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THE DUAL CHALLENGE OF AIR LEAKAGE AND THERMAL EFFICIENCY - THE 1 STEP SOLUTION

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ABSTRACT

In masonry cavity walls, sprayed polyurethane foam (SPF) provides special benefits as an air barrier: permanence, resistance to air flow, structural soundness and continuity. SPF also delivers distinctive advantages as thermal insulation. These advantages include the elimination of convective air flow, the control of moisture transfer and condensation, and minimizing of thermal bridging. In addition, SPF acts effectively as a vapour retarder.

INTRODUCTION

With the introduction of The National Energy Code for Buildings (based on ASHRAE/IES 90.1), building construction professionals are focusing attention on the problem of providing building envelopes which are both energy efficient and cost effective.

What sets SPF apart as a building envelope system is that in a 1-step process it provides a gap free, air tight, monolithic envelope of low permeability, closed cell, moisture resistant insulation that adheres tenaciously to virtually all surfaces, smooth or irregular.

As a result:
- SPF is an effective air barrier
- SPF eliminates convective air flow
- SPF effectively controls moisture transfer and condensation through the building envelope
- SPF minimizes thermal bridging
- SPF is less costly than 2 step systems.

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The SPF used for building wall envelopes has a nominal density of 32 kg/m^3 (2 lb/ft^3). They are formed by the reaction of two components: an A side (isocyanate) and a B side (resin, catalysts, blowing agents and additives). These two components are supplied in drums, pumped through separate heated hose lines at 60°C (140°F) and externally mixed at the head of a spray gun. The product emerges as a liquid spray; it then rapidly expands to thirty times its original volume and hardens within minutes. Thickness is continuously built up in 25-38 mm (1-1½") passes to the thickness required.

Central to the equipment used for applying the SPF are fixed ratio positive displacement pumps which precisely monitor equal amounts of the two components at all times. For this reason SPF, as applied on site, has the same predictable qualities as plant-manufactured foams. (In fact, plant-manufactured board foams are made with a similar type of spray equipment that moves horizontally across a moving conveyor depositing a layer of foam onto a backing material. Another backing material comes from above onto the top side of the foam; the resulting board than passes through a roller press.)

Typical minimum physical properties of SPF are shown in Can/CGSB 51.23. An additional assurance of quality is the Can/CGSB 51.39, an on site application standard for SPF. Sprayed polyurethane foam has been performing very successfully in Canada for the past quarter century. When first introduced in the mid 1960's, designers saw SPF as a premium quality insulation for particularly demanding applications such as freezers, coolers and controlled atmosphere storage rooms. The SPF monolithic envelope solved the problem of air leakage and consequent frost buildup far more efficiently than any other insulation. Designers also noted that SPF performed a triple function: thermal insulation, air barrier and vapour retarder. Consequently, they utilized it in many commercial projects. Two such buildings are shown in Fig 1 and 2. The building envelopes in both of these buildings have been giving the owners effective, trouble-free performance since completion.

SPF AS AN AIR BARRIER

Resistance to Air Flow
As an air barrier, SPF exceeds The National Research Council of Canada (NRCC) suggested air leakage rate for Type III air barriers (> 55% RH 21°C). In a definitive study (CMHC 1990) on air barriers applied to masonry walls, SPF had an air leakage rate of non-detectable to 0.0004 l/s/m^2 at 75 Pa (0.011 psi).

The air leakage rate at 75 Pa is an important criterion for comparing air barriers. Nevertheless the behaviour of an air barriers under gust wind loads and sustained wind loads are far more critical as indicators of long term building envelope performance.

The CMHC study tested three samples of SPF. It also tested twenty-four sheet membranes (12 torched-on, 12 peel and stick), 9 trowelled-on membranes and 5 mechanically fastened membranes. All the membranes, except one trowelled-on membrane, met the air leakage requirements for type III barriers at 75 Pa.

Gust Loads. When subjected to 3000 Pa (0.435 psi) pressure difference for 10 seconds, all

Fig 1. Health Sciences Centre, Penetanguishene - 1969 - Gilleland & Janiss Architects, Toronto; SPF 25 mm (1") thickness to masonry backup cavity wall. Exterior precast panel.

