Addressing the Geographical Restrictions Placed on Full Fill Cavity Wall Insulation in the UK Due to Driving Rain

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The work contained in this work is my own.

Peter Batchelor

Abstract

The two main home insurers in the UK, Zurich and the NHBC, impose restrictions on the use of full fill cavity wall insulation in very severely exposed areas. This is due to the perceived risk of water penetration. These restrictions limit the market for full fill insulation manufacturers. Existing literature and data on water penetration claims were insufficient to support anything other than conservative recommendations on construction. A liaison group was set up involving the insurers and other industry regulators, with a view to address these restrictions. This resulted in a programme of experimental testing.

Empirical testing was undertaken to gauge water penetration as a function of cavity width, for both fully filled and empty cavities. In these tests, contrasting standards of workmanship were investigated. Computer models were developed to analyse fluid flow in a cavity at junctions, which are known problem areas. The Rainscreen Principle was investigated using pressure equalisation across outer leaves.

All test walls with extremely bad standards of workmanship failed, apart from a 150mm fully filled wall in 'moderate' levels of exposure. The walls built to a typical standard exhibited no dampness problems, apart from a 50mm fully filled cavity in 'very severe' exposure. The performance of the empty cavity was on par with the fully filled walls. The pressure equalisation of the outer leaf could inhibit the passage of water across the cavity wall. Although the analysis of the data provided a convincing argument to relax the fully filled cavity restrictions, insulation manufacturers may have to take on a proportion of liability in order for the insurers to relax them. Future wall constructions will probably feature wider cavities that will have an effect on the water penetration properties. Further work is required in order to compile good quality data from which confident, impartial assertions can be made.

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Introduction

Cavity wall construction is currently the most common type of domestic external wall in the UK. This is because of its flexibility, cost and potential for insulation. Cavity walls have been in use since the nineteenth century but it was the building boom in the 1930s that first produced large numbers of cavity construction dwellings. During the 1970s, the energy crises caused by the OPEC export embargo drove an increasing interest in energy efficiency. In particular, the increasing cost of fuel for space heating caused people to look at insulating their homes. The existing empty cavity walls were an ideal opportunity for installing cavity wall insulation. With successively? onerous standards of the thermal performance of dwellings in the Building Regulations (DCLG, 2006b), from around 1980, cavity wall insulation started to be 'built in' at the time of construction. Additionally, there was a great deal of retrofit work undertaken on the existing housing stock. Properly insulating a dwelling also makes the occupants' lives more comfortable: indeed, a recent article in the British Medical Journal reported that cavity wall insulation carried further health benefits (Howden-Chapman et al, 2007).

There is, however, an anecdotal belief in the construction industry that cavity walls were 'put there for a reason', and fully filling the cavity will cause water ingress from the outside leaf. This is supported by the industry's key legislators and insurers imposing geographical restrictions on the use of full fill insulation in severely exposed areas of the UK. For example, the principal home insurer in the UK forbids the use of full fill cavity wall insulation in most of Wales, south west and north east England, and the whole of Scotland. These areas have a higher incidence of driving rain than other parts of the UK. These restrictions however represent an opportunity for the manufacturers of full fill insulation products. Addressing these restrictions and understanding on what basis they were introduced was the main aim of this project. This thesis documents a research project, which was funded under the Knowledge Transfer Partnerships (KTP) scheme. KTPs are government run schemes that aim to transfer knowledge and expertise from Universities to small and medium sized businesses in the UK. This fosters innovation with a view to increase the business' bottom line. The ensuing research is not only of commercial value but is of academic value, as this type of research has not been carried out before. Rockwool Ltd, an insulation manufacturer in South Wales was the company partner in this particular KTP project. Unusually, this project featured two Knowledge Base Partners: Leeds Metropolitan University and University College London.

This programme of research possessed both exploratory and influencing strands. The main objectives were to:

- develop an understanding of the physical processes that drive water through masonry walls;
- understand the historic basis for the current restrictions on the use of full-fill insulation;
- explore empirically if the wider cavities (see figure 1.0) that have resulted from successive revisions to the building regulations will reduce the risks of rain penetration in severely exposed and very severely exposed areas of the UK;
- engage with decision makers in the British Board of Agrément , Building Research Establishment and major insurers, with a view to easing or lifting the restrictions currently placed on such insulation.

Figure 1.0, A 142mm cavity (yet to be filled) that could satisfy future thermal performance demands. This width of cavity was used in a trial on a recently built housing estate in the north of England.

In order to obtain the 'buy in' of the key decision makers, a liaison committee was brought together. This enabled a canvassing of options and also steered a programme of experimental testing.

The experimental work had two components – theoretical and practical. The theoretical component consisted of an analytical computer model of fluid flow at wall junctions. This area of construction was known to be a source of dampness problems. The model allowed key physical parameters to be varied in order to illustrate the principles at work and to explore a variety of options for improving resistance to driving rain.

The practical work involved the industry standard driving rain test rig. This enabled research into the effect of varying cavity width on water penetration across the wall system. It also enabled pressure experiments to be conducted across the outer leaf of a cavity wall system.

What became apparent from the outset was that the standard of workmanship was a key issue as to whether or not a cavity suffered dampness problems. Therefore, this was a key focus of the experimental work. A bricklayer was employed in constructing the test rig walls (the experimental procedure is detailled in the methodology section). Through simply observing his work, vital information on typical site habits (good and bad) and methods of construction were discovered.

This project addressed a complex and real world problem that needed to be tackled in a business setting. The research approach that was adopted was correspondingly complex. The following sections of this thesis go on to descibe the current research on this subject, the programme of work undertaken and the conclusions that can be drawn from the results obtained.

Literature review

Assessing the Exposure Index

The concept of comprehensively expressing wind driven rain began in 1976 with the Building Research Establishment's Driving Rain Index (Lacy, 1976). Lacy's work was the first to feature a large-scale map of an annual mean index, a product of the mean annual rainfall and mean annual wind speed. A key driver for Lacy's work was the growing popularity of cavity wall insulation, in response to the higher fuel prices and shortages of the 1970s. At the time, previous work (BRE Digest 23, 1962 and BRE Digest 127, 1971) would have been of insufficient detail to allow a decision on the suitability of full fill cavity insulation to be made. Lacy's report featured a much larger-scale driving rain map, up-to-date data and a better system of corrections to allow for local variations in the degree of exposure.

Lacy's work featured a 1:625,000 scale map showing the annual mean index in m^2s^{-1}. The wind speed used in the calculation of the annual mean index was for an open, level site 10m above ground. However, the intensity of driving rain varies locally, so the quantity of driving rain for a particular construction and local area is expressed as the Driving Rain Index. The document provided rules for modifying the map values to allow for such local variations in exposure. Two variation factors were used – topographic and terrain roughness. In Lacy's document, the topographic factor accounted for the nature of the land around the building area, for example hills and valleys. Terrain roughness concerns anything that interferes with the free flow of wind at a smaller scale, such as buildings and trees. Lacy provided tables with these correction factors to enable the local value of the driving rain index to be calculated for each individual site.

An interesting point to note is that Lacy claimed that installing insulation in a cavity wall increases the risk of water crossing the cavity. The BRE's Leaflet 23

‘Cavity wall insulation: unlocking the potential in existing dwellings’ (BRE, 1995) offers a different view: ‘there is no statistical evidence that cavity wall insulation increases the risk of rain penetration’. This evidence consisted of a performance study in 1993/94 of 11,061 homes with fully filled cavities and 2,229 homes with unfilled cavities. Leaflet 23 stated that rain penetration problems were reported on 0.26% of homes with full-fill and 0.22% of home with unfilled cavities. It is worth bearing in mind, however, that cavity wall insulation was still in its infancy around the time of Lacy’s paper. As such, the manufacturing and installation industry in the mid 1970s was perhaps not fully aware of the risks that could result from poorly installed cavity insulation.

The British Standards Institution (BSI) and British Board of Agrément (BBA) offer separate methods of assessing the quantity of driving rain incident on a building. Both the BSI and BBA’s documents extend the concept of Lacy’s Driving Rain Index and refine the local variation factors that affect the amount of wind-driven rain. The variations arise due to the effects that topography, terrain and building height have on incident wind speed. The BBA detail their methodology in their Information Sheet 10 (BBA, 1983a) and this is chiefly based on Lacy’s 1976 document. However, there is one confusing factor. The BBA refer to the Lacy’s ‘raw’ annual mean index as the Driving Rain Index, or DRI. There is no mention why this is the case. From now on, Lacy’s nomenclature will be used with annual mean index representing the ‘raw’ map data, and DRI accounting for local correction factors. In the BBA’s document, two factors exist for refining the annual mean index. As in Lacy’s document, the topographic factor describes the effects produced by the surrounding ground contours. The terrain and building height are expressed in a combined factor. This factor expresses the effect of ground roughness, the way in which velocity varies with height and also the situation of the building (for example, on the top of a hill).

- The topographic factor, T, varies from 0.9 to 1.1, representing steep sided, enclosed valleys to very exposed hillcrests or valleys that produce a funnelling of the wind.

- The terrain factor, *R*, ranges from 22 to 39 and represent locations ranging from the coast to city centres and also buildings of up to three storeys in height.

There are several significant differences between these factors and the factors used in Lacy's document. Firstly, Lacy's topographic factor ranges from 0.8 to 1.2, rather than 0.9 to 1.1 (see above). Secondly, the BBA use a 'category 0' in their terrain and building height factor. This extended the range of the correction process, as the BBA's categories 0 and 1 are scaled either side of Lacy's category 1.

In the BBA's document, the annual mean index values (given in Lacy's document) are then scaled to provide a 'Geographic factor', *(G)*. This is effectively converting a set range of annual mean index values in m^2s^{-1} to an arbitrary value. For example, the range $2.0 < \text{annual mean index} \leq 2.5$ gives a *G* value of 15. The Exposure Index (*E*) is a sum of these three factors:

$$E = G + T + R \qquad (1.0)$$

E, is comparable to Lacy's *DRI*. The maximum possible *E* is 119.

It is important to note that Lacy does not use this approach. Lacy's tables work directly on the annual mean index and do not require any 'substitute' values to be used. This suggests a less obscure means of calculation.

The BBA's information sheet 10 also refers to BSI CP3, Code of Practice for Wind Loads (1972). BS 5618, Code of Practice for Thermal Insulation (1978) is based on this document.

Lacy also refers to the classification of the country into three 'zones' of increasing exposure. These zones are sheltered, moderate and severe. The BSI extended this concept of classification, as detailed below.

The approach described in BS 8104: 1992 is based on more recent work. BS 8104 was born out of the Draft for Development document 93. BS 8104 also based on BS 5618: 1985, Code of Practice for Thermal Insulation and BS 5628: 1985, Code of Practice for use of Masonry.

The British Standard takes into account the fact that heavy rainfall is usually associated with strong winds. Rain penetration is most likely to occur with high intensity driving rain, therefore BS8104: 1992 provides maps showing the quantity of wind driven rain falling on vertical surfaces during the worst likely spell of bad weather in any three year period. It defines 'spells' as periods of wind driven rain interspersed with periods of up to 96 hours without appreciable wind driven rain. The spell method is therefore more accurate than Lacy and the BBA, who simply compute an annual index. Other differences are that the BS also takes into account the orientation of the wall. In the BS, the airfield spell index or D_s, describes the quantity of driving rain 10m above ground level in the middle of an airfield, for a given direction, in units of litres per square metre per spell. The term 'airfield' is used because it is a large expanse of flat, unobstructed land. Four correction factors are then used to refine D_s:

- terrain roughness factor, R;
- topography factor, T;
- obstruction factor, O, which allows for buildings, fences or trees providing shelter to the very local environment;
- wall factor, W, which allows for the characteristics of the proposed wall. It is the ratio between the quantity of water falling on the wall and the quantity falling in equivalent unobstructed space.

The equation 1.1 details the wall spell index D_{WS}, which is defined as *'The quantity of wind-driven rain in litres per square metre per spell at a point on a given wall, based on the airfield spell index and correction for roughness, topography, obstruction and wall factors'* (BS 8104, 1992).

$$D_{WS} = D_S RTOW \tag{1.1}$$

The BS offers a more accurate method of expressing variation in local exposure due to the further refinement and addition of correction factors.

An attempt at a comparison between the ‘Draft for Development’ 93 (1984) (which preceded BS8104 (1992)) method of classification of exposure zones and Lacy’s more simplistic classification is given in BS 5628-3: Use of Masonry (1985). This is shown in table 2.0 below.

Table 2.0, Adapted from the ‘Classification of exposure to local wind-driven rain’ (BS5628, 1985)

Exposure category	Local spell index calculated as described in DD93 (L/m2 per spell)	Exposure category as in Lacy's document (1976)
Very Severe	98 and over	Severe
Severe	68 to 123	
Moderate / Severe	46 to 85	Moderate
Sheltered / Moderate	29 to 58	
Sheltered / Moderate	19 to 37	Sheltered
Very Sheltered	24 or less	

The table shows six classifications of exposure of zone, which is twice as many as Lacy suggested. BS 5628–3 (1985) claimed the increase of classifications was necessary because of developments such as the introduction of insulation in cavity walls and the advent of improved meteorological data. BS 5628-3 (1985) explains that the indices shown are not precise, since they are derived from inherently variable meteorological data. BS 5628-3 then explains that this variability is therefore reflected in the definitions of the exposure categories by overlapping the indices at their boundaries. This seems a rather baffling explanation for the overlapping boundaries. Furthermore, later versions of BS5628-3 feature exposure categories that are discreetly defined with no overlap. In 2001, BS5628-3 was updated and featured a revised classification of exposure zones (see table 2.1 below).

Table 2.1, Wind driven rain exposure categories (adapted from BS5628-3 (2001))

Category of exposure		Calculated quantity of wind-driven rain* (l/m2 per spell)
1	Sheltered	Less than 33
2	Moderate	33 to less than 56.5
3	Severe	56.5 to less than 100
4	Very Severe	Not less than 100
*Maximum wall spell index calculated using the wall spell index method specified in BS8104		

The categories in table 2.1 are identical to those defined in the BRE document 262, 'Thermal Insulation: avoiding risks' (2002). The reason for the reduction from six exposure categories to four was to bring BS5628-3 into line with the then current edition of BRE 262 (1994).

The BRE document 262, 'Thermal Insulation: Avoiding Risks' (2002) is based on BS 8104 (1992). The exposure zone map shown in 262 (figure 2.0) is created by calculating values using the method in BS 8104. This exposure zone map is frequently used by house-builders to determine the suitability of cavity wall constructions.

These restrictions are also published in Approved Document C (DCLG, 2004), which brings the issue of driving rain and BRE Document 262 (BRE, 2002) into the building regulations.

