

## COUNTERACTING HIGH WINDS WITH LOW PRESSURE: DEVELOPMENT AND TESTING OF A NEW ROOF VENT SYSTEM

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### ABSTRACT

*Roof system failures are common during high wind events. In locations subject to high wind conditions, membrane roofing systems must typically be either physically attached or fully adhered to the substrate or ballast may be added to weigh down the membrane. An alternative to these installation approaches could be to use aerodynamics principles such as the Bernoulli and Venturi effects to create a low-pressure region beneath the membrane roof that is lower than the ambient pressure and thus counteracts the uplifting force. A new omnidirectional vent has been designed and tested that takes advantage of these aerodynamics principles to induce low pressure under the membrane layer. This new vent operates with no moving parts and was tested in the high-speed stability wind tunnel at Virginia Tech to wind speeds up to 233 km/h. The results demonstrate that this new vent generates pressures lower than the ambient when subjected to high wind conditions. This paper presents the design principles and performance test results for this new roof vent system and other applications for roof vent technologies.*

### KEYWORDS

roofs; wind forces, vacuum vent, vented roofs, negative pressure

## 1. INTRODUCTION

### 1.1. The problem with wind

Ever since the first structures were erected, wind forces have threatened to tear them down. Over time, these forces have become better understood, and perhaps better anticipated, but building failures due to storm damage continue to devastate communities worldwide. In the U.S., while Hurricane Katrina tops the chart in terms of Federal Emergency Management Agency (FEMA) relief costs at \$7.2 billion (FEMA, 2010), its damage was overwhelmingly related to flooding rather than high winds. Lessons related to widespread wind damage can be learned from Hurricane Andrew, the fifth most disastrous storm in FEMA's ranking, which necessitated \$1.813 billion in FEMA relief costs alone (FEMA, 2010).

The effects of Andrew were recorded and analyzed in a document prepared by FEMA's Federal Insurance Administration. Members of the Building Performance Assessment Team dispatched to southern Dade County, Florida, the area hit by Hurricane Andrew on August 24, 1992, observed that roof failures were the most prevalent form of damage (FEMA, 1993). Loss of roof cladding was the primary vehicle of failure, leading to subsequent destruction of interiors due to wind and rain. The low pressure present on roof surfaces, coupled with the intensification of internal pressure within a building caused by the failure of doors, windows and other building envelope components, created a powerfully destructive force. The failures observed by the assessment team were the result of observed peak sustained wind speeds as high as 141 mph and observed peak wind gusts of over 160 mph (FEMA, 1993).

In 1989, Hurricane Hugo caused damage leading to \$1.307 billion in FEMA relief, putting it tenth on FEMA's list (FEMA, 2010). In an extensive report evaluating the performance of roofing systems during Hurricane Hugo, McDonald and Smith (1990) observed and cataloged damage to various roofing systems, including low-slope roofs.

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They witnessed roof membranes tearing at the locations of fasteners in mechanically attached roofs, failure at locations of missing adhesive at fully adhered roofs, and scour and loss of aggregate on ballasted roofs. Many of the roofs also experienced failure of the edge condition, including damage to wood nailers and metal flashings, copings, and gutters.

Building codes and standards attempt to protect the public against the disastrous results of storms such as Hurricanes Andrew and Hugo. Researchers collaborate with the roofing industry to develop products with improved uplift resistance through improvements in fastener technology, membrane tensile strength, and other material parameters. Testing agencies attempt to replicate the forces generated by the wind to rate the performance of various roofing systems, as seen in Figure 1.



Figure 1- A mechanically fastened roofing system tested to the point of failure

Even with careful design and construction, standard methods of roof attachment are prone to damage caused by dynamic, fluctuating pressures present on the roof surface during an unpredictable wind event. An ideal roof system would be able to quickly equalize the pressure between the roof surface and the pressurized building interior, resisting tear-off of the roof membrane and its substrate.

### **1.2. *The need for low-slope, energy-efficient roofs***

The research presented in this paper is aimed toward low-slope, rather than steep-slope, roofs due to their frequent application in large commercial and industrial facilities. For reasons of energy efficiency and reduction of the urban heat island effect, low-slope reflective membrane roofs have become a widespread solution to the roofing needs of these project types. Particularly in large, one-story buildings in hot, humid climates, these roofs can significantly reduce the cooling load to be handled by mechanical refrigeration systems. Organizations such as the U.S. Green Building Council (USGBC) have recognized this potential and assign points through the Leadership in Energy and Environmental Design (LEED) system for including reflective roofs in building projects. Many warm climates, including those on the highly developed Atlantic and Gulf coasts of the southeastern U.S. and in the islands of the Caribbean, could benefit from the installation of single-ply, reflective roof membranes. Unfortunately, these climates are also prone to hurricanes and other tropical storms, which pose unique challenges to low-slope membrane roofs.

