

# BLISTERING IN BUILT-UP ROOFS: A REVIEW

**ALISON MURRAY**

Queen's University  
Kingston, Ontario, Canada

**ROBERT BOOTH**

Hansed Booth Inc  
Dalkeith, Ontario, Canada

**RALPH PAROLI**

Institute for Reserach in Construction  
Ottawa, Ontario, Canada

Blistering is a common problem with liquid applied exterior systems such as built-up roofs. Blisters are raised surface areas over voids which contain entrapped air or moisture or both. In general, these voids can be attributed to the materials used and the installation methods that cause unadhered layers, entrapped debris, curled felts, uneven substrates and skips in bitumen mopping. All these variables make installing a perfect void-free roof virtually impossible. Blistering is a common problem and the causes of blister formation and the proper treatments are well understood; people need to be made more aware of these facts. This paper will review the literature on blister formation and discuss methods to reduce blister formation.

## KEYWORDS

Adhesion, asphalt, blister, bubble, built-up roof, built-up roofing (BUR) membrane, diffusion, entrapped air, moisture, off-gas, void.

## INTRODUCTION

The National Roofing Contractors Association (NRCA) defines a blister as an enclosed pocket of air, which may be mixed with water or solvent vapor, that is trapped between impermeable layers of felt or membrane or between the membrane and substrate.<sup>1</sup> This paper focuses on blisters within the layers of a built-up roof. Blisters in the surface coating of asphalt (berry blisters) are not discussed.

Blistering is a considerable problem and a definite factor in the deterioration of roofs. In 1994, blistering was reported to be the most common problem in built-up roofs, forming 24 percent of the 3120 problems associated with this type of roof.<sup>2</sup> Research has focused on determining the causes of blisters and providing solutions.

An increased occurrence of blisters was noticed when plastic foam insulations became widely used and, because of this, much research with membranes over plastic foams was undertaken in the late 1970s and the 1980s. Initially, it was thought that cell gases emitted from plastic foam insulation might cause bubbles that eventually become blisters. Many types of plastic foam insulations were investigated for possible emissions.

A thin fibrous insulation board, adhered directly to an impermeable substrate, appears to alleviate blisters created when hot asphalt vaporizes the small amounts of water found on the surface of the substrate. This has been attributed to the moisture venting and absorption characteristics of the

fibrous material, which reduce the likelihood of moisture entrapment and subsequent blisters. Decreasing the potential of water on the overlay will also decrease the blistering problem.

Higher temperatures cause blister growth as the pressure in blisters increases, and the void expands. Gases pass through fissures in the membrane and contribute to blister growth, with air being forced in and out as the temperature changes.

General overviews of the blistering process have been put forward by: the Canadian Roofing Contractors Association (CRCA),<sup>3</sup> Griffin et al.,<sup>4</sup> Korhonen et al.,<sup>5</sup> Dupuis,<sup>6</sup> Tarmac,<sup>7</sup> Griffin,<sup>8</sup> Dwight et al.,<sup>9</sup> Curtice et al.,<sup>10</sup> Lindholm<sup>11</sup> and Warden.<sup>12</sup> Overviews of research into blistering describe the participation of groups including: the NRCA, the Midwest Roofing Contractors Association (MRCA), the Southwest Research Institute (SwRI), and the Thermal Insulation Manufacturers Association (TIMA).<sup>13,14,15</sup>

The following summary of past research will sequentially go through the layers found in a BUR membrane and describe the techniques used to determine the causes of blistering. Discussion will move from the bottom to the top layers, including the interfaces between the materials. The cross-section of a BUR roof system includes: the substrate (insulation and usually a thin fibrous insulation board), and the membrane with alternate layers of asphalt and felts, with or without a top surfacing. Blistering problems in built-up roofs are similar to those found in asphalt highways, and research in this area has also been reviewed. The layers making up roads are soil, gravel, and asphalt.