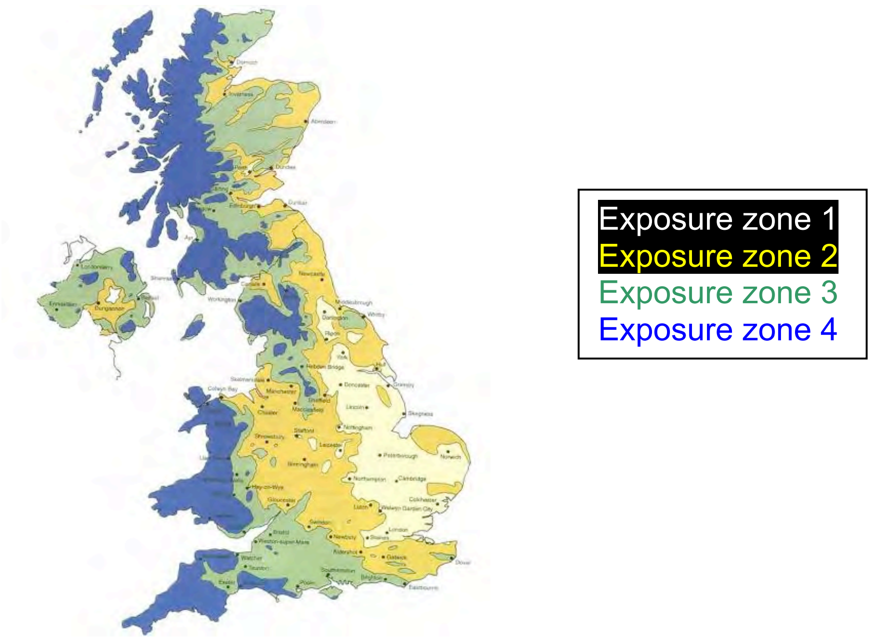


Figure 2.0 – UK exposure zones. (BRE, 2002)

The BRE then provide a table of recommended restrictions of minimum cavity wall widths for use in each of the four exposure zones, shown below.

Table 2.2, Adapted from the maximum recommended exposure zone table, Thermal insulation: avoiding risks (BRE, 2002)

		Maximum recommended exposure zone for each construction			
Wall constuction	**Min. width of filled**	**Rendered Finish**		**Facing Masonry**	
	or clear cavity (mm)	**Full height of wall**	**Above facing masonry**	**Tooled flush joints**	**Recessed mortar joints**
Bulti-in full fill					
	50	3	3	2	1
	75	4	3	3	1
	100	4	3	3	1
	125	4	3	3	1
	150	4	4	4	1
Injected fill not UF foam					
	50	3	2	2	1
	75	4	3	3	1
	100	4	3	3	1
	125	4	3	3	1
	150	4	4	4	1
Injected fill UF foam					
	50	3	2	1	1
	75	3	2	2	1
	100	3	2	2	1
Partial fill					
Residual 50mm cavity	50	4	4	3	1
Residual 75mm cavity	75	4	4	4	1
Residual 100mm cavity	100	4	4	4	2

The Code of practice for use of masonry – Part 3: Materials and components, design and workmanship (BS 5628-3, 2001) stresses that the exposure zones map published in BRE 262 assumes worst case conditions and therefore provides conservative guidance. It observes that, as the exposure zones map can restrict the choice of construction, the assessment given in BS 8104 gives a greater and more accurate choice in determining which construction to use.

The two main home insurers in the UK, the National House Building Council (NHBC) and Zurich Insurance adopt the BRE's exposure zone map in their technical standards literature (NHBC 2005 and Zurich 2005). Zurich follows the BRE's restrictions detailed above. However, the NHBC has more stringent restrictions on the use of cavity insulation in high exposure zones. For example, in the case of facing masonry, the BRE would allow full-fill cavity batts to be used in the maximum exposure zone, so long as the cavity is a minimum of 150mm. NHBC do not allow full fill cavity insulation in the 'very severe' exposure zone and the whole of Scotland.

Figure 2.1, shows the relationships between the documents published by BSI, BBA and BRE on driving rain.

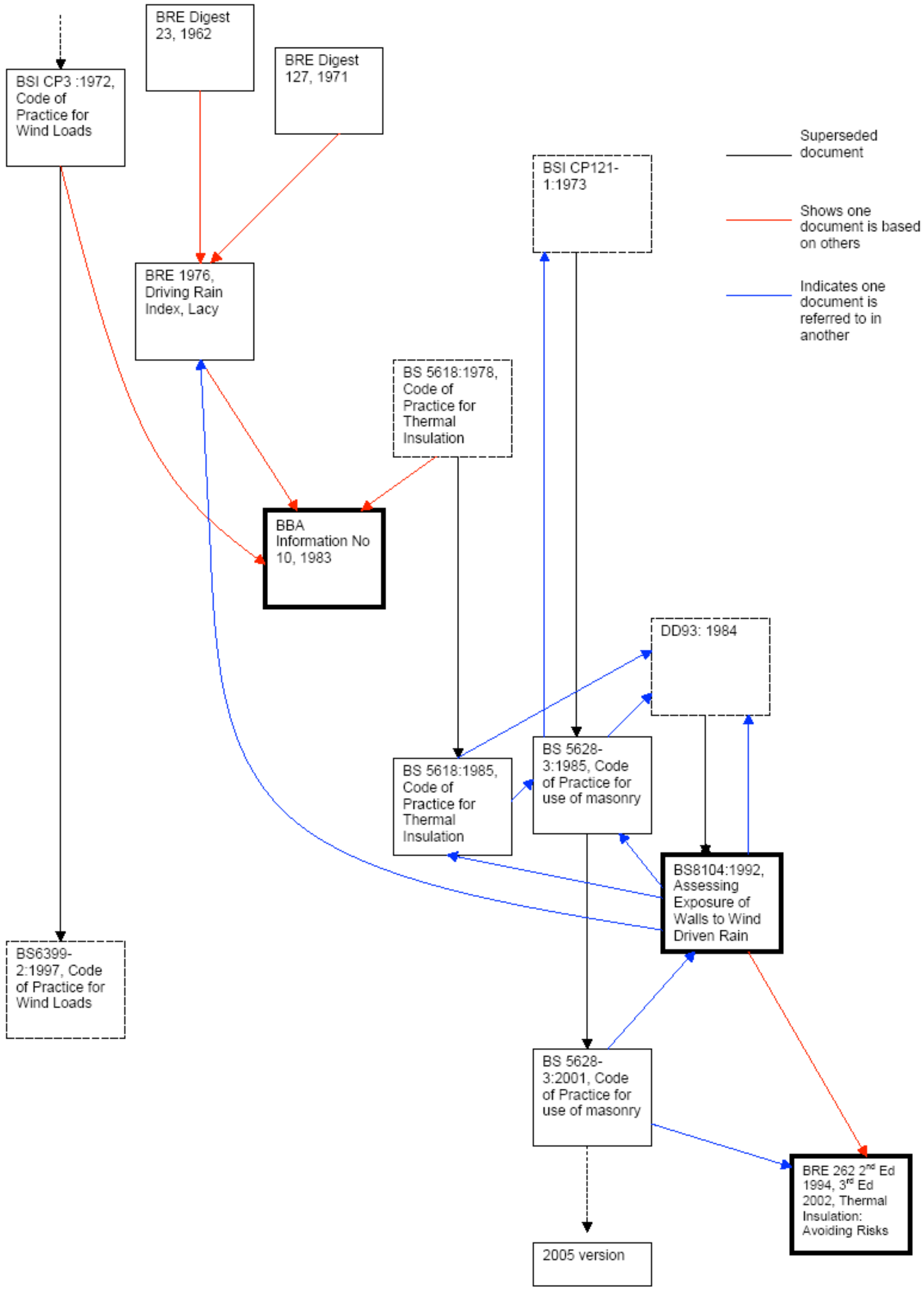


Figure 2.1, The relationship between driving rain literature

Issues of workmanship

There is an anecdotal belief held by a considerable proportion of the construction industry that filling cavity walls increases the chance of water ingress. After all, one of the original reasons for creating a cavity was to allow any water to run down the inside of the outer leaf and exit through weep holes. However, the substantial amount of data derived from testing and 'real life' examples suggest that any differences are very modest and not necessarily significant. For example, Vagn Korsgaard (1965) noted this concern and built an external test house and a laboratory test rig in order to measure any water penetration that occurred. He concluded that 'driving rain does not seem to have had any noteworthy effect on the insulation value of the filled cavity brick walls, and none of them have ever shown any visible signs of rain penetration' (Korsgaard, 1968:p5). He also concludes in the same paper that 'in Demark there is hardly any risk that cavity insulation will cause moisture problems from driving rain' and 'as the amount of driving rain, the workmanship, the bricks, the mortar and the construction principles in England are comparable with those in Denmark, it should be allowable to draw the same conclusions regarding the insulation of cavity walls in England'. It is useful to note that he was referring to England, and not Scotland and Wales, both of which have a much larger proportion of very severely exposed areas. Therefore, if he had compared the whole of the United Kingdom with Denmark, it is possible that he may not have made such a statement. In addition to this, the northwestern areas of England are classed as very severely exposed (figure 2.0). Here, Lacy's annual main index is around $10m^2s^{-1}$. In Jutland, where Korsgaard conducted his tests, the annual rainfall is 664mm with an average wind speed of 6.0 ms^{-1} (Met office data). This equates to an annual mean index of around 4.0 m^2s^{-1}, which is significantly lower than northwestern parts of England. Therefore, Korsgaard was perhaps erroneous in his sweeping statement. Vagn Korsgaard (1965) also conducted testing using a driving rain test rig to determine if insulation type affected the water penetration properties of the cavity wall. He also investigated the amount of water uptake of the insulation materials. Taking these two factors into account, the mineral wools and polystyrene pearls were considered suitable for cavity wall insulation in driving rain areas. However, clay clinkers and Vermiculite, which are not used as insulants anymore, did not perform well.

BS 5628-3 (2001) gives guidance on workmanship issues when constructing cavity walls. Matters such as pointing, bricklaying and details are included. Although the guidance given is commendable, it is, nevertheless, written from a very theoretical viewpoint. It is likely that few bricklayers are aware of the document's existence. Even the most conscientious will prefer to consult the home insurer's own technical guidance or the Accredited Construction Details (DCLG, 2006a).

Thermal insulation: avoiding risks (BRE, 2002) states that 'moisture transmission to the inner leaf of cavity walls is more likely where walls contain building defects and cavity insulation'. On first glance this statement seems a fair assumption. But what if the cavities are built that are significantly wider that those common in the past? With the thermal requirements of Part L of the Building Regulations (DCLG, 2006b) becoming progressively more stringent, we are seeing the consequent widening of insulated cavity walls to meet this requirement. Despite an exhaustive search, the author has found no test results that show the variation of the risk of water penetration as a function of cavity width. Therefore, there is apparent scope to fully investigate this relationship so that the table of restrictions (table 2.2) can be fully substantiated. This is discussed further in the Results & Discussion section.

The NHBC and Zurich issue technical standards that give technical requirements, performance standards and guidance for the acceptable design and construction of dwellings. These are similar to BS 5628-3 (2001), however they appear more practical and specific, rather like the examples given in Accredited Construction Details (DCLG, 2006a). Zurich uses the BRE's recommended restrictions in their technical standards (Zurich, 2005). The minimum thickness of fully filled cavity batts with facing masonry in very severely exposed areas is 150mm. Conversely, the NHBC issue more stringent restrictions on the use of such insulation: 'In areas of *Very Severe* exposure to driving rain and in Scotland the cavity should not contain full fill insulation'

(NHBC, 2005). The NHBC increased their restrictions after the storms of the late eighties and early nineties. In July 1992, the NHBC therefore increased their restrictions and introduced 'a better surveillance scheme for retro fill insulation and at the time had inspection campaigns to reduce the risk of defects being built in'. (Crane, P., NHBC, 25th September 2006, E-mail to P. Batchelor).

Lecompte (1987) measured the effect that varying levels of workmanship had on the airtightness of masonry walls. Airtightness and the ability of a wall system to resist water are of course linked, because 'wind gusts can actually 'pump' a considerable amount of rainwater through the wall.' (Lecompte, 1987). Lecompte also measured two other parameters: the pointing of the joints and the plastering of the inner leaf. Inner-leaf pointing could be classed as a form of workmanship, as this is a time-consuming process, it is often overlooked on site and the wall airtightness suffers as a result.

Lecompte's paper provides a very useful example of how critical workmanship is on the fluid tightness of a wall. His work provided some empirically determined equations linking the airflow through a wall q, the pressure difference Δp. This equation provided the basis of the quantitative fluid model of a 'junction' that is described more fully, later on in this thesis.

$$q = a\Delta p^b$$

Where a and *b* are coefficients that varied considerably with workmanship, pointing, plastering and type of bricks and blocks used.

A study into Airtightness in Masonry Dwellings by Lowe et al (1994), expands on Lecompte's work and measures the airtightness of window / wall junctions. This is a known area of weakness in terms of water penetration, and therefore any data on this area are useful. Lowe et al found that 'conventional window reveal detailing is reasonably airtight, but can be improved considerably with minor modifications'. These modifications were taken from detailing used in a number of low-energy houses in Germany. They also concluded that the filling of wall cavities with *in situ* foamed polyurethane insulation appeared to improve the airtightness in houses with timber first floors. This provided a starting point for the research detailed in this thesis, as qualitative data for cavity walls insulated with rock wool insulation were needed.

Claims information

In 2003, the Cavity Insulation Guarantee Agency (CIGA) conducted an analysis of water penetration complaints for retrofit blown insulation and presented the findings in their report 'Analysis of CWI water penetration complaints 1995 to 2003' (2003). As CIGA deal solely with retrofit cases, the cavities in question varied from 50-70mm. The key driver for the paper was to try to convince the NHBC to re-address its restrictions on cavity insulation. The paper analysed CIGA cases of water penetration in relation to incidence rates, seasonality, geographical location and evolution over time. Areas of interest were the incidence rates – the absolute rate of complaints as a percentage of installations, and geographical location, and any correlation between incidence rates and exposure zones.

The data given for the incidence rates were typically 1 in 140,000 to 1 in 40,000 for any particular year. The sample size was over one million and averaged over eight years. A more accurate failure rate could be achieved with current data, as CIGA have now, issued around two million guarantees (as of 2007). The geographical location data showed complaints as a percentage of the number of guarantees issued in each postcode area. The graphical representation (a map of the UK with a variable sized '#' showing the amount of complaints) (see figure 2.2) of this data is fairly unclear and no 'raw' data were provided to make further sense of the map. In addition to this, the supporting text claimed that complaints are not concentrated in the high exposure zones. The map contradicts this claim, as two out of the four largest '#' are situated in South Wales, an area of very severe exposure. However, it is useful to note that as these data were based on retrofit constructions, the typical cavity width would be 50-60mm, far narrower than the BRE's minimum recommended width of 150mm. On the other hand, many of these houses had external rendering and not exposed facing masonry. Irrespective of these factors, however, it is difficult to agree with the statement in the conclusions section: 'Analysis of complaints by region does not indicate any obvious increase in the background rate of complaints for properties in areas of higher wind driven rain'.

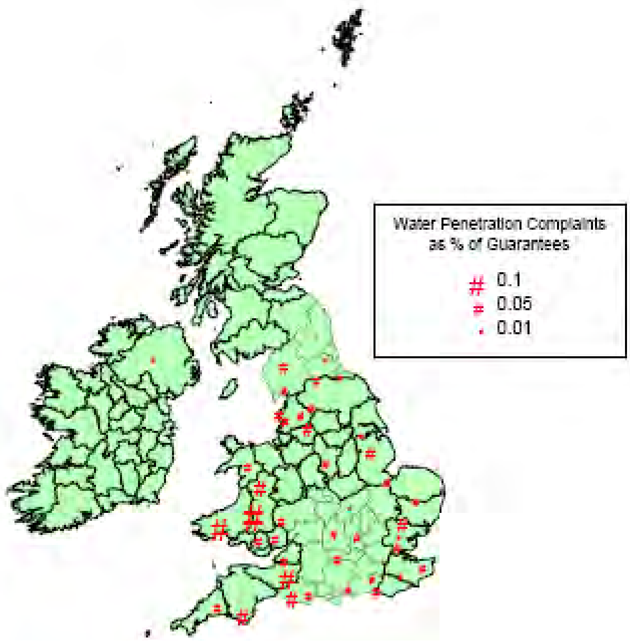


Figure 2.2 – Complaints as a percentage of guarantees in each postcode area (CIGA, 2003).

