WIND-TUNNEL STUDIES TO MITIGATE SNOWDRIFT INTO ROOFTOP AIR-HANDLING VENTILATORS

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ABSTRACT: A wind-tunnel measurement program was performed to study the effectiveness of snow fences, diversion walls, canopies and flat roofs for sheltering air-handling courts on the penthouse roof of a university health center from snow entrainment. Snow blockage of building inlet filters located in air-courts or on building walls is a major source of winter-time failure in ventilation systems. The measurement program used smoke visualization and a novel "snow-storm" simulation technique to document the relative snow entrainment of different architectural structures proposed to intercept, divert or stabilize snow about air-handling courts. Some sixty-eight smoke visualization tests and forty snow drift tests were performed to evaluate the relative effectiveness of different combinations of snow fences, diversion walls, canopies and flat roofs. A 1:150 scale model of the entire hospital complex was constructed to evaluate over-all air flow patterns, and a 1:50 scale model was constructed of the upper floors and penthouse region to evaluate snow simulant entrainment. Air flow through the air-filter screens were simulated by incorporating small fans in the 1:50 scale model. A mitigation solution was chosen based on the model tests which promised to reduce the mass entrained by a factor of 25.

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INTRODUCTION

A wind-tunnel measurement program was performed to study the effectiveness of snow fences, diversion walls, canopies and flat roofs for sheltering air-handling courts on the penthouse roof of a university health center from snow entrainment. Snow blockage of building inlet filters located in air-courts or on building walls is a major source of winter-time failure in ventilation systems. The measurement program used smoke visualization and a novel "snow-storm" simulation technique to document the relative snow entrainment of different architectural structures proposed to intercept, divert or stabilize snow about air-handling courts. Some sixty-eight smoke visualization tests and forty snow drift tests were performed to evaluate the relative effectiveness of different combinations of snow fences, diversion walls, canopies and flat roofs. A 1:150 scale model of the entire hospital complex was constructed to evaluate over-all air flow patterns, and a 1:50 scale model was constructed of the upper floors and penthouse region to evaluate snow simulant entrainment. Air flow through the air-filter screens were simulated by incorporating small fans in the 1:50 scale model. A mitigation solution was chosen based on the model tests which promised to reduce the mass entrained by a factor of 25.

WIND TUNNEL AND MODEL ARRANGEMENT

The experiments were performed in the Environmental Wind Tunnel (EWT) at Colorado State University. This wind tunnel, especially designed to study atmospheric flow phenomena, incorporates special features such as an adjustable ceiling, a rotating turntable and a long test section to permit adequate reproduction of micrometeorological behavior. Mean wind speeds of 0.1 to 15 m/sec in the EWT can be obtained. Boundary-layer thickness up to 1.2 m can be developed "naturally" over the downstream 6 m of the EWT test section by using vortex generators at the test section entrance and surface roughness on the floor. The flexible test section on the EWT roof is adjustable in height to permit the longitudinal pressure gradient to be set at zero.

A model scale of 1:50 was chosen to simulated the roof and penthouse of the health center. Only the upper floors were modeled since the kinematics of the snow were expected to be dominated by roof top features such as parapets, satellite dish, and roof-top access structures. A large model scale was chosen to maximize experimental resolution. Since the 1:50 scale model produced a blockage percentage equal to 7.1%, the EWT ceiling was adjusted upward 15 cm to reduce blockage and minimize longitudinal pressure gradients over the structure.

Model Approach Flow Simulation

Similitude of air movement about buildings requires that the velocity and turbulence intensity profiles are matched at equivalent heights. However, since this study emphasizes roof top air movements, only the rate of change with height of wind speed and turbulence at roof top levels are significant. In this model study a nearly uniform velocity profile at roof levels was acceptable since velocity gradients were expected to be small. A scaled model approach wind profile was sought such that:

$$(u'/u)_{prototype} = (u'/u)_{model}.$$

The turbulence intensity was maintained at a typical suburban scale (15%). The uniform velocity and high turbulence flow was achieved by a combination of spires at the entrance of the wind tunnel, a 7.5 in high barrier 9 ft from the spires and a cross bar grid 15 ft downstream from the barrier.

Model Snow Simulation

Following the arguments of Anno (1989), the ratio of particle fall velocity to threshold friction velocity was presumed to govern the movement of real and model snow particles. All the tests used borax as a snow simulant (white, granulated, nearly correct density, and close to equivalent fall velocity).

