the straight line (Figure 8)

In the unlikely case that two or more measurement points have the same distance from the straight line, the algorithm can be repeated with a reduced or extended number of measurement points. Doing so, the slope of the straight line is changing slightly what will affect the results of distance evaluated. This can be repeated until a biunique result is achieved.

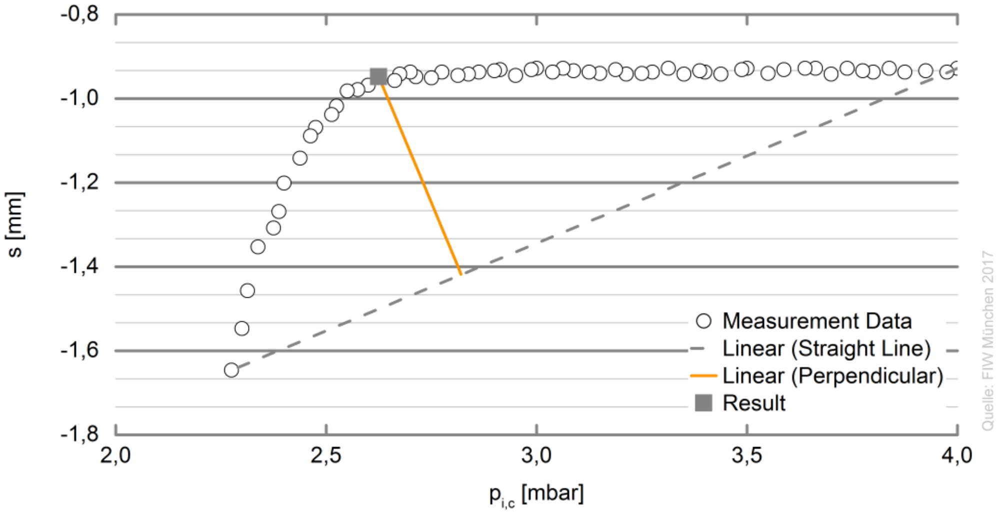


Figure 8: Utilization of the triangle method on exemplary real measurement data

4 Conduction of the Tests

4.1 Investigation of boundary conditions

Table 4 shows the summary of all measurements. The specimens are from four different manufacturers (A, B, C, D) and are numbered for distinction from 1 to 5. From the column of the dimensions can be taken, that a large variety of types has been involved in the tests. The aging of some of the panels is already at an advanced stage with a higher internal pressure. Furthermore different foil types and positions of welding seams are available due to different manufacturers.

Table 4: Experimental matrix of all conducted measurements containing specimen specification and measurement method. The specimen are of four different manufacturers (A B,C, D)

No.	Dimensions [mm]	Method							
		M1	M2.1	M2.2	M2.3	M3	M4	M5	M5+
A.1	300x300x10	■	■						
A.2	300x300x30	■	■						
A.3	500x600x30	■	■				■ x	■ x	■ X
A.4	600x500x10	■				■ x	■ x	■ x	
A.5	600x500x10	■				■ x		■ x	■ X
B.1	300x300x10	■							
B.2	300x300x30	■	■						
B.3	500x600x30	■	■	■	■	■ x		■ x	■ X
B.4	600x500x10	■	■			■		■	■ X
B.5	600x500x10	■	■			■ X	■ X		■ X
C.1	300x300x10	■	■						
C.2	300x300x30	■							
C.3	500x600x30	■	■			■ x	■ 2x	■ 2x	
C.4	600x500x10	■						■	■ 2x
C.5	600x500x10	■						■	■ x
D.1	500x250x20	■		■					
D.2	500x500x20	■		■			■ x		
D.3	300x600x20	■			■				
D.4	300x600x20	■			■				
D.5	600x600x20	■		■					
E.1	500x500x15	■	■					■	■
E.2	500x500x15	■	■					■	■
E.3	500x500x15	■						■	
E.4	500x500x15	■						■	
E.5	500x500x15	■						■	■

The variations of method M2 were tested with the different ring seals (10 and 12 mm) and without ring seal.

The time and the level of ventilation of the chamber in between the single lift-off procedures is a further element of the boundary conditions and important for the quality of the data analysis. The pressure difference obtained by ventilation of the chamber defines the horizontal parts in the distance curves. The larger the difference, the longer are the horizontal parts and the more measurement points are available to calculate the used tangent. The necessary pressure range is depending on the pressure inside the chamber and the evacuation rate of the pump. It has to be set to ensure sufficient ventilation. Moreover the height of foil movement away from the core has to be defined otherwise in this flank no tangent can be defined.

4.2 Validation of the lift-off technique

For the tests to validate the lift-off technique, specimen of three different foil types and three different connector base plate materials are built. Specimen Type I consists of a fumed silica core of 300 x 300 x 15 mm and the base plate of fiber core material measuring 200 x 200 x 40 mm under atmospheric pressure. Three different foil types were applied. Specimen Type II-a consists of the same fumed silica core but an incompressible porous ceramic product usually used for vacuum clamping serves as base plate. The dimensions of this core material are 250 x 250 x 20 mm, only one foil type was applied here. Specimen Type III-a is used to prove the applicability of the measurement technique for other panel dimensions. Therefore a fumed silica core of 300 x 300 x 30 mm is inserted into the envelope. Moreover, as third version of support material a solid aluminum measuring 200 x 200 x 30 mm, with drilled channels for evacuation is used in this specimen.

Table 5: Combination of foil type and core material from specimen used for tests for the validation of the lift-off technique

	Foil Type A	Foil Type B	Foil Type C
Specimen Type I-a	X		
Specimen Type I-b		X	
Specimen Type I-c			X
Specimen Type II-a	X		
Specimen Type III-a	X		

The suction bell measurements took place after manufacturing the specimen Type II-a. A pressure gauge connected to the leak-tight connector was recording the internal pressure behavior while the suction bell was measuring the foil lift-off on the silica core part of the specimen. Figure 9 shows the setup of the suction bell measuring device during a measurement at the specimen. The measurements of the other six panels were conducted in the same way.