Fig 2. The Orthopaedic & Arthritic Hospital, Toronto - 1972 - Howard D. Vandewater, Architect, Toronto; SPF 38 mm (1½") thickness to masonry backup cavity wall. Exterior brick wall.

samples of SPF showed no delamination or loss of adhesion. In contrast, 30% of the other membranes tested showed some evidence of delamination ranging between 0.5% and 7.5%. An additional 8% showed appreciable delamination (>15%).

Sustained Wind Loads. At 1000 Pa (0.145 psi) pressure difference for one hour, the SPF again showed no delamination or loss of adhesion. In contrast, 59% of the other air barrier membranes showed delamination or failed the test. (47% of the membranes showed delamination between 0.5 and 8% and 12% failed the test with membrane delamination between 27% and 60%).

The high performance of SPF under different loads is due to its excellent tensile strength and adhesion to building surfaces. A study (Ortech 1994) on SPF applied to concrete block confirmed SPF's high adhesion. SPF had an average adhesion of 30.9×10^4 Pa (44.8 psi).

Continuity

Because it is sprayed, SPF provides a greater degree of buildability to all exterior envelopes. It maintains continuity over the many imperfections and discontinuities in wall components. Irregular walls, corners, gaps, masonry ties, equipment penetrations, changes in plane and soffits are easily and effectively air sealed.

When using SPF, the termination points with other elements of the building envelope (roofs, windows etc.) are completed with a sheet membrane. In warm weather, this membrane is usually an SBS modified bitumen peel and stick membrane with a non-slip finish. A test report (Ortech 1994) showed that when SPF was sprayed over this type of membrane applied to a primed concrete block, the adhesion of SPF to the membrane was higher than adhesion of membrane to concrete block. In the pull tests on this assembly, the membrane pulled away from the concrete block at 14.2×10^4 Pa (20.7 psi) while the SPF stayed adhered to the membrane. (As SPF adheres poorly to polyethylene, peel and stick membranes with this type of backing should not be used. Because SPF adheres well to torched-on membranes, these membranes may replace the peel and stick membranes.)

The application of SPF over membranes at termination points improves the adhesion of the membranes to the backup walls. These are two reasons for this: one is the warm application temperature of the SPF (hose lines at 60°C-140°F), and the other is the exothermic heating produced during the formation of the foam. Because the membrane has been heated, it is softened, enhancing its adhesion. In addition the SPF bonds very firmly to the softened membrane forming an air tight seal.

Fig 3 and Fig 4 illustrate details at termination points with SPF and sheet membranes. When through-wall flashing are used for the wall-foundation wall connection (see Fig. 3), SPF can be applied in two ways. First, the through-wall flashing can be lifted up and SPF applied to the backup wall. Alternatively the SPF can be applied completely down the front face of the backup wall and the flashing to the wall-foundation wall. As the SPF has excellent water resistance and adhesion to membranes, it provides a water and airtight seal in both instances.

In Fig. 4, the SPF provides a very effective solution to a challenging air sealing problem. Because the precast panel must be fastened from within the building, it must be connected either before the masonry backup wall is erected or, if the masonry wall is erected, holes must be left in the backup wall for attaching the precast panels to the steel supports in the concrete floor.

The solution with SPF is as follows. The masonry backup wall on the floor below the precast panel is erected. The precast panels are then installed. The SPF is applied to the precast panels and structural steel supports. The masonry backup wall below the precast panel is sprayed and sealed to SPF precast panels. The masonry backup wall that is on the same floor level as the precast is erected; the SPF is trimmed at the top of the precast panel. A sheet membrane is applied to the masonry backup wall and to the SPF. A metal flashing for the panels is installed and the balance of wall is sealed with SPF.

Thermal Cycling of Air Barrier. Neither the temperature cycling of the SPF itself nor the temperature changes of the backup wall will affect the continuity of the SPF envelope. In order to assess the severity of dimensional changes in any material due to temperature variation three factors must be known (Latta 1972):

1. The response of the material to a given change in temperature.
   The co-efficient of linear expansion for a typical 32 kg/m^3 (2 lb/ft^3) SPF is 6.2×10^{-2}mm/m/°C (3.5×10^{-5} in/in/°F).