Model Intake Simulation

There are two air-handling courts on the roof top of the medical building. The intake air flow rates were scaled to maintain a similar dimensionless volume flux ratio

$$(Q/UL^2)_{model} = (Q/UL^2)_{prototype}$$

The intake flow rates were simulated by using three shop-vacuum cleaners adjusted to the appropriate suction conditions with voltage regulators. The rate that simulant snow accumulated in the air-handler well was measured to characterize the efficacy of each roof-top modification.

Barrier and Canopy Configurations

Sixteen different configurations of barriers, fences and canopies were examined in an effort to identify an optimum snow control strategy. Three solid barrier arrangements were examined: Solid A, Solid B and Solid C (Figures 1, 2, and 3). All the solid barriers had the same height of 1.2 in, which is equivalent to 5 ft in the field. Fences with 50% porosity were also evaluated for different locations on top of the roof. There were four configurations: Fence A, Fence B, Fence C and Fence D (Figures 4, 5, 6, and 7). The fences also had a uniform height of 1.2 in.

Five kinds of canopies were studied: A pitched roof Canopy A, which could be adjusted to two different heights to form Canopy D (the height is 0.6 in of model scale and 2.5 ft of prototype) and Canopy E (the height is 1.8 in, equivalent to 7.5 ft of prototype), and also roof with extended overhanging eaves Canopy B and Canopy C . One combination of canopy and solid barrier and one combination of canopy and fence were tested. The first case was referred to as Combine A while the second case was referred to as Combine B . See Figures 12, 13, and 14.

Finally, two additional configurations were examined by covering the intake areas with flat roofs with overhangs on all four edges, and the flat roofs with a half roof height solid barrier under the roofs along the intake edges.

INSTRUMENTATION AND DATA ACQUISITION

Approach flow wind conditions were sought in the wind tunnel which replicate typical urban velocity profile and turbulence conditions. Considering the presence of the surrounding hospital complex a roof-top turbulence level of 15-20% was selected as appropriate. Velocity measurements were made with single-hot-film probes and anemometry equipment manufactured by Thermo-System, Inc. (TSI). A calibration curve yielded hot film anemometer velocities that were always within 2 percent of the known calibrator velocity. Considering the accumulative effect of calibrator, calibration curve fit and other errors the model velocity time series should be accurate to within 10 percent.

A visible plume was produced by passing the simulant gas, whose flow rate was controlled by the mass flow meter, through a smoke generator (Fog/Smoke Machine manufactured by Roscolab, Ltd.). The smoke was directed through tubing to different locations upwind and around the model. The visible plumes for each test were recorded on VHS video cassettes with a Panasonic Omnivision II camera/recorder system. Numerous views were taken for different orientations and canopy configurations.

Snow storms were simulated by using a modified fertilizer spreader (Model CB1000 manufactured by Cyclone), whose speed was controlled by a AC motor through a voltage regulator. There was a feeder opening underneath the hopper of the spreader, which could be adjusted by a lever arm by means of the guide bracket. By adjusting the AC motor and the lever arm, the snow fall rate was controlled.

The spreader was set upstream in order to let the falling "snow" cover the entire roof area. By opening the feeder at the bottom of the hopper for two minutes, a snow storm lasting for an equal period was generated for each simulating study. From the assumption that the model wind speed is equal to the field speed, the time factor is equal to the length scale factor, that is the time factor is 1:50. This implies that 2 minutes of modeling time is equal to 1 hour and 40 minutes of field snow storm period. The video camera taped the entire two minute period of snow fall for each run. The amount of simulant snow which fell into each ventilation well was weighed separately and recorded in Table 1. Finally, a vacuum cleaner was used to remove all the borax from the roof top before the next test.

RESULTS AND DISCUSSION

The wind tunnel tests were performed to identify an optimum roof-top shelter arrangement to protect air-hanDler courts from snow blockage. Differentiation between various alternatives were based on the collective examination of smoke visualization, snow simulant visualization, and snow accumulation measurements within the air-handler wells.