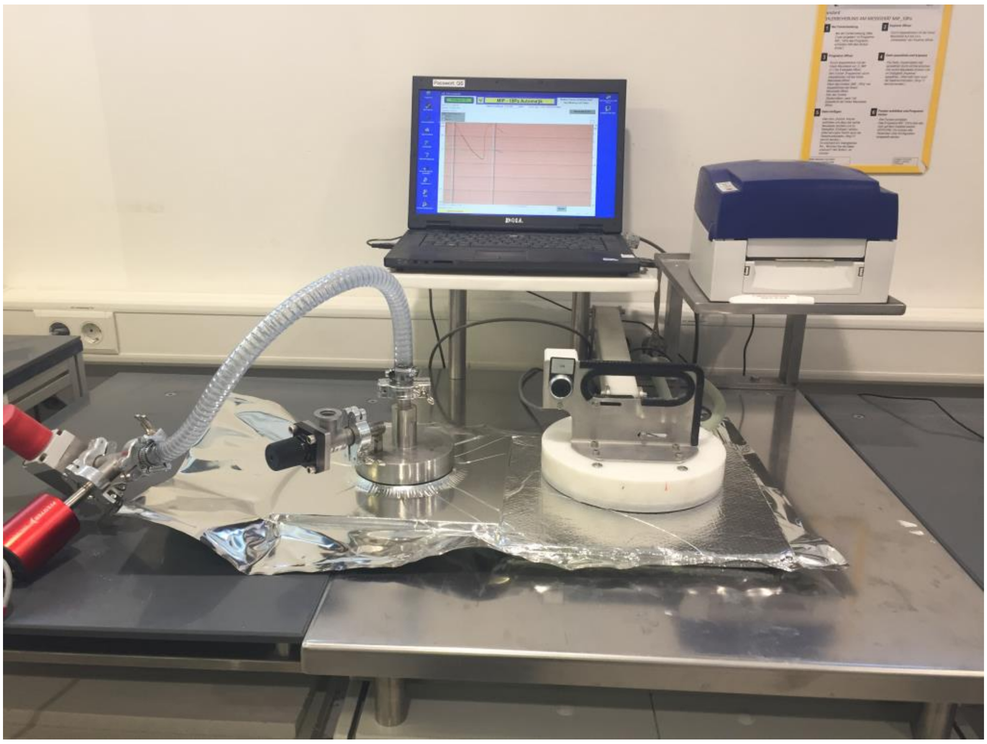


Figure 9: Suction bell under operation measuring the internal pressure of the specimen

4.3 Development of algorithms for data analysis

For validation of performance of the two algorithms, both methods were applied to a set of internal pressure measurements. The processing of the test data was performed with the software SCILAB 5.4.1. The script both includes a guided but manually process for data cleansing (clipping of the separated lift-off stages) and afterwards performs the tangent method for different threshold levels of q (0.1 %, 0.5 %, 1.0 %, 5.0 %) and the triangle method on the same set of data points. The data cleansing was performed in a way that an isosceles triangle of test data with straight flanks was achieved. However there is no automated process of clipping the test data available right now, as there is certain deviation in test data pattern mostly due to individual kinks in the foil and in some cases uneven panels what affects the bearing situation.

Five lift-off sequences were performed. The first lift-off is discarded to avoid influence of adhesive effects between the foil and the core material. In some cases, the ventilation of the chamber between two lift-off sequences was too short to gain a data curve adequate for evaluation. Therefore, the number of lift-off sequences for one panel varies from three to four.

To evaluate the robustness of the algorithms to spreading and clipping of test data also investigations on artificial test data have been performed. The sensitivity in variations of the spreading of the test data, the clipping of test data and different sampling rates is a point of interest. Out of those parameters the interdependencies between the value of q and the shape of the lift-off sequences as pattern of quality of the data can be pointed out. Different forms of typical test data patterns and the location of the corresponding tangents for different threshold values for q and the results of the triangle method evaluation are shown in Figure 10. The variation of the results between the two algorithms is depending on the shape of the lift-off sequence. Also for the tangents of different q-values the shape sometimes leads to equal tangents and sometimes to different ones as the two examples top right and bottom right are showing. For low values of q, only very few measurement points are included in the tangent. This often leads to effects as can be seen in the top left diagram for q = 0.1 % and a significant lower determination of the internal pressure.

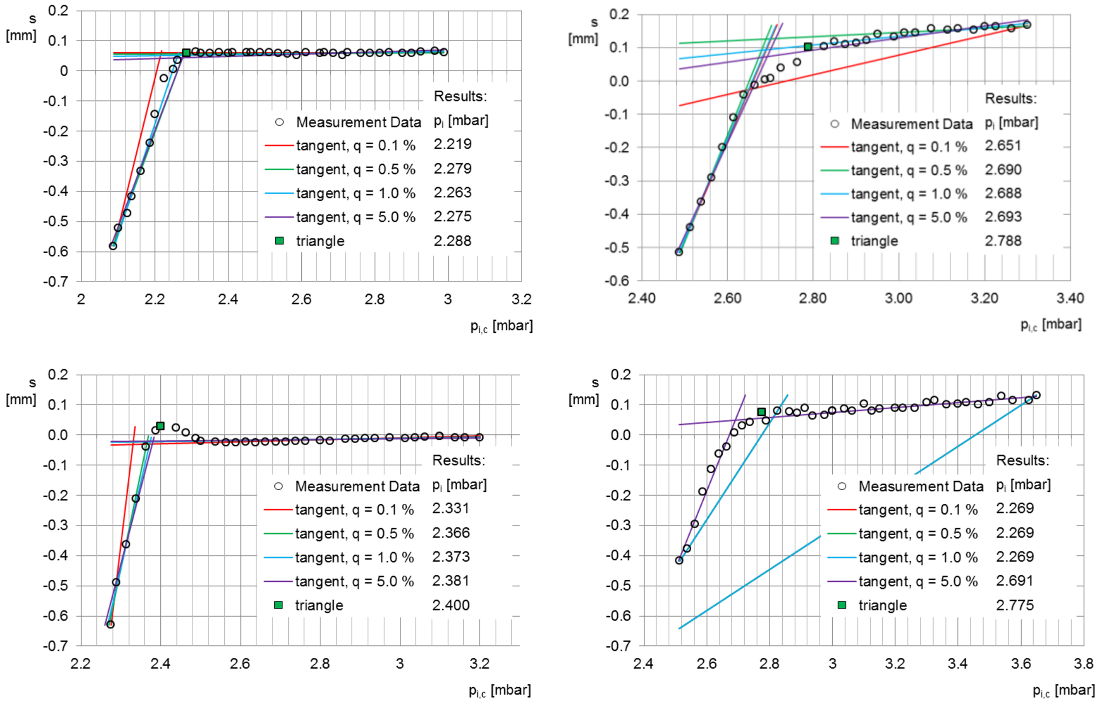


Figure 10: Typical forms of test data including results for the tangent method with different threshold values for q (0.1 %, 0.5 %, 1.0 %, 5.0 %) and the triangle method. Top left: straight flanks and a sharp kink in the bent transition zone; top right: straight flanks and a round bent transition zone; bottom left: straight flanks and a reciprocal foil behavior before the lift-off; bottom right: higher spreading of individual measurement data points (equal tangents for 0.1 %, 0.5 % and 1.0 %)

5 Results

The assessment of quality of an internal pressure measurement contains many factors.

5.1 Investigation of boundary conditions

All measurement data was transferred into graphs like the one in Figure 1. A visual comparison gave clear indications on which method is suitable or not. Doubtlessly it can be stated that the bearing has to prevent the specimen from deflection, no matter what thickness it has.

Furthermore, the measurement template used for method M2 does not lead to useful data, no matter which ring seal or none was inserted. Too many of the measurements were not evaluable with any of the algorithms due to the small size of the circle and the stiffness of the foil and/or the circular shape itself. New wrinkles appeared during the measurement within the measuring area and cause problems for the laser sensors to observe the surface movements resulting from pressure changes.

Also method M3 can be excluded because of deformations of the whole bottom plate of the vacuum chamber during its evacuation. This is important information one has to be aware of when designing a new bearing system.