2. The change in temperature to which any material may be subjected.
   The recommended temperature for application of SPF is between 0°C to 32°C (32°F to 90°F). Temperature in the wall cavity ranges from -40°C (-40°F) to 60°C (140°F) and

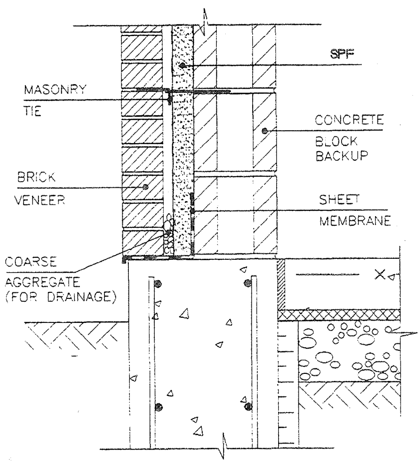

Fig 3. Wall-foundation wall connection.

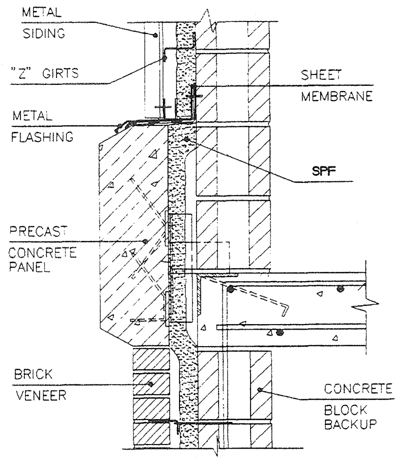

Fig 4. Masonry backup wall with precast concrete panels and steel siding connection.

therefore the largest temperature increase in the SPF is 60° C (108° F). Application temperature of SPF is 0° C and maximum wall temperature is 60° C. The largest temperature decrease is 70° C (126° F). Application temperature of SPF is 30° C and minimum wall temperature is -40° C.

3. <u>The freedom the material has to change dimension in response to a change in temperature.</u>
   This factor is the most critical. In order to assess the potential deformation of SPF three questions must be answered. First, how much stress is induced by SPF's restraint? Second, what is the adhesion of SPF versus the restraint stresses? Finally, is the substrate movement in the elastic region of the SPF?

If free to move, the unrestrained maximum expansion or contraction of SPF due to temperature change is:

$$\Delta L = [C\,(T_m - T_a)]L \qquad [1]$$

Where
ΔL = expansion or contraction (negative), mm
C = co-efficient of thermal expansion mm/m
Tm = maximum or minimum temperature, °C
T_a = temperature of application, °C.
L = length of wall, m

For a one metre length , temperature increase

$$\Delta L = [0.062\,(60°-0°)]l = 3.7\text{mm/m}\ (0.045\text{in/ft}).$$

In tension, SPF has a straight line relationship where stress would be proportional to strain up to its yield point. The modulus of elasticity, in tension, for a typical 32 kg/m^3 (2 lb/ft^3) SPF is $10.6x10^6$ Pa (1533 psi), its yield point is $38.6x10^4$ Pa (56 psi) and it occurs at a strain of 7%.

$$\sigma = E \cdot \varepsilon \qquad [2]$$

Where σ = Stress, Newtons /m^2 (Pascals)
E = Modulus of elasticity, Newtons/m^2 (Pascals)
ε = Strain, m/m.

Consequently, Stress = $10.6x10^6x0.0037$ = $39.2x10^3$ Pa (5.7 psi)
For a one metre length, temperature decrease:

$$\Delta L = [0.062\ (-40-30)]\ 1 = -4.34 \text{ mm/m } (-0.05 \text{ in/ft}).$$

In compression, the typical stress-strain curve for polyurethane foam has an elastic region where stress is nearly proportional to strain. While the curve is slightly S-shaped, the deviation is small enough to be neglected in these calculations. The modulus of elasticity in compression for SPF is $5.63x10^6$ Pa (816 psi). Its yield point of $18.5x10^4$ Pa (27 psi) occurs at a strain of 6.3%.

$$\text{Stress} = 5.63x10^6x0.0043$$
$$= 24.20x10^3 \text{ Pa } (3.50 \text{ psi})$$

As the average adhesion of SPF to concrete block is $30.9x10^4$ Pa (44.8 psi), it can be seen that for both temperature increase and decrease the adhesion of SPF far exceeds the restraint stresses necessary to hold it in place.