The map clearly shows that there is a higher incidence of complaints in South Wales and the north west of England. Such sweeping claims by CIGA could act to discredit their research. It must be remembered that they are an organisation with commercial interests. Therefore, there is an opportunity for an independent investigation into incidences of driving rain across different geographical locations. This, however, was attempted during this project, but such information lies with the house insurers (such as the NHBC and Zurich) and they are very reluctant to give out such information.

The BRE has produced several reports on the incidence of water penetration problems in homes. As the BRE is seen as an independent third party with little commercial interest in the subject, the documents proved a useful source of information. The previously mentioned Leaflet 23 (1995), was brought out in 1995 (shortly after CIGA was set up). Starting with a sample size of 13290, it examined the difference in water penetration complaints between filled and unfilled cavities. It found that less than three houses per thousand (0.26%) with cavity filled walls suffered problems attributed to rain penetration. A similar failure rate of 0.22% was quoted for non-filled walls. These data suggest that the risk of rain penetration from fully filled cavity walls is negligible. It is hard to compare these figures with CIGA's data, as the BRE do not quote a time period in which these failures occurred. CIGA give a value of 0.01% 'failure rate per year'. There is, however, a problem with this data. The failure rate was calculated by taking the total number of failures reported and rectified during CIGA's first eight years of operation, and dividing by the total number of guarantees issued. The value obtained is then divided by 8 (years) to give an annual 'failure rate'. Once a house has had remedial work undertaken to rectify the problem, the problem is unlikely to reappear. Also, it would be expected that a house would suffer water penetration problems every year until the construction was rectified.

As these data were cumulatively compiled over an eight year period, one would expect failures for existing housing in the next eight period to be solely due to a change in weather conditions. However, new guarantees are being granted continuously, so this statement cannot hold true.

From this discussion, it seems that the problem is far from straightforward and requires further work to get to the bottom of the statistical evidence.

The Rainscreen Principle and Junctions

The Canadian Mortgage and Housing Corporation's publication '*Building Technology – Wood Frame Envelopes'* (1999), describes a method of resisting rain penetration in a cavity wall known as the Rainscreen Principle. A Rainscreen consists of a leaky outer leaf that deflects the bulk of the incident water and a cavity that allows water that passes through the outer leaf to drain out. The key feature of such a construction is that the differential pressures across the outer leaf are equalised. This construction is shown in figure 2.3.

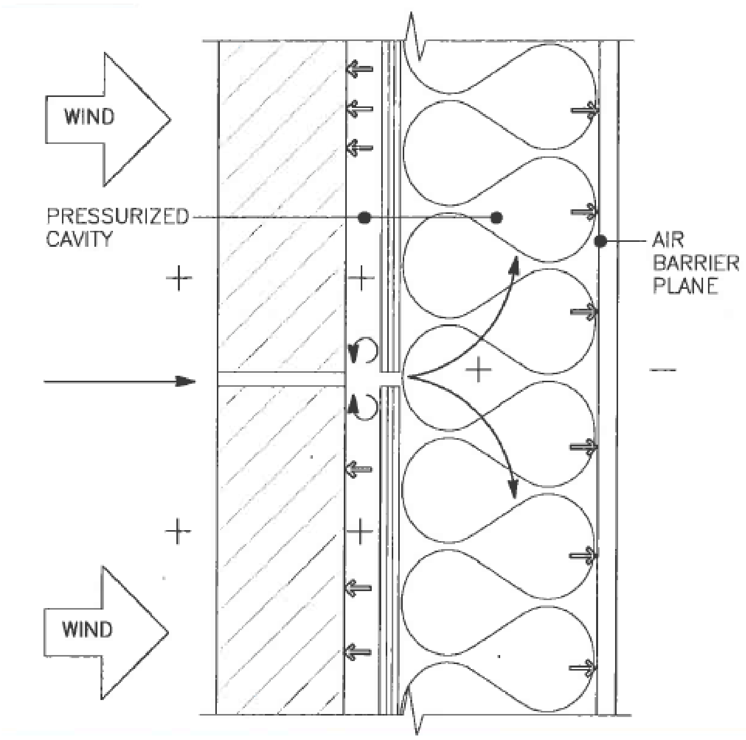


Figure 2.3, The Rainscreen principle, Canadian Mortgage and Housing Corporation, 1999

When wind blows on a normal cavity wall, a pressure difference is created across the outer leaf. This is one of the main mechanisms for water penetration. In figure 2.4, the cavity is vented from the outside, so when the wind blows on the outer leaf, the pressure in the cavity increases until it reaches the exterior pressure. As the pressure difference across the outer leaf nears zero, one of main forces of rain penetration is reduced. This concept, however, requires the inner leaf to be practically airtight. This may be possible in the near future, as UK building regulations are now introducing factors for airtightness in their criteria for approval (Building Regulations, DCLG, 2006b).

The Canadian paper then goes on to suggest a system to achieve the Rainscreen principle. Fluid flow through a normal cavity (Building A) can cause dampness problems, so if the flow through the cavity can be prevented (Building B), this problem may be eliminated. To prevent fluid flow, the cavity sections are compartmented by airtight barriers. The Δp across each cavity section of Building B is therefore zero.

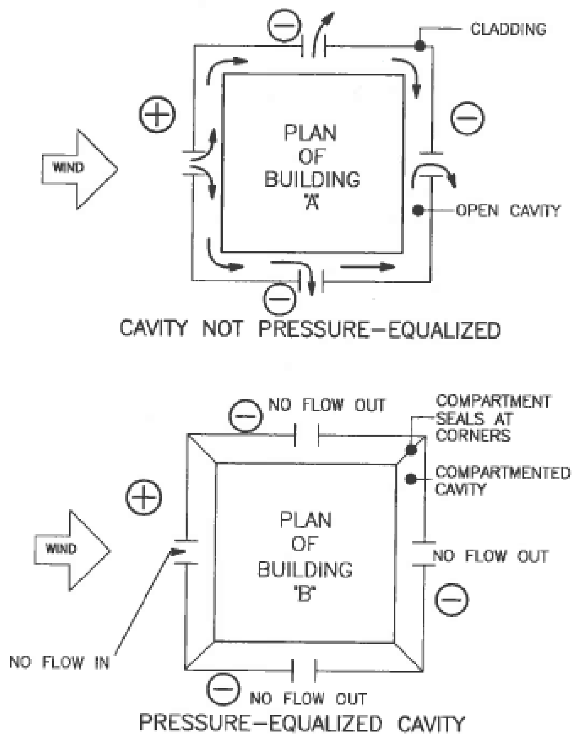


Figure 2.4, Compartmenting a cavity, Canadian Mortgage and Housing Corporation, 1999

As compartmenting a cavity is virtually unheard of in the UK, this seemed an interesting avenue to explore, and it formed the basis of a section of the practical testing and theoretical work that is detailed in the following chapters.

Methodology

Introduction to methodology

The main objectives of this project were firstly, to explore the factors that affect driving rain performance of masonry walls and secondly to engage with key industry decision makers with a view to relax the restrictions placed on cavity insulation in severely exposed areas of the UK. The research called for a considerable amount of reflection on current systems of testing and ideas about the problems surrounding wind driven rain and housing. This kind of reflection, subsequent challenge and the mechanism of change of existing ideas is akin to the Action Research Approach (Greenwood et al, 1993) . This complex project possessed several strands: an influencing strand, an analytical strand and a empirical strand. However it was important that all strands would be complementry and the combination of activities would lead the project to a successful conclusion.

Formation of a Project Liaison Committee

It became apparent from the start of this project that the key decision makers (the insurers and other regulartory bodies) needed to be involved in the project's decision making process. Using industry contacts, a liaison committee was brought together consisting of:

- Head of Standards of the **National House Building Council (NHBC).** The NHBC are the biggest house insurer in the United Kingdom. It was therefore imperative to secure their involvement. The restrictions that the NHBC impose are more stringent than any other comparable body.
- Technical Manager at **Zurich Building Guarantee**. Zurich are second to the NHBC in terms of their size in the house insurance sector. Their

restrictions are based on the BRE's recommended restrictions (table 2.2).

- Technical Director of the **Building Research Establishment (BRE).** The BRE is considered to be a primary source of technical expertise in the construction industry. It also publishes a document containing recommended restrictions placed on cavity insulation (table 2.2).
- Project Manager at the **Britsh Board of Agrément (BBA).** The BBA offer certificates for construction products. The products that successfully obtain certificates have to pass certain tests that are devised and conducted by the BBA. As a condition of insurance cover, the NHBC and Zurich require BBA certificates for cavity wall batt. One of these tests for cavity wall insulant is a water penetration test. This uses a test rig known as the driving rain test rig.
- A representative from the Standards and Qualifications section of the **Construction Industry Training Board (CITB).** Workmanship and good site practice are key issues within this project, as the quality of a cavity wall greatly determines its water resistance properties. The CITB were involved because they are involved in training and qualifications within the construction industry.

The Project Liaison Committee, which involved key decision makers, was used as a steering group for the programme of experimental testing. The results of the experiments would allow sound decisions to be made on the suitability of cavity insulation in very severe exposure zones. This 'feeding back' of results to the committee formed the basis of the disucssions in the meetings.

The experimental work had two components – theoretical and practical. The theoretical component consisted of an analytical computer model of fluid flow at wall junctions. This area of construction was known to be a source of dampness problems (see the Literature Review section). The computer model was able to simulate a wide range of constructions and environmental conditions through a small number of variable parameters.

The practical work involved the use of a driving rain test rig, identical to the one used by the BBA. This enabled the following to be researched:

- the effect of varying cavity widths on water penetration across the wall system;
- the impact of a variety of different pressure regimes across the outer leaf of a cavity wall system.

As mentioned before, this project was funded by the Government's 'Knowledge Transfer Partnerships' scheme. There was a finite amount of resources – namely time and funding that were available. Therefore, cavity wall systems with details– for example, window reveals – were beyond the scope of this investigation. Also, as the failure rate of a cavity wall is somewhere in the region of 1 in 400 - 70,000 per year, it would have been extremely costly and time consuming to conduct a similar number of tests. Although the relatively small number of tests that were undertaken were unlikely to prove conclusive, there was a need to explore the problem empirically, at a level of detail that could not be achieved in the field. In addition to this, they provided a focus for the attention of the liaison committee, so as to reveal where the problems, risks and obstructions really lay. A discussion of the statistics of this testing and also details of real life claims information with a large sample size, is covered in the Results and Discussion section.

This section will deal with the cavity thickness experiments, then the pressure experiments and finally the quantitative analysis of fluid flow at wall junctions.

Cavity thickness experiments

Introduction to cavity thickness experiments

The method of testing the extent of water ingress in cavity walls was taken from the BBA's test method for measuring the water resistance of a cavity wall after installing insulation. Rockwool possessed a test rig that had been accredited by the BBA in the past. However, as the rig was at least 20 years old, it had to be overhauled before the test programme was conducted. This considerable undertaking involved fixing the plumbing system, rebuilding the wall leaves and modifying the rig to cope with wider cavities, all of which is discussed further on in this section.

Through the initial meetings involving the liaison committee, it was clear that the members wanted some data on water penetration as a function of cavity width. Further meetings highlighted the need for data on fully filled versus empty cavities, especially around the 100mm cavity width, as it was the most common width of cavity used to satisfy Part L (DCLG, 2006b) over the duration of the project.

The standard BBA test was run over a 15-day test period, with 3 x 5 day stages of increasing severity. After consulting the committee, it was agreed that the most efficient use of time would be to run a 'super severe' test of 24 hours continuous duration with the rig on the highest 'setting'.

The following types of cavity wall were tested:

- Fully filled 150mm, at zero & 500 Pa pressure differential.
- Fully filled 100mm, at zero & 500 Pa pressure differential.
- Empty 100mm, at zero & 500 Pa pressure differential.
- Fully filled 50mm, at zero & 500 Pa pressure differential.

Each test could have two outcomes – either damp penetrated to ‘inner leaf’ or the inner leaf remained completely dry (fail or pass). The size of the damp area would also give an indication of the extent of the water ingress, although this was not quantitatively measured.

Apparatus

The test apparatus shown in figure 3.0 consists of two sets of cavity walls with a brickwork outer leaf (inside the rig) and blockwork inner leaf (outside the rig). The dimensions of the walls are 3 metres by 3 metres. A sparge pipe, providing water spray, is positioned 150mm from the top of the outer leaf. The existing test rig at Rockwool was capable of supporting cavities of up to 100mm. Major modifications were required to allow 150mm cavities to be tested (see ‘Modifications to test rig’). The internal chamber is pressurised by an air blower situated on the top of the rig (see below) that can pressurise the chamber up to 500 Pa above laboratory pressure

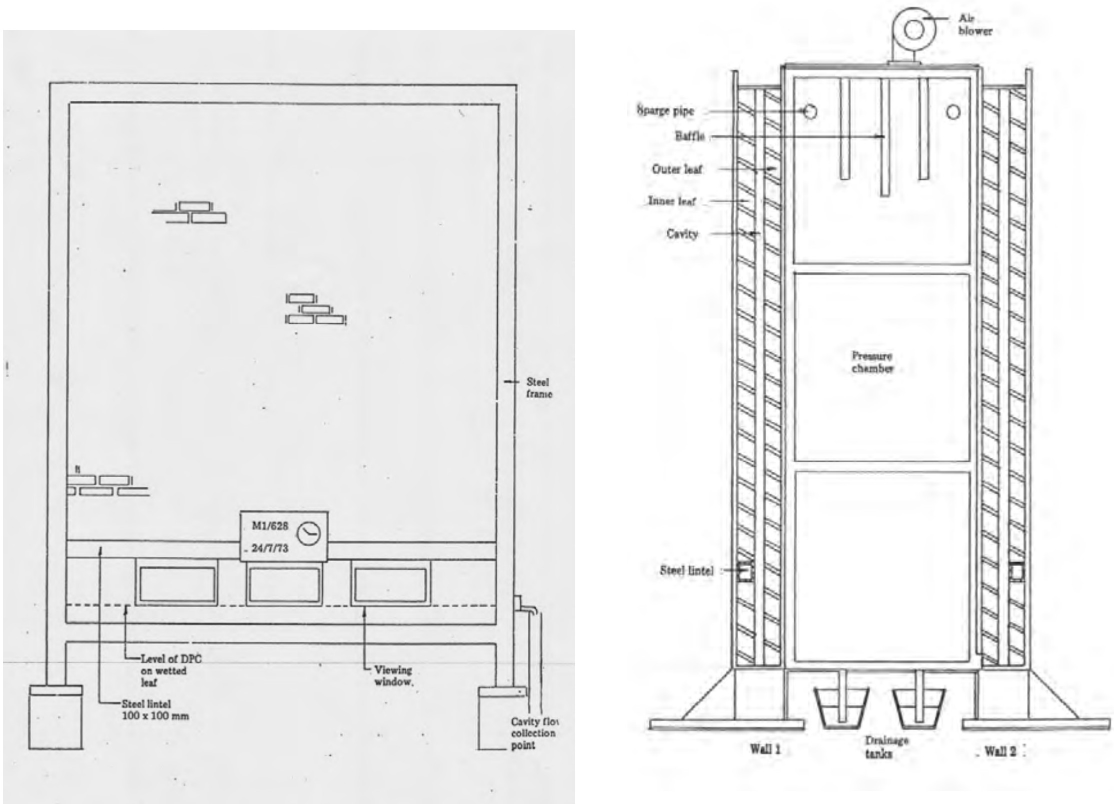


Figure 3.0, Diagram of the BBA test rig apparatus (BBA, 2001)

Materials

The ‘outer’ leaf was constructed of Fletton bricks laid frog upwards in 1:6 (cement: sand) + plasticiser mortar mix.