But the restriction of the measurement area by a square shaped profile on both sides of the panel leads to acceptable results throughout the tested amount of specimen. No additional wrinkles are occurring and the lift-off distance of the foil away from the core is not restricted to small values. The measurement areas now have the same size which means that the same area of foil will move away from the core during a lift-off leading to more comparable results than in method M1 for example. To receive more precise lift-offs for the bottom laser, additional weight has to be added to the lightweight aluminum profile on top of the specimen. A total weight of 3 kg is sufficient. The resulting setup is depicted in Figure 11. The integration of the elastic nylon fabric is meant to smoothen the surface of extremely wrinkled panels. The laser sensors measure the lift-off of this nylon fabric and there is no influence of slightly moving or the rearrangement of wrinkles caused by relaxation of the core material.

The newly designed bearing system has to follow the following principles:

- Coupling of panel bearing and laser sensor mounting
- No contact to the center of the chamber´s base plate
- Contact points between frame and chamber in as few points as possible and those points should be close to the edges of the chamber

- Possibility to adapt to different panel thicknesses
- No sharp edges or connections to protect panels from damage

Figure 11: Modified Setup with square-shaped restriction of the measurement area on both sides of the specimen

Because of the mentioned reasons, the final evaluation of the internal pressure values was only done for the methods M1, M5 and M5+ with the tangent method. The considered laser positions are the one at the bottom and the one at the same position from the top (center of square profile). A comparison of the obtained results can be seen in Figure 12, where no symbols for one specimen means no measurement under the observed method. This can also be compared with Table 4 but only one symbol meaning that the second laser delivered unevaluable data. The small differences and the fact that one laser position does not always lead to smaller internal pressure values is an indication, that gravitational force does not pull the foil towards the bottom laser.

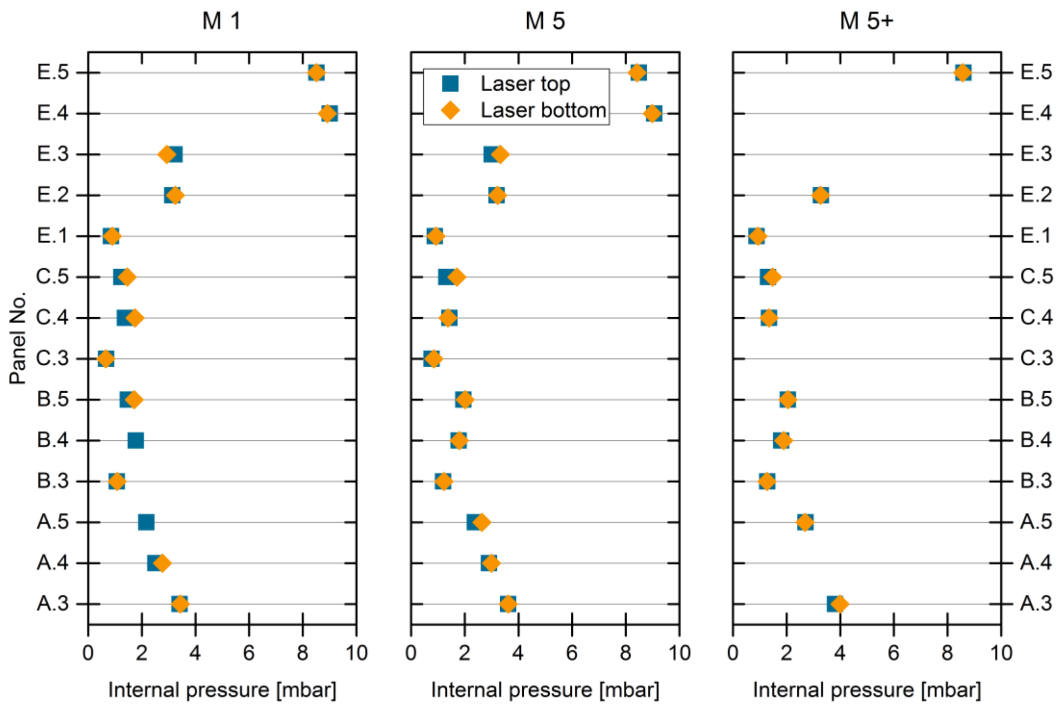


Figure 12: Difference of internal pressure results for two laser positions on top and at the bottom of a VIP obtained for three different measurement methods

As most common vacuum chambers have a similar shape as the one at FIW (horizontal dimension larger than vertical dimension), a vertical bearing of the panels is impossible. A vertical measurement and horizontal bearing would only work with surfaces free from wrinkles, foil flaps at the edges or sticking out seams, what could theoretically detect the lift-off precisely but this are typical characteristics of VIPs.

To have one final internal pressure value as result of the measurement, the highest accuracy can be obtained by calculating the mean value of the two laser positions from above and underneath the panel position. In the case, that the two laser positions deliver different results and it is not possible to state one value as wrong because of inacceptable measurement curves, the mean value leads to better results than the decision to choose the value of one certain, maybe wrong position.

It turned out that passing through five lift-offs within one measurement cycle leads to good results. The first lift-off is discarded to be sure that adhesion of the foil and fleece liner to the core does not affect the measurement. Out of the remaining four lift-offs an appropriate mean value can be calculated. More lift-offs are more time consuming during the measurement but do not lead to better or different results whereas only one or two lift-offs for evaluation can be too less especially if one of them is difficult to evaluate. The following table shows experimentally derived values for the ventilation procedure to define those five independent lift-off segments. They are minimum values which are very important for clear and easy data processing. When using a vacuum pump with a high evacuation rate, the pressure difference has to be adapted and might be higher. The minimum height of the movement of the foil away from the core during a lift-off is around 4 mm.

Table 6: Values for the ventilation of the vacuum chamber to distinguish independent lift-off segments

Pressure inside the chamber at lift-off [mbar]	Ventilation of the chamber for the next lift-off to: [mbar]
≤ 1	5
1 to 5	+ 5
5 to 10	+ 10
> 10	+ 20

Easier to remember: Ventilation of the chamber up to a value of at least twice the pressure where the previous lift-off happened.

5.2 Validation of the lift-off technique

For the specimen Type I with the combination of silica and fiber core materials, a typical graph is shown in Figure 13. One new curve is included in these measurements due to the second pressure gauge recording the actual internal pressure inside the panel. Independent from the pressure range, a significant pressure drop can be detected from the data of the directly connected second pressure gauge from the point of time when the surrounding of the specimen is evacuated. The graph for small pressure values, close to the proceeding evacuation process is shown in Figure 14. To be able to compare the actual pressure inside the panel without the influence of an evacuated surrounding with the results gained from the foil lift-off measurement, a linear regression curve is also visible in the graph (LinReg(pressure VIP)).