Visualization Results

A total of 68 smoke test cases were performed to evaluate the effectiveness of various fence, canopy and flat roof configurations for minimizing the amount of smoke drawn into the ventilation wells. The tests were grouped by configuration in a progressive order of wind orientation. Examination of the visual records of these experiments revealed the following:

a) *Vacuum Intake* Test were performed with and without the air-handler intakes operating. When the vacuum system was operating, the smoke would largely be captured by the vent wells, while without the vacuums in operation, the smoke would spread over the surface.

b) *Vent Location* As a result of the relative locations on the roof top of the wells, and the elevator building, flow separation often occurs which directs the smoke over the intakes. With the building features and vacuum intakes working in combination, the smoke can be seen to flow perpendicular and even opposite to the primary wind direction.

c) *Solid Fence* Three different configurations of solid fences were tested. They tended to slow and lift the smoke as it approached and passed over the fence, but they did not significantly reduce the amount of smoke reaching the intake vents regardless of the fence configuration.

d) *Porous Fence* Four fence configurations were tested by using a screen material with 50% porosity. Aside from slowing the air flow slightly, the porous fence did little to prevent the smoke from entering the intake vents.

e) *Canopy* Canopies with varying heights and overhangs were tested. They seemed to deflect slightly more smoke as their height decreased, and their overhang increased. The height appeared to have considerably more influence than any other factors for preventing the smoke's entrance into the vent areas.

f) *Fence and Canopy Combinations* A considerable amount of smoke was directed over the canopy roof as a result of the upwind fence, however the fence on the downwind side tended to re-direct the flow such that smoke passing across the canopy was drawn back down into the ventilation wells.

g) *Flat Roof Cover* The flat roof appeared to have a similar effect to that of the canopy on the flow of the smoke. Smoke below the roof level of the cover was sucked down into the vents, and most smoke passing above the cover went downwind undisturbed.

h) *Flat roof Cover and Solid Fence Combination* A fence one half the height of the flat roof cover was located around the intake wells, underneath the flat roof cover. This combination appeared to be quite effective in diverting most of the smoke away from the vents. Locating the fence under the cover and not simply around its perimeter seemed to provide a considerable advantage.

i) *Site Orientation: N, NE, E, SE* The model was rotated to examine a variety of approach wind directions. As the flow interacted with the structure and shelter configurations, the smoke plume's trajectory was modified into various streamline patterns.

Several patterns reoccurred no matter which building configuration was examined. Winds from the NE and SE directions were split by the building's corners(and the elevator building), and were convected directly over the intake vents.

j) *Wind Speed* While higher velocity winds did allow slightly more smoke to pass over the intake vents, they did not significantly mitigate smoke intake by the ventilation wells.

Conclusions from Smoke Visualization Tests:

The visualization tests provided observations which provided focus for the simulated snow experiments. The major conclusions were:

- The solid and porous fences, without regard to location were ineffective in minimizing smoke inhalation by the two ventilation wells.
- The canopy and flat roof covers appeared to significantly reduce the amount of smoke entering the wells. Other factors, such as reducing the distance from the top of the well to the bottom edge of the canopy (or cover), or the addition of a solid fence below the cover (or canopy) appeared to assist in diverting the smoke away from the intake wells.

Snowdrift Results

A total of 40 simulated snow test cases were performed to evaluate the effectiveness of various fence, canopy, and flat roof configurations. The tests were grouped by configuration in a progressive order of wind orientation. Figure 15 and 16 indicate the snow deposition rates for each configuration for two wind directions. Abbreviations for different shelter configurations are noted in Table 1.

a) *Solid Fence* Three different solid fence configurations were tested (A, B and C). The fences stopped snow close to the roof top, but had little effect on snow that was deflected over the fence. Drifts of snow accumulated in front of the solid fences, indicating that they could be used to control snow drifting problems on the building roof top.

b) *Porous Fence* Four different porous fence configurations were tested (A, B, C and D). The porous fences were located further away from the vent intakes than were the solid fence. The porous fences stopped some snow in their immediate vicinity, but failed to have much effect upon the snow entering the ventilation wells. Configuration D was probably the most effective of the porous fences, perhaps due to its closer proximity to the smaller intake.

c) *Canopy* Canopies of various heights and overhang were tested. This style of mitigation shelter proved to be quite effective. The amount of "snow" (borax) deposited in the intake wells was reduced by a factor of ten or more (refer to Figures 1 and 2). As the height of the canopy was reduced, its effectiveness increased. Increasing height reduced the ability of the canopy to prevent the snow's entrance to the well.

d) *Fence and Canopy Combination* The results from these tests were disappointing. The presence of the fence around the outer edge of the canopy appeared to redirect the vacuum from the intake in such a way that snow passing near or just over the canopies was forcefully sucked down into the vent. Placement of the fence further away had little measurable effect on the amount of snow collected in the intake vents.

