

# A STUDY OF THE BEHAVIOR OF LOOSE-LAID, BALLASTED SINGLE-PLY ROOFING SYSTEMS SUBJECTED TO VIOLENT WINDS

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**T**he explosive growth of the single-ply roofing market in recent years has produced a flood of information, making it difficult for design professionals, building owners, and contractors to keep abreast of the ever-changing industry. The same has been true with standards and testing criteria; those which could be derived from existing BUR Standards were the first on line. Some items, however, could not be tested by adopting past tests and performance studies. The behavior of the loose-laid, ballasted membrane in violent wind conditions is one aspect of single-ply roofing that is unique. Wind tunnel testing of all types has given us a profile of the effects of wind on various roof configurations, but actual wind effect data on the loose-laid, ballasted membrane was lacking. Scale model tests of specific product designs have added insight, but the limitations of size and testing economics have made actual duplication of conditions impractical.

Although the installation numbers were growing, field experiences were difficult to find due to the "better safe than sorry" method of code application to the product, which rightfully limited use to those areas of exposure where the most information could be gained. Some scattered reports from localized exposure to high winds had been reported, but the scarcity of the reports precluded finding any logical patterns of behavior.

In 1982, the eastern slopes of the Rocky Mountains were to experience some of the most violent winds ever recorded. Akin to foehn winds of France, these winds are not strangers to the area and are called "Chinooks." Factory Mutual (FM) classifies this area on its Wind Force Map as being in the 80- to 90-mph design range (annual extreme, 100-year occurrence interval). The moment was opportune; codes had not limited the growth of the single-ply market, and the area's rapid population growth resulted in numerous installations on varied building types and exposures.

## METHODOLOGY

Of foremost consideration was the recurring exposure to violent winds of long duration at two separate peak periods—one in January and one in April. To form a nucleus for the study, a major manufacturer in the single-ply market provided warranty applications on a variety of buildings in the area. This information aided in the reduction of time between occurrence and investigation because it gave me contact names, phone numbers and addresses of the owner, architect, contractor and supplier as well as descriptions of deck construction, insulation and roof system installation. Unusual conditions also were noted.

Since investigation was to occur "after the fact," a

method for collecting overlapping information was developed in an attempt to provide cross-references for substantiation of data wherever possible. Sources for obtaining information included:

- eyewitness reports;
- owners' information;
- architects' information;
- news reports;
- contractors' information;
- insurance claim information;
- manufacturers' information; and
- United States Weather Bureau data.

The extent of available information for each project depended upon the response and reliability of its various sources.

Two classifications were used in assembling the information and in providing a guideline for its organization: the grouping of buildings by location, and the classification of failures by type. Grouping of projects by location was as follows:

- **Group A:** eight projects in the Fort Collins area, about 50 miles north of Denver
- **Group B:** seven projects in the Boulder area, about 25 miles northwest of Denver
- **Group C:** five projects in the Colorado Springs area, about 60 miles south of Denver
- **Group D:** seven projects in the Denver area, including Golden, about 10 miles to the west.

To eliminate the vagueness of the term "failure" and to better compare the various buildings, the reported wind effects were classified as follows:

- **Class I:** the greatest effect, usually noted as membrane rupture and subsequent loss of insulation
- **Class II:** the displacement of insulation below the membrane, usually requiring splitting of the membrane to make repairs
- **Class III:** the displacement or scouring of ballast, leaving uncovered vulnerable membrane areas
- **Class IV:** no observed or reported damage to the roofing system in the field

## OBSERVATION AND EVALUATION

With respect to interpretation of the data presented in this section, the following clarifications should be noted:

- Descriptive details such as roof area, building height, parapet height, new or reroofing, and substrate type were

obtained from direct observation, manufacturers warranty applications or both.

- Wind reports, in most cases, have been conservatively adjusted by established guidelines to reflect rooftop wind velocities, depending upon the reliability of the available reports.
- Orientation to wind is broadly categorized as either perpendicular or oblique because precise data for wind direction was limited.
- Ground roughness descriptions also are included in the tabulations, representing subjective on-site evaluations of upwind terrain conditions based on the best available estimates of wind direction at the time of failure.
- Reported repair costs are actual charges to perform the indicated repairs, as provided by insurance claims and contractors records.
- Roofing ballast in all cases was the typical large round river rock, usually specified as "¾-1½-inch river-washed stone."

## GROUP A PROJECTS—FORT COLLINS

### A1. Colorado State University (CSU) Canine Facility

A single-story, non-windowed research facility on the main campus. The building size was approximately 35 feet by 85 feet. The EPDM roof was new construction on a precast concrete slab with 12-inch parapet walls.

**Class IV**—No damage was reported, although winds were established to have reached 110 mph in the area. Large grain bins and storage buildings in the area were overturned and damaged. (*Table A.*)

### A2. CSU—Center for Disease Control

A new two- and three-story office and lab facility in the foothills campus area. The roof was new construction on a concrete slab with moderate parapet walls. The single-ply rubber roof was a limited area covering an elevator and entry addition on the leeward side, protected by higher building projections.

**Class IV**—No damage was reported from winds higher than those reported for the main campus area, which were in excess of 130 mph.

### A3. CSU—Engineering Research Building

A two-story classroom and lab building in the foothills campus, reroofed over an original concrete deck with low parapet walls. The original roof had been removed. The EPDM roof was over an east-west wing with a high aspect ratio, 40 feet wide and 200 feet long.

**Class II**—During a January wind, the northwest corner formed a classic, scouring vortex, resulting in the displacement of ballast and subsequent ballooning and pulsing of the membrane. The insulation was displaced and the membrane received numerous minor abrasions from the rough concrete deck. Wind was reported in excess of 130 mph at the adjacent U.S. Weather Bureau atmosphere research center. BUR roof loss and other damage was reported in the area. A 20-square-foot area of insulation was repositioned and a 10-square-foot area of membrane was replaced as a precautionary measure. The repair included approximately 100 feet of parapet and hatchway flashing, with pavers added at the northwest and northeast corners.

### A4. CSU—Microbiology Building

A three-story 40-foot-high classroom and lab building in the educational cluster of the main campus. It was reroofed with rubber over the original 65-foot-by-120-foot concrete deck construction with low, 6-inch parapet walls. The original roof was removed prior to reroofing.