Deformation of Main Building Wall.
An SPF envelope reduces the temperature variation in all backup walls. Assuming backup wall has an interior temperature of 20°C (68°F), its maximum temperature increase would be 20°C (68°F). Application temperature of SPF is 0°C (32°C). The maximum temperature decrease is -12°C (22°C). Application temperature of SPF is 32°C (90°F). The co-efficient of thermal expansion for normal density concrete block walls is $1x10^{-2}$mm/m/°C($5.6x10^{-6}$ in/in/°F).

For a one metre length, temperature increase:

$$\Delta L = [0.01\ (20-0)\ 1] = 0.20 \text{mm/m}$$

For a one metre length, temperature decrease:

$$\Delta L = [0.01(32-20)1] = -0.12 \text{ mm/m}.$$

Concrete block masonry may shrink up to 0.3-0.6 mm/m (0.0037-0.0074 in/ft.) after manufacture. Most of this shrinkage occurs prior to application of SPF.

As can be seen from the above calculations for SPF, it has much greater capability for movement than masonry block. Also, all the movement is in the elastic region of the SPF.

Steel has a co-efficient of thermal expansion approximately that of concrete block masonry $1.2x10^{-2}$ mm/m/°C($6.7x10^{-6}$ in/in/°F). Thus SPF accommodates the expansion and contraction of steel contained within the interior wythe due to thermal movement. (For steel beams designed to have large deflections under loading, a sheet membrane should be applied at interface of steel beam and backup wall to accommodate movement.)

SPF AS THERMAL INSULATION

R-value

The "R" value of all closed cell cellular plastics which incorporate a blowing agent, such as extruded polystyrene, polyurethanes, polyisocyanurates and phenolics, decreases with time. The rate of this decrease varies with different insulations and is affected by two main factors. The first factor is the percent of blowing agent entering and saturating the polymer matrix. The second factor is the air diffusing into the foam cells and diluting the cell gas. As the thermal conductivity of the blowing agent is significantly lower than that of air, the cell gas dilution by air will reduce the overall "R" value of the insulation. The rate of change decreases exponentially with time and loses its significance after 5 years. Consequently, the CGSB committee on long term "R" values selected the value at 5 year aging at ambient temperatures as the long term design "R" value. The CGSB Committee determined that by 5 years a steady state condition would be reached and any further aging and reduction in "R" values would be minimal.

In the past, a few manufacturers did publish 5 year aged "R" values. However, because of the change to non CFC (HCFC) blowing agents by all the manufacturers of closed cell cellular plastics, a 5 year aged "R" value no longer exists.

The 28-day "R" values for HCFC blown foams are slightly higher than for CFC blown foams. Therefore, the Canadian Construction Materials Centre (CCMC) at the NRCC in their Evaluation Reports and Listings, ruled that the assigned "R" value for extruded or expanded polystyrene must not exceed the values outlined in CGSB Standard 51.20 M87 for types 1, 2, 3 and 4. The CCMC also ruled that for type 1 moulded polystyrene, the value is RSI 0.68 (R3.87 per inch) and for type 4 extruded RSI 0.88 (R 5 per inch).

CCMC made two separate rulings on the other cellular plastics, including polyisocyanurates, polyurethanes and phenolics. First: when tested, if the "R" value is less than RSI 1.05 per 25 mm (R6 per inch), the product is assigned the test result as the long term "R" value. Second: if on the other hand the value exceeds RSI 1.05 (R6 per inch), the product's value is "capped" at RSI 1.05 (R6 per inch). The only time when CCMC will validate an "R" value in excess of RSI 1.05 (R6 per inch)) is when a 5 year old sample is submitted for test, at which time the resulting test value will be the assigned long term "R" value.

As the switch to non CFC blowing agents took place in 1993-4, no 5 year samples exist for polyurethanes, polyisocyanurates and phenolics. The "R" value of all those insulations will be RSI 1.05 per 25 mm (R6 per inch). The initial "R" value of SPF after 2 days at 23°C (73°F) is RSI 1.37 (R 7.78 per inch). As with other gas-filled cellular plastics, the design "R" value will be RSI 1.05 per 25 mm. (R6 per inch).