The ‘inner’ leaf used Aircrete blocks of density 650 kgm^{-3}. A 1:6 (cement: sand) + plasticiser mortar mix was used.

The finished blockwork was whitewashed to allow the easy identification of damp spots.

Wall ties – The BBA stipulate ‘whatever is typically used on site’. For the 100mm test – a type 4 staifix tie was used. For the 150mm, large vertical twist ties were used. See ‘Construction of the wall systems’ for further information.

The sparge pipe spanned the full width of the wall. The pipe featured holes of 1.0mm diameter at 100mm spacings. This enabled a spray rate of 0.4 – 10.0 litres min^{-1} to be achieved.

The amount of water that drains from the cavity was measured via the cavity flow collection point (figure 3.0). The amount (in litres) of water drained from the cavity per minute is known as the cavity flow rate.

The construction of the test walls is detailed further on in this chapter.

Test Procedure

The test rig initially had to be calibrated. This involved turning the water pump on overnight to wet the walls. The pressure was then set to 500 Pa. The spray rate through the sparge pipes was then adjusted until there was a cavity flow rate of 1.4 ± 0.1 litres min^{-1}. The measure of the cavity flow rate must be carried out after at least 10 minutes from starting the rig to ensure stabilisation. The cavity flow rate must remain within the given rate for at least half an hour.

The test duration was 24 hours at the calibrated spray rate and at a pressure of 500 Pa.

The following factors were observed:

- start time;
- pressure every two hours;
- appearance of dampness.

Photographs of the whitewashed ‘inner’ leaf walls were taken at the start of the day and at least 1-hour intervals thereafter.

BBA driving rain test rig

This is the accredited test rig at the BBA site in Garston. There are several minor differences between this and the rig at the Rockwool site in South Wales.

The BBA’s rig has a continuous metal gutter along the bottom of its structure (see below).

At Rockwool, the rig had discontinuous plastic guttering to catch any water leaking from the ‘inner’ leaf.

The BBA’s rig has Perspex windows at the bottom of the structure in which blown fill is extracted (see below left). At Rockwool, the section below that supporting beam was covered with steel sheet (below right).

One other difference is where the BBA's rig features side panels that allow access to the cavity for the extraction of fill (below left). As these panels are only used for the extraction of blown insulants, it was decided to weld the panels up (below right).

At the time of writing (May 2007), the BBA plan to build a new rig, which will be structurally identical to the existing rig, although it will be fully automated and set up for self-calibration.

The current BBA rig can accommodate larger cavities widths than Rockwool's rig, as originally built. The increased thermal performance demands of the 2006 Part L Building Regulations (DCLG, 2006b) mean that cavities widths will tend to be larger. For this reason, it was decided to modify Rockwool's driving rain rig.

Modifications to test rig

The existing driving rain equipment could only take cavity widths up to a maximum of 100mm. A 150mm cavity would have meant an unacceptable blockwork overhang (see below).

The reason why the rig had to be extended is further illustrated below, where the insulation batt sits far into the original joist that supports the block work.

In order to test wider cavities the test rig had to be modified. A structural engineer was asked to produce drawings that detailed the extension to the existing I-beam (see figure 3.1)

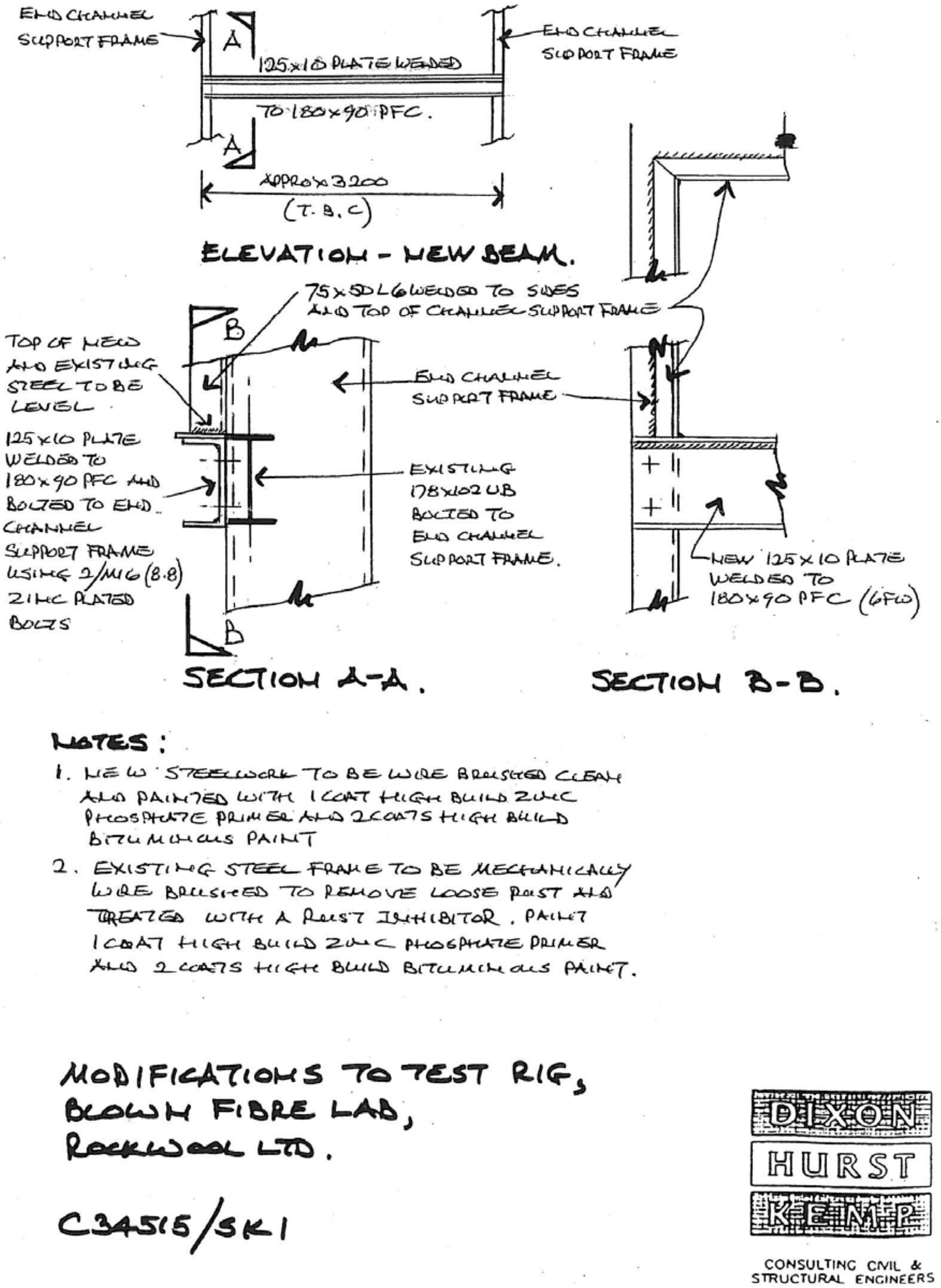


Figure 3.1, Proposal for the extension of the test rig

The pictures below show the modifications at different stages of construction.




The picture below shows the extension of the frame that encloses the block work. The join was then sealed with bitumen to prevent leaks.

The picture below on the left shows the cavity drain channel. The drain channel's purpose was to collect all the water that drains from the cavity and channel it into the sink where the flow rate was measured (see below right).

Construction of the wall systems

Originally when the walls were first constructed, the blockwork mortar mixture consisted of 1:6 (lime: sand) mix, as in the BBA's test specification. However, when the blockwork was first constructed with this mixture, the walls failed to cure (see below) even when industrial heaters and dehumidifiers were brought into the test rig room. With a test pressure of 500 Pa (equivalent to 5000 N over the 10 m^2 test piece), failure to cure led to a risk of catastrophic failure of the wall and of injury to anybody in the test room.

Therefore, the blockwork was removed and rebuilt using a 1:6 (cement: sand) + plasticiser mortar mix to ensure the blockwork cured and was safe to work around.

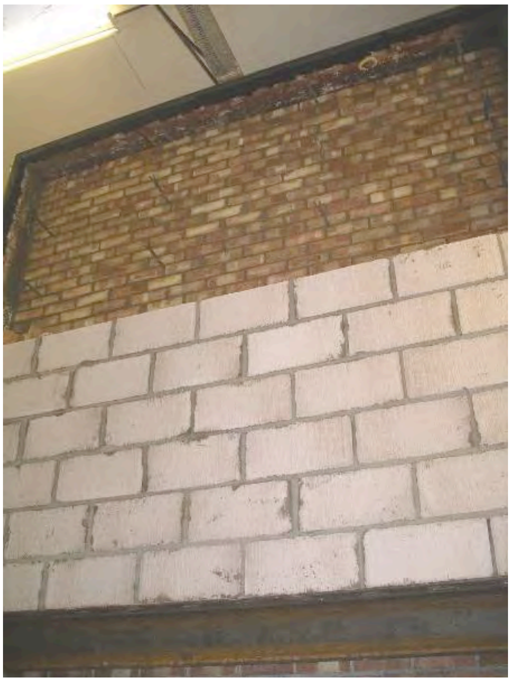
When the rig was first inspected, the 'outer' leaf was considered useable. However, during preliminary testing it seemed impossible to obtain the desired cavity flow rate of 1.4 litres min^{-1}.

After speaking with the BBA, it was discovered that minerals in the tap water gradually block up the pores in the brickwork that allow water through. Therefore, the 'outer' leaf was rebuilt, and was considered good by the BBA for at least five or six tests, depending on whether 'hard' or 'soft' water is used.

100mm and 150mm fully filled and the brick leaves

The construction of the brick and block walls was a critical factor in obtaining some worthwhile results for this test. It was necessary to supervise the bricklayer during wall construction. However, careful attention was made not to 'micro-manage' the bricklayer and supervision was as unobtrusive as possible. This was done for two reasons: 1) to ensure the complete co-operation of the bricklayer 2) in leaving the bricklayer to his own devices the standard of workmanship was realistic and could be replicated on site.

However, several designed 'faults' were built into the bottom halves of each wall system, including intentional gaps in insulation batts, intentional mortar snots and intentional empty perpends. The precise location of all these faults was recorded during wall construction (see figure 3.2).



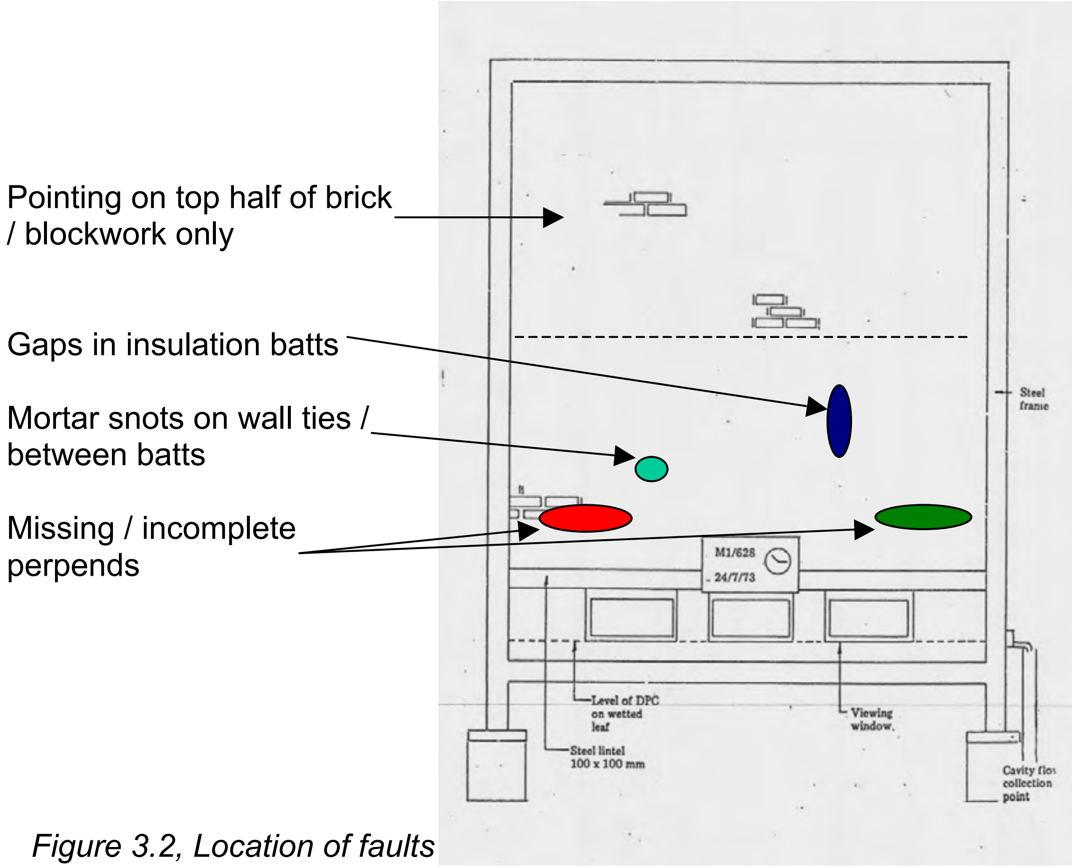


Figure 3.2, Location of faults

The mortar snots replicated typical mortar droppings on ties and on horizontal layers of batts:

Gaps between insulation batts:

Missing perpends:

However, in many instances, the next layer of mortar often filled the missing perpend situated below:

Several bricks on the lower halves of the walls were purposely ‘tip jointed’ (below left) rather than solid filled (below right). The bricklayer commented that the faster method of tip jointing was a very common site practice.

The bottom halves of the walls featured rows of five wall ties. The top halves of the walls featured rows of four:

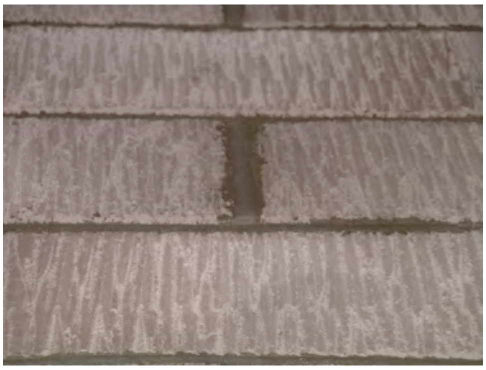
The 100mm cavity featured a type 4 tie (below left). The 150mm cavity featured vertical twist type ties (below right):

The BBA use butterfly type ties (right). However, these are less commonly used on site now, and so the BBA declare that it is satisfactory to use any tie that is commonly used on site.