Frequently, vegetated roofs are used in conjunction with, or as an alternative to, reflective roofs to earn LEED points, as discussed in Section 1.3. While vegetated roofs do provide additional benefits beyond the reduction of rooftop temperatures, such as reducing the volume and slowing the rate of roof runoff, they are considerably more costly than reflective roof membranes. Depending on the system selected, they may also be prohibitively heavy for retrofit applications. Furthermore, vegetated roofs may not be ideally suited for locations vulnerable to high winds. Special measures must be taken in such situations to protect plants and lightweight growing medium from uplift until the plants' root systems are fully established. It is also worth noting that the National Roofing Contractors Association (2009) recommends that the waterproofing membranes underlying

vegetated roofs be adhered. This can add considerable cost to a project, which may be avoided with the installation of a low-pressure system in a single-ply roof membrane, such as the system described in this paper. Based on the design constraints of the hot, humid, hurricane-prone regions of the U.S., use of the low-pressure roof vent in conjunction with white reflective roof membrane systems is suggested to reduce ambient temperatures at rooftops, thereby reducing heat flux into buildings and mitigating the urban heat island effect.

### **1.3. The impact of LEED**

The USGBC's LEED Green Building Rating Systems are in essence a set of elaborated checklists of potential credits to be earned by a proposed building project. The total number of credits, determined during the certification review process conducted by the USGBC, establishes the level of the project as certified, silver, gold or platinum. The LEED Rating System Product Portfolio includes rating systems for new construction and major renovations, existing buildings, commercial interiors, and a growing array of new standards currently under development. LEED has been criticized for its checklist approach which gives static weights to a wide range of building strategies, but despite its shortcomings, it is being referenced and often required by an increasing number of governmental organizations.

LEED's Heat Island Effect: Roof credit is intended to mitigate the effects of heat islands on the natural and manmade environment. To earn the credit, a building must satisfy one of three options including the provision of a vegetated roof on 50% of the roof area, or a roof with a Solar Reflectance Index (SRI) of 78 or higher for a low-slope roof (29 or higher for a steep-slope roof) on 75% of the roof area, or some combination of the two strategies. Since white reflective roof membranes are invariably less expensive than vegetated roofs, it seems likely that they will frequently be selected on low-slope projects where the earning of this LEED credit is a priority

## **2. SCOPE OF STUDY**

During high wind events, low-slope roofs are vulnerable to detachment from uplifting forces. These forces are especially damaging when winds strike the corner of a building, creating vortices. When suction pressures are transferred to the roof membrane, common methods of attachment may fail. By contrast, pressure-equalized roof systems use the power of the wind to transmit low pressure to the space immediately beneath the roof membrane, pulling the membrane down to the roof surface.

The authors' previously-published research (Grant et al. 2007) described an omnidirectional roof vent designed to be installed as part of a single-ply membrane roof assembly. This vent, shown in its further-developed form in Figure 2, uses the Bernoulli and Venturi effects to create a low-pressure zone beneath the roof membrane. Optimized for ease of manufacturing and installation, the vent is capable of channeling wind from any direction.



Figure 2 - Omnidirectional low-pressure vent

Continuing research described in this paper has provisionally determined the permissible amount of infiltration into the depressurized roof system, the tributary area of each vent, and the interaction with the underlayment beneath the membrane. A subsequent test of the vent conducted by Underwriters Laboratories Inc. determined that a single low-pressure vent in a test apparatus can resist uplifting pressures up to 9,340 Pascal. Research is ongoing to extend the benefits of the low-pressure technology to other applications such as parapet vents and ridge vents, and to investigate other uses for the technology, such as drying wet roof assemblies and venting attic spaces.

### **3. BACKGROUND**

#### **3.1. *Pressure-equalizing concept***

Resisting the effects of high winds and wind gusts is a critical parameter in roofing design. During periods of wind activity, pressure variations develop on the surfaces of buildings. The focus of this paper is on low-slope, single ply roofing and its ability to resist wind-generated forces. On a building with a low-slope roof, high pressure is generated at the windward face of a structure, while low pressure is generated at the leeward and roof surfaces. The low pressure on the exterior of the roof system becomes problematic because the interior face of the system is simultaneously subjected to the relatively higher static pressure present inside the building. The permeability of the roof deck and insulation determines the degree and speed with which the roof membrane is affected by the pressure differential between the interior and exterior (Dregger 2002).