e) *Flat Roof Cover* The flat roof configuration was slightly more successful in preventing the entrainment of "snow" into the vents than the canopy. Its flat, rather than tilted roof allowed the air flow to carry the "snow" over the vent with less disturbance.

f) *Flat Roof Cover and Solid Fence Combination* This style of mitigation measure was the most effective of the configurations tested. The shorter fence, just inside the perimeter of the flat cover added to the effectiveness of the cover in preventing snow from entering the intake vents.

g) Site Orientation N, NE The model was tested in two primary wind directions for all the configurations. The same snow patterns were consistently observed on the roof top, with slight discrepancies being caused by the various mitigating measure being examined.

h) *Wind Speed* Considerably higher velocity winds (about 4 m/s) were required to cause the deposited snow on the building's roof to move and form new snow drift patterns. When movement occurred, it did not result in much additional snow deposition in the intake wells.

i) Vacuum Intake Tests were performed with and without the vacuum intakes operating. The general snow patterns were relatively unchanged by the presence or absence of the vacuum. But the amount of snow in the vent wells with the vacuums in operation larger than that without the vacuums in operation.

Conclusions from Simulated Snow Tests

- The fence configurations, both solid and porous, had very little impact upon the amount of snow which accumulated in the intake wells. Their measurable impact decreased as their proximity to the vents decreased.
- Both the canopy and flat roof cover proved to be consistently very effective in preventing large amounts of snow from entering the intake wells. Factors such as decreased height also improved their performance.
- A fence inside the perimeter of the cover added to its effectiveness in preventing the simulated snow's entrance to the vent.

Final Recommendation

Based on the configurations examined during this study a flat topped canopy should be constructed over each air-handler well on the health center roof-top. The canopy should have eaves which overhang the edges of the well by a distance approximately equal to their height above the roof. Snow entrainment can be further reduced by placing a barrier wall under the edge of the canopy. This barrier should rise about half the height of the canopy itself, and it should be placed half way between the edge of the well and the roof overhang.

REFERENCES

Anno, Y. (1989), "Froude Number Paradoxes in Modeling of Snowdrift," Sixth U.S. National Conference on Wind Engineering, Houston, Texas, Vol.II, A6-(44-46).

Table I Snowdrift Test Data

Run #	Config.	Abbrv.	WD	Speed	Lg. Area (gram)	Sm. Area (gram)
1	None	N	N	1 m/s	24	11
2	None	N	NE	1 m/s	14.75	6.25
3	None	N	E	1 m/s	30.5	4.5
4	None	N	N	3 m/s	0	0
5	Solid A	SA	N	1 m/s	37.75	8
6	Solid A	SA	NE	1 m/s	29.75	6
7	Solid B	SB	N	1 m/s	28	7
8	Solid B	SB	NE	1 m/s	3.5	1.8
9	Solid C	SC	N	1 m/s	26.5	3.5
10	Solid C	SC	NE	1 m/s	23.8	3
11	Fence A	FA	N	1 m/s	26.5	5
12	Fence A	FA	NE	1 m/s	24	4.2
13	Fence B	FB	N	1 m/s	26.5	7.5
14	Fence B	FB	NE	1 m/s	20.5	3
15	Fence C	FC	N	1 m/s	24	6
16	Fence C	FC	NE	1 m/s	14	2.75
17	Fence D	FD	N	1 m/s	24.8	5
18	Fence D	FD	NE	1 m/s	23.5	3.4
19	Canopy A	CA	N	1 m/s	0.75	3.75
20	Canopy A	CA	NE	1 m/s	1.3	1.6
21	Canopy B	CB	N	1 m/s	0.5	3.3
22	Canopy B	CB	NE	1 m/s	2.8	1.5
23	Canopy C	CC	N	1 m/s	1.3	4
24	Canopy C	CC	NE	1 m/s	3.3	1.3
25	Combin A	CBA	N	1 m/s	1.5	1.5
26	Combin A	CBA	NE	1 m/s	1	3.5
27	Combin B	CBB	N	1 m/s	1	2.8
28	Combin B	CBB	NE	1 m/s	0.75	7
29	None(S)	NS	N	1-3 m/s	0	0
30	None(I)	NI	N	1-3 m/s	----	----
31	None(NV)	NV	N	1-4 m/s	19.5	7.8
32	None(NV)	NV	NE	1-4 m/s	5	9
33	Canopy D	CD	N	1 m/s	4.2	0
34	Canopy D	CD	NE	1 m/s	7.75	0
35	Canopy E	CE	N	1 m/s	16.8	1
36	Canopy E	CE	NE	1 m/s	5	1
37	Flat A	FTA	N	1 m/s	2.5	0.5
38	Flat A	FTA	NE	1 m/s	2.5	0.6
39	Flat B	FTB	N	1 m/s	1	0.4
40	Flat B	FTB	NE	1 m/s	1	0.6

Comments: "S" indicates that the snow was sprayed on the top.
"I" indicates that the snow was dropped at 1 m/s then the speed was increased to 3 m/s.
"NV" indicates no vacuum operating.