## PREVIOUS RESEARCH

### Substrate

The material properties of the substrate components have an important influence on the occurrence of blisters.<sup>8,16,17</sup> These include a material's ability to absorb and desorb moisture, as well as the rate at which this takes place. Most research has demonstrated that moisture contributes to blistering.<sup>5,8,10,18,19</sup> Rossiter et al.<sup>16</sup> examined polyurethane systems and found that moisture was not absolutely necessary for blister formation. Also, research into the waterproofing layers on concrete bridges found that water was not necessary for blistering.<sup>20</sup>

Rossiter et al.<sup>16</sup> also found the temperature to be too low to cause decomposition of the insulation foam. This was studied by monitoring the temperature between the insulation foam and the felt insulation facing, using a copper-constantan

thermocouple to determine the maximum temperature to which the materials were exposed when hot asphalt was poured onto the foam.

In September 1988, the National Roofing Contractors Association published Bulletin No. 9,<sup>21</sup> which was concerned with: minimizing blisters between the top facer sheet of insulation and the BUR membrane, minimizing the localized crushing of insulation, and minimizing facer delaminations. The insulations included were polyisocyanurates, polyurethanes, and phenolic foams. The NRCA recommended placing over the insulation "a thin layer of wood fiber board insulation, perlite board insulation or glass fiber board insulation." This bulletin superseded NRCA Bulletins No. 4 (1978) and No. 7 (1979), which also recommended using thin layers of fibrous insulation boards. These recommendations have greatly reduced the occurrence of roof membrane blisters.<sup>22,23</sup>

The use of perlite overlay boards has been recently questioned because of blistering that has occurred over some perlite insulation. Researchers have determined that the amount of cellulose filler in the perlite affects its moisture absorption properties, for example, its short-term moisture gain and loss.<sup>17</sup> This research recommended that these properties need to be considered in ASTM C 728, the material standard for perlite, as they will affect the performance of insulation that is exposed to different relative humidities while in transit, storage and in the field.

Another example of using vapor-release layers in another system was reported in Germany, where a membrane was laid over a concrete bridge deck. The membrane consisted of a glass fiber vapor-release layer, a sealing mastic and a surface course of a bituminous mastic concrete.<sup>20</sup> Direct attachment of hot asphalt membranes to concrete was similar to direct attachment of hot asphalt to foam insulation because Terry felt that both substrates were relatively impermeable. If surface water is present, the water vapor created when hot asphalt is applied is more likely to be trapped between the membrane and an impermeable substrate.

Earlier literature on highway blistering cited moisture from soil as a cause; however, subsequent research suggested that in this case blisters were due to the thermodynamic effects of air and water vapor trapped between the substrate and the overlay.<sup>24</sup> Other highway research found that bubbling in new asphalt concrete mat resulted from the movement of moisture trapped in old asphalt concrete mat.<sup>25</sup>

#### Interface Between Substrate and Asphalt Membrane

Lindholm<sup>11</sup> furthered the understanding of blister formation at the time of asphalt application. He studied the temperature gradient across the substrate and asphalt interface and the relative vapor permeabilities of the following materials: urethane, fiber board, perlite, fibrous glass, plywood, and asphalt felt. His work was theoretical and was supported by observations. Discussion focused on urethane, as the other materials allowed the diffusion of water vapor through the insulation. Because of the presence of moisture and urethane's low thermal conductivity and permeability compared with traditional, porous insulation materials, blisters did form. Urethane's low thermal conductivity created temperature gradients consisting of high temperatures at the interface of the substrate and asphalt and a heat flow away from the interface towards the asphalt. The low vapor permeability

of the urethane would result in little movement of gases within the substrate. Any vapors from there would move downwards, away from the interface, where the temperature would be higher. Any gases from the interface would be driven from the interface towards the asphalt, because of the temperature gradient. Also, any vapors would move through the asphalt rather than the urethane because of the better vapor permeability.

Dupuis et al.<sup>6</sup> investigated the effect of hot asphalt on commonly used insulations, including polyisocyanurate and phenolic foams. Some insulation samples were preconditioned in high humidity and it was found that moisture that adhered to the surface of such foams could result in foaming of the asphalt. If roof materials are not dry, the impermeable nature of plastic foams allows little lateral or downward venting of the surface moisture that vaporizes when hot asphalt is applied. Fibrous overlay boards were recommended even with hot BUR membranes reinforced with porous glass-based roofing felts.