#### **3.2. *How traditional roofing systems resist wind-induced pressure***

The most prevalent traditional methods of attaching a low-slope, single ply roofing membrane to its substrate are fully adhered systems, mechanically fastened systems, and loose-laid ballasted systems. In a fully adhered system, the membrane and underlayment work together to withstand uplifting forces. In a mechanically fastened system, the low pressure above the membrane often results in an upward deflection of the membrane, causing an expansion of the thin layer of air immediately below the membrane, thereby reducing the pressure. This pressure then acts on the roof deck immediately below this thin layer of air. The roof deck then resists the upward pull of the low pressure. If the deck is relatively impermeable, it will resist much of the load. If, however, the deck is permeable, positively

pressurized air from the interior of the building will infiltrate into the space between the membrane and the deck, forcing the membrane to balloon upward as it resists the uplift forces, consequently creating significant stress on the fasteners. This process is illustrated in Figure 1. In a ballasted system, the ballast weighs down the membrane, allowing it to deflect upward only if the uplift pressure exceeds the force of gravity on the ballast.

### **3.3.     *How existing pressure-equalized roof systems resist wind-induced pressure***

Existing pressure-equalized roof systems, also known as vacuum systems, are a less common method of membrane attachment. These systems are fully adhered at roof edges and penetrations and loose-laid, without adhesive, in the field of the roof. Equalizer vents permit wind-generated low pressure at the roof surface to transfer to the thin layer of air just beneath the roof membrane, causing the membrane to be pulled downward. The roof deck must be carefully detailed to prevent air pathways between the building interior and the space beneath the roof membrane. The negative pressure generated beneath the roof membrane must be sufficient to resist the effects of higher-pressure air infiltrating from beneath the deck. Fortunately, the faster the wind speed, the lower the pressure generated on the roof surface and the better the system works. Such systems rely on wind vortices generated at building perimeters and corners to create the necessary low pressure at the vent locations. The equalizer vents are placed in the locations of the vortices to take advantage of the low pressure created when the wind stream is disturbed by the building edge.

### **3.4.     *How the new omnidirectional low-pressure vent resists wind-induced pressure***

The system discussed in this paper differs functionally from other pressure-equalizing vent systems currently on the market in several ways. First, the wind vent developed in this project is positioned in the uninterrupted wind stream in the field of the roof, rather than at a roof area's corners and perimeter. The vent itself creates the low pressure required to hold the roof membrane in place, rather than relying on low pressure induced by wind vortices at roof edges. The principle of operation of the omnidirectional vent is depicted in Figure 3. When wind passes between the two convex solid surfaces (domes) of the vent, its speed increases, and according to Bernoulli's law the pressure drops. The pressure in the upper dome is lowered due to an opening in the upper dome located at the narrowest point of the gap between the domes. Consequently, air is pulled from the lower dome through the hollow posts to the upper dome and out the opening to the free air stream.

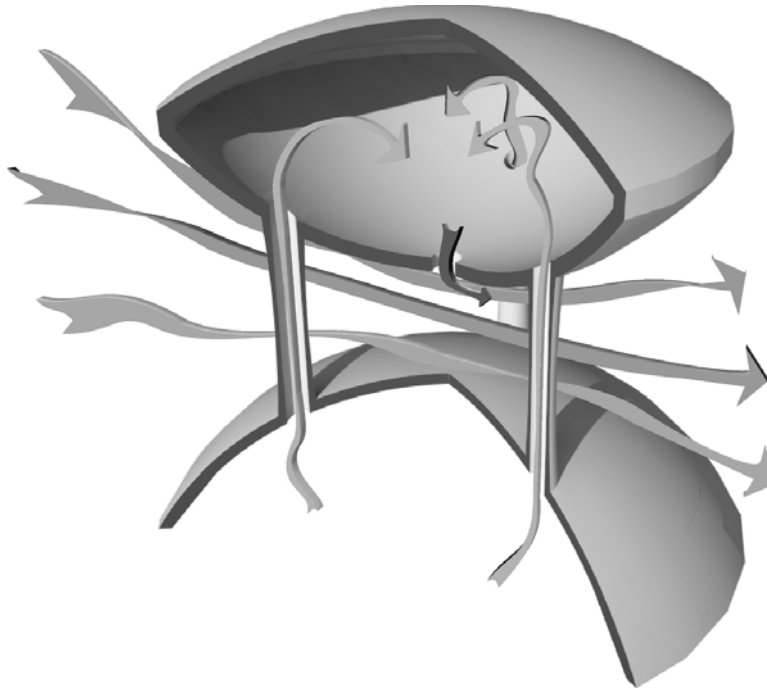


Figure 3 – Illustration of wind forces at omnidirectional low-pressure vent

It is anticipated that the proposed system will perform even better than existing pressure-equalized roof systems, which work by transferring low ambient pressures at the roof surface to the space below the membrane, because the shape of the new vent will induce pressures beneath the roof membrane even lower than those occurring at the roof surface. Additionally, the new vents, by creating pressure lower than that naturally present above the roof, will allow the system to tolerate a certain amount of infiltration, lessening the reliance of the system on a completely sealed roof deck key to the success of current pressure-equalizing roof systems. The low pressure generated by the proposed vent system will compensate for some quantity of air entering the interstitial space between the roof membrane and the roof deck due to tears in the roof membrane (a potentiality in storm conditions with wind-blown debris) and infiltration from the building interior due to inevitable gaps in the roof deck and insulation beneath the roof membrane. Wind tunnel testing conducted in the Stability Wind Tunnel at Virginia Tech during the development of the low-pressure vent included the introduction of a measurable amount of infiltration.