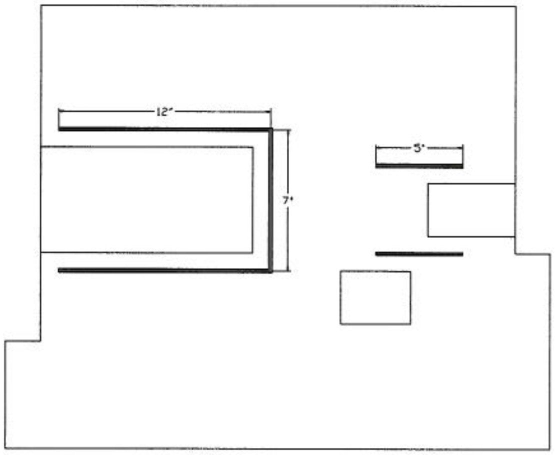

Figure 1 Solid Barrier A

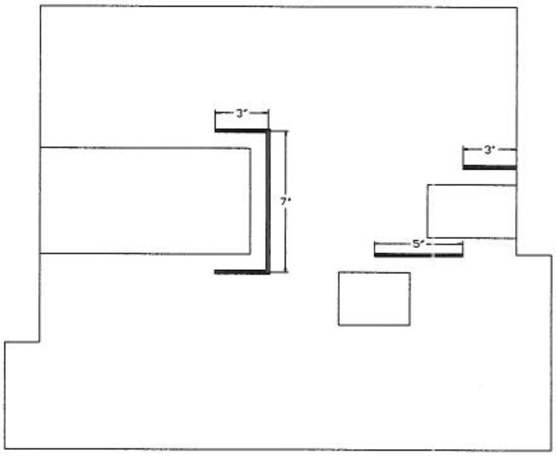

Figure 2 Solid Barrier B

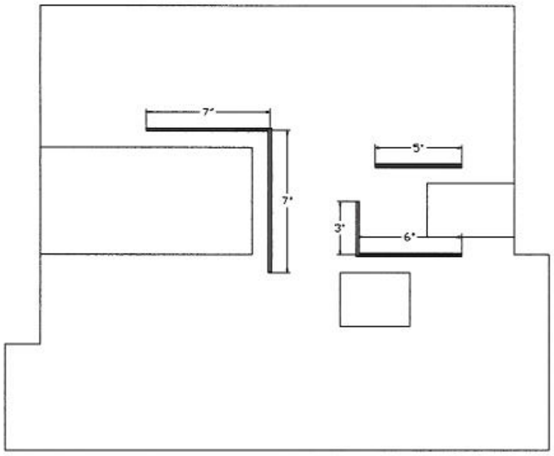

Figure 3 Solid Barrier C

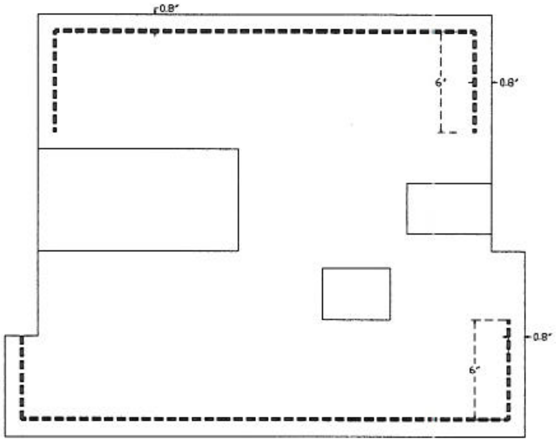

Figure 4 Fence Configuration A