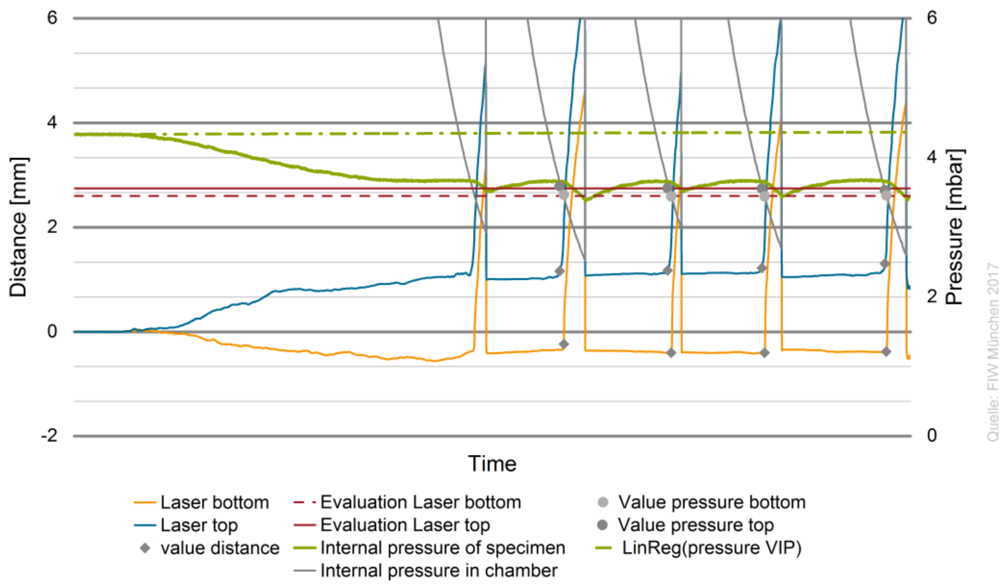


Figure 13: Measurement data for the validation of the lift-off technique including the direct measurement data and internal pressure results

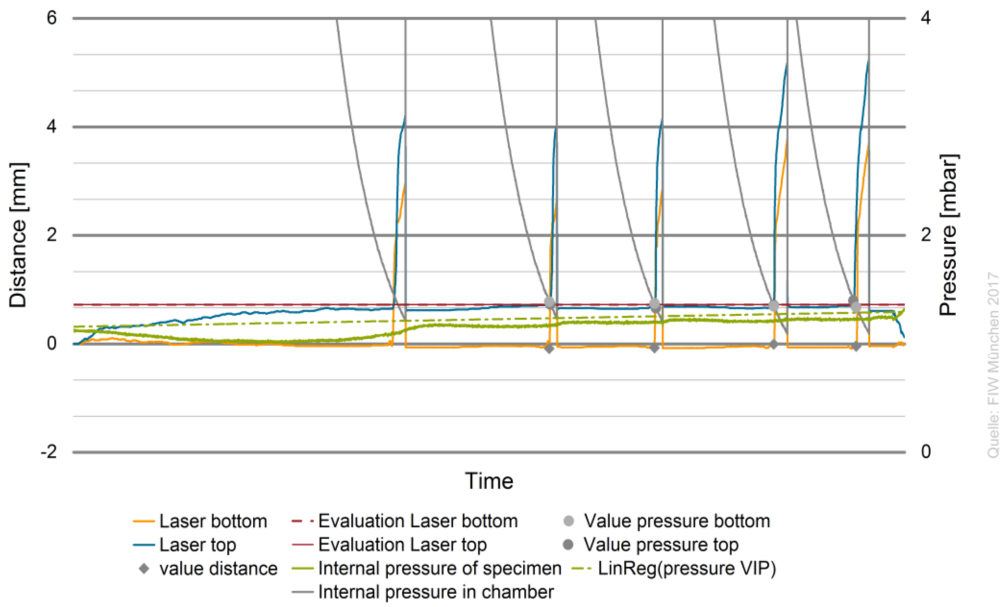


Figure 14: Measurement data for the validation of the lift-off technique for small internal pressure values

The mean values as well as the single results of the four considered lift-offs evaluated by the tangent method are also shown in the measurement data. The good accordance of the pressure values and the direct pressure measurement curve at the lift-off point of time represents the functionality of the measurement technique to detect the currently existing internal pressure. The difference between the red lines and the dashed green line is subject of the correlation to find the relationship between the direct and indirect measurement technique. For both laser positions, this difference in [%] is shown in Figure 15 as height of the columns.

All other specimen types show similar measurement curves. The main difference lies in the shape of the pressure drop in the direct measurement curve. Resulting from the characteristics of the support core material, change of volume and porosity the height of the pressure drop and the measurement values via foil lift-off method vary. The comparison of the differences between the two measurement techniques shown in Figure 15, Figure 16 and Figure 17 indicate this behavior.

In general, the lowering of the internal pressure when lowering the external pressure of a specimen by evacuating the vacuum chamber is reasonable because of the correlation between pressure and volume. A lower external pressure means lower external load and a relaxation of the core material. With the fiber core in specimen Type I an inflation of the core is clearly visible. But a larger volume also arises from the lift-off of the foil. Wrinkles and edges are flattening way before the real lift-off and contribute to a larger volume. The development of the two distance curves of the laser sensors in Figure 13 before the first lift-off also show that the panels' dimensions are changing with changing of pressure.