The ties were situated between the insulation batts:

The brickwork was built ahead of the block work, in accordance with Rockwool's recommendations:

Both halves of the brick work were pointed. Only the top half of the blockwork was pointed (see below):



The edges of the brickwork were pointed to the test rig metal frame.   The old viewing panels were also sealed and welded over so that the interior of the rig frame was flush (see below):

Fitting the insulation: the batts were cut to ensure a snug fit:

The results from the fully filled 150mm and 100mm prompted an investigation into several other cavity widths:

- 50mm fully filled (at zero pressure and 500Pa); and
- 100mm with an empty cavity (at zero pressure and 500Pa).

At the time of writing (2006/7), newly-built cavities of 50mm are rare, but it was still considered useful to obtain control experimental data from this cavity width, as there is a large proportion of older housing stock with 50mm cavities. A number of these older houses have the potential for retro-fit cavity insulation and there is a substantial amount of data already on this thickness of construction. Therefore, if the same failure rate is obtained with 100mm in a very severe category as occurs with 50mm in a moderate one, then the risks are comparable (see table 2.2). Consequently, it could be argued that as 50mm is allowed in moderate regions, then 100mm should be allowed in very severely exposed areas.

100mm empty and 50mm fully filled

For these two constructions, the 'inner leaf' block work was dismantled and re-built with the same faults in the same positions. As the outer brickwork leaf remained in place, the existing wall ties were ground off and retro-fit wall ties were fitted (see below).

The same faults as the previous 150mm and 100mm were built in to these walls. With the empty 100mm cavity, the only faults that could be built in were the mortar snots on the wall ties (see below), as all other faults required batts to be used. See figure 3.2 for the position of these faults.

A preliminary inspection of the 50mm side revealed that there was insufficient support area from the central I-beam (see below left). This was because the brickwork was built slightly too far into the chamber. Therefore, a metal strip was welded (below right) to provide support for the blockwork.

The figures below show the 50mm fully filled faults:

Product quality tests

Each batch of Rockwool Cavity insulation was tested for its oil content, ignition loss and water absorption. The oil content and ignition loss relate to the water repellent properties of the insulation, so it was crucial that these are on specification. The water absorption properties of the material also affected how well the cavity wall resisted water penetration. All insulation was required to meet the minimum standards in these areas. The Environmental and Quality Assurance department at Rockwool undertook these tests.

Equalising pressure with a Perspex box

This experiment was intended provide a visual demonstration to the liaison committee of what happens to the flow of water when the pressure difference *Δp* across the outer leaf of a cavity wall is zero.

To model the effect of a zero *Δp*, an airtight Perspex box was constructed to fit on the 'inner' side of the 'outer' leaf of the test rig wall (see figure 3.3 and 3.4 below).

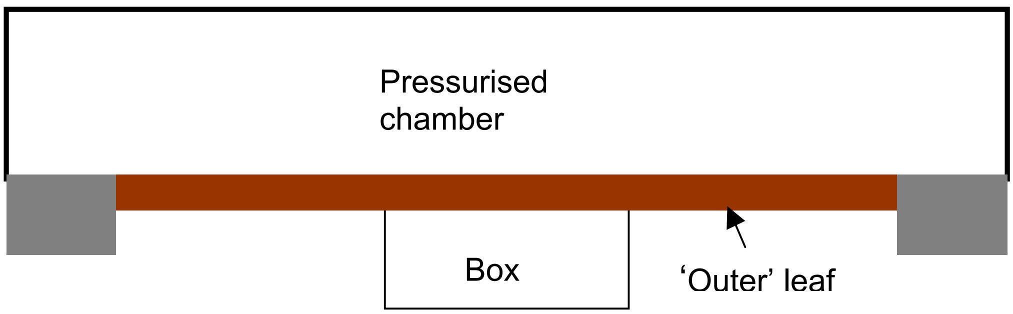


Figure 3.3, Plan view of test rig (only one wall shown).

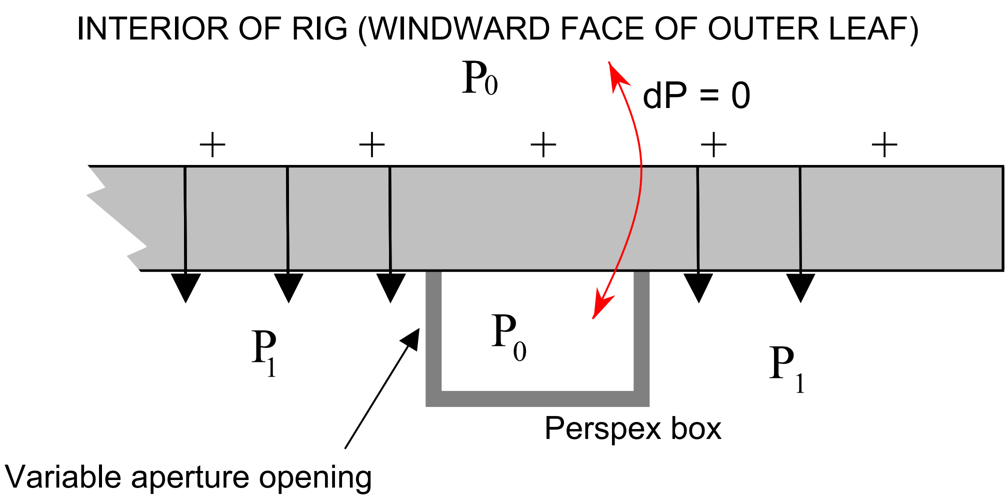


Figure 3.4, Diagram of the pressure across the outer leaf

A picture of the box attached to the test rig is shown below.

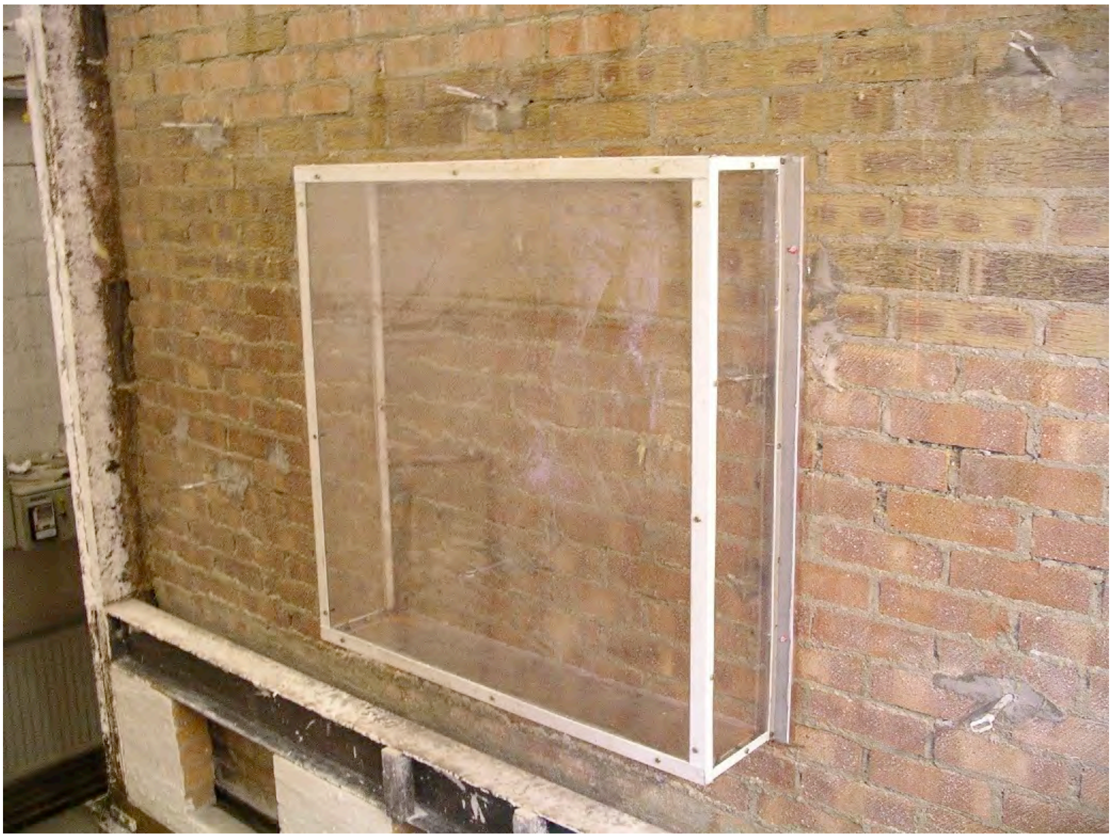


Figure 3.5, Perspex box attached to brickwork

Any water that collects on the bottom of the box was drained away via a plastic tube. The tube was blocked during the experiment to ensure the box was as airtight as possible. A further hole was drilled in the side of the box and also through the brickwork. These allowed access for two manometer probes. The fan that pressurises the chamber was run at its maximum setting. This enabled a more pronounced result to be recorded. The maximum differential in pressure was expected to be 600 Pa, or 6 mBar. Therefore, the most suitable manometer to use was a Digitron P200UL (see appendix 2 for certificate of calibration).

The *Δp* was varied by means of a large orifice in the centre of the box. The orifice had a diameter of 0.1m. This hole could be sealed fully or partly by insulation tape to form an airtight seal. The effect of having wet and dry brickwork was also investigated, by wetting the walls via the spurge pipes in the rig or running the experiment with dry walls. Please note that neither the orifice nor the pipes are shown in figure 3.5. The following water and pressure combinations were tested:

- hole in box closed, water off;
- hole in box open, water off;
- hole in box closed, water on;
- hole in box open, water on.

The results of these experiments will be described in the Results & Discussion section.

Analytical model

Through previous research and discussions with the insurers, it became apparent that the areas of construction particularly prone to dampness problems are at junctions and window reveals. It was therefore decided to undertake some theoretical work to investigate the fluid flow around these areas, with a view to complementing the practical work using the driving rain test rig.

Figure 3.6 shows the ‘front end’ of fluid flow model. As can be seen, the corner of a cavity wall or ‘junction’ is the subject of the analysis. The effect of varying the standard of workmanship (and therefore the airtightness) of the inner and outer leaves was investigated for the following reasons:

- It was hypothesised that varying the airtightness of the inner or outer leaves would have a substantial effect on the water penetration properties of the wall.
- Also, building regulations are increasingly pushing for housebuilders to demonstrate good levels of airtightness with a construction. If it was confirmed that airtightness was a major factor, it would be reasonable to assume that future housing under more stringent regulations would be less prone to water penetration problems.

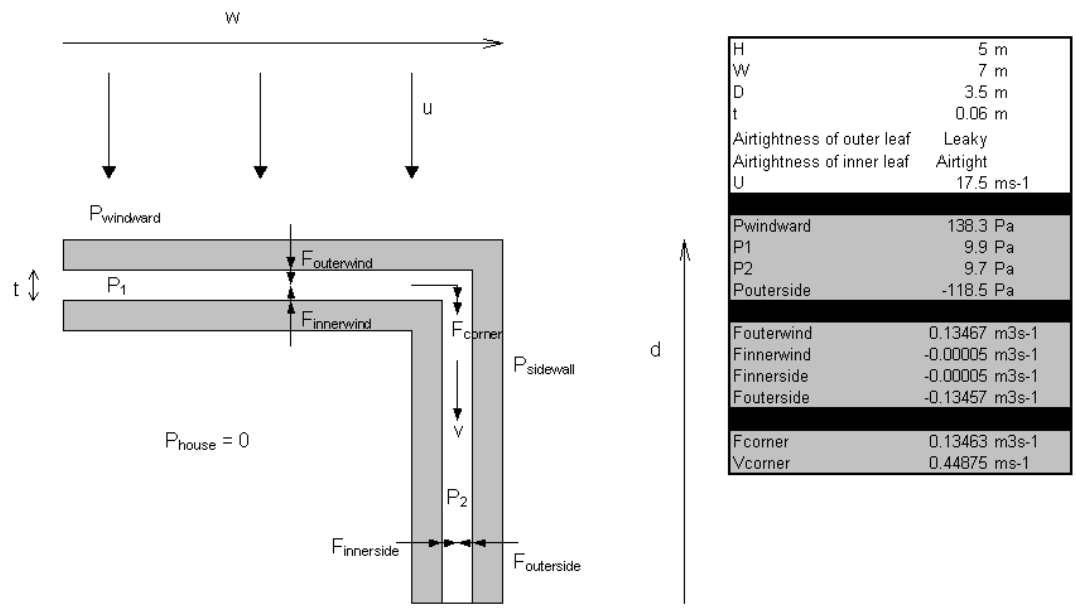


Figure 3.6, The front end of the analytical model

The following parameters are used in this model:

h – height of building (m).
w – width of windward face of building (m).
d – depth of building (m).
t – cavity width (m).
u – incident wind speed (ms^{-1}).
v – air speed in cavity (ms^{-1}).
C_p – surface pressure coefficient (no units).
$p_{windward}$ – pressure on windward wall (Pa).
$p_{sidewall}$ – pressure on side wall (Pa).
p_1 – pressure in wall cavity on the windward wall (Pa).
p_2 – pressure in wall cavity on the side wall (Pa).
p_{house} – The pressure inside the house (assumed to be zero).
Δp_{corner} – pressure drop across the junction (Pa).
$F_{outerwind}$ – air flow through outer leaf of windward wall (m^3s^{-1}).
$F_{innerwind}$ – air flow through inner leaf of windward wall (m^3s^{-1}).
$F_{outerside}$ – air flow through outer leaf of side wall (m^3s^{-1}).
$F_{innerside}$ – air flow through inner leaf of side wall (m^3s^{-1}).

The following convention was used: fluid that flowed into the cavity was a positive value. Fluid that flowed out of the cavity was a negative value.

To work out the instantaneous air pressure due to the incident wind speed on the different sides of the building, the following equation was used:

$$p = C_p \frac{\rho}{2} u^2$$

Where C_p is the surface pressure coefficient. In this model, the pressure across each face of the building is assumed to be constant. This is a rough approximation, as in real life, the pressure across a windward wall varies. For a typical simple house, C_p on the windward side is 0.7, and on the sideward surface it is –0.6. These values are taken from BS 5625 (1991).

The central equations in this model are taken from Lecompte's paper, 'Airtightness of masonry walls' (1987), linking the airflow through a wall q, the pressure difference across a wall Δp, and the density of the fluid flowing through the wall ρ.

$$q = a\Delta p^b$$

a and b are coefficients that vary considerably with workmanship, pointing, plastering and type of bricks and blocks used. Therefore these could be varied to simulate an airtight or leaky leaf.

There are four leaves in the model (figure 3.6), therefore there are four instances of Lecompte's general equation. Each one will use appropriate values of a and b:

$$F_{outerwind} = a_{outer}(p_{windward} - p_1)^{b_{outer}} \tag{3.1}$$

$$F_{innerwind} = a_{inner}(p_1)^{b_{inner}} \tag{3.2}$$

$$F_{innerside} = a_{inner}(p_2)^{b_{inner}} \quad (3.3)$$

$$F_{outerside} = a_{outer}(p_2 - p_{outerside})^{b_{outer}} \quad (3.4)$$

The junction of the cavity wall can be modelled as a duct with a 90-degree bend. The following equation describes the pressure drop across the bend:

$$\Delta p = k\rho v^2$$

For an abrupt bend, k=1.25. (CIBSE Handbook, 2003)

If F_{corner} is expressed as:

$$F_{corner} = vtH$$

the two can be combined as:

$$\Delta p_{corner} = k\rho\left(\frac{F_{corner}}{tH}\right)^2$$

as

$$F_{corner} = F_{outerwind} + F_{innerwind}$$

$$\Delta p_{corner} = k\rho\left(\frac{F_{outerwind} + F_{innerwind}}{tH}\right)^2 \quad (3.5)$$

Alternatively F_{corner} can be expressed as:

$$F_{corner} = tH\sqrt{\left(\frac{\Delta p_{corner}}{k\rho}\right)} \qquad (3.6)$$

The model centred around the concept of iteratively varying the p_1 across the junction to give zero for the addition of flows. The law of the conservation of mass in a system was approximated to the conservation of flows in this model, therefore all the sum of all flows must equal zero.