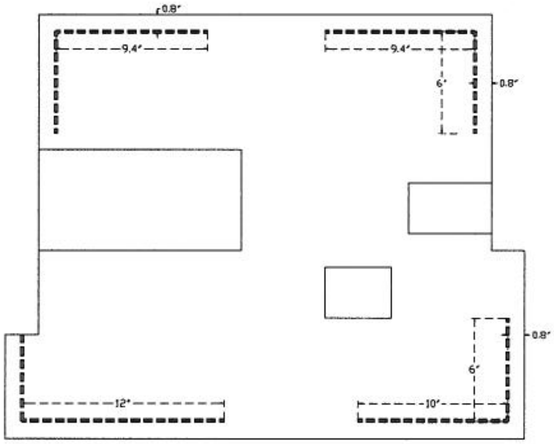

Figure 5 Fence Configuration B

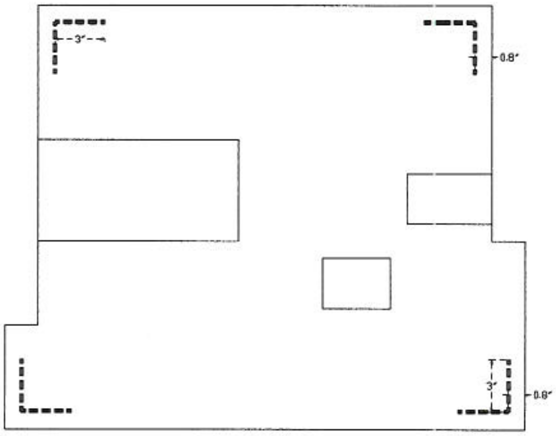

Figure 6 Fence Configuration C

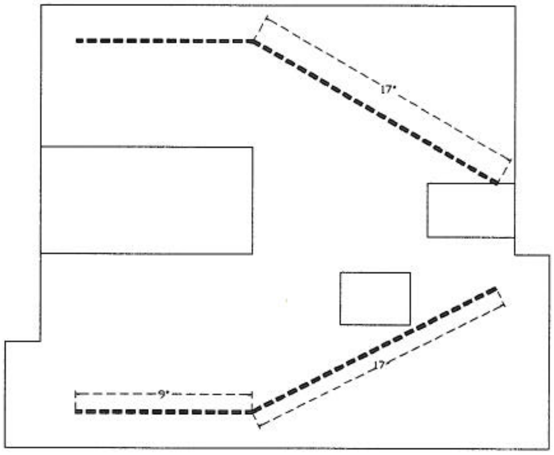

Figure 8 Fence Configuration D

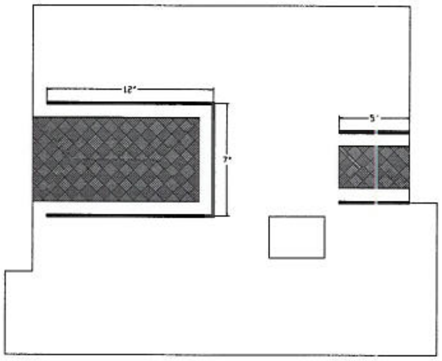

Figure 7 Combine A