**Class III**—Ballast was displaced at the northwest and northeast corners and a small balloon formed during a January wind, which was reported in excess of 100 mph. Skylights and atrium spaces nearby were damaged. Other roof damage was reported. The ballast was redistributed by physical plant personnel. No damage was reported on the higher penthouse roof which has 12-inch parapet walls.

### A5. CSU—Liberal Arts Building

A three-story, 35-foot high atrium classroom building in the educational cluster of the main campus. It was reroofed with EPDM over the original concrete deck construction having 24-inch parapets. The original roof was removed.

**Class IV**—No damage reported. Surrounding buildings experienced miscellaneous minor damage including some roof damage.

### A6. CSU—Engineering Building (East Wing)

A two-story, 25-foot-high classroom building on the main campus. This building was shielded by others and was reroofed over the original 135-foot-by-50-foot concrete deck construction, with 8-inch parapet walls. The single-ply EPDM roof is the east wing of an "E" shaped building. The aluminum-faced modified bitumen system on the stem portion of the E showed signs of delamination.

**Class IV**—No damage was reported.

### A7. Larimer County Vo-Tech Buildings A, B and C

This is a single-story complex of buildings housing various vocational areas, classrooms and support facilities. EPDM reroofs covered precast concrete slabs with 6-inch to 12-inch parapets. The original roof was removed. The buildings were of different irregular shapes, but of approximately equal dimensions except for Building B, which has two 40-foot wings of lengths up to 120 feet.

Damage was categorized as follows:

- **Building A: Class III**—Ballast was displaced on the northwest corner, and redistributed.
- **Building B: Class III**—Same as Building A
- **Building C: Class II**—Ballast was displaced on the northwest corner and a balloon formed, resulting in displacement of insulation. The membrane was weighted with masonry units during exposure. The membrane was slit to replace insulation, and ballast was redistributed with pavers added at the corner.

It is believed that the original scouring occurred during the 100 mph wind reported in January, and that any ballooning went unnoticed. The subsequent April winds of equal or greater speed caused the damage noted above. Note that Building C consisted of a number of overhead doors serving the auto bays. These openings allowed greater infiltration during the periods of wind. This area had experienced subsequent scouring at another corner during some unknown period. Short period of high winds were evidently common at this location.

### A8. First Tower Building

A 13-story office building in downtown Fort Collins. It was reroofed over original metal deck with high parapet walls, using an adhered system for EPDM membrane attachment. Winds in January were reported at over 100 mph.

**Class IV**—No damage reported to the membrane and roof; however, repair was required to reattach a coping metal piece on the southwest corner, which was loosened during January winds.

## GROUP B PROJECTS—BOULDER

### B1. Martin Park Elementary School

A one-story, 12-foot high classroom complex with a high roof (20 feet). Some areas of original built-up roof and a small area of adhered EPDM single-ply were observed in addition to the ballasted EPDM sections. It was reroofed over an original metal deck. There were no parapet walls except for one section with a 12-inch parapet (*Table B.*)

**Class II**—In January, during reported winds of 100 mph, the high roof over the multi-purpose space scoured and ballooned in the northwest corner and to the rear of a roof-mounted unit near the center of the roof and in alignment with the corner, following the direction of the wind. Damage remains, with the exception of added masonry units to provide weight in scoured areas. Water had collected in the low areas where insulation was missing. The section surrounded by the 12-inch parapet was not damaged even though it borders the windward edge of the building.

### B2. KSA Building

A one-story, 14-foot high manufacturing building, 120 feet square, with a 22-foot high roof crane bay in a commercial park of 18 buildings. This is new construction employing EPDM over a metal deck with a very low parapet edge. Winds in the area toppled transmission lines, dropped garages, and lifted roofs, while maximums in excess of 130 mph and one period of gusts over 120 mph constituted the peak problem periods.

**Class I**—In January, the northwest corner ballooned and subsequently ruptured, displacing insulation. Consequently, additional membrane and insulation was lost over an area of approximately 60 square feet. It was the architect opinion that the balloon ruptured due to a puncture from flying debris, possibly a metal coping piece.

### B3. RAW 4

A one-story, 12-foot-high structure, one block west of the KSA building and receiving similar exposure, with wing lengths of 120 feet forming an ell-shape with 30- and 50-foot widths. The high parapets (12-24 inches), however, limited damage.

**Class III**—There was scouring of ballast. The shape and exposure of this structure caused a linear scour action along one ell-shaped wall. A high exposure area, this site would be considered a choice testing spot due to comparable building shapes and roof types. Other buildings in this park received varying amounts of damage.

### B4. Fleischmann Building

A single-story building of varying levels (12 to 20 feet high) or irregular shape having high parapets (30 inches) relative to building size. Winds of 100 mph were noted in January. The single-ply areas were of both adhered and ballasted systems of limited relative size and were reroofed (old roof

removed) on plywood deck. The largest ballasted area was 25 × 45 feet; two smaller areas also were included.

**Class IV**—No damage reported.

### B5. Siemens Building

A two-story, 25-foot high office complex serving an adjacent manufacturing facility north of Broomfield, Colo. and east of Highway 36. The roof was a new ballasted single-ply over precast deck sections. The roof was approximately 60 × 160 feet and was exposed to winds in excess of 100 mph, both in January and April 1982.

**Class II**—In January, the ballast at the west end of the building was scoured, and resultant ballooning caused some minor displacement of insulation. The immediate area behind the northwest parapet was slightly scoured in a linear fashion, widening as it reached the northeast end of the structure. Insulation was replaced without membrane splitting and rock redistribution for a total of a few hundred dollars. Following a similar but less severe scouring in April, paver stones were installed.

### B6. Storage Technology Building Number Five

The central building in a complex of structures, two stories and 30 feet high. Structures Four and Seven (to either side) were BUR membrane and metal panel, respectively. Building Six (Project B6-B) is located to the rear of Building Four, and was not accessible due to "classified work" but was viewed from the roof of Building Five. All perimeters were constructed without parapets.

**Class II**—In January, with winds of 120 mph reported, the ballast of the northwest corner was scoured and insulation was displaced on Building Five and an additional area near a mechanical unit was scoured slightly. Building Six was similarly damaged, with scoured areas affecting some 25 percent of the roof.