## 4. TESTING

### 4.1. *Testing the effects of infiltration*

One of the objectives of the study of the low-pressure vent prototype was to test the effects of infiltration on the ability of the vent to maintain negative pressure beneath the roof membrane. If the vent could tolerate some leakage, this would demonstrate a certain factor of safety in the system, proving that certain levels of infiltration would be acceptable at given wind speeds. These levels would give some indication of how airtight the roof deck would need to be for the system to work effectively. To test the hypothesis that the wind vent would generate sufficient negative pressure to counteract a measured amount of infiltration, a 19-millimeter diameter plastic tube was inserted into the void beneath the lower dome and connected to a check valve in the line, allowing measurement of the gauge pressure with and without infiltration. This setup is shown in Figures 4 and 5. The low pressure zone in this proof-of-concept test was limited to the void immediately beneath the dome, sealed with duct tape to the floor of the wind tunnel. The propagation of this low pressure zone under a roof membrane was explored with further testing explained in Section 4.2.



Figure 4 - Experimental setup in the Stability Wind Tunnel at Virginia Tech

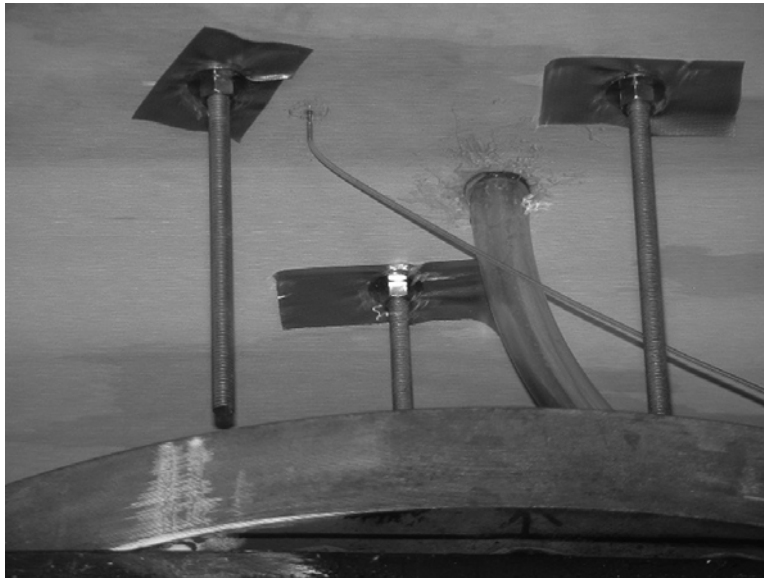


Figure 5 - Underside of plywood platform with plastic tubing

The flow meter attached to the line measured the infiltration flow rate in liters per hour. The pressure was recorded at wind speeds from 77 to 233 km/h with no infiltration, and again with the check valve opened at the same wind speed. The amount of infiltration was also recorded at each wind speed interval. Table 1 shows the pressure coefficient  $C_p$  versus the wind tunnel speed for the assembly with and without infiltration introduced into the void beneath the lower dome.  $C_p$  is defined as the quotient of the gauge pressure, or difference between the static pressure under the lower dome and the static pressure in the free air stream, divided by the dynamic pressure. The degree to which this drop in static pressure occurs is a function of the geometry of the wind vent and is manifested in the pressure coefficient. The lower the pressure coefficient, the more effectively the vent creates the desired negative pressure.

Table 1 – Stability Wind Tunnel data

Speed (km/hr)	Leakage (L/hr)	C <sub>p</sub> (no leakage)	C <sub>p</sub> (with leakage)	% diff in C <sub>p</sub>
77	No data	-1.11	-1.08	2.65
106	No data	-1.07	-1.06	0.99
130	1.7	-1.07	-1.05	1.64
150	2.2	-1.06	-1.05	0.62
167	2.8	-1.05	-1.04	1.01
183	3.5	-1.03	-1.02	0.85
198	4	-1.01	-1.01	0.75
211	4.5	-1.02	-1.00	1.96
225	5.2	-1.02	-1.01	1.14
233	5.5	-1.03	-1.02	1.16

As the wind speed increased, the rate of leakage also increased. The pressure beneath the lower dome decreased at roughly the same rate, which kept the pressure coefficient  $C_p$  fairly constant throughout the full range of wind speeds tested. The average difference in  $C_p$  between the sealed model and the model with leakage was 1.28%, suggesting that the prototype generated sufficient low pressure to tolerate significant infiltration without a noticeable loss of performance.