Mirra<sup>26</sup> determined that a cause of blistering was large differential movement between the polyurethane foam and the built-up membrane. He placed strain gauges on the insulation, the first roofing felt, and in the asphalt between the two. The recommendations from this study were that the polyurethane foams should be able to expand and contract together and that there should be good adhesion between the foam and the BUR; in this way, the materials would remain as one unit and not buckle as the temperature fluctuates.

Curtice et al.<sup>10</sup> studied the dimensional stability of urethane and found that it had no bearing on the production of blistering during the installation. It was predicted that problems in the roofing system may develop later because of the low dimensional stability for some of the urethane materials compared with wood fiber board, perlite and fibrous glass.

During construction, Baxter<sup>27</sup> and Dwight et al.<sup>9</sup> found that it was extremely important to ensure good bonding between all materials to avoid the formation of voids. A small percentage (less than 5 percent) of small voids generally did not result in membrane blisters; however, large voids and non-bonded areas generally did result in blister formation.

#### Blisters

There is widespread agreement that blisters in built-up roofs originate with the formation of a void, or unadhered area, in the mopping bitumen, either between the felt plies of the membrane or between the substrate and the membrane.<sup>4</sup> Analysis of more than 10,000 built-up roof samples showed that blisters could only develop if initial voids, or unbonded areas, were present in the membrane construction.<sup>9</sup>

There is an increase in the size of blisters when the temperature rises, especially during the day, because the gases inside the void expand. Some experiments have shown that the pressures inside blisters were measured to be much lower than those calculated for totally entrapped gases experiencing roof temperature fluctuations. The low pressures have been attributed to fissures and other sealing imperfections in blister surfaces. The imperfections allow air to be forced out during the day and sucked in at night. It is this breathing or pumping action that leads to blister growth.<sup>3,5,7</sup> Curtice et al.<sup>10</sup> were able to show how temperature variations caused pressure variations inside the voids, resulting in volumetric

changes. They also concluded that these volumetric changes, and any diffusion of gases through the materials, may explain the growth of blisters.

To determine if off-gassing of materials causes blisters, gases within the blisters have been analyzed by techniques including gas chromatography and mass spectrometry, both for roofing<sup>10,15,16,26,28</sup> and for highways.<sup>24</sup>

Rossiter et al.<sup>16</sup> analyzed the composition of the gas in the blisters and found it to be comparable to that of air, with slightly less oxygen than in ordinary air. He found some chlorinated fluorocarbons (CFCs) (generally 1 mole percent or less) which came from the insulation foam, either as off-gassing during construction or from diffusion at a later time. The preliminary results of Curtice and others<sup>10</sup> found the major gases liberated at the time of asphalt application to a variety of insulation materials (wood fiber board, perlite, fibrous glass and urethane materials) were from the asphalt and the water vapor. Mirra<sup>26</sup> used mass spectrometry to analyze the gases in blisters and determined that the CFCs were in such small concentrations that they could not cause blisters, but rather the expansion and contraction of the different layers caused mechanical stresses leading to blisters. Mirra also compared the gas in the cells of the foam and the gas from the blisters and found them to be very different in composition. Thomas<sup>15</sup> also found that CFCs were not a major factor in blistering. He described one case where 0.09 m<sup>3</sup> (1 square foot) of foam insulation released a total of 0.000147 m<sup>3</sup> (9 cubic inches) of gas and only 0.0000475 m<sup>3</sup> (2.9 cubic inches) of gas were due to CFCs.

#### Asphalt Membrane

Different properties of the membrane have been discussed as being important in the blistering process, including permeability, the ability to vent gases, mechanical properties, and dimensional change of membrane with temperature.<sup>3,8,17,20,29,30</sup> Griffin<sup>3</sup> recommended coated felts over saturated felts, as saturated felts promoted blisters. He also recommended coated felts over uncoated felts, as uncoated felts were, among other reasons, thicker and more difficult to broom. Also dead-level asphalt (Type I) was preferred over steep asphalt (Type III), as steep asphalt was more difficult to put down because of the high temperatures required, and because it was viscosity sensitive. Dupuis<sup>17</sup> found the porosity of felts used to reinforce roofing membranes important, as the pores allowed gases to escape up through the upper layers. These include glass fiber felts that are usually naturally porous and organic felts that can be perforated. Smith<sup>29</sup> recommended using Type IV felts over Type VI, as Type VI felts are stiffer, making it more difficult to get continuous embedment of the felt into the substrate.