### B7. Wind Energy Center (U.S. Department of Energy)

An experimental station for the study of wind energy strategically placed in a known high-wind area. The building was a three-level roof of both precast (at 15 and 23 feet) and acoustical metal deck at 32 feet. The lowest level had 12- to 24-inch parapets with battered rear surfaces, while the upper levels had flush edges at the low sides and 8-inch parapets elsewhere. Both adhered and ballasted systems were used.

**Class I**—In January, extreme winds blew over a three-day period, causing scouring, ballooning, insulation displacement, ballast and paver displacement, and ultimate rupture and loss of insulation over this roof. Also lost was the higher level of ballasted roof on the acoustical metal deck, a 100 percent loss. Roofs over acoustical decks are good candidates for loss due to the infiltration allowed by the perforated ribs, and are not FM-approved. Engineers recorded damage at various wind speeds up to the loss of their anemometer at 147 mph. The first reported ballast scouring occurred at 97 mph. CSU evidently tested a model of this building also, and found that its configuration produced multiple wind-speed vortices at the corners, seven to eight times actual recorded speed. The intermediate roof, an adhered EPDM system, was undamaged. Repairs consisted of reinstallation of the damaged areas as adhered, and unused ballast was added to the undisturbed ballasted areas for increased weight. Subsequent April winds in excess of 100 mph caused no damage.

## GROUP C PROJECTS—COLORADO SPRINGS

### C1. High Plains Elementary School

A single-story, low parapet design, basically an irregular ell-shape with a precast concrete deck structure. The building was approximately 19,500 square feet and was located in a new suburban area. It formerly was known as Briargate Elementary School.

**Class II**—In April, the ballast and insulation in a northwest corner and along the west wall was displaced in a small area by winds of 110 mph. Insulation was replaced and stone was redistributed at a cost of less than \$800, including addition of a "MARS" system at the exposed edges on approximately 3-inch centers.

### C2. Foothills Elementary School

Formerly known as Comstock Elementary School, it was a repeat of High Plains in all but orientation. The damage was nearly identical and the cost of repair the same. Another school, a high school which was under construction, suffered a major roof loss with a BUR system and cost over \$175,000 to repair. Even the deck was damaged from weld breaks. Area winds were reported at the Air Force Academy nearby at 100 to 110 mph with gusts to 137, which damaged the anemometer. The Academy's Atrium Building also was reported as losing a BUR system.

### C3. Mostek Manufacturing

A complex of buildings, consisting of a main manufacturing and office structure (C3-A) and two smaller structures to the south with mechanical (C3-C) and water treatment (C3-D) capabilities. Adjacent to the east and also observed was the United Technologies Building (UTC, C3-B). There were parapet walls of 18 to 36 inches on the two major structures, and six to eight inches on the smaller. The structures had precast concrete deck on the UTC, lightweight concrete over metal deck on the Mostek, and metal decks on the support buildings. The UTC Building was approximately 200 square feet; the Mostek Building was 300 square feet; the mechanical and water treatment buildings were 80 × 120 feet. The main structures were approximately 30 feet high, the support buildings 15 feet high. Exposure was high, with the exception of the water treatment facility which was shielded by the Mostek structure. The earth form created a wide wind tunnel effect in which the involved structures occupied the windward edge of the earth formation. Reported winds of 80 mph sustained speed and 110 mph gusts would be expected to be significantly higher for this area.

The reported damage was categorized as follows:

- **Mostek (C3-A): Class II**—In April, this structure was subject to scouring, ballooning, and insulation displacement over a large area inward from the northwest (windward) corner.
- **UTC (C3-B): Class II**—Severe ballooning with insulation displacement, punctured by roofers who were called to control the ballooning effect. Cost of repair was \$15,000 and included time spent on-site to control ballooning during periods of high winds.
- **Mechanical (C3-C): Class I**—High infiltration due to large garage bay doors resulted in membrane rupture and loss of insulation. Total repair costs for both the main Mostek Building and the Mechanical Building were \$27,000.
- **Water Treatment (C3-D): Class IV**—No damage; protected by higher main structure.

### C4. Hewlett Packard Building

A connected complex of structures directly to the north and slightly west of the Mostek complex. Similar high landform exposure conditions existed but slightly less severe. This structure was 370 × 180 feet square; two-story, metal decked, and without parapets. The ballasted EPDM single-ply was installed over the existing roof.

**Class III**—During April 1982, small scoured areas were formed at the northwest corner and against a higher center section of wall. Repair was less than \$450 to redistribute and add stone ballast as a precaution. Damage to an adjacent structure was of greater consequence to the owner. This structure has a BUR system. Extent and cost of the BUR roof repair was unknown.

### C5. Pike's Peak Center

This structure was a multi-level auditorium complex with its highest level the 95 feet high stage area. The larger main auditorium level was 75 feet high and the office area roof was 30 feet high. The shape of the roof was irregular and the deck was metal, with six- to 12-inch parapets at all roofs except the auditorium, which had 24-inch walls. Smoke vents on the upper roof increased infiltration potential. A general wind report indicated winds of 80 mph sustained, with gusts of 110 mph. All roofs were new ballasted EPDM Systems.

**Class I**—While still under construction in April, the upper stage-area roof was scoured, ballooned, and ruptured on the northwest end in the area of smoke hatches. The office area roof was scoured along its intersection with the higher auditorium wall, and one ballooned area ruptured. The auditorium-level roof, with a combination of high parapets and partial protection by the higher elevation, was undamaged. Following membrane repair, the insulation was replaced and the ballast redistributed. Some perimeter mechanical bar attachments on three-foot centers were added to inhibit subsequent damage. Repair was done for \$4,800, including reinforcing the perimeter and adding additional ballast in selected areas.

## GROUP D PROJECTS—DENVER AND GOLDEN, COLORADO

### D1. Colorado School of Mines (CSM-Brown Hall)

A three-story, 40-foot high engineering classroom structure of rectangular design, approximately 85 by 200 feet square with a lower, one-story wing on the west side. This new EPDM roof over metal deck construction was an observation platform at the approximate center of the upper level. During the visit in October some slight scouring was observed in the northwest corner, along the raised deck, and at scupper locations. Ballast appeared light in some areas. Winds in this area were high several times a year. While specific wind speed reports were not available, a minimum of 70-80 mph winds was confirmed.