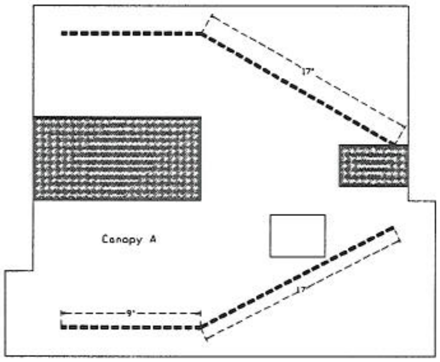

Figure 9 Combine B

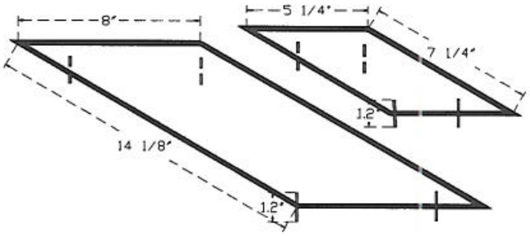

Figure 10 Flat A

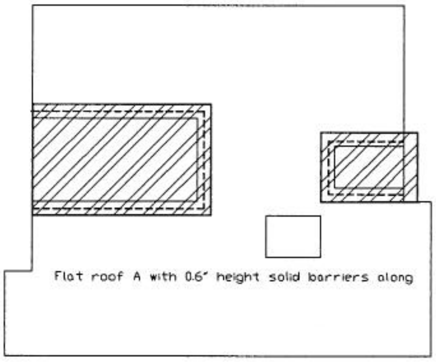

Figure 11 Flat B

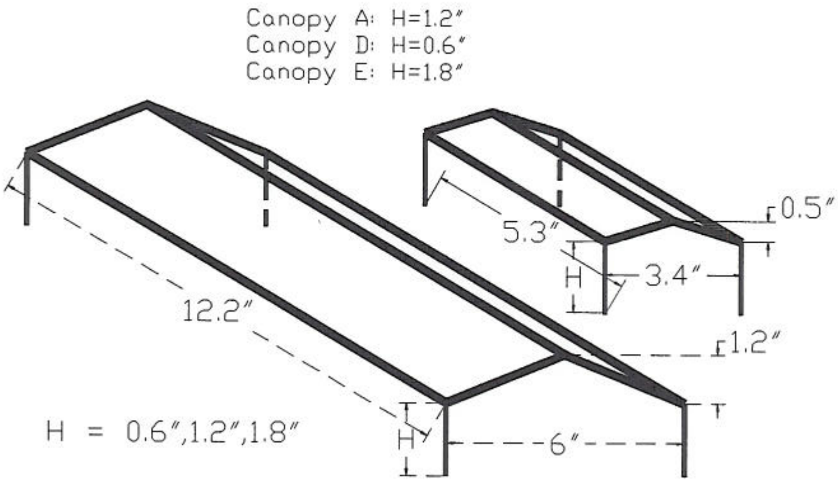

Figure 12 Canopy A, D & E

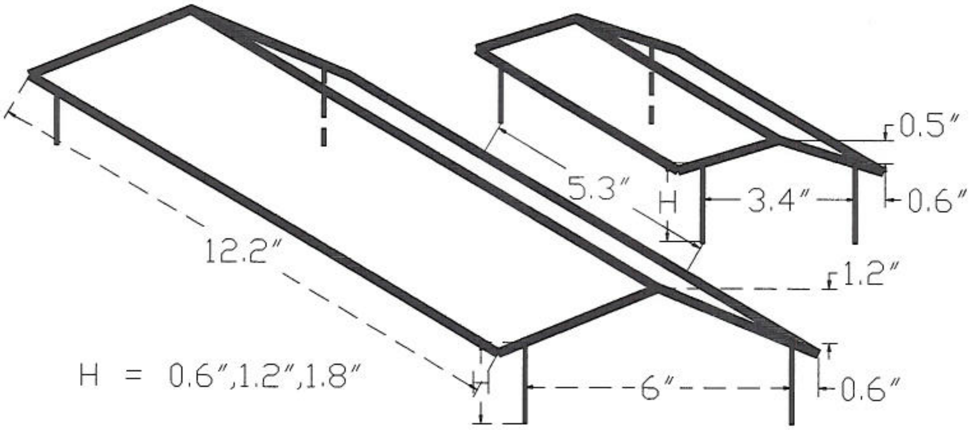