Curtice et al.<sup>10</sup> performed field mopping tests using baseline insulation materials (wood fiber board, perlite and fibrous glass) and urethane materials (urethane/perlite composite, urethane/fibrous glass composite, urethane-glass reinforced, urethane, and urethane-glass reinforced). Temperatures were taken under the felt facing of the insulation boards and on top of the asphalt felt, using thermocouples. Bubbles, which may lead to blisters, were only found for urethane materials. The number, size and distribution of bubbles were recorded. The number of bubbles decreased at positions where the number of asphalt and felt layers were

built up. Channeling, formed from the bubbles, was also found in the asphalt, between the spacer sheet and the base ply felt, but not above the base ply. This work was felt to be preliminary, but pointed to the need of studying heat capacity, thermal conductivity, gas permeability, and viscosity, as these properties for urethane were much different than other insulation materials; this research was taken up by Lindholm<sup>11</sup> and was discussed previously in "Interface Between Substrate and Asphalt Membrane."

Curtice et al.<sup>10</sup> also used the test, "Procedure for Measuring Vacuum vs. Pressure of Isotropic Diffusion," developed by Parker at Shelter Insulation Systems in order to take pressure measurements inside a desiccator containing a sample and hot asphalt, and relate this to the isotropic diffusion of materials. The tests on perlite and urethane/fibrous glass composite were not useful for explaining the production of bubbles at the asphalt-insulation interface; they were, however, able to describe the pressure changes inside voids with changes in temperature, as previously discussed in "Blisters."

As discussed in "Blisters," the membrane is not thought to be impermeable and indeed may have fissures. For example, Mirra,<sup>26</sup> whose work was discussed in that section, calculated that the low CFC concentration was due to its diffusion through the asphalt BUR membrane. The fact that the foaming agent or CFC is very miscible in the asphalt was discussed at the 15th Session of the *1981 Roofs and Roofing Conference*.<sup>19</sup>

#### Surface of Asphalt Membrane

The influence of the environment on blisters is most evident in the increase in the size of blisters when the roof temperature rises. If this expansion creates larger forces than can be restrained at the perimeter of the blister, then the blisters will grow in area.

The profile of the blisters has been monitored to show that their size increases with temperature, particularly at certain times of the day and during the summer.<sup>12,24,28</sup> Warden monitored the profile between the temperatures of 9°C (48°F) and 70°C (158°F).

An infrared thermography scanner was used to detect wet insulation, which was thought might help to determine the cause of blistering in a BUR.<sup>31</sup> The resulting thermograms (photographs taken from the infrared scanner's display screen) found voids and variations in thickness of the BUR system that had been built-in during construction. Specific installation problems were: thick and uneven moppings caused by the asphalt being too cold at application, a void from a curled felt edge, and a lack of asphalt-to-felt adhesion, both from improper brooming. Core samples were taken to verify the results.

#### Calculations for the growth of blisters

The growth mechanics of blistering have been calculated theoretically (using methods including thermodynamics and finite element analysis) and experimentally. The works of a few researchers are examined here in greater detail. Warden, Laaly and Korhonen were investigating roof systems while Beijers, Lai, Hironaka and Bicheron were studying bridge or highway systems. Some terms have been assigned different letters for this paper in order to maintain consistency.

Beijers<sup>29</sup> stated that the forces acting at the interface for a waterproofing system over concrete include:

P = pressure of the air in the voids of concrete near the interface;

A = adhesion between the asphalt material and the concrete;

W = weight per surface area of the total waterproofing system.

The pressure of air in a blister caused by heating can be calculated with the universal gas law:

$$PV = mRT/M$$

where:

P = pressure of the gas in the blister;

V = volume of the blister;

m = mass of the gas in the blister;

R = universal gas constant;

T = temperature of the gas in the blister;

M = molecular mass of the gas in the blister.