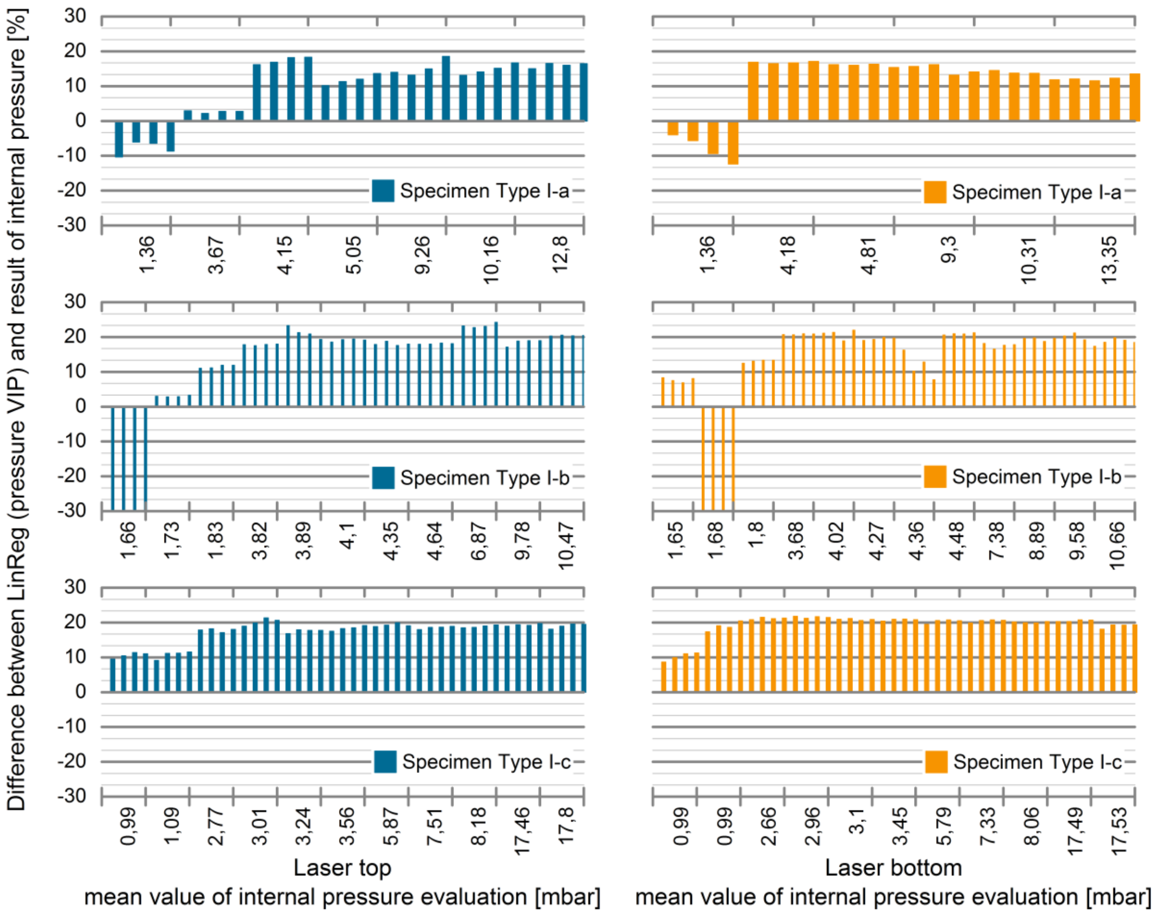


Figure 15: Deviation of the pressure value from linear regression of the internal pressure reading and the result of the evaluation of the internal pressure gained from the foil lift-off measurement for specimen type I. Data classified to mean values of the internal pressure evaluation to show which four lift-offs belong to one measurement.

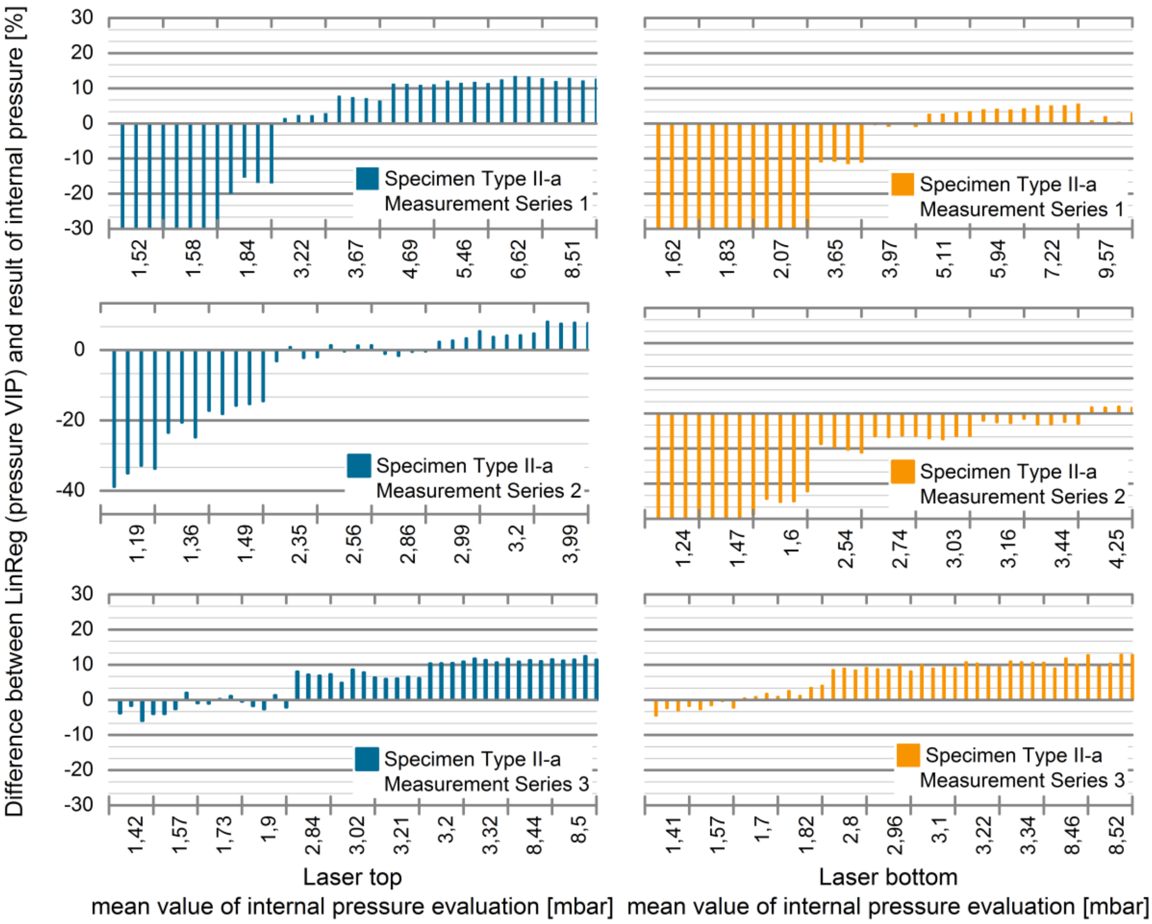


Figure 16: Deviation of the pressure value from linear regression of the internal pressure reading and the result of the evaluation of the internal pressure gained from the foil lift-off measurement for specimen type II. Data classified to mean values of the internal pressure evaluation to show which four lift-offs belong to one measurement.

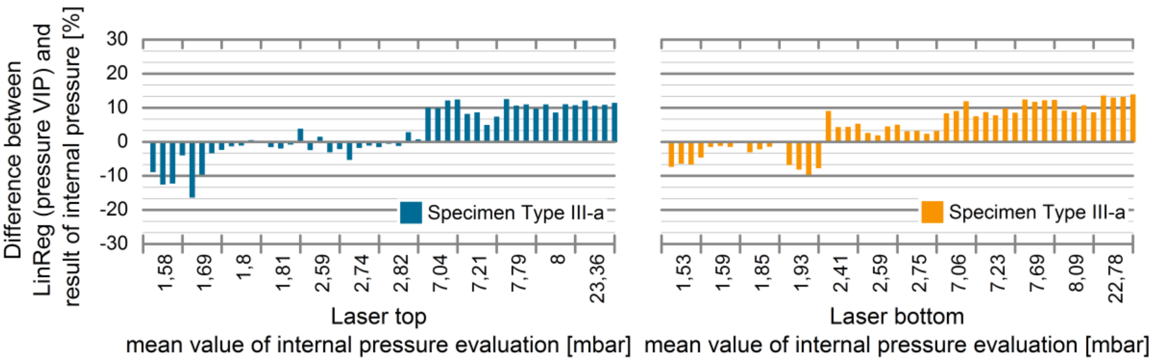


Figure 17: Deviation of the pressure value from linear regression of the internal pressure reading and the result of the evaluation of the internal pressure gained from the foil lift-off measurement for specimen type III. Data classified to mean values of the internal pressure evaluation to show which four lift-offs belong to one measurement.

Regarding the absolute values for Δp, the measured ones via the foil lift-off technique are up to 1.25 mbar lower than the regression curve. This is not a general value but the maximum value of the Specimen Type II and Type III measurements shown in Figure 16 and Figure 17 in the pressure range between 1 mbar and 10 mbar. The measurement at 23 mbar (Type III-a) for instance has a Δp of 3.63 mbar what does not indicate a consistent result anymore. The pressure range of the absolute delta p values is visualized by the box-plot in Figure 18.