**Class IV**—No damage reported (Refer to Table D).

### D2. Bear Creek Elementary School

A single-story structure 15 feet high with a lightweight concrete deck of irregular shape and a secondary roof elevation at 25 feet with a lightweight deck. Areas were both ballasted EPDM systems with flush edges on the lower level and six-inch parapets on the upper level. The reroof was installed over the existing BUR membrane, and some old BUR remains. Winds in the area were 100 mph, with trees lost to the rear of the school property.

**Class IV**—No damage reported. Some slight corner scouring of unknown origin was noted during this study, both on BUR and ballasted roof areas.

#### **D3. 104 Inverness Building**

A three-story structure 30 feet high having a precast deck of rectangular shape, 100×150 feet square, and parapets estimated at 12 inches high. Access could not be gained to this roof, so no notes on its condition were made. Winds in the areas were reported at 100 mph.

**Class IV**—No damage reported.

#### **D4. Denver Tech Tower II**

This eleven-story office tower is one of a three-tower complex south of Denver. All buildings are similar, approximately 180×80 feet square with eight-inch parapets and window stanchions at the perimeters. Construction was new, and the deck of precast concrete. Roofs are ballasted EPDM.

**Class II**—In April, with winds reported at 100 mph, Tower II (D4-A) had scouring and resultant ballooning and insulation displacement. Tower I (D4-B) was reported as having slight ballooning, and Tower III (D4-C), which was under construction, sustained similar damage but this condition was corrected by the contractor. Slight scouring was apparent at the time of inspection, and moderate winds were causing slight ballooning in scoured areas. Insulation was replaced and ballast redistributed, but the cost of repair was not known.

#### **D5. Lawrence Street Center**

A 13-story residential office building in downtown Denver. Access could not be gained to this roof. Winds of 80 mph were reported in the Denver area in April 1982.

**Class IV**—No damage reported.

#### **D6. May D & F**

A two-story commercial space within a mall shopping center, 30 feet high, with 18-inch parapets and steel deck construction. Insulation was mechanically attached, while the EPDM membrane was loose-laid and ballasted. The project was under construction and open at the time that winds were experienced. A higher penthouse roof with parapets of 24 inches received no damage; the penthouse shell construction had already been completed.

**Class I**—In April, the ballast was scoured; ballooning and subsequent rupture occurred with loss of insulation. Winds were estimated at 120 mph. Damage evidence indicates that the insulation fasteners caused punctures in the pulsating, ballooned, rubber membrane, destroying the membrane after insulation dislodged. Repairs consisted of replacement of insulation and membrane in an area along the west side. The repair cost of \$6,900 represented six percent of the original installation cost.

#### **D7. One Denver Place**

A 50-story complex with two towers and a lower ten-story arcade connector in downtown Denver, which experienced winds of 80 mph in April 1982. This was new construction with ballasted EPDM. The windown washing tracks and siding were detailed to form a 12-foot parapet surrounding the roofs.

**Class IV**—No reported damage.

## **CONCLUSIONS**

This initial investigation and subsequent studies are but a start toward the ultimate goal of standardization. Admittedly, the data collected in the initial investigation was largely empirical and often required subjective estimation. Some of the information gathered would have to be characterized as opinion because of the "after the fact" nature of the investigation. Nevertheless, while this data may be tenuous in many respects, interpretation of the results appears to be valid and the conclusions are significant.

A number of anomalies become apparent when the information is reviewed. Analysis and synthesis of the data are facilitated by inspection of the recapitulation tables at the end of the report. The following observations are noteworthy.

- Forty-three ballasted EPDM roof areas totalling over 778,000 square feet are encompassed in the study. The number of failures in each class is as follows:

**Class I**—seven of 43, or 16.3 percent

**Class II**—11 of 43, or 25.6 percent

**Class III**—nine of 43, or 20.9 percent

**Class IV**—16 of 43, or 37.2 percent

For further ease of correlation we define "significant failures" as Class I or Class II damages, and "ballast failures" as Class I, II or III occurrences. Thus 27 of the 43 roofs showed ballast failures (62.8 percent), and 18 roofs experienced significant failures (41.9 percent of the total). Sixteen owners (37.2 percent) reported exposure to damage, but actual investigation proved no damage. Two-thirds (18/27) of the damaged roofs progressed beyond the ballast failure stage to more severe damages.

- Of the 27 ballast failures, parapet heights of 12 inches or less were found on 22 roofs, or 81.5 percent, but only 62.5 percent (10/16) of the undamaged Class IV roofs had parapet heights this low.

- Although only 15 of the 43 roof decks (34.9 percent) were metal (not including lightweight concrete on metal), a remarkable six out of seven, or 85.7 percent, of the Class I failures had metal decks, while the seventh Class I roof had a structural concrete deck. Conversely, of the eleven Class II failures, only one metal deck was included (9.1 percent); nine of the remaining 10 Class II roofs had structural concrete decks, and the tenth was lightweight concrete on metal.

- Of the three roofs installed over existing BUR surfaces, two were undamaged and one showed only slight scouring under severe exposure conditions. Furthermore, two of these roofs had no parapets at all, while the third was surrounded by a mere six-inch curb.

- Also statistically conspicuous, but of questionable import, is the prominence of new construction in the significant failure categories. All seven of the Class I failures were new, as well as eight of the 11 Class II roofs, for a combined total of 83.3 percent of these two classes. Fifty-six percent (14/25) of the Class III & IV roofs were new installations. Further investigation of numerous specific construction details is needed for evaluation of this statistic.

- With respect to wind velocity, it is noted that all four failure categories list wind speeds as low as 80 mph and as high as 130 mph, indicating the need for a wide range of

speed in analyzing the behavior of roofs subjected to high winds. In one case (A2) a very small area with 12-inch parapets, protected by a higher elevation, withstood winds in excess of 130 mph with no damage; more significant perhaps was a 1600-square foot penthouse roof (D6-B) with 24-inch parapets which was not damaged by 120 mph winds. Note that in the latter case, the lower level major roof area of this project, surrounded by 18-inch parapets, suffered a Class I failure due to high exposure from the underside—the building shell was not completed. Class I failures also were observed at relatively low speeds (80-110 mph) on one project, C5, with low parapets and high infiltration potential. This structure showed a Class IV condition for a large area which had 24-inch parapets and was protected by a higher elevation.