When there is no adhesion between the layers, P will have to be greater than W for a blister to form:

$$W = \rho dg.$$

where:

$\rho$  = density of the waterproofing system;

d = thickness of the waterproofing system;

g = acceleration due to gravity.

Lai<sup>22</sup> analyzed the adhesive fracture for a flat infinite subsurface covered by a second material, which was only debonded in a circular area. The first equation used to solve for the deformation was:

$$w(r) = (1/64) (P/D) (a^2 - r^2)^2$$

where:

w = deformation;

r = radius;

P = pressure in the void;

D = flexural rigidity (stiffness factor) of the covering layer =  $E d^3/12 (1 - \nu^2)$ ;

a = unbonded radius;

E = elastic modulus (considering both tension and shear) of the covering layer;

d = thickness of covering layer;

$\nu$  = Poisson's ratio of the covering layer.

The critical internal pressure for debonding and the blister increasing in size was determined using the equation:

$$P_c = ((512 E d^3 \gamma_a) / (3(1 - \nu^2)) \cdot 1 / (2a)^2) \frac{1}{2}$$

where:

$\gamma_a$  = adhesive fracture energy.

Lai used the above equations to explain: the effect of void size on deformation, the effect of layer thickness on deformation, the effect of layer stiffness on deformation, factors affecting the critical pressure, the effect of adhesive layer thickness, the pressure developed in a blister, the effects of material properties, the thermorheological behavior of asphalt concrete, the adhesive fracture energy, the effect of stripping the asphalt from the aggregate, and the growth of blisters.

Warden<sup>20</sup> showed that the rate of blister growth is controlled by the permeation rate of air through the asphalt membrane, as the diffusion rate of moisture vapor is greater than air. This is based on the premise that the membrane is

semi-permeable. He used Fick's law for straight diffusion mechanisms for relatively inert gases.

$$W = (K A \Delta P t) / d$$

where:

W = weight of gas diffused;

K = permeability (diffusion rate);

A = area of membrane;

$\Delta P$  = pressure differential;

t = time;

d = thickness of membrane.

Hironaka et al.<sup>24</sup> discussed whether thermodynamics of the gas in the blisters could cause blisters to grow. Using the universal gas law, a rise in temperature from 27°C to 49°C (80°F to 120°F) could not explain the complete increase in volume of the blister; however, if the gas and water vapor were included, the effects could cause blisters to form.

Mechanical tests were used to investigate the quality of adhesion between plies of felts in BUR membranes.<sup>18</sup> Some factors that affected adhesion were: moisture in the asphalt felt or fabric, compressive loads on the membrane surface, and the viscoelastic behavior of the binder. Blistering in waterproofing layers over concrete bridges was also investigated.<sup>20</sup> After preliminary work, future areas of research that needed consideration included: 1) adhesion (the main consideration), 2) change of volume of the mastic asphalt during radiation period (the preliminary work used infrared radiators for 11 days instead of solar radiation), 3) analysis of air in the blister which may contain gases from the asphalt, and 4) adhesion strengths, considering water and vapor transport in the asphaltic concrete after the waterproofing material were put in place.<sup>20</sup> Both Korhonen et al.<sup>3</sup> and Bicheron et al.<sup>28</sup> showed experimentally that the pressure inside the blisters was less than the calculated pressure.

## SUMMARY

Blisters originate from voids, or unbonded areas, in roofs. Factors influencing blistering are largely determined at the time of a roof's design and construction. They include the materials used, the weather conditions and the quality of the workmanship. The most important recommendations are to use a wood fiber board insulation, perlite board insulation or glass fiber board insulation between the insulation and the asphalt and to install the BUR during dry weather conditions. After construction, roofs are exposed to harsh environments that may aggravate the blisters and cause them to grow. These environments include large daily temperature fluctuations, extreme temperatures, and continuous wetting and drying cycles. Regular roof inspection enable blisters to be seen, monitored and repaired as necessary before they result in failure.