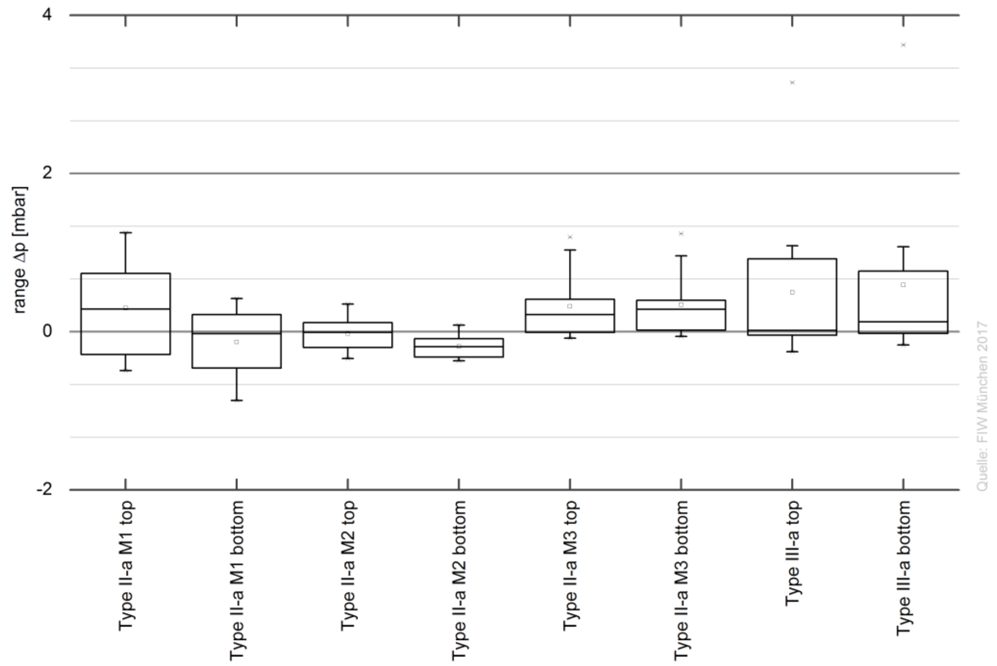


Figure 18: Box-plot of the Delta p pressure range

The measurement uncertainty on delta p consists of the merely technical factors and various not easily calculable factors. The combined measurement uncertainty resulting from pressure gauges and laser sensors can be calculated by the following formula:

$$u_c(y)^2 = \sum_{i=1}^{n} u(x_i)^2 \cdot (\frac{\partial(y)}{\partial(x_i)})^2$$

Table 7: Measurement devices influencing the measurement uncertainty

Measurement device	**Accuracy taken from data sheet**
Pressure sensor	0.2 % of measurement value
Laser distance sensor: Linearity	0.2% of measurement range
Laser distance sensor: Resolution	0.02 % of measurement range

The further influencing uncertainties result from individual selection of included data points for the evaluation of the foil lift-off measurement as well as the data selection for the linear regression curve. Moreover technical aspects such as leakage of valves and tubes, stiffness of foil and core material or incomplete pressure equilibrium cannot be included in the calculation because no values can be assumed.

A measurement uncertainty higher than the Delta p values indicates that the deviation of the two measurement techniques is within the uncertainty range. An exemplary graph showing the measurement data of Specimen Type III-a top (Figure 19) shows that besides the negative Δp-values, the uncertainty is only a little smaller than the Δp.

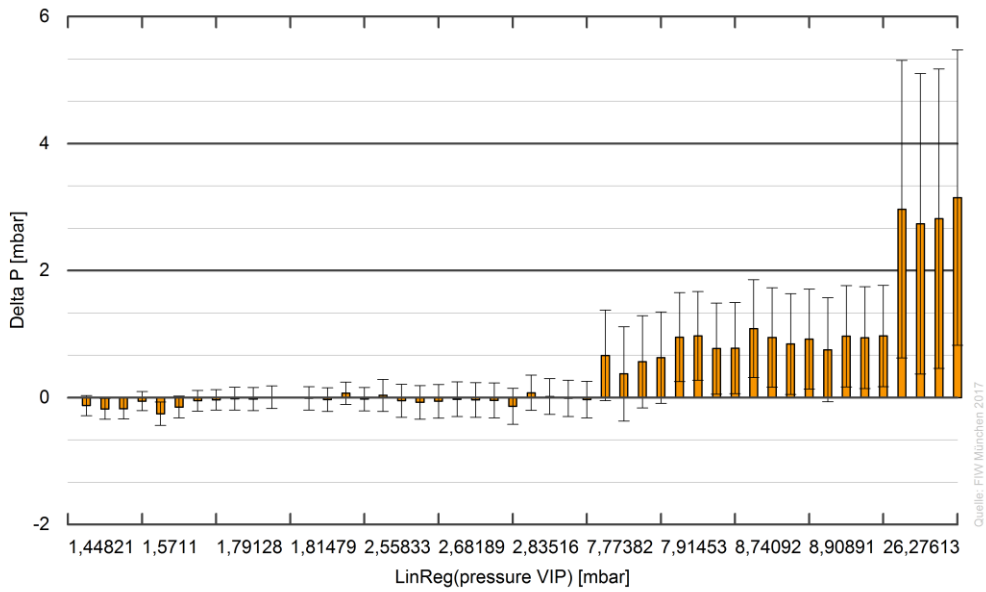


Figure 19: measurement uncertainty resulting from technical devices on Delta p of the two measurement techniques

Because of the fumed silica core and the low pressure, the processes inside the specimen do not follow fluid mechanics principles anymore but diffusion caused by pressure differences. This diffusion takes a long time to reach equilibrium. The fact that the evacuation of the specimen and further on the recording of the internal pressure is implemented on the part of the specimen of the support core material, only this pressure status can be observed. Figure 20 shows the process on the set-up over time where a small amount of residual air molecules are trapped inside the silica pores over a long time.