The sum of the flows was entitled *error term2* and was expressed equation in equation 3.7:

$$-F_{outerwind} - F_{innerwind} - F_{innerside} = F_{outerside}$$

$$\Rightarrow -\left(F_{outerside} + F_{outerwind} + F_{innerwind} + F_{innerside}\right) = 0 \qquad (3.7)$$

An equation for p_1, p_2 and Δp_{corner} could be constructed to also equal zero. This was called *error term1* and was expressed as:

$$\Delta p_{corner} = p_1 - p_2$$

$$0 = -p_1 + p_2 + \Delta p_{corner} \qquad (3.8)$$

The spreadsheet was then programmed to vary p_1 to satisfy equation 3.7. This had to be done iteratively, via a macro. The particular macro was called 'solver'. This is shown in figure 3.7.

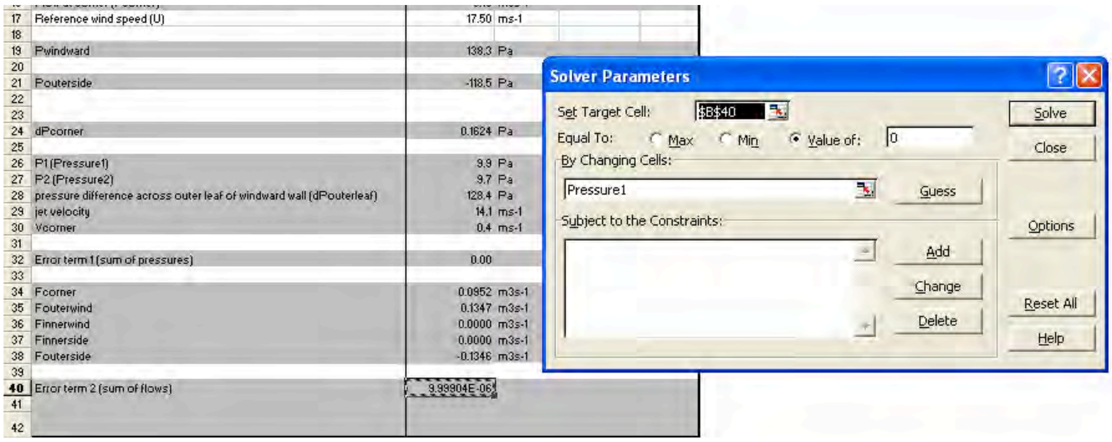


Figure 3.7, The 'solver' macro

Figure 3.7 shows that the macro set cell B40 (error term2) to zero, by changing *pressure1*, or p_1.

See Appendix 1 for the code used for this macro.

Changing p_1 therefore indirectly affected $p_{windward}$, $p_{sidewall}$, p_2, Δp_{corner}, $F_{outerwind}$, $F_{innerwind}$, $F_{outerside}$, $F_{innerside}$. This allowed a solution to be computed that satisfied both equation 3.7 and 3.8. This is shown in figure 3.8.

Corner pressure loss coefficient (kcorner)	1.25	Pa s4 kg-1		
CPWindward	0.7			
CPSidewind	-0.6			
Density (ro)	1.29	kgm-3		
Height of 'building' (H)	5	m		
Width of building (W)	7	m		
Depth of building (D)	3.5	m		
Width of cavity (t)	0.06	m		
Lecompte's a for outer leaf	2.7E-04			
Lecompte's b outer leaf	0.69			
Lecompte's a for inner leaf	2.9E-07			
Lecompte's b inner leaf	0.96			
Discharge coefficient for a flat plate orifice (disco)	0.61			
Reference wind speed (U)	17.50	ms-1		
Pwindward	138.3	Pa		
Pouterside	-118.5	Pa		
dPcorner	0.1624	Pa		
P1 (Pressure1)	9.9	Pa		
P2 (Pressure2)	9.7	Pa		
pressure difference across outer leaf of windward wall (dPouterleaf)	128.4	Pa		
jet velocity	14.1	ms-1		
Vcorner	0.4	ms-1		
Error term 1 (sum of pressures)	0.00			
Fcorner	0.0952	m3s-1	dPcorner	0.1624
Fouterwind	0.1347	m3s-1	Pwindward-P1	128.3838
Finnerwind	0.0000	m3s-1	P1-Phouse	9.888085
Finnerside	0.0000	m3s-1	P2-Phouse	9.725725
Fouterside	-0.1346	m3s-1	Psidewall-P2	-128.2445
Error term 2 (sum of flows)	9.99904E-06			

Figure 3.8, Spreadsheet for the analytical model.

V_{corner} is the velocity of the air around the corner of the junction. It is possible that rapid air flow around the corner might lead to water being transported across the cavity. Further empirical work would be needed to find out what speeds are problematic. This could then be used to determine if the cavity should be compartmented as suggested in the Canadian Mortgage and Housing Corporation's publication '*Building Technology – Wood Frame Envelopes'* (1999) (see literature review for further details).

It was also useful at this stage to gain an idea of the extent at which water might 'jet' through the outer leaf and into the cavity, for example, through the many random small cracks and gaps that occur at construction joints in the outer leaf of brickwork. Were this phenomenon to occur in conjunction with a gap in the layer of insulation, the water jet could directly hit the inner leaf and cause dampness problems. Consider an orifice in a plate of thickness *dx* and area *A*. The orifice is 'plugged' by fluid of mass *dm*. As there is a pressure differential across the plate, the fluid 'plug' will initially move with a jet velocity *v*.

The kinetic energy of the plug can be expressed as:

$$\Delta p dx A = \frac{1}{2} dm v^2$$

$$\Delta p dV = \frac{1}{2} dm v^2$$

as:

$$dm = \rho dV$$

$$\Delta p = \frac{1}{2} \rho v^2$$

therefore:

$$v = \sqrt{\left(\frac{2\Delta p}{\rho}\right)} \qquad (3.9)$$

Equation 3.9 can then be compared to the standard orifice equation:

$$Q = C_d A \sqrt{\left(\frac{2\Delta p}{\rho}\right)} \qquad (3.10)$$

Where *Q* is the flow rate (m^3s^{-1}), C_d is the coefficient for a flat plate orifice. To obtain the velocity of a fluid 'plug' that is ejected from the orifice, equation 3.10 was divided though by *A:*

$$v = C_d \sqrt{\left(\frac{2\Delta p}{\rho}\right)} \tag{3.11}$$

For a flat plate orifice, C_d=0.61. This coefficient takes into account the geometry of the orifice and is empirically determined.

Once the model was constructed, the analysis of different wall types was carried out. The outer (brick) and inner (block) leaves were modelled with good and bad standards of workmanship and the various parameters were recorded: the flow through the inner leaves, the flow at the corner and the velocity at the corner. This provided an indication of how different standards of construction resisted fluid, and therefore water penetration. The results of this analysis is presented and discussed in the Results & Discussion section.

Results & Discussion

Introduction to Results & Discussion

This section will detail the results from the practical and theoretical experiments that were conducted. The testing programme was designed around the steering meetings with the liaison committee. These provided an opportunity for the committee to review the programme of work and to provide feedback and ideas to ensure the testing remained relevant and worthwhile. The outcome of the committee meetings and the subsequent impact on the programme of testing will also be detailed in this section.

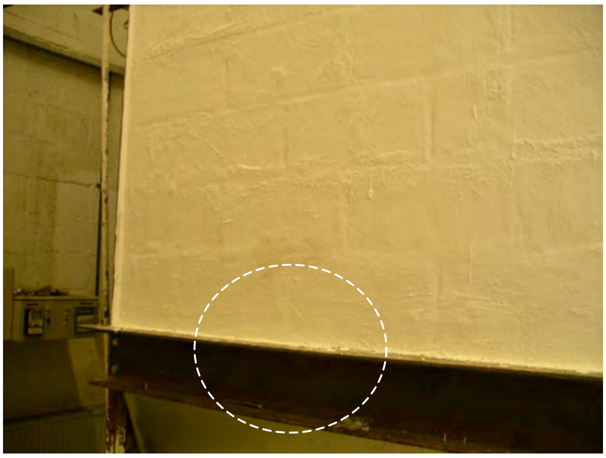
The initial plan was to conduct the 150mm and 100mm fully filled tests at 500Pa. However, after both tests showed signs of dampness, it was decided to run the tests again at a zero pressure differential, as this would provide information on the performance of the walls in 'moderate' conditions. It was also hypothesised that 150mm at zero pressure would not show any dampness areas, given the large width of the cavity and moderate conditions of exposure. It was useful, therefore to test this hypothesis as a 'pass' would provide far more information than repeated failures.

Results of 150mm fully filled at 500Pa and zero pressure differential

As stated in the Methodology, the test was over 24 hours with the test rig on the highest setting. Pictures were taken every hour to record the appearance and spread of damp.

150mm FF at 500Pa:

t=15min



t=25min

t=24hrs

The photographs show the onset of dampness within 15 minutes. This area of dampness grew steadily throughout the test period. Discussions with the BBA revealed that if a product were to fail a test, it would do so in the initial hour or so. As figure 3.2 shows in the methodology section, this area of dampness correspond to missing / incomplete perpends and mortar snots on wall ties / between batts.

150mm FF at zero pressure:

t=24hrs

There were no recorded instances of damp throughout this test.

Results of 100mm fully filled at 500Pa and zero pressure differential

100mm FF at 500 Pa

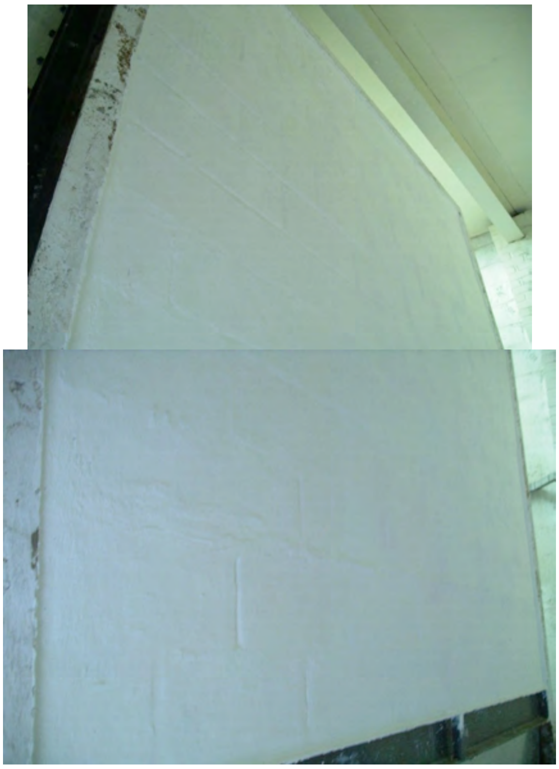
t= 25 minutes

t= 24 hrs

The photographs show the inset of dampness with 25 minutes.   The photograph shows a larger area of dampness than the damp spot on the 150mm fully filled 500Pa test. This would make sense, as the cavity size is narrower, allowing a shorter path for any water that tracks across the cavity. The dampness spots in this test corresponded to missing / incomplete perpends and mortar snots on wall ties / between batts.

100mm FF at zero pressure:

t=0



t=24hrs

The dampness area was around one third of the size of the dampness area at the end of the very severe test. The dampness spots in this test corresponded to missing / incomplete perpends and mortar snots on wall ties / between batts.

Dismantling the 150mm and 100mm fully filled cavity walls

This test provided an opportunity to dissect the walls and find the root cause of the dampness problems.

An important point to note is that when the insulation was removed, the side facing the brickwork was wet. The side facing the block work was dry.

The reason for this is that the 'inside' of the 'inner leaf' was wet. This is perfectly normal, indeed, there has to be a certain amount of cavity 'run off' in order to calibrate the rig.

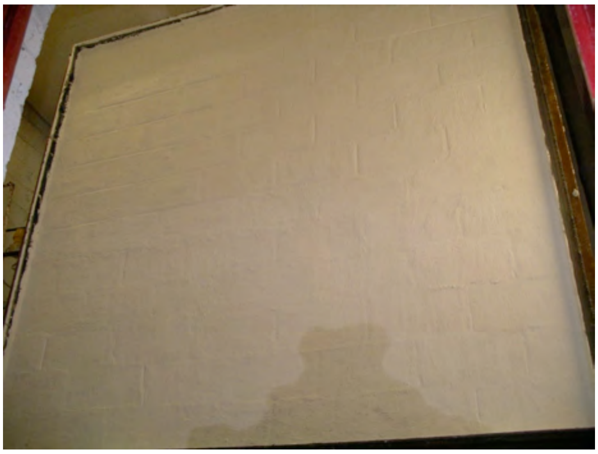
The picture to the right shows remaining mortar snots on the inside of the outer leaf. These were situated towards the bottom left hand corner of the rig (see figure 3.2) and can account for many of the failures.

The picture to the left shows the rig half way through the dismantling process.

Results of 100mm empty at 500Pa and zero pressure differential

100mm empty at 500Pa:

t= 24 hrs



This test produced an interesting result. The area in which the failure occurred was not in an area where faults were deliberately placed. A boroscope was used to investigate the cavity around and above the area of dampness. It was found that mortar snots had fallen down the cavity as the wall system had been built up. These mortar snots had accumulated at a point one course above where the dampness patch was situated. This had bridged the cavity and provided a path for water to track across to the blockwork. The mortar snot that had accumulated here was larger than the intentionally 'built in' mortar snot that had not caused dampness.

100mm empty at zero pressure:

t=24 hrs

This test produced an area of dampness in the same location that the high pressure dampness patch originated from. Again, this can be traced to the accumulation of mortar snots on the wall tie, one course above the dampness.

Results of 50mm fully filled at 500Pa and zero pressure differential

50mm FF at 500Pa

t=3 hrs

t= 24 hrs

This test produced the greatest area of dampness. The damp areas appeared almost immediately and became well established within 3 hours (see photo). There were two main areas of damp, and each correspond to missing / incomplete perpends and mortar snots on wall ties / between batts.

However, small patches of dampness also occurred in the upper half of the rig (see photo below).

t= 24hrs

These failures were situated in an area where the walls were built to a typical standard. When the rig was dismantled, no ‘accidental’ faults around the dampness area were recorded. However, due the inclusion of cement in the mortar mix, sledgehammers had to be used in the dismantling process. This meant that delicate faults could have been missed. On the other hand, it is also possible that the water tracked across simply because the cavity was so narrow and the extreme settings forced water across the wall system. This result is consistent with the BRE’s recommendation that 50mm cavities are not to be used in any but the most sheltered areas.

50mm FF at zero pressure:

t=3 hrs

t=24hrs

This test produced similar results in the bottom half of the rig to the high pressure test. However, the dampness patch was slightly smaller. As in the very severe test, the damp areas also appeared almost immediately and became well established within 3 hours (see photo). There were two main areas of damp, and each corresponded to missing / incomplete perpends and mortar snots on wall ties / between batts.

No dampness was recorded on the upper half of the rig, where typical standards of workmanship were adhered to.