Convective Air Flow - Brick Veneer Masonry Backup Wall
"Thermal insulation must be in intimate contact with the air barrier system. In this way the insulation is not subject to local convection currents and the insulation can perform its intended function. Even a small space between the insulation and the air barrier substrate will drastically reduce the thermal efficiency." (CSC TEK-AID 1990)

While intimate contact between insulation boards and substrate is an ideal goal, achieving this with board insulations is very difficult, if not impossible. Many types of construction details prevent intimate contact. Here are some examples.
- Masonry walls are not flush or true to line.
- The seams in sheet air barrier materials at masonry ties, joints and corners.
- Extra mastic for sealing around masonry ties.
- Cutting and fitting of boards at corners and projections through the building.
- The thickness of masonry ties.

As a result of the problems described above, insulation boards may touch the back up wall in one place and be 10 mm to 20 mm ($^3/_8$" to $^3/_4$") away in another.

Many studies (including Lorentzen et al. 1962, Brendeng et al. 1974, Brendeng et al. 1980, LeCompte 1990) over the past 30 years have shown the dramatic drop in "R" value due to convective air flow around the joints in non-permeable rigid board insulation.

In particular, a recent (Trethowen 1991) study shows that a mere gap of under 1 mm (between 1/32" and 3/64") for walls and a gap of 4 mm (1/8") for ceilings is sufficient to initiate convective air flow around board insulation and reduce "R" values. This study showed that insulation gaps of ½% of total wall area will more than halve (reduce by 55%) its total "R" value. The standard masonry ties used with board insulation along with other anomalies in the wall invariably produces a gap exceeding ½% of the wall area. The "R" value reduction due to convective air flow around such gaps is the significant factor in determining in-place performance of non-permeable board insulation. SPF, in contrast, tenaciously adheres to backup walls and seals around masonry ties and corners providing a 100% gap-free monolithic layer of insulation, totally eliminating any convective air flow and loss of "R" value. Fig 5 & 6 show how easily the monolithic envelope of SPF maintains contact with irregular walls to eliminate convective air flow.

Convective Air Flow - Brick Veneer Steel Stud Backup Wall
The necessity of cutting the exterior sheathing to fit the wrap around masonry ties in this type of construction leaves large gaps in the sheathing (see Fig 7). While a combination of sheet and mastic air barrier materials can be used to provide a seal around these gaps, it is very difficult and very time-consuming to install them flush with the face of sheathing. As a result the insulation will not be in contact with backup wall. In addition to the joints in the board insulation fitting the insulation around the masonry ties leaves many additional gaps. The end result is significant convective air flow and "R" value reduction. Fig. 8 shows how SPF solves this problem with a joint free, air tight seal with full adhesion to backup wall, eliminating convective air flow and "R" value reduction.

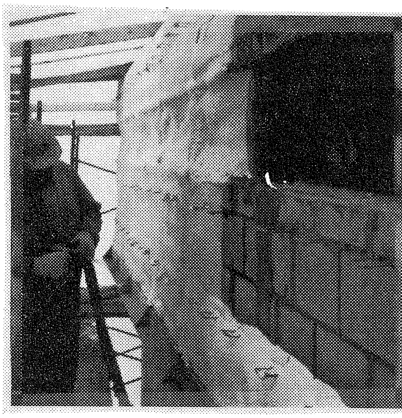

Fig 5. SPF applied to masonry backup wall, steel I beam and behind shelf angles.

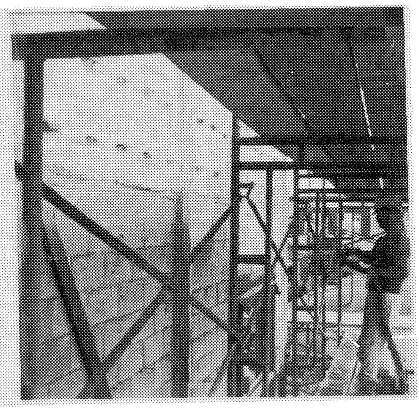

Fig. 6: SPF applied to steel frame and masonry infill panel.

MOISTURE CONTROL WITH SPF

Moisture transport through and condensation within a building envelope are dependent on five factors:
(1) Moisture diffusion through vapour retarder
(2) Continuity of vapour retarder/air barrier
(3) Continuity of thermal insulation
(4) Thermal bridging
(5) Moisture resistance of insulation.