Research has emphasized the role that moisture can play in the formation and growth of blisters. This has included the moisture content, and moisture release and gain properties of the substrate. All studies show that moisture will exacerbate blistering problems. The thin layer of insulation, installed between the substrate and the asphalt, and recommended by the NRCA in Bulletin No. 9, should be able to vent any gas bubbles caused by moisture.

A significant amount of research has investigated the increased potential for blisters to occur over foam plastic

insulations. It was initially thought that cell gas emissions could cause blisters but researchers have found little evidence for this. The occurrence of blisters in hot applied BUR membranes directly over foam insulations has been related to the impermeable nature of foam insulations, which did not allow downward or horizontal venting of gases that are generated during hot asphalt membrane applications.<sup>10,11</sup> Industry recommendations to use glass fiber felts and cover boards over foam insulations have greatly reduced the occurrence of roof membrane blisters.<sup>22,23</sup>

Guidelines for workers and test methods to evaluate the quality of roofs are available;<sup>5,7,9,27,31,38,54</sup> the ARMA/NRCA's publication is very detailed. Recent treatment methods to repair blisters have also been published.<sup>5,22</sup>

## REFERENCES

1. *The NRCA Roofing and Waterproofing Manual*, Fourth Edition, National Roofing Contractors Association (NRCA), Rosemont, IL, 1996.
2. Russo, M. "Tracking the Performance of BUR," *Roofing-Siding-Insulation*, May 1994, 29, 28-29.
3. "Blistering in Built-Up Roofs," *Technical Bulletin*, Canadian Roofing Contractors Association, 45, July 1996.
4. Griffin, C.W. and R. Fricklas. *Manual of Built-Up Roof Systems*, 3rd ed., McGraw-Hill, New York, 1996, 230-231 and 240-252.
5. Korhonen, C. and B. Charest. "Roof Blisters, Cause and Cure," Office of the Chief of Engineers, U.S. Army Corps of Engineers, Cold Regions Research & Engineering Laboratory, Special Report 95-19, July 1995.
6. Dupuis, R.M., V.O. Martin, and H.B. Martin. "Application Effects of Hot Asphalt on Roof Insulation," Structural Research Inc., Research Report, Prepared for National Roofing Contractors Association and Midwest Roofing Contractors Association, August 1988.
7. *Flat Roofing: A Guide to Good Practice*, Second Edition, Tarmac Building Products (now Ruberoid), 1983.
8. Griffin, C.W. *Manual of Built-Up Roof Systems*, 2nd ed., McGraw-Hill, New York, 1982, 279-303.
9. Dwight, F. and P.E. Jennings. Preventing Blistered Built-Up Roofs, *Proceedings of the Second International Symposium of Roofs and Roofing*, J.O. May, Ed., Vol. 1, Society of the Chemical Industry, London, 1981, 368-376.
10. Curtice, D.K., N. Eng, and D.R. Williams. "Effects of the Application of Hot Asphalt to Roof Insulation," Southwest Research Institute, Final Report, Project No. 02-5444-130, Prepared for the National Roofing Contractors Association and the Midwest Roofing Contractors Association, January 1980.
11. Lindholm, U.S. *On the Development of Blisters during the Application of Hot Asphalt over Urethane Roof Insulation*, Southwest Research Institute, Final Supplementary Report, Project No. 02-5444-130, Prepared for National Roofing Contractors Association and Midwest Roofing Contractors Association, June 1980.
12. Warden, W.B. "A Theory of the Mechanism of Blistering," *A Study to Improve Bituminous built-up Roofs*, Monograph No. 1, Building Research Institute/National Academy of Sciences/National Research Council, Washington, D.C., 1960, 14-26.
13. LaCosse, R.A. "Membrane Blistering Over Foam Roof Insulations," *1989 International Journal of Roofing Technology*, Volume I, NRCA, Rosemont, IL, 1989, 12-15.