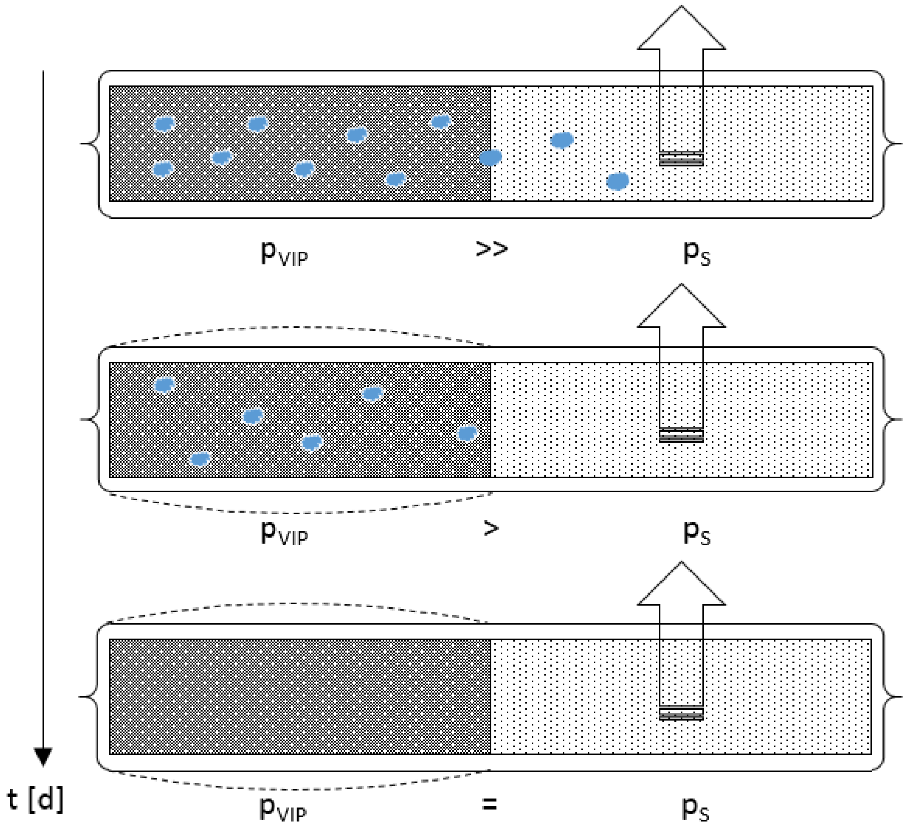


Figure 20: Schematic illustration of the pressure diffusion taking place in the two different types of core material within one specimen. The arrow indicates the position of the leak tight connector where evacuation and internal pressure measurement are conducted.

Out of this reason, a new specimen with only one type of core material was built to examine the influence of different porosities. Two of the incompressible ceramic compound material cores were used here, having larger pores than fumed silica. The overview of the measurements conducted on the specimen Type IV is given in Figure 22. There are only small negative values at one measurement and the height of the columns indicates the highest deviations among all specimen types. The consideration of the time span to reach positive deviations leads to a shorter period until pressure equilibrium is reached.

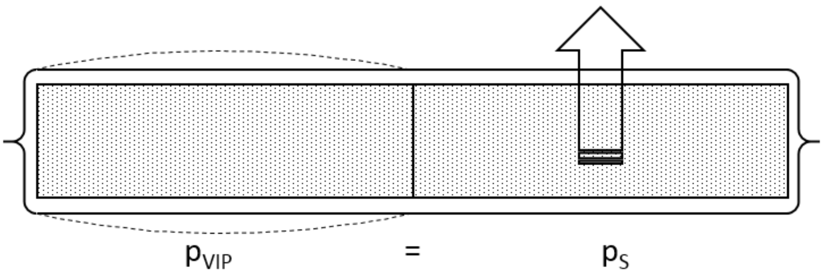


Figure 21: Schematic illustration of the pressure diffusion in a specimen with only one type of core material.

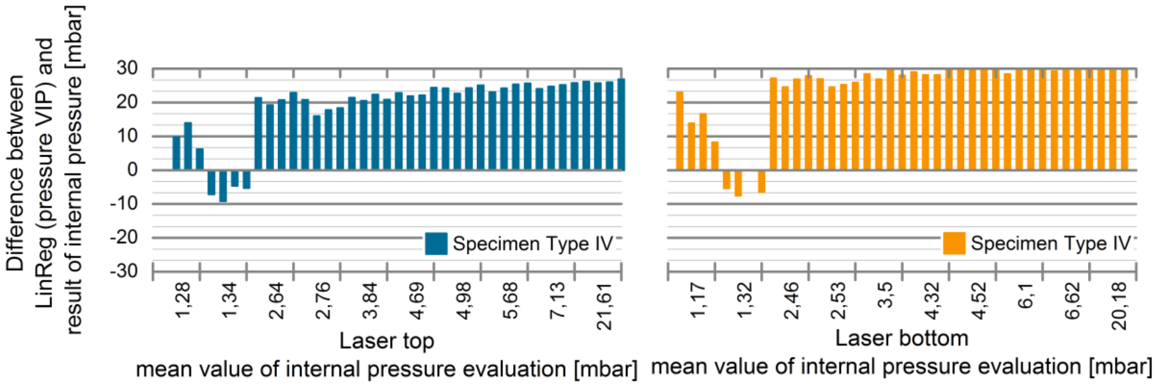


Figure 22: Deviation of the pressure value from linear regression of the internal pressure reading and the result of the evaluation of the internal pressure gained from the foil lift-off measurement for specimen type IV. Data classified to mean values of the internal pressure evaluation to show which four lift-offs belong to one measurement.

For the suction bell measurements the graphical visualization of the internal pressure data during the measurement period looks like the green curve in Figure 23. The points of time when a suction bell measurement took place are marked by grey circles whereas the result of the suction bell evaluation is depicted by dark green dots. The distance between these two points stands for the deviation of the applied measurement technique and the actual pressure value. As there is absolutely no influence of the ongoing measurement to the pressure increase recognizable, it can be stated that the deviations are smaller than the ones in Figure 15.

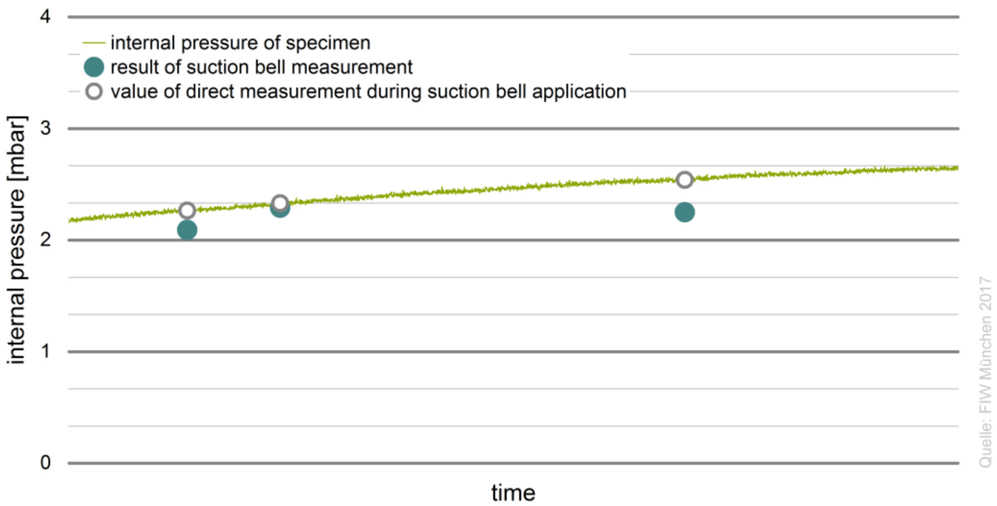


Figure 23: internal pressure behavior during suction bell measurements

The further suction bell measurements of the mentioned six panels were conducted without the possibility of direct internal pressure recording. But less than twenty hours before these measurements the same panels were measured inside the vacuum chamber. The internal pressure results of both lift-off measurement techniques are plotted in Figure 24 for all panels. The second panel has big foil flaps folded and stuck around the edges to the panel surface and a large welding seam in the middle of the small panel. For this reason the measurement system does not operate reliable and the measurement result cannot be taken as correct. Another panel was outside the measurement range of the suction bell. Pressures below 1 mbar are not detectable with the suction bell but the results of the vacuum chamber measurement are lying pretty close together having a value of 0.74 mbar respectively 0.76 mbar.