#### **4.2. Spacing of vents and evaluation of underlayment materials**

Another research question arising from the initial testing of the low-pressure vent prototype was the required spacing of the vents. If the roof membrane were loose-laid, the tendency might be for the low pressure to attach it firmly to the substrate in the immediate location of the vent, effectively creating a seal in this area. This might in turn leave large areas of roof membrane not near a vent vulnerable to uplifting forces. While the typical solution to this problem, used with previous pressure-equalized roof systems, is to leave “wrinkles” in the roof membrane, the research team was concerned that the strong suction created by the vent might create sufficient low pressure to flatten out these wrinkles and thus defeat their purpose. To help address this question, Manoj Kumar (2006), then a master’s student at Virginia Tech, investigated the propagation of the low-pressure zone beneath the roof membrane. Using a vacuum pump to simulate the low-pressure zones created by the vent, he took pressure readings at set distances from the vent to determine how far the low-pressure zone extended. The experimental setup was installed atop the Research and Demonstration facility at Virginia Tech. The installation was tested with four different underlayment products, which Kumar hypothesized would extend the low-pressure zone away from the vicinity of the vent. The four underlayments tested were a spun-bound polyester unstitched fleece; a spun-bound polyester fleece, stitched at fixed intervals to create air channels in the fabric; a non-woven, multi-dimensional mesh, manufactured from nylon and polyester; and a waterproof, dimpled plastic membrane which allows air to move freely. Of these four options, the steady-state analysis results showed that the non-woven, multi-dimensional mesh product provided the greatest propagation distance, extending the low-pressure zone to approximately 3 meters away from the vent.

The omnidirectional low-pressure vent has been installed in multiple locations by the roofing firm that helped to develop it, Acrylife, Inc. A typical installation is shown in Figure 6.





Figure 6 - Vent system installation at VT KnowledgeWorks building, Blacksburg, Virginia

As part of the ongoing testing of the low-pressure vent, Acrylife Inc. submitted the vent for testing by Underwriters Laboratories Inc in 2009. In a typical wind uplift test setup, a single-ply reinforced PVC membrane was loose-laid on top of two strips of 300-millimeter wide polypropylene filter fabric which crossed in the center of the apparatus, on top of a plywood substrate fastened to wood joists. The PVC membrane was adhered to the plywood at the perimeter with acrylic tape. The vent was installed in a hole in the membrane at the center of the platform, and its flange was welded to the membrane. The top of the apparatus was a 3-meter by 3-meter section which applied suction pressure to the top of the membrane in 720 Pascal increments, applied at one-minute intervals. The membrane sustained an uplift pressure of 9,340 Pascal before it began to delaminate from its substrate. While this test cannot be extrapolated to infer the performance of the vent in a larger roof system, it was encouraging as a further proof of concept.

## 5. CONTINUING RESEARCH

### 5.1. *Parapet vent*

The current design for the omnidirectional roof vent is most applicable on low-slope roofs in the free air field in the wind reattachment zone away from the perimeter of the building. As a result, at the perimeter of the roof where the vents are less effective, the roof membrane must be either fully adhered or mechanically attached. This adds cost to the roof assembly and reduces the benefits of the vent system. If, however, the current vent design could be modified for application to perimeter wind flow patterns at parapet wall assemblies, then the need for perimeter attachment could be eliminated. This would reduce the cost of the roof installation and improve its resistance to uplift. The research team that designed the original vent has developed an alternative design specific to parapet wall applications. The new design is a linear solution designed to top the parapet wall, with a modified geometry intended to address and take advantage of the convergence of vertical and horizontal air flow streams near the top of an exterior wall. The proposed geometry acts to converge and accelerate these flow streams to induce a low-pressure zone at the vent, similar to the original design.

The new perimeter vent would be mass-produced with injection molding of a recycled plastic material, and would be produced and marketed in standard construction lengths such as four, eight, or twelve feet. The proposed design for parapet walls would include a flange extending over and down the parapet wall to provide a path to transfer the low-pressure zone beneath the roof membrane. This flange would also permit simple attachment of the vent to the roof membrane.