- The data generated by this investigation reveals no clear-cut statistical correlation between failure mode and roof size, building height, orientation to wind, or ground roughness.

In attempting to generalize the results of the investigation, particularly with respect to the information contained in items three, four, and six above, the following significant key patterns were extracted. Buildings which were open (under construction) suffered greater damage. Buildings of greater infiltration capabilities showed greater damage than their tighter cohorts. Construction types allowing more infiltration at the roof deck level showed more damage at earlier stages of engagement. Peculiar configurations caused unpredictable and complex effects, and sometimes disastrous results.

Of special significance is the fact that far more damage resulted in the installations incorporating bare metal decks without a "pressure retarder" such as a layer of gypsum board, lightweight concrete, or even an original BUR. Generally, behavior of substrate types involving lightweight concrete and reroofing over existing BUR systems was outstanding. These elements obviously act to retard the effects of interior pressurization due to infiltration of wind.

Several significant conclusions can be drawn as to the causes of the observed behavior. In a number of situations, the information served to reinforce presently used concepts. Scouring of ballast, for instance, often was observed to correspond to "textbook solutions" with respect to building configuration, parapet height, orientation to wind, adjacent structures, and other established factors. Anomalous damages were frequently noted, however, and are concluded to have been primarily related to interior pressurization, substrate conditions, and oscillation of the membrane. Extrapolation of this finding leads to the realization that wind damage in general is influenced more than previously thought by the following aspects.

- **Membrane Elasticity**—This allows formation of balloons, and subsequent oscillation due to wind uplift and bellows action of the substrate results in tossing or catapulting of ballast in a pulsating trampoline-like fashion at the base of the balloon, enlarging the affected area (refer to the series of graphics at the end of this report).
- **Building Dynamics and Structural Stability**—Wind loads applied to the entire structural system affect the initial formation of balloons and displacement of insulation. A twisted substrate surface, for instance, results in a lowering of the energy required to lift above-deck components,

so a stiffer structure is less susceptible to wind damage than a more limber one.

- **Deck Flexibility**—Actually a subset of the above, deck response is critical to displacement of all above-deck components for the same reasons as those outlined for building dynamics and structural stability.
- **Integrity, Interfaces, and Compatibility**—Interior pressurization from any cause results in a lifting force on the underside of the roofing assembly "sandwich" which complements the exterior wind uplift force and facilitates balloon formation. Integrity of the roof deck and insulation are particularly critical. Holes in the deck, which occur either by design or accident, increase the passage of air as a concentrated stream rather than a gradual infiltration. Breaks or gaps in insulation have a similar pressure concentration effect for nucleation and growth of balloons (see graphics).

Further, inspection of insulation in areas of ballooning was made possible in some cases by the need to split the membrane in order to reposition displaced insulation. In all cases, it was observed that the edges of the boards were rounded, evidently due to repeated scraping of adjacent board edges against each other in an alternating flutter motion. This realization led to a key concept of substrate behavior and its impact on ballooning of the membrane. Briefly, the alternating flutter motion of loose-laid insulation boards is believed to result in an air pumping effect similar to the action of a one-way valve. The result is a dramatic vertical and lateral oscillation of the balloon, which tosses away or catapults the ballast off the surface.

The "oscillating balloon" behavior of the more flexible single-ply membranes now is considered to be the most significant stage leading to increased loss of ballast, membrane rupture, and loss of insulation. The extent of ballast tossing determines the eventual size of the balloon, since ballast thrown from the immediate vicinity is not available for windrow formation and so the size of the balloon is self-limiting.

Although the experimental data with respect to thermoplastic (PVC) membrane behavior is very limited (incidental observations only), the lack of damage to PVC installations in close proximity to EPDM system failures suggests that, in comparison to EPDM, the PVC membrane systems are not as susceptible to wind damage caused by puncturing by flying debris since the targets are smaller. The internal molecular friction and resultant elongation properties affect the size, height, and steepness of ballooning, as well as the amplitude and frequency of oscillation. The more flexible materials form larger balloons, and so are more susceptible to failure.

An unexpected result emerged from the study with respect to repair costs, which always were relatively low due to the self-limiting nature of the ballooned areas imposed by immovable accumulations of ballast. Furthermore, the single-ply membrane is flexible and "flags" in the wind, eventually becoming its own "spoiler" to some extent. Comparable BUR failures encountered under similar exposures were significantly more expensive to repair, since the failures form in sheets which create additional surface area to capture the wind, producing additional uplift and the familiar "vicious cycle" effect. Even in the event of a Class I failure, described as rupture of the membrane and loss of insulation,