Figure 13 Canopy B

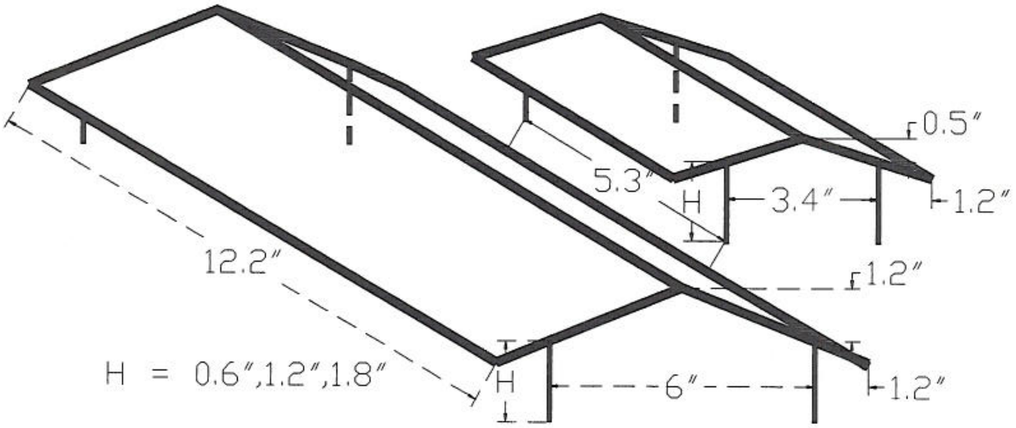

Figure 14 Canopy C

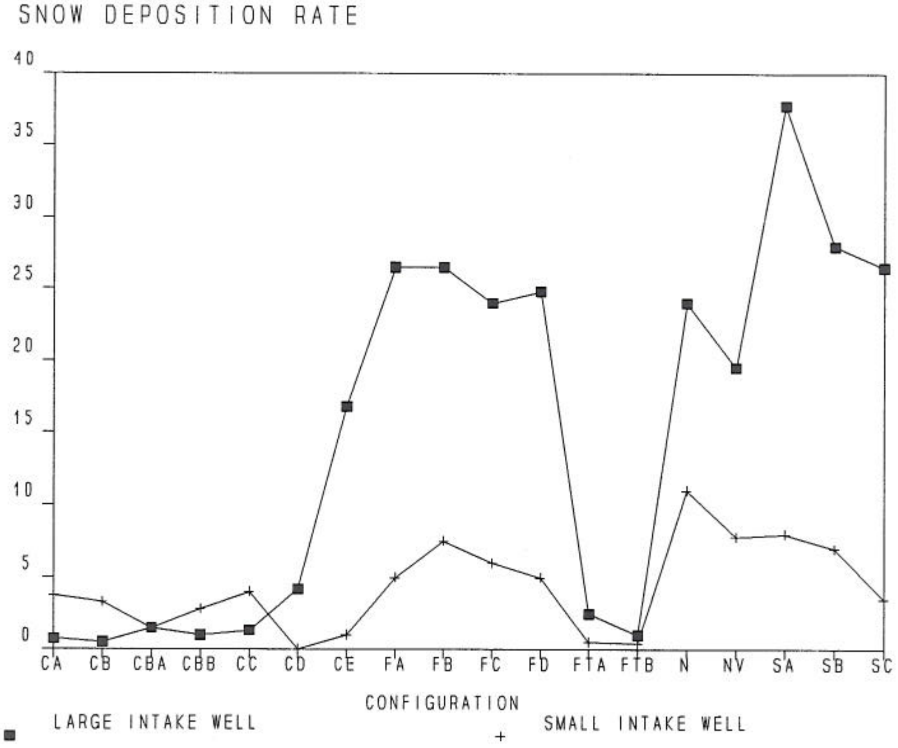

Figure 15 Snow Deposition Rate for N Wind Direction

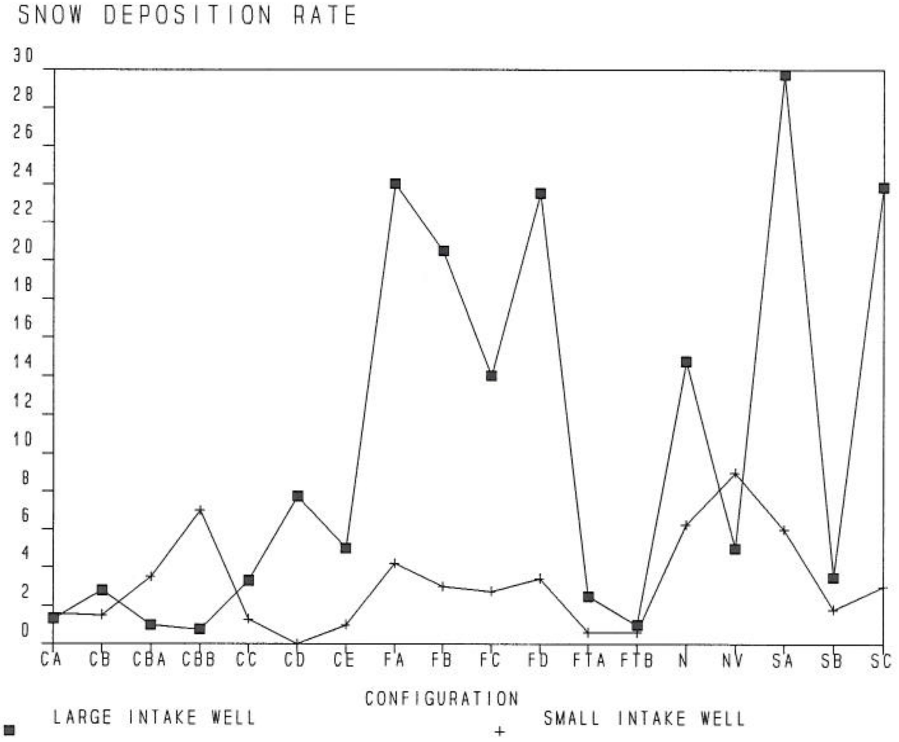

Figure 16 Snow Deposition Rate for NE Wind Direction