## 5.2. Ridge vent

Another project under development is a new system for steep-slope roofs incorporating a vent that will counteract the uplifting pressures of high winds. The new invention is designed to generate low pressures in the interior of buildings rather than between the roof membrane and its underlayment. To be applied as part of a complete roof system it will be necessary to ensure that there are few leaks in the building envelope and that the pressure inside the building will be kept lower than the low ambient pressure developed on the roof by storm or hurricane winds. When the vent operates, interior pressures lower than the ambient will be generated and the roof of the structure will be sucked down and firmly attached to the walls of the structure. This action will counter the typical failure point between roofs and walls during high wind events. This mechanism will essentially harness the power of the storm winds to develop suction inside the building that will be even lower than the uplifting suction effect of the wind. The concept is shown in Figure 8.

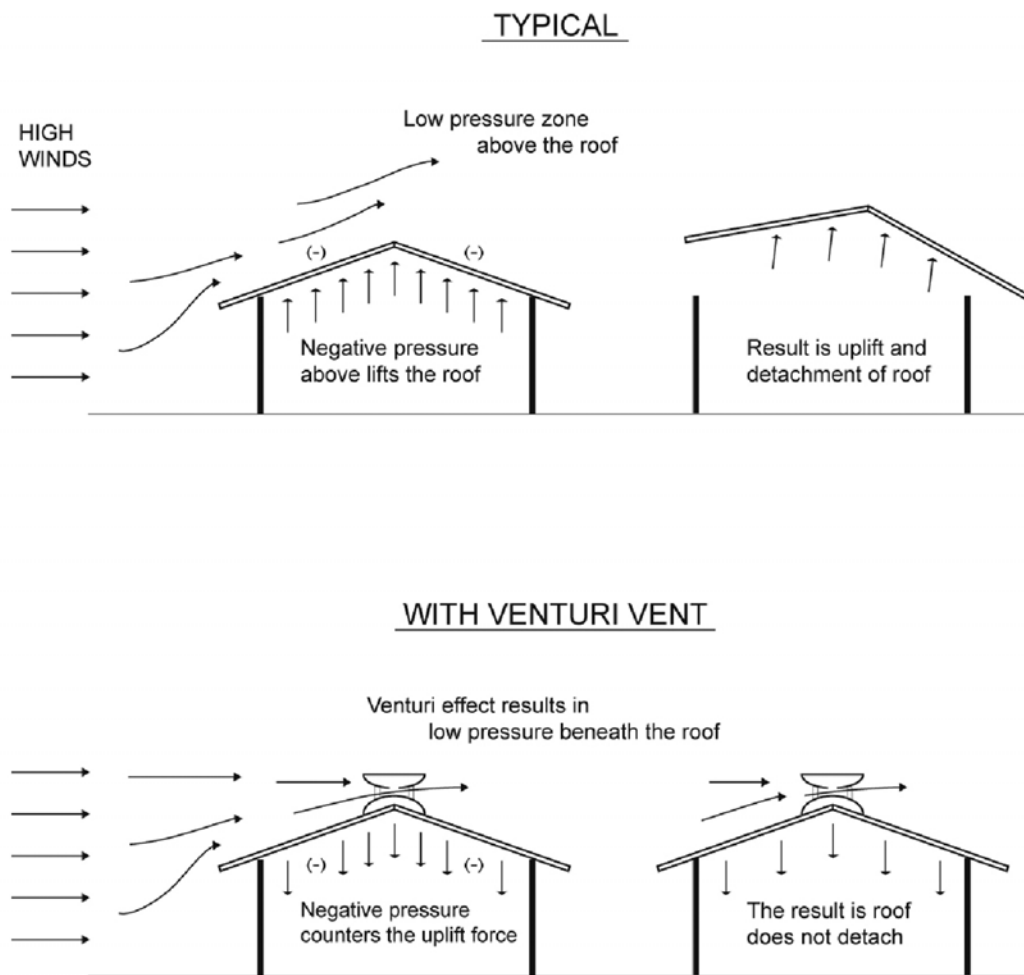


Figure 7 - Concept of new ridge vent

For low-slope roofs, the shapes of the domes should be such that they present convex surfaces to the wind, as shown schematically in Figure 8a. But for steep roofs, such a design may not work as well. This is because, as shown schematically in Figure 8b, air flowing along the steep roof may stagnate close to the hole of the upper dome. The area around the stagnation point is characterized by elevated, not lower pressure, and therefore such a design

may have the opposite effect than the desired lowering of the pressure. This difficulty can be surmounted with alternative designs shown in Figures 8c and 8d. The idea is to move points of stagnation away from the hole, and guide the flow so that the gap between the two domes is the smallest right at the location of the hole. This will force the flow velocity to be the highest at this point, which in turn implies that the pressure will be the lowest.