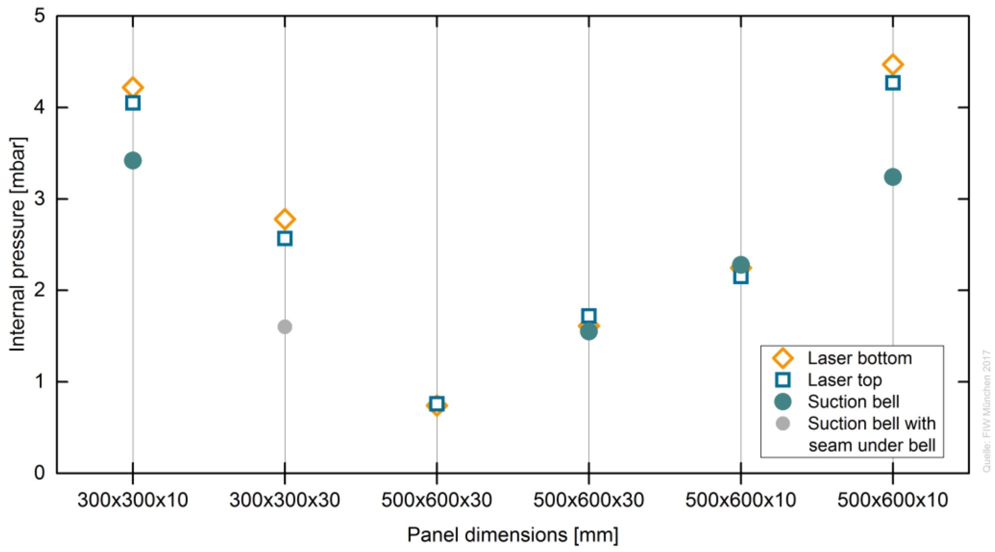


Figure 24: Comparison of the two lift-off measurement techniques. Values from two laser sensors of the vacuum chamber measurements were evaluated by the tangent method

5.3 Development of algorithms for data analysis

The comparison of results after the evaluation of real test data by both methods on a set of 30 VIP with similar internal pressure shows that the median value and distribution of internal pressure is very similar. Also the standard deviation between the evaluated lift-off sequences of one measurement shows the influence of the variation of the threshold value of q.

The triangle method often leads to results that are close to the beginning of the lift-off. The tangent method in opposite determines a value that is positioned in the middle of the transition zone of the test data. This effect is especially visible in case of curved transition zones instead of transition zones with a sharp kink.

As most significant effects occur with spreading of test data, the robustness of the algorithms to spreading was tested on artificial test data with the sharp kink of the transition zone at a set pressure. With choosing a suitable threshold value of q, even for a spreading of ± 0.04 mbar a good coincidence to the target value can be reached. Whereas the triangle method shows a precise determination of the target value throughout all data spreading scenarios.

Because of the uncertainties in the validation of the lift-off technique, the values of both algorithms are within the accuracy at present state. Only with the possibility to determine the true internal pressure it is possible to conclude if one result is more accurate.

6 Summary

The foil lift-off technique is an adequate method to determine the internal pressure of VIP. The implementation of the developed boundary conditions on the bearing situation of the panels and the data logging leads to unproblematic data processing. A quadratic shaped profile to restrict the measurement area is applicable for all panel dimensions and types of foil. Also the positioning of the laser distance sensors is clearly defined by the center of this profile.

For data analysis both tangent and triangle method are suitable. The examination of real test data has shown that the triangle method seems to be more robust to different test data pattern that can be observed due to specific behavior of the recorded foil displacement that can be influenced by overlying movements of the panel due to the specific bearing situation or if the observed foil area is not undisturbed, e.g. in the case of kinks or a welding zone inside the measurement zone.

The examination of artificial test data has shown that the tangent method is sensitive to spreading of the test data, geometrical shape of the clipped test data sequence and the sampling rate. With regard to an optimum and robust fit quality of the tangents an adequate threshold value of q, an isosceles triangle shaped test data sequence and a sampling rate that is tuned to the evacuation rate of the vacuum pump is necessary. In case of an individual test setup (bearing situation), spreading of test data (accuracy of test equipment and individual foil lift of behavior) it is not possible to conclude general recommendations to balance the listed parameters.

The currently used measurement setup for the validation of the foil lift-off technique does not lead to generally applicable rules how to further process and average the results. It turned out that measurements straight after manufacturing or rather evacuation do not measure the real internal pressure. A certain time of at least 24 hours is necessary to reach pressure equilibrium and only then pressure measurements are to be performed. Because of the increase in volume while conducting a lift-off measurement the results gained through the foil lift-off are lower than the internal pressure before or after the running measurement. Depending on the pressure level, the deviation of the pressure in the range between 1 mbar and 5 mbar is quite small. Larger internal pressure leads to a higher absolute pressure drop.

7 Recommendations for users

For the measurement of the inner pressure of VIPs it is recommended to make use of the following boundary conditions:

- It is recommended that the bearing for the VIP and the mounting for the laser devices is combined in one rack
- Restriction of measurement area on both sides of panel by 250 x 250 mm profiles is appropriate
- Choose measurement area in center of the specimen but apart from foil seams or flaps
- Very wrinkled surfaces can be smoothen with adhesive tape at laser position or a thin fabric could be used at a small distance to the surface to detect the “real” lift-off easier
- At least two laser devices are recommended: combine measurement from above and underneath the panel
- Perform five lift-off sequences at each measurement and discard the first one for the evaluation
- Perform the lift-off of the foil to a distance of approximately 5 mm is recommended
- Ventilation of vacuum chamber in between lift-offs up to a pressure level of at least twice the pressure when proceeding lift-off took place is recommended

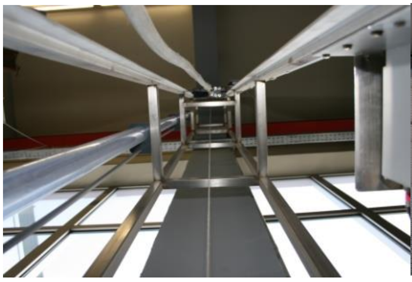
8 Outlook

It is the aim of the members of VIPA to integrate the findings of this study into the upcoming product standard for VIP in CEN TC 88 WG 11. Therefore the strategic approach is to implement the recommendations from Chapter 7 of this project report in Annex G of prEN 17140. This can be done by using the official CEN comment form during the upcoming inquiry for the standard and writing technical comments. Inquiry will start in July and be finished in September. FIW will write these comments on behalf of VIPA and will ask the German mirror committee to be the official submitter.

One of the next steps should be to check if the described procedure can be extended to measuring fiber core panels.

In parallel, a further modification of the setup is recommended to reduce the pressure drop during a measurement to a value that only results of the relaxation of the silica core and the movement of the foil. Therefore the design of the adapter and the length, diameter and the material of the vacuum tubing has to be thought over.

If the extension of the foil lift-off method for fiber core panels is not successful, the alternative could be a direct measurement of the internal pressure using minimized pressure sensors on computer chips that are integrated in the VIP foil bag. A cross-check with the foil lift-off method and in addition to that also the adapter method is inevitable.



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