Summary of the empirical testing programme

A summary of the cavity thickness tests are shown below in table 4.0

Table 4.0, Summary of cavity thickness experiments

	50 FF		100 FF		100 Empty		150 FF	
	Moderate	V Severe	Moderate	V Severe	Moderate	V Severe	Moderate	V Severe
Extreme Faults	Fail	Fail	Fail	Fail	Fail	Fail	Pass	Fail
Typical Standard	Pass	Fail	Pass	Pass	Pass	Pass	Pass	Pass

From these test data, is can be shown that walls built to a typical standard passed in all cases apart from 50mm fully filled in very severe conditions. Conversely, all the walls that featured extreme faults exhibited dampness areas apart from the 150mm fully filled in moderate conditions. Clearly, workmanship was an issue, with all walls showing signs of water penetration with extreme faults present. On site, rain, poor storage, a muddy or dirty site, poor overseeing and time pressures can all affect the quality of workmanship. Bricklayers are paid for amount of bricks and blocks that they lay, rather than the insulation batts themselves (J Little, Construct Ireland, 2006). This opens up scope for the extreme faults that cause dampness problems (see figures 4.1 and 4.2). Clearly, a change of culture is needed in order to address these issues.

Figure 4.0 shows the common passages of water through an empty cavity wall.

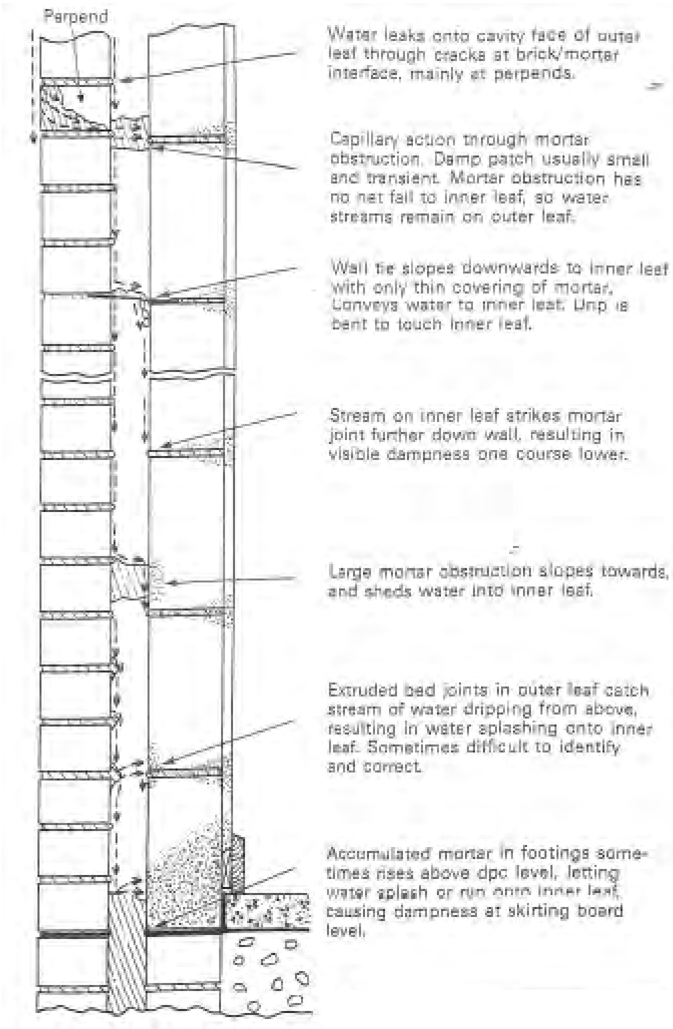


Figure 4.0, Potential routes for water penetration across an unfilled cavity, (BBA, 1983b)

Figure 4.1 shows the common passages of water through a fully filled cavity wall.

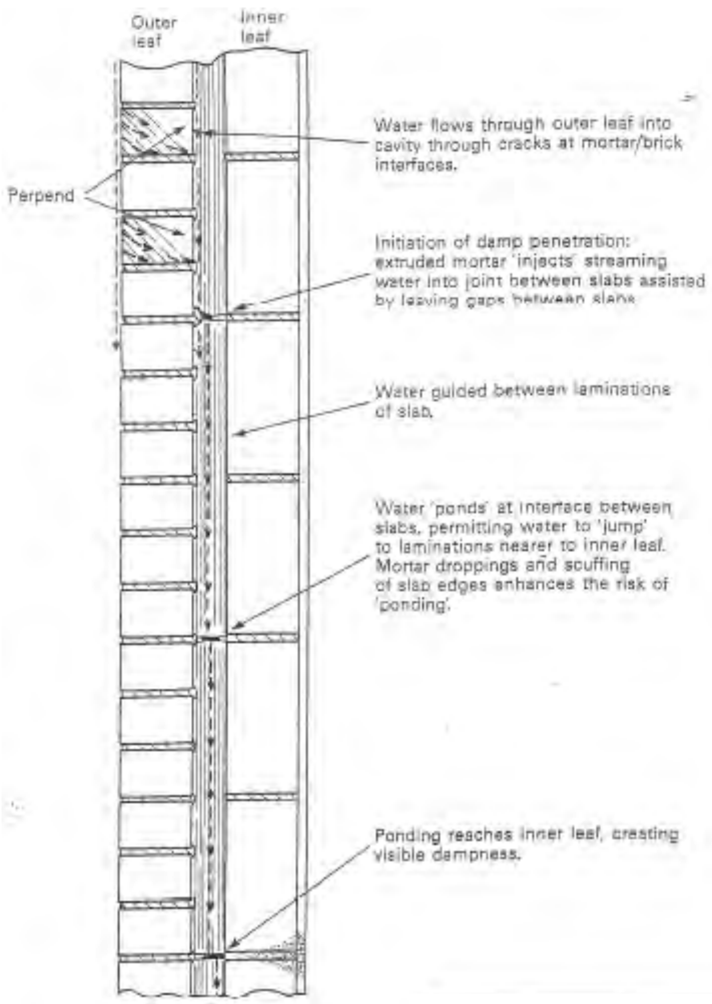


Figure 4.1, Potential routes for water penetration across a fully filled cavity, (BBA, 1983b)

Reaction of the liaison committee to the experimental results

Table 2.2 in the Literature Review section details the maximum recommended exposure zones for certain cavity widths. There has been, to date, a lack of experimental data on the performance cavities as a function of width. It therefore seems a precautionary approach has been adopted by the BRE to restrict certain cavity widths. As stated previously, the NHBC go one step further and prohibit the use of full fill in areas of very severe exposure. From discussions with the NHBC, it appears that these extra restrictions were a 'knee-jerk' reaction to the increased amounts of claims that the company received as a result of the storms of 1989 and 1991. These results go some way in shedding light on the issues. They suggest 100mm fully filled cavities are acceptable in areas of very severe exposure, so long as a typical (not necessarily good) standard on workmanship is maintained. About half-way through the project, the Construction Industry Train Board (CITB) were involved in the liaison committee. The CITB provided a valuable insight into the current training programmes that are provided for the trowel occupations. It was apparent, however, that this project would have little influence on the standards of training set by the CITB. This project was more about influencing the insurers and the BRE, so the CITB were not involved in subsequent meetings.

After about three quarters of the way through the programme, a liaison committee meeting was held where the results of the experimental work were presented. The insurers treated the results with a little scepticism. Their main issues concerned the fact that there was no field test data to consider. Their opinion was that the laboratory work involving the test rig was useful but not enough to convince them to remove the restrictions. An interesting point is that probably the best source of failure rates 'out in the field' is in the insurance companies' domain. Current Building Regulations (DCLG, 2006b) require about 100mm of mineral wool insulation in cavity walls. However, around the time of the introduction of the restrictions by the insurers and the BRE, the thermal performance requirement of the building envelope was considerably less. As such, 100mm fully filled cavities were practically unheard of in the early nineties. Therefore, there is a lack of field data of the performance of wide cavities with facing masonry in very severely exposed areas. The Building Regulations (DCLG, 2006b) since the early nineties have called for greater robustness in detailing (for example, the use of cavity closers). As such, one would expect cavity walls to be better equipped now to resist the passage of water across the cavity than when the restrictions were introduced.

A source of claims and failures data for retrofitted 50-70mm cavities rested with CIGA. They produced a report (CIGA, 2003) that analysed the water penetration complaints during their first eight years of operation: 1995 – 2003. This report is detailed in the Literature Review section. CIGA had presented this report to the insurers a few years prior to this project in the hope that the geographical restrictions could be removed. They were unsuccessful, however, and discussions with CIGA revealed that they ended their project shortly after. After the deadlock that was faced during the committee meeting, some lateral thinking was required. The next steps in the approach to the problem are detailed in the Conclusions section.

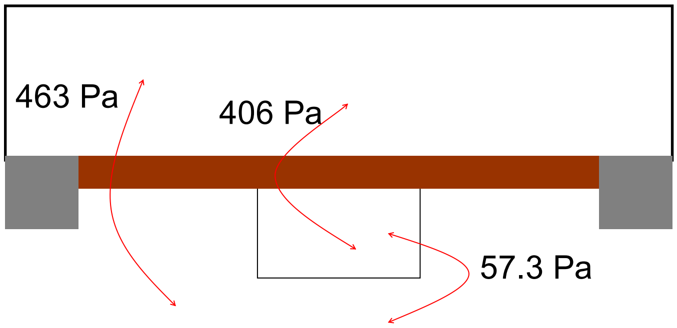
Analysis of the testing programme, existing procedures and literature

In order for an insulation product to obtain a BBA certificate, it has to pass one water penetration test which uses the test rig rig that is employed in this testing programme. This is an n=2 sample, as there are two identical cavity wall systems present on the rig. With such a small sample, the resultant standard error, S, will be very large. The NHBC and Zurich require a BBA certificate for insulation materials. From dicussions with the BBA, it was discovered that Rockwool cavity full fill slabs were tested at a 75mm width. It seems counter intuative that the insurers accepted the BBA's test but claimed that the testing programme detailed in this thesis was insufficient evidence.

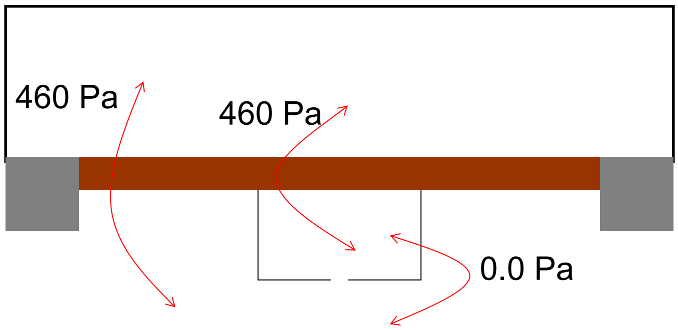
The BRE's Leaflet 23 'Cavity wall insulation: unlocking the potential in existing dwellings' (1995), givens a full fill failure rate of 0.26% from a sample of 11,061 homes. Give this failure rate, a sample size of around 400 would have to be taken to expect one failure. This is far greater than the BBA's testing programme. However, it would be prohibitively costly and impractical to introduce a testing programme of 400 samples. Another issue to consider, however, is that considering simply the number of walls may not be an accurate way of measuring the statistical power of the rig. Would increasing the area of the walls to represent a larger number of standard size tests have the same effect as simply increasing the number of standard tests? If all the parameters (for example, choice of bricklayer) are the same, the answer is yes. Therefore, the assumption that more standard tests equals more confidence is erroneous. Conceivably a more accurate way of measuring confidence is to look at where dampness often occurs – wall ties and incomplete perpends for example. This is why faults were deliberately built into the test rig walls used in this testing programme. This provided more far information than simply building the walls to a good standard of workmanship. Each wall features 30-40 wall ties, and it could be argued that these provide a sample size of n=60-80 for each test. What this demonstrates is that the answer to this problem is far from straightforward, and that the existing certification test procedure is not sufficiently exhaustive.

Perspex box tests

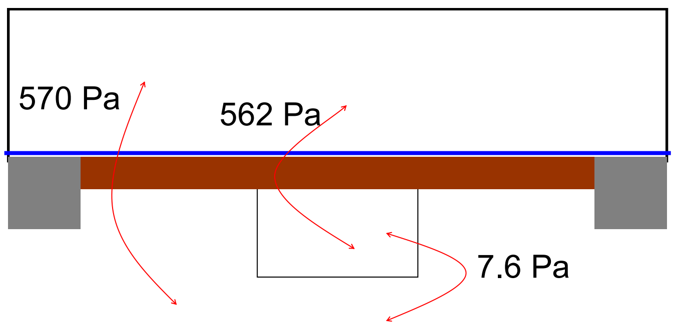
As stated in the Methodology, this experiment was purely for demonstative purposes only. The idea was to show members of the liaison committee that equalising the pressure across the windward face and the cavity inhibits the transfer of moisture across the outer leaf. The following diagrams detail the results of the Perspex box results.



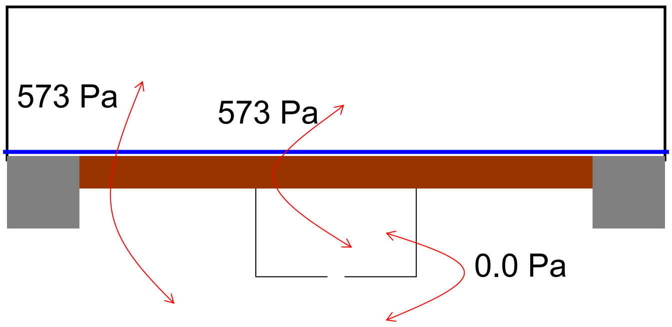
Hole in box closed, water off



Hole in box open, water off



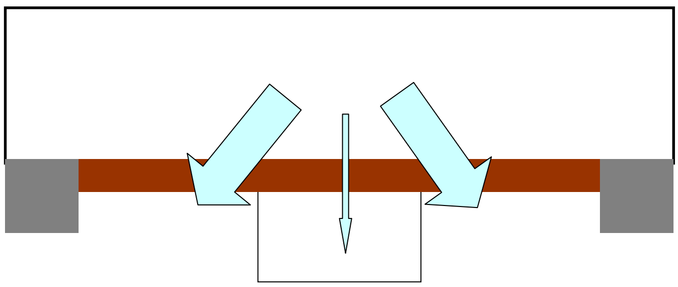
Hole in box closed, water on



Hole in box open, water on

As expected, opening the hole equalised the pressure between the box and the lab. As stated in the methodology, the fan that pressurises the chamber was run at its maximum setting. Therefore, the maximum pressure of the chamber varied with each test. When the water was turned on the brickwork became wet, the pressure of the chamber increased by around 100Pa. This was because the water blocked the tiny holes in the brickwork that usually allow fluid through the leaf.

According to the Canadian Mortgage & Housing Corporation paper (1999) (see figures 2.3 and 2.4), a pressure difference of less than 25 Pa between the chamber and the box must be maintained in order to control rain penetration. These experiments did not achieve this. This was explained by figure 4.2.



The fluid flow finds the easiest
route out of the chamber

Figure 4.2, Showing fluid flow paths from the chamber

The fluid flow finds the easiest path out of the chamber. When the box is closed, there is a smaller pressure difference between the chamber and the box interior, and the chamber and lab. Therefore the majority of the fluid flows out through the walls, thus limiting the pressure difference that can be achieved between the chamber and box interior. However, covering the entire face of the brickwork with a $9m^2$ section on Perspex proved impracticable. The box method did, on the other hand, affect the amount of water that penetrated the section of wall that it covered compared to the rest of the uncovered rig.