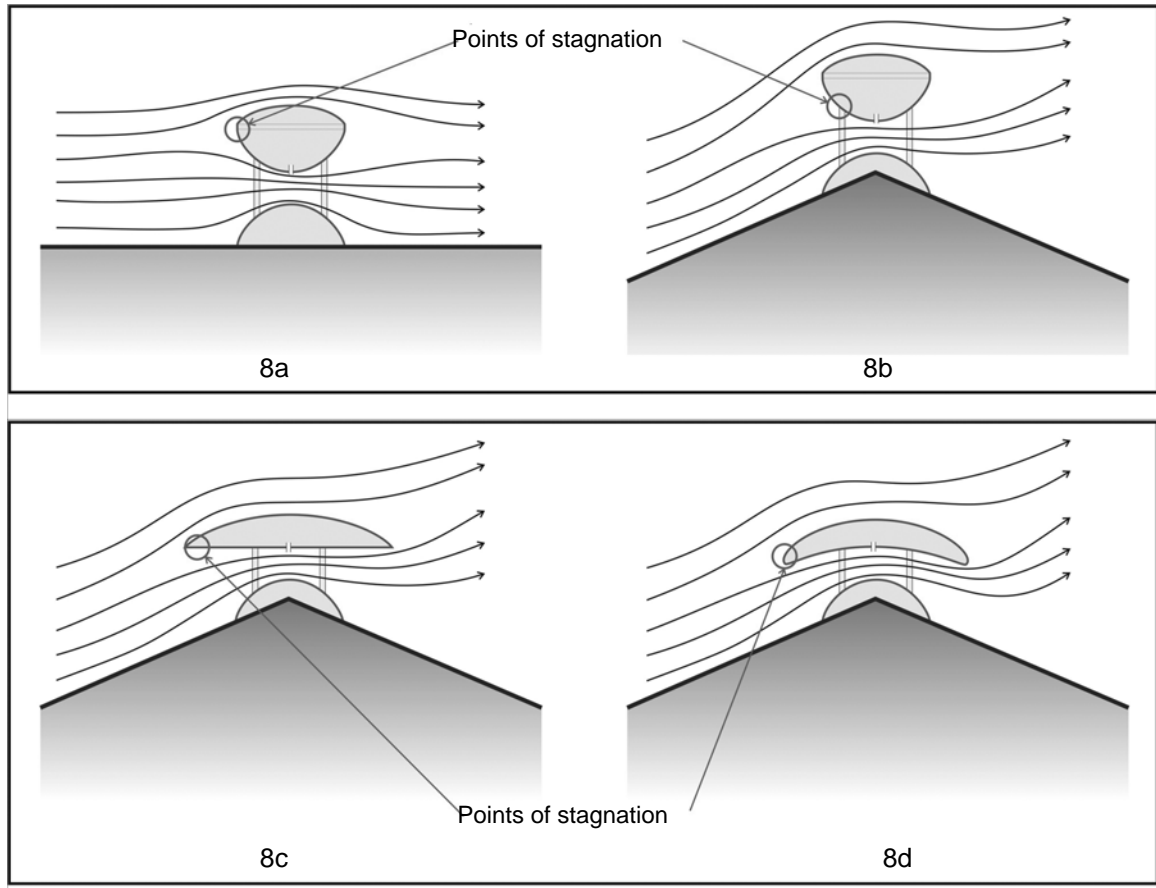


Figure 8 - Diagrams of new ridge vent

The consequences of these differences in pressure conditions between the existing design and the new application are as follows:

- 1) The geometry of the upper element must change to extend beyond the edge of the lower element to act as a funnel of the wind through the gap between the two domes,
- 2) The upper element may have either a smooth or concave geometry to further act as a wind funneling mechanism,
- 3) The vent base will have two rather than one flange element to accommodate multiple roof layers, and
- 4) The device may be configured as either a circular or linear roof element.

The expected outcome of this ongoing inquiry is the generation and optimization of a circular and/or linear device for equalizing wind-induced pressures between the exterior of a roof and the interior of a structure. This roof vent, when implemented as part of a whole-building strategy, will prevent roof uplift in high-wind situations.

## 6. ADDITIONAL BENEFITS OF PRESSURE-EQUALIZED ROOF SYSTEMS

Another possible benefit of pressure-equalized roof systems is their purported ability to dry out a wet roof assembly. In existing pressure-equalized roof systems, equalizer vents are equipped with one-way valves that allow air to exit

the space beneath the roof membrane while preventing air on the surface of the roof from entering. This feature permits warm, moist air to escape the roof assembly when the flap is lifted by the low pressure generated by the wind, but when winds are absent, the flap is re-seated and prevents backflow of humid air into the roof assembly. Due to the radiation of the sun and the stratification of air within the interior of a building, the air within the roof assembly tends to be hotter than the air in the building below. If the roof assembly contains liquid water, it is vaporized due to the elevated temperature of this air. When the wind blows, the low pressure generated by wind vortices is transferred beneath the membrane by equalizer valves, contributing further to the vaporization of water and accelerating the drying process. Theoretically, water-vapor laden air is pulled out of the roof space by the low pressure generated by the wind when the valve is open. The degree to which this passive process removes water from roof assemblies remains to be fully proven. The current iteration of the omnidirectional low-pressure vent has been designed with one-way flaps to prevent exterior air from being pulled beneath the roof membrane by an adjacent vent. Therefore, these vents may be able to provide the same drying function as equalizer vents, and may in fact perform more efficiently because of the greater suction pressure they provide.