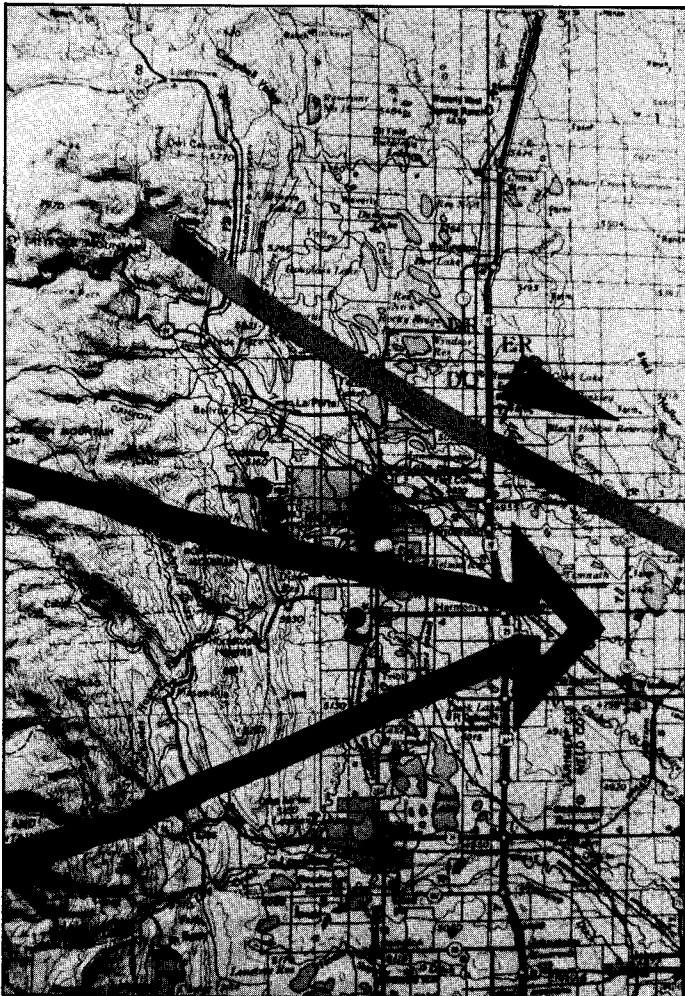


the greatest cost for repair of single-ply systems in this study involved less than 20 percent of the original installation costs. An average of 5 percent of original cost was generally adequate for repairs. It also should be noted that only in extreme cases did a failure expose the structure and its contents to the possibility of further damage from inclement weather for more than the few hours required to effect repairs. In most cases, repairs could be delayed to await favorable weather.

Perhaps the principal effect of this effort in conjunction with other research efforts lies in its dramatic support of the revision of codes and standards for application of single-ply systems by ICBO, NRB, and ANSI (see ICBO Research Report 3826). While Factory Mutual retains its justifiably conservative position approving loose-laid, ballasted systems on an individual basis only, the recently released Technical Advisory Bulletin, adjunct to Loss Prevention Data Sheet 1-29, dated October 1984, also reflects the results of this study.

It is concluded that uplift effects at various wind speeds can be adjusted to reduce scales recently adopted in lieu of those previously used, assuming that certain design criteria have been implemented. This study further concludes that no failure should occur for winds of moderate duration up to 80 knots (92 mph) in areas designated as Ground Roughness "B" (FM) for buildings 30 feet or less in height, having ¾- to 1½-inch river-washed stone ballast, and otherwise meeting standard manufacturer's Factory Mutual, and code requirements for construction.

Finally, the author wishes to reiterate the importance of continuing effort by all those interested in the refinement of this complex and highly technical concern. Further comprehensive statistical contributions to this meager foundation are required in order to proceed with the development of reliable design criteria necessary for the establishment of acceptable standards.



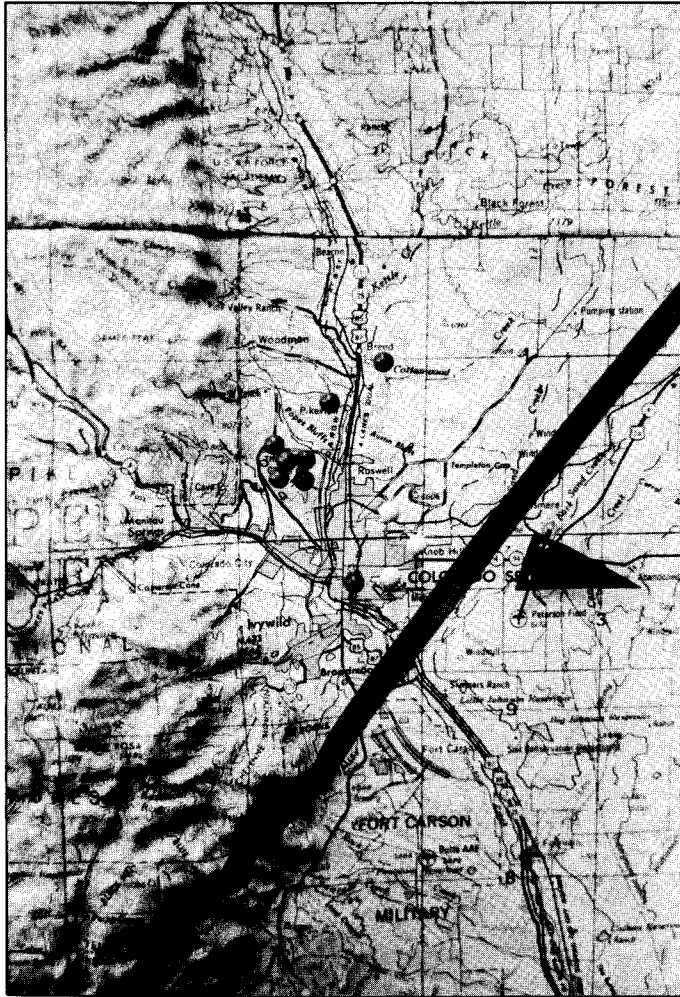
**Group A Map—Ft. Collins, CO**

Color-coded pins show locations of reported roof damage. Mean elevation in Ft. Collins is 5100'. Pin at upper left is Class I rupture; lowest pin is minor Class II; flag is U.S. Weather Station, Yankee Field.



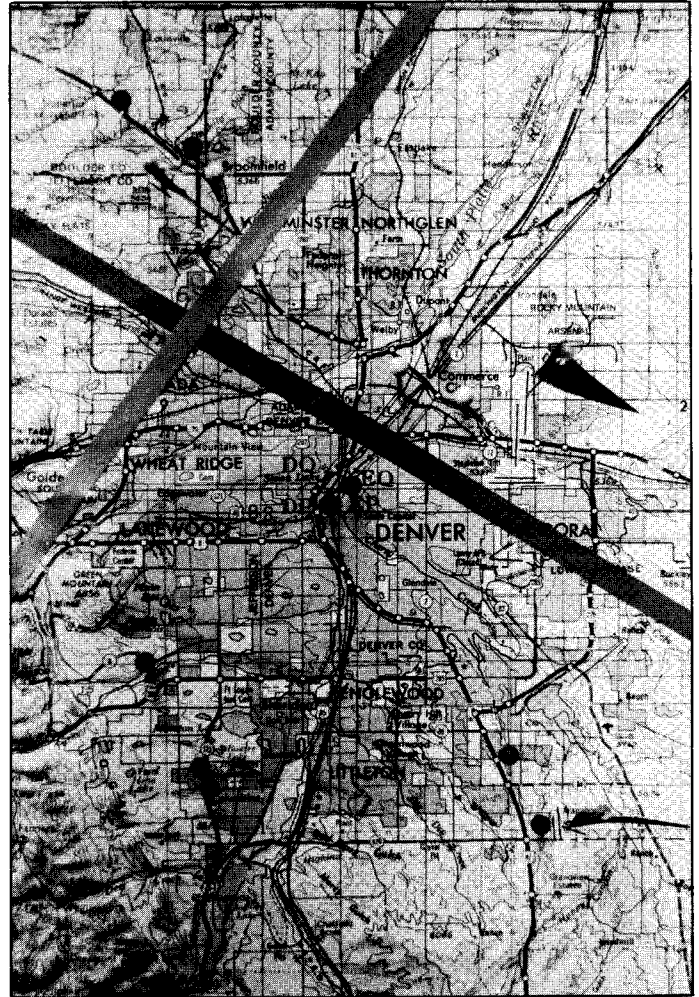
**Group B Map—Boulder, CO**

Lowest pin in center (arrow) is USDOE, strategically located in venturi between two peaks