SPF as Vapour Retarder.
A 25 mm (1") thick cut sample of SPF (with no skins) when tested to ASTM E 96-90 has a water vapour permeability of 62 ngs/Pa·s·m^2 (1.1 perm inches). Because higher density skins, which have a lower permeability, are formed on the contact surface and the exterior surface of the foam, a 25 mm (1") thickness of field applied SPF would have a lower value. Also, as the permeability of SPF is proportional to its thickness, greater thicknesses have lower values.

In part 5 of the National Building Code (NBC) 1990 (Wind, Water & Vapour Protection) no specific value for the permeability of vapour retarders is mandated. (Section 5.2 Control of Vapour Diffusion. Subsection 5.2.1 Vapour Barriers).

In section 5.2.2 Assemblies with Low Permanence Exterior Components, a continuous vapour retarder is recommended on the inside wall if an air barrier/vapour retarder is applied to the outside of the thermal insulation. The building code authorities are concerned that an air barrier/vapour retarder in this position will entrap moisture. Use of SPF eliminates this problem as the small amounts of moisture that enters SPF passes through it. A study (Scanada 1992) of a steel stud wall, with mineral fibre batt insulation in the stud space, and

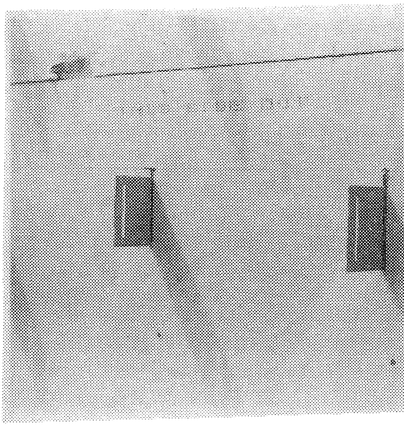

Fig 7: Steel stud backup wall with gaps in exterior sheathing at wrap around masonry ties.

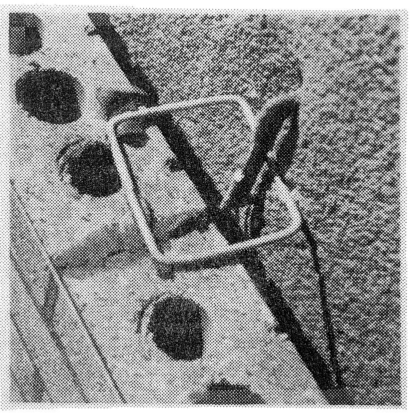

Fig 8: The same wall sealed with SPF.

a 50 mm (2") thickness of SPF applied to the exterior of the sheathing, reported the following. "Clearly the addition of 30-50 mm of polyurethane foam insulation/air barrier out board of the sheathing does produce a trouble-free wall under any reasonable condition of construction and usage.

Despite the intentional 'worst case' bias in the simulation (extreme winter climate, overly humidified indoor condition, grossly flawed vapour barrier), the wall accumulates extremely little condensation in the winter because the urethane insulation sheathing is seldom below the effective dew point and there are no through-leaks of air. Further, the 'drying regime' strongly outweighs the wetting regime so there is no year over year accumulation; the winter's moisture gains are dissipated by early spring."

In Part 9 of the NBC (Housing and Small Buildings) Subsection 9.25.6.3 part (b) eliminates the need for a vapour retarder when the insulation is a foamed plastic insulation with a permeance rating of not more than 230 ng/Pa·s·m^2 (4 perm inches) and is installed in continuous contact with masonry or concrete walls.

Continuity of Vapour Retarder/Air Barrier.

While vapour retarder qualities are a consideration in wall design, building science authorities have long recognized that air leakage can carry 50-100 times greater quantities of moisture into walls than diffusion. (Drysdale 1994). In his section on vapour barriers, R. Brand asserts that barriers against diffusion of water vapour are seldom, if ever, needed despite code requirements to the contrary. (Brand 1990). The NBC concurs in Appendix A Subsection 9.25.6.3 - "Most serious problems from moisture condensation , however, are the result of leakage of moist air from inside the building into concealed wall spaces during colder weather. In most cases vapour diffusion accounts for only a small fraction of total moisture."