The photo on the left shows the exposed area of the rig's brickwork when the water was on and the chamber is pressurised. Relatively large amounts of water penetrated the brickwork. The photo on the right shows a small amount of moisture collected on the bottom of the box while the rig was on. Therefore, the pressure difference between the lab and box of 7.6 Pa seemed to slightly affect the amount of water that penetrates through the brickwork. However, the pressure difference was not enough to completely stop the water penetration.

It could be argued that the pressure could be equalised by simply not pressurising the chamber. However, this slightly misses the point, as the purpose of the experiment was to demonstrate a method of reducing water ingress with a wind load on the outer leaf. The liaison committee probably would have been unconvinced if the chamber had remained un-pressurised.

Results of the analytical model

The analytical work investigated the effect of having either practically airtight, or leaky outer or inner leaves around cavity wall junction. It was found that the most practical and efficient way of preventing fluid from flowing through the inner leaf (and thus preventing water penetration) was to create a relatively 'poor' and therefore leaky outer leaf and a well built and therefore practically airtight inner leaf. Figure 4.3 below shows the front end of the model in this arrangement.

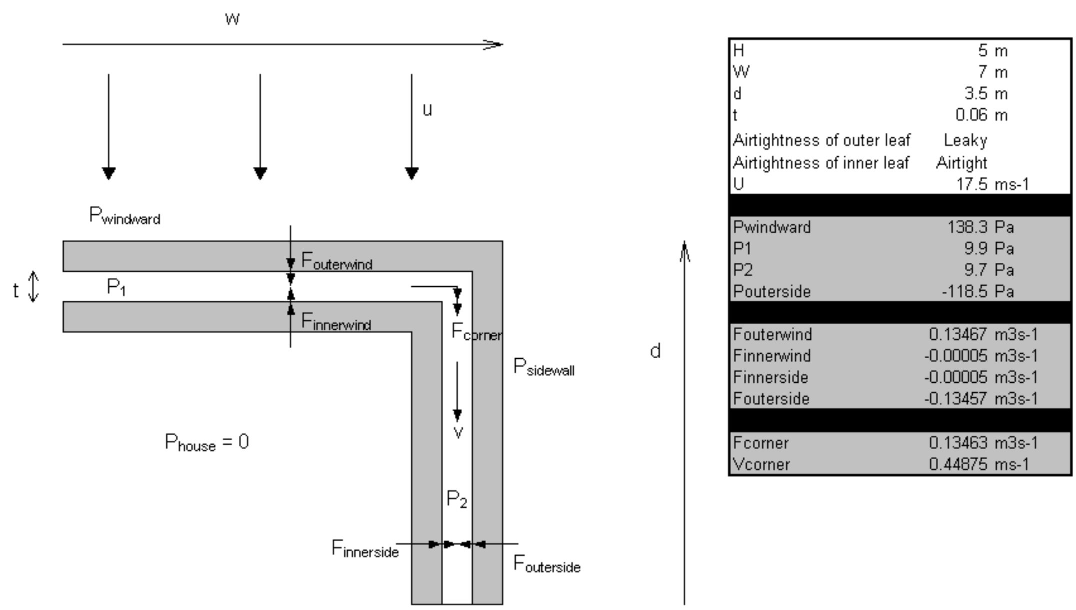


Figure 4.3, Front end of the analytical model with a leaky outer leaf and airtight inner leaf

$F_{innerwind}$ and $F_{innerside}$ are very close to zero, therefore the fluid flow through the inner leaves is negligible. This model is effectively demonstrating the rainscreen principle that is detailed in the Canadian Mortgage and Housing Corporation's publication '*Building Technology – Wood Frame Envelopes'*

(1999), (see the Literature review, figures 2.3 and 2.4). This model could be refined by varying *Cp* values across the windward facing wall.

The concept of pressure differentials between the lab and the cavity can be applied to the current rain penetration test rig. In a real cavity wall in a house, the cavity is pressurised to a degree, because of the wind load on the outer leaf causing fluid flow around an uncompartmented cavity (see figure 2.4). The BBA’s test rig has an open cavity – that is, the side panels that enclose the cavity wall system feature large openings that allow the cavity to be drained into the cavity flow collection point (see figure 3.0). This in effect causes the cavity pressure to equal the lab pressure, and therefore does not entirely replicate real life conditions. The test rig that was used in this programme of testing featured narrow bore pipes that drained the cavity and so had a smaller effect on the pressurisation of the cavity. It is reasonable to expect the BBA’s rig to show the water penetration properties of a cavity walls with insulants in a less favourable light, due to the larger pressure differential between the chamber (or ‘outside’) and the cavity.

Conclusions

Methodology and the Action Research Approach

The problem of rain penetration in fully filled cavity walls is complex. Therefore, the approach to this problem required a complex and multi-stranded research approach. Key to this approach was the engagement with key industry decision makers in the project liaison committee. The three diverse methods of research - the influencing strand, the analytical strand and the empiricalstrand all complemented each other and the consultations with the liaison committee enabled the programme to stay relevent and goal-orientated.

The methodology used was similar to the Action Research Approach (Greenwood et al, 1993), in that progress was made toward defining and resolving a difficult and complex problem by a process of action and collective reflection on action. A straightforward experimentalprogramme was unlikely to be as effective, as the underlying structure of the whole problem was unclear to the participants from the outset. A summary of the state of knowledge at the beginning of this project is as follows:

- The author was not in possession of all the literature on the subject, and it is possible that neither was anybody else.
- The existing theoretical models of the principles of transport of water across a cavity were crude (see figures 4.0 and 4.1).
- The key players and decision makers were not known.
- The way that the driving rain test related to field performance was not known.
- The statisticalweakness of the driving rain test had not been considered.
- The weight ascribed to the driving rain test by the insurers was unknown.
- The fact that a table of acceptable constructions (table 2.2) had been created in the absence of empirical data was not yet realised.

- There was no empirical data, either from laboratory test or from the field, on the impact of cavity width on driving rain performance.
-

Despite these uncertainties, work commenced:the assembly of a liaison group; development of a testing programme;the testing of walls; gauging the impact of the test results on the members of the liaison group; and finally, assembling the author's knowledge of the technicaland socialprocesses at work (from bricklaying to policy making by the main insurers and Government).

Meanwhile, the liaison group provided a wide range of infonnation, some of which (such as the NHBC's blanket ban on full fill cavity insulation in Scotland) was quite unexpected. Had the work been deferred until greater clarity had been acquired, it would probably have never got underway.

The methodology used was similar to the Action Research Approach (Greenwood, 1993) in the following additional ways:

- It addressed real life problems.
- It was change orientated.
- It emphasised a participatory approach in which participants and researchers generated knowledge and understanding through collaborative processes in which all participants' contributions were valued.
- It was an eclectic approach that embraced ideas, knowledge and theory from any source that was able to contribute to the goalof addressing the research problem.

Although this approach had to be managed very effectively, it worked well and facilitated a two way learning process between the researchers and the liaison committee. This programme of testing and collaboration produced many interesting results and points for discussion.

Results of the Study Programme

It is worth remembering that the existing claims information from CIGA (2003) and the BRE (1995) gave a typical failure rate of 1 in 400 - 10,000 houses in the field. Therefore, the results from the test rig and the computer analysis were never going to rule out any risk associated with a particular type of construction, because of the relatively low number of tests that were conducted. Additionally, these test walls did not contain windows or other components, nor junctions with other elements of construction such as roofs and other walls. However, several assertions can be deduced beyond a reasonable amount of doubt:

- Increasing cavity width increases the resistance of the wall to water penetration and ingress.
- Observed failures centred on certain faults - namely missing / incomplete perpends and mortar snots on wall ties / between batts. The extent of dampness associated with such faults appeared to decline with cavity width.
- When building empty cavity walls or, indeed, when installing partial fill, extra care has to be taken due to the risk of mortar snots accumulating on wall ties on lower courses. The failures that could result from such faults are equally as severe as the intentional extreme faults that were built-in to the rig walls.
- Pressure equalisation and the compartmenting of cavities is an area that could yield some promising results. The rainscreen principle was shown to work in the computer model.
- It would be very difficult to devise driving rain wall tests that cover all details, for example window reveals, and junctions with other walls and roofs.

It has been proven that workmanship is a key factor in causing water penetration in a cavity wall. On site, bricklayers are paid for the amount of brick and blocks that they lay, rather than focussing on the insulation batts. Also, the batts are effectively invisible once the walls are built. This inevitably focuses the mind away from the potential risks of incorrectly fitted batts and mortar snots on walls ties. A recent article stated that a possible solution is retraining, particularly focussing on insulation and its significance on CO_2 emissions. A different pay structure could also help change this culture (J Little, Construct Ireland, 2006).

There is a whole group of assertions made by the BRE, the insurers and CIGA that have little empirical basis. Clearly, it seems that this whole area is under explored. As stated in the Results & Discussion chapter, the BRE and the insurers introduced restrictions at a time when narrow filled cavities (smaller that 100mm) were commonly used. The result is a lack of field evidence of the performance of filled cavities larger than 100mm in very severely exposed areas. The experimental work involving the test rig provided a valuable insight into the mechanisms of water penetration, but it was impractical to conduct the hundreds and possibly thousands of tests required to give significant statistical confidence in the results. The closest thing that this project uncovered was CIGA's 2003 analysis into retrofitted blown cavity wall insulation complaints from 1998-2003. However, these only covered cavities of 50mm to 70mm. On the other hand, as discussed in the Literature Review, the statistical presentation of even these data are flawed.

A Possible Future Strategy for Rockwool

In the Results and Discussion section, it was mentioned that both the NHBC and Zurich required more convincing in order to remove the restrictions. Even though they differed in that the NHBC did not allow any full fill insulation in very severely exposed areas of the UK and Scotland, and Zurich required a minimum 150mm cavity width in such areas, they both were unwilling to move to allowing 100mm in the most exposed areas. One plan to get round this stalemate is to introduce a CIGA-type guarantee that insulation manufacturers will issue. As it stands, Rockwoolissue guarantees for blown mineral wool insulation for new build housing. There have been no known reports of the company paying out for any customer complaints that have occurred. Indeed, Rockwool investigates failures in retrofitted Rockwool blown insulation on CIGA's behalf, and not once has the fault been caused by the insulation product. After speaking to an installer of blown mineral wool,it was found that many insulation installers issue their own guarantee certificates for new build blown insulation. This is an extraordinary situation - clearly the risk seems so low that the installers are prepared to take the risk on themselves. It seems that Rockwool could now take on liability for the new build full fill cavity slabs in areas of very severe exposure. Future meetings with the Technical Director of the BRE are planned to look at their exposure restrictions and discuss any opportunities for relaxing them. After discussing this possibility with the insurers, clearly some negotiation is required to bring Rockwool's liability down to a sensible level.

The Code for Sustainable Homes (DCLG, 2006c) details future improved energy performance standards. It is widely accepted that the most effective areas are to firstly reduce heat loss from the building envelope, and then address renewable and low carbon energy sources. As the U values of the building envelope fall, the cavities in the wall systems will increase in width. The results of this work therefore suggest that the incidence of dampness will tend to decrease in future housing.

Both the insurers are very conservative in their stance. The construction industry lacks a strong research culture, and in recent years, government support for research has reduced by 69% (House of Lords Science and Technology Committee, 2005). This lack of investment in research coupled with conservative culture of the industry may no longer serve to minimise risk.

Recommendations for Further Work

The following points should be considered for future work:

- The driving rain test rig could be modified to include windows or other opening where dampness problems can occur.
- The cavity in the test rig could be pressurised to accurately simulate field conditions. Also, the pressure over the face of the inner leaf could be mapped using several manometers. This work could be used to refine the computer model.
- The area of dampness that occurs during a test could be measured. This would give an idea of the extent on water penetration.
- A thorough investigation of claims due to water penetration should be conducted.
- An analysis of the liability that Rockwool could take on should be completed. This would determine if liability for water penetration complaints is an acceptable risk that Rockwoolwould be prepared to take. This could persuade the insurers to allow full fill insulation in very severely exposed areas.

The issues surrounding water penetration in very exposed areas of the UK are far from transparent. Further work is required in order to compile good quality data from which confident, impartial assertions can be made. This will require further collaboration with the insurers, BBA and BRE, but also the major housebuilders, the installers of retrofit cavity wall insulation and CIGA. As the thermal requirements of Building Regulations (DCLG,2006b) become more onerous,the task of finding a solution for compact, thermally efficient external walls lies with these groups. In short, collaboration is the way to achieve this.

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Appendix 1

Visual Basic Code for solver excel spreadsheet

```
Sub Macro1()
'
' Macro1 Macro
' Macro recorded 03/04/2006 by Peter Batchelor
'

'
    SolverOk SetCell:="$B$40", MaxMinVal:=3, ValueOf:="0",
ByChange:="$B$26"
    SolverSolve
End Sub
```

Appendix 2

Certificate of calibration for the micromanometer

CERTIFICATE OF CALIBRATION

Issued By INLEC UK Ltd.
Date of Issue 21 December 2005

Certificate Number
INLB38449

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Forty Foot Road,
Middlesbrough,
TS2 1HG
Tel: 01642 875555
Fax: 01642 875566

Approved Signatory
S.K

☐ A. Tremain ☐ A. Robson ☐ D. Rain ☑ S. Brown

Customer : Inlec UK LTD
The Cleveland Calibration Centre, Forty Foot Road
Middlesbrough TS2 1HG

Date Received : 07 December 2005

Instrument -

System ID :	DUL005615	Job Number :	33115
Description :	Manometer	Ref. Number :	420B007
Manufacturer :	Digitron		
Model Number :	P200UL		
Serial Number :	056/15	Last Certificate Number :	INLB38056
Procedure Version :	100mBar	Last Calibration Date :	11/11/2005

Environmental Conditions

Temperature : 20°C +/- 2.0°C
Relative Humidity : 45% +/- 10.0%
Mains Voltage : 220V +/- 5.0V
Mains Frequency : 50Hz +/- 5.0Hz

Comments

All tests passed calibration

Traceability Information

Instrument description	*Serial number*	*Certificate number*	*Cal. Date*	*Cal. Period*
Budenberg Air DWT Piston 1/2" (in H2O)	D218	N7465	02/01/2003	260

Calibrated By : R.Cowie
Date of Calibration : 21 December 2005

This certificate provides traceability of measurement to recognised National Standards, and to the units of measurement realised at the National Physical Laboratory or other recognised National Standards laboratories.
Copyright of this certificate is owned by the issuing laboratory and may not be reproduced except with the prior written approval of the issuing laboratory.
This certificate complies with the requirements of B.S.5781, part 1 1992. (ISO 10012 - 1 1992).

CERTIFICATE OF CALIBRATION

Certificate Number
INLB38449

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Test Title	Tolerance	Applied Value	Reading	Pass/Fail
Low Pressure Range: 0 - 19.99 mBar				
5inwater	42.4uBar	12.46mBar	12.42mBar	Pass
High Pressure Range: 0 - 100mBar				
10inwater	224.9uBar	24.9mBar	24.7mBar	Pass
20inwater	249.8uBar	49.8mBar	49.6mBar	Pass
30inwater	274.7uBar	74.7mBar	74.8mBar	Pass
40inwater	299.7uBar	99.7mBar	99.8mBar	Pass

Uncertainties