**Group C Map—Colorado Springs, CO**

Here, popular wood-shingled residential roofs receive customary annual repair due to “normal” wind damage



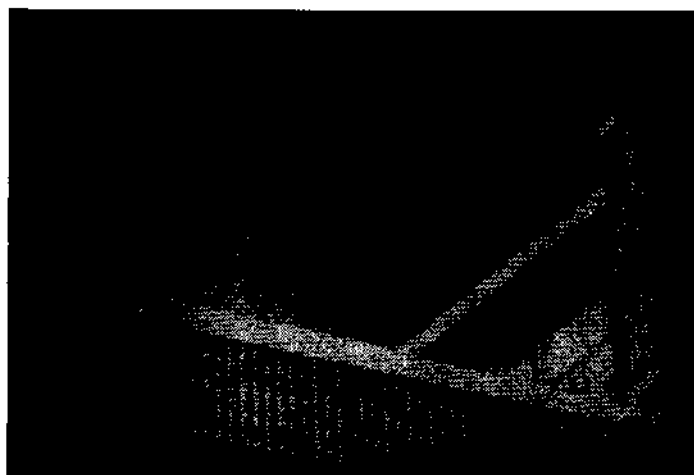
**Group D Map—Denver, CO**

Even though tall buildings present good targets for “Chinooks”, use of high parapets and proximity of other buildings provide “spoilers” for keeping ballast in place





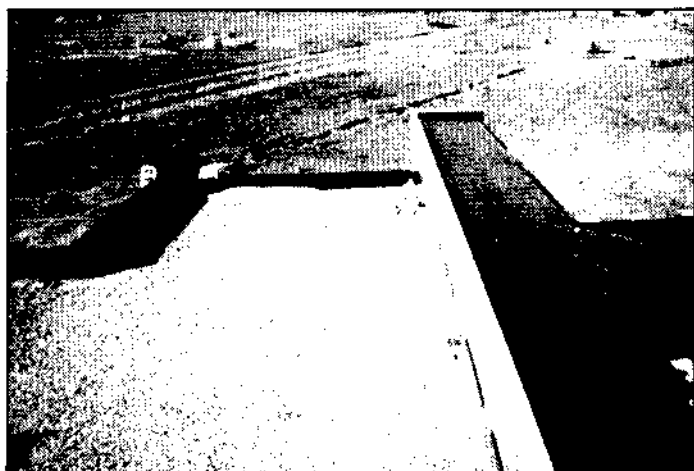
*Figure 1* Three-dimensional map was used to study overall patterns of winds and roof performances. Dark arrows are April 1982 winds; Light is January's.



*Figure 2* Dramatic photo of catapulted ballast, caught in mid-air being tossed over parapet wall during violent winds



*Figure 3* Taken during fatal wind, photo above shows critical configurations of ballasted EPDM. Far balloon is 5'4" high as wind speed increases from 147 mph. Note ballast dam in foreground.



*Figure 4* Overall view of USDOE roofs show typical scouring of ballasted EPDM vortex at interior corner. Long, thin upper roof is fully adhered EPDM. Note pavers added around perimeters and at base of clerestory wall.

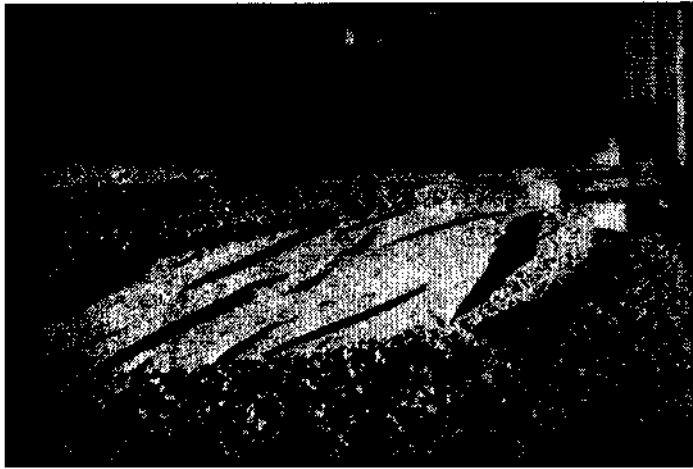


Figure 4a Close-up of scoured area shows typical pattern and wind direction by wrinkles left. Even though pavers were added, note solid concrete blocks in upper right for "insurance".