SPF displays excellent resistance to air leakage under all wind loads. It also displays high

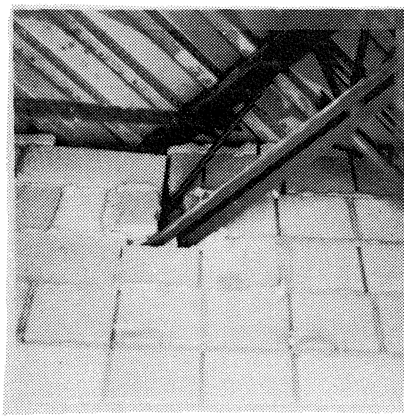

Fig 9: Soffit space.

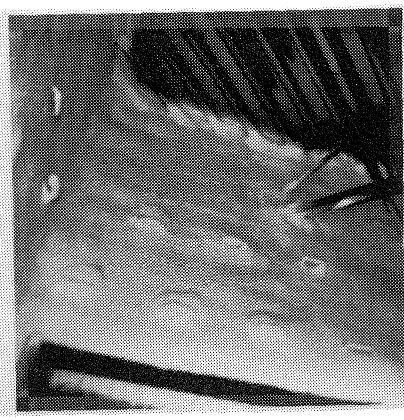

Fig 10: Soffit space after SPF application.

structural strength and adhesion to all surfaces smooth or irregular. By maintaining its integrity under adverse conditions, it controls air leakage and the attendant moisture transfer. The hard-to-insulate soffit space shown in Fig. 9 and 10 illustrates the effectiveness of SPF.

Continuity of Thermal Insulation

As mentioned previously, the gaps common to all board insulation systems allow convective air flow. This not only reduces the R value but at the same time it may cool the interior wall surface. If cooled sufficiently, condensation can easily occur on the interior surface of the back up wall without any air leakage. The monolithic seal provided by SPF completely eliminates this problem.

Thermal Bridging

Major areas for thermal bridging are structural elements, such as girders, purlins, columns, beams, studs, etc. which are usually connected to points near, or outside, the building envelope. Additional thermal bridges are caused by envelope penetrations which are usually metallic: masonry ties, shelf angles, hangers, fasteners for mechanically attaching insulation, utility conduits and pipes.

Fitted insulation leaves air spaces around the thermal bridge. These spaces generate lateral heat flow which cause a much greater heat loss than that via conduction alone through the thermal bridge. Such large heat loses in turn result in serious condensation of moisture on backup walls This problem was described in a ASHRAE study. (Brown 1986). In this study, the thermal bridges caused by steel girts and purlins within a metal wall were investigated. The results showed that heat transfer through the Z girts, with typical spacing of 2.4 m (8') and 150 mm (6¼") mineral fibre insulation, accounted for 35% of the total heat transfer. Furthermore this loss was 33% greater than the ASHRAE parallel heat flow calculations which do not account for lateral heat flow.

One main advantage of SPF is that by providing an air tight seal around thermal bridges, it eliminates lateral heat flow. In the case of a thermal bridge penetrating the envelope, the heat loss approximates that caused by conduction alone which minimizes the cooling effect of the thermal bridge. This can be clearly seen in figures 4, 5, 6 and 8.

Moisture Resistance of Insulation.
A cut sample of typical SPF (with no skins) when tested to ASTM D2842-90 (complete immersion with 51mm head for 96 hours) has a moisture absorption rate by volume of 0.48%. Thus SPF was shown to be resistant to moisture absorption from the moist environment common to cavity rain screen walls.

SPF is not corrosive toward metals in cavity rain screen walls. A study (Elliot 1986) on steel, copper, aluminum and galvanized steel sprayed with foam found the corrosion rates to be so low as to be negligible. Elliot's results have been corroborated by over a quarter century's experience.

COST EFFECTIVENESS

The application of SPF with a sheet membrane at termination points reduces costs by 25% or more in comparison to using a separate air barrier plus thermal insulation.

In conclusion, all the five main benefits of SPF which I have discussed can be explained by the fact that it provides a monolithic envelope for any structure. To recap: these five benefits are, first, it is an effective air barrier; second, it provides gap free, non-compressible closed cell insulation; third, it eliminates convection in all walls; fourth, it minimizes thermal bridging; and, finally, it acts uniquely as its own vapour retarder.□

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