Existing pressure-equalized roof systems ostensibly assist the expelling of air from equalizer vents by strategically placing them in the areas of lowest pressure to provide a superior drying potential. The ability to dry out a wet roof is especially important in re-roofing applications where it is physically or economically infeasible to remove existing damp insulation and/or sheathing board from a roof. Warren French (2003), in his study of the drying capacity of a pressure-equalized roof system on a re-roofing project in Houston, Texas, observed that wet roofing materials contribute to the premature failure of roof assemblies through several vehicles, including corrosion of metal fasteners, steel roof decks or steel reinforcing in concrete roof decks, and structural steel supporting the deck. Moisture-laden substrates can also contribute to the accelerated degradation of roof membranes. Further, wet insulation has a reduced thermal resistance, permitting undesirable energy transfer through the roof assembly. French found that, over a five-year period, there was a trend toward overall drying in the roof studied, with a significant reduction in the maximum moisture content of lightweight insulating fill.

In an earlier study, Tobiasson, et al. (1983) reported disappointingly slow rates of drying by one-way, two-way, and solar-powered “breather” vents used to remove moisture from perlite and fibrous glass insulation in compact roof test assemblies. However, in a separate set of field tests, they observed that a vacuum cleaner was able to remove a significant amount of water from wetted fibrous glass roof insulation, restoring most of its original thermal resistance.

While further research is necessary to evaluate the overall success of the drying potential of pressure equalizing roof systems, French’s study points to the roofing industry’s interest in this application, and its inherent benefits. Because the omni-directional low-pressure vent creates suction pressure similar to the action of a vacuum cleaner used in the study by Tobiasson et al., it may provide drying potential superior to that of passive venting strategies. Continuing research utilizing the low-pressure concept may also prove that the concept is useful not only for drying out wet roof insulation in low-slope assemblies, but also in venting humid attic spaces in steep-slope assemblies fitted with the proposed ridge vent discussed above.

## **7. CONCLUSIONS**

Research to date on the omnidirectional low-pressure vent has proven that it is possible to harness the power of the wind to secure the roof membrane to its substrate, even in storm conditions. The implications of this finding for economic and environmental sustainability are significant. Removing or reducing the need for fasteners or adhesives reduces labor and material costs, and decreases the embodied energy of the entire system. The success of the current omnidirectional low-pressure roof vent system, and all future systems derived from it, relies on the provision of a reasonably airtight system that provides some degree of tolerance for inevitable infiltration. All future research will rest on this premise as new prototypes and systems are explored.

## REFERENCES

- Dregger, P. (2002). "Air infiltration: the enemy of wind resistance and condensation control." *Interface*, 20(5), 21-29.
- Federal Emergency Management Agency. (1993). *Building performance: hurricane Andrew in Florida: observations, recommendations, and technical guidance*. Washington, D.C.: Federal Insurance Administration.
- Federal Emergency Management Agency. (2010). Top Ten Natural Disasters Ranked By FEMA Relief Costs Retrieved July 7, 2011, 2011, from <http://www.fema.gov/hazard/topten.shtm>.
- French, W. R. (2003). "Further evaluation of a pressure-equalized single-ply roofing system to determine drying effects on a moist cementitious roof deck". *Interface*, 21(9), 5-12.
- Grant, E., Jones, J., & Vlachos, P. (2007). "Design and wind tunnel performance testing of a new omnidirectional roof vent." *Journal of Architectural Engineering*, 13(1), 18-21.
- Kumar, M. (2006). *In-situ monitoring of an omni directional roof vent on a low slope single ply roof to indentify most efficient porous underlayment for maximum pressure propagation* (Master's thesis).
- McDonald, J. R. & Smith, T. L. (1990). *Performance of roofing systems in hurricane Hugo*. Lubbock, TX: Institute for Disaster Research, Texas Tech University.
- National Roofing Contractors Association. (2009). *The NRCA vegetative roof systems manual, second edition*, National Roofing Contractors Association, Chicago.
- Tobiasson, W., Korhonen, C., Coutermarsh, B., & Greator, A. (1983). "Can wet roof insulation be dried out?" *Thermal insulation, materials and systems for energy conservation in the 80's, ASTM STP 789*, ASTM International, West Conshohocken, PA, 626-639.