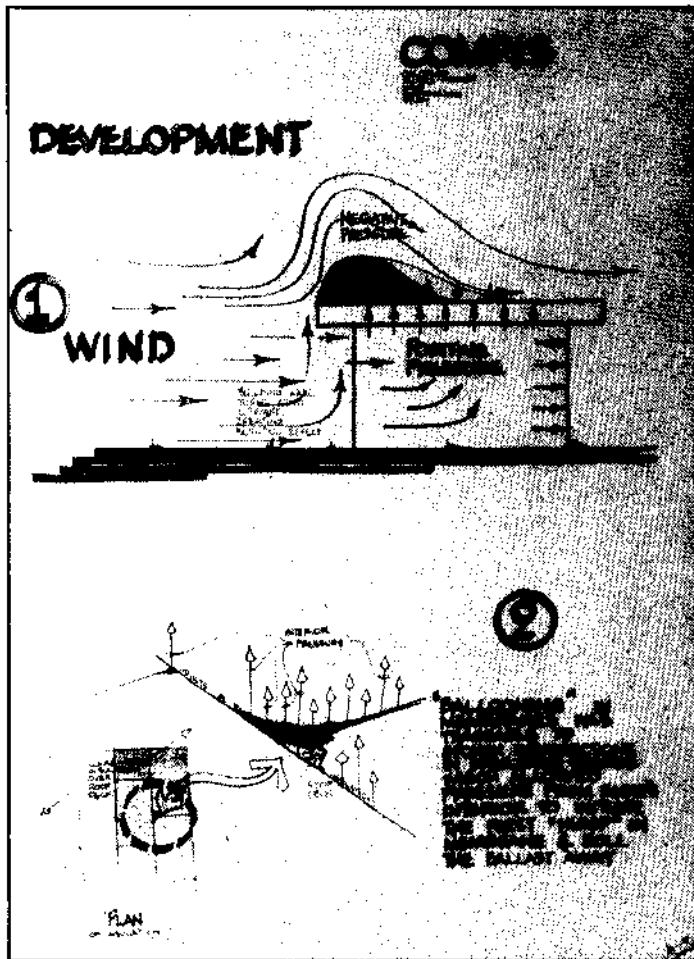


Figure 5 1. Wind is turned upward at vertical building walls creating Bernoulli effect on roof surfaces and cracks around windows and doors allow interior pressurization of building envelope. 2. Interior pressure penetrates spaces between decks, roofing insulation boards, etc. and ballooning begins from a combination of interior pressure and exterior suction. Ballooning in membranes was traceable to broken intersections in insulation boards which permitted the first "hump" in membrane and rolling away of the ballast.

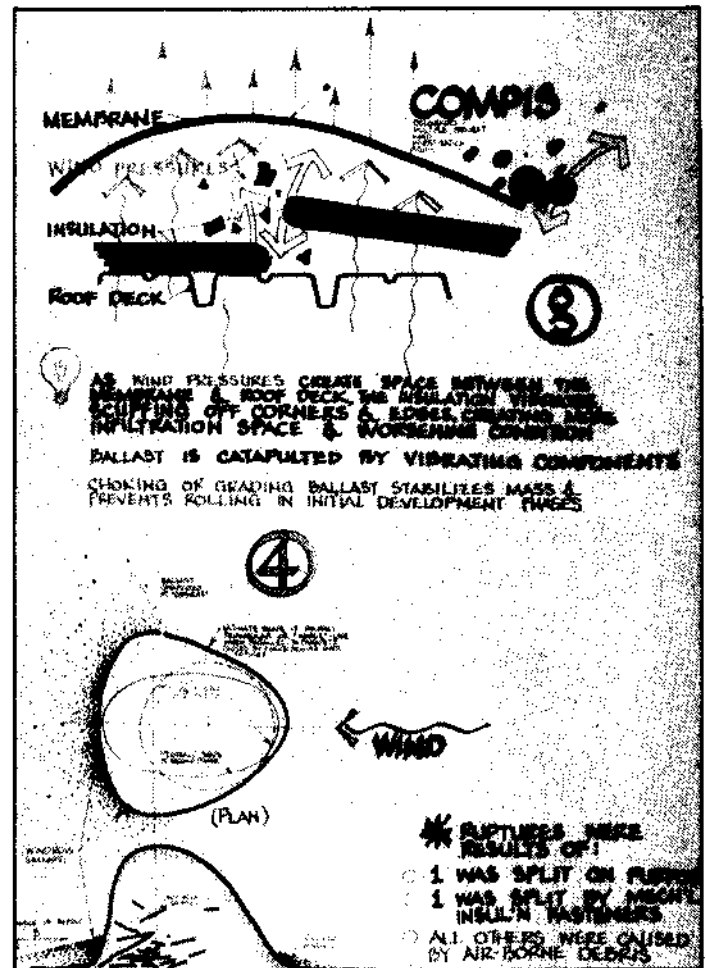


Figure 6 3. As wind pressures separate the membrane from the deck the insulation begins to vibrate in the space created between the membrane and roof deck, scuffing off corners and edges, thus creating more infiltration of space and worsening the condition. An "air valve" is created by vibrating components and ballast is catapulted by undulating action. Choking and grading of ballast stabilizes the mass and prevents rolling in initial development phases.

4. Ultimate shape of the mature balloon is roughly rounded, triangular or "whale-like"; when parallel to parapets, configuration conforms to corkscrewing pattern over copings.

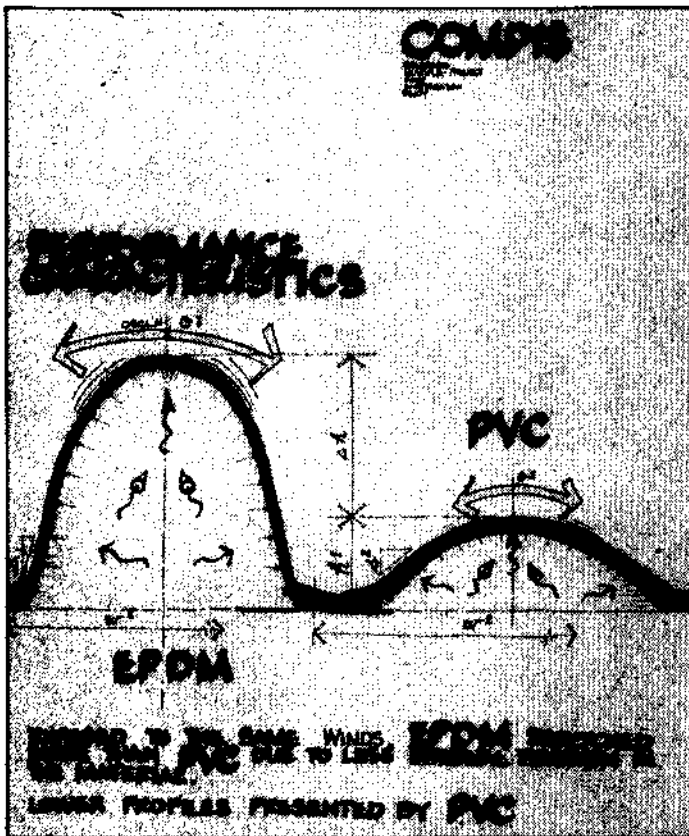


Figure 7 Exposed to the same winds, ballasted EPDM stretched more than the PVC due to less internal friction of the material. Lower profiles by PVC presented smaller targets for flying debris.