14. Porcher, H. "Blistering Over Urethane," *Proceedings of the Sixth Conference on Roofing Technology*, Gaithersburg, Maryland, 46-49.
15. Thomas. "Blisters Over Urethane," *The Roofing Spec.*, 26, May 1980, 18-24.
16. Rossiter, W.J., Jr. and R.G. Mathey. "Risk of Blistering of Built-Up Roofing Membranes Applied to Polyurethane Foam Insulation," *Thermal Insulation: Materials and Systems*, ASTM STP 922, E.J. Powell and S.L. Matthews, Eds., American Society for Testing and Materials, Philadelphia, 1987, 431-448.
17. Dupuis, R.M. and O. Ilievsky. "Short-Term Moisture Gain Behaviour of Perlite Rigid Insulation," *Roofing Research and Standards Development: 3rd Volume ASTM STP 1224*, Thomas J. Wallace and Walter J. Rossiter, Jr., Eds., American Society for Testing and Materials, Philadelphia, 1994.
18. Laaly, H.O., O. Dutt, and R.F. Feldman. "Interply Adhesion and Blistering of Bituminous Built-Up Roofing Membranes," *Durability of Building Materials*, 2, 1985, 209-228.
19. May, J.O., (ed.) "Discussion of Session No. 1," *Proceedings of the Second International Symposium on Roofs and Roofing*, Vol. II, Society of the Chemical Industry, London, 1981, 209-228.
20. Beijers, G.M.H. "Research to the Formation of Blisters Which Occur by Application of Waterproofing Layers of Concrete Bridges," *Proceeding of the Association of Asphalt Paving Technologists*, 45, 1976, 552-576.
21. National Roofing Contractors Association (NRCA), Bulletin No. 9, *NRCA Statement on Polyisocyanurate, Polyurethane and Phenolic Foam Roof Insulations*, Technical Developments, Rosemont, IL, September 1988.
22. Carlson, J. "Repair techniques for BUR blisters," *Professional Roofing*, March 1997, 20-24.
23. Smith, T.L. "Understanding and coping with blisters," *Professional Roofing*, September 1995, 62.
24. Hironaka, M.C. and T.J. Holland. "Blistering of Asphalt Pavement Overlay on Runway" 14-32 at MCAS Beaufort, South Carolina," Naval Civil Engineering Laboratory Technical Note, AD-A165 751, TN 1744, January 1986.
25. Potts, C.F. "Surface Distortion Investigation," Research Report 172, State of Florida, Department of Transportation, Office of Materials Research, Job No. 29180-8425, FAP No. 1-75-3 (48) 150, November 1972.
26. Mirra, E. "Blistering Phenomenon and Urethane Insulation," *Roofing/Siding/Insulation*, 71, December 1976, 58-61.
27. Baxter, R. "Recommended Application Tolerances for Bituminous Built-up Roof Membranes," *Proceedings of the 7th Conference on Roofing Technology*, NRCA, 1983, 41-44.
28. Bicheron, G., P. Lopez, F. Quentin, X. Fournier, and F. Pawlak. "L'asphalte, les feuilles, les cloques et les gonfles," *Bull. liaison Labo. P. et Ch.* 191, May-June 1994, 27-30.
29. Bonafont, R.L. "Research into Mechanical Behaviour of Waterproofing Membrane Systems," *International Symposium on Roofs and Roofing*, Brighton, England, September 9-13, 1974, 9/1-22.

30. Jones, G.M., M.I. Darter, and G. Littlefield. "Thermal Expansion-contraction of Asphaltic Concrete," *Proceedings of the Association of Asphalt Paving Technologists*, 37, 1968, 56-100.
31. Korhonen, C. and A. Greateorex. "Examination of a Blistered Built-Up Roof: O'Neill Building, Hanscom Air Force Base," New York District Corps of Engineers, Contract DACA51-80-C-0030, 1983.
32. Lai, J.S. *Investigation of Causes of Blistering of Asphalt Layers*, Georgia Department of Transportation, Office of Materials and Research, Report No. FHWA-GA-88-8508, September 1987.
33. *Quality Control Guidelines for the Application of Built-Up Roofing*, ARMA/NRCA, 1993.
34. Isaksen, T., E.M. Paulsen, and H. Juul. "Roofing Felt on Polystyrene," Oak Ridge National Laboratory tr-4679, Part of The National Program for Building Thermal Envelope Systems and Insulating Materials, 1979.