NEW ENGINEERING CRITERIA FOR SNOW FENCE SYSTEMS

Ronald D. Tabler, Rocky Mountain Forest and Range Experiment Station, U.S. Forest Service, Laramie, Wyoming

New engineering criteria for snow fences have been used to design a snow control system that is unusually effective in preventing drifts, improving visibility, and reducing the formation of road ice. This paper describes these criteria and the research results on which they are based. The amount of blowing snow arriving at each site was estimated from an equation relating the snow transfer coefficient, the transport distance, and the precipitation received over the contributing distance. Measurements in southeast Wyoming show the "equivalent transport distance" to range from about 500 to 1200 m. The height and number of rows of fencing at each site were selected to provide the required capacity. An equation for computing the cross-sectional area of the saturated lee drift behind the new Wyoming Highway Department standard-plan fence is given. Tall (3.8-m) fences have been used in preference to shorter ones because experience has shown taller structures to be more efficient in trapping snow and to have a much lower construction cost per unit of storage. Because studies have shown the average trapping efficiency of a fence from onset of accumulation to time of saturation to be about 85 percent, storage capacity is made about 20 percent greater than the estimated amount of blowing snow. Terrain can be used to greatly increase the capacity of snow fences; for example, capacity is increased 15-20 percent for each 0.017 rad of downslope behind a fence and about 15 percent for each 0.017 rad of upslope in the approach zone. Because wind sweeping around fence ends reduces storage capacity significantly over a distance from the ends of 12 times the height, length of fences should be at least 30 times their height and staggered barriers should be overlapped at least 8 times their height.

•AS a result of 14 years of testing snow fences to increase usable water yields from the windswept plains, we have developed several techniques that promise to improve the economy and performance of snow fence systems in other applications as well. In 1971, the Wyoming Highway Department offered a unique opportunity to test our ideas on a large scale when they asked us to engineer a snow control system for a newly constructed 70-mile section of Interstate-80 in southeastern Wyoming. At present, about $1,000,000 worth of snow fencing has been built using the innovations described in this paper. Two years' experience has demonstrated the new fence systems to be unusually effective in preventing drifts as well as for improving visibility and reducing road ice (8).

This paper summarizes the following factors that have contributed to the success of the I-80 snow fences: (a) a method of estimating snow storage capacity required at fence sites, (b) a new design for the fence itself, (c) the preferred use of tall (3.8-m) fences, (d) allowance for trapping efficiency, (e) the use of terrain to increase the capacity of fences, and (f) criteria for overlap and minimum length of fences.

ESTIMATING REQUIRED CAPACITY

Basic to our method for estimating the amount of blowing snow arriving at a fence site is the concept of "transport distance", R_a, defined as the average distance a snow particle must travel before completely sublimating (Figure 1). The "contributing dis-

Publication of this paper sponsored by Committee on Snow and Ice Control.

Figure 1. Diagram of the transport distance concept used to estimate sublimation loss from wind-transported snow. The transport distance, R_m, is defined as the average distance over which a snow particle (shown between the convergent dotted lines) must travel before it completely sublimates. The contributing distance, R_c, is defined as the distance upwind that contributes blowing snow to a site and may be equal to or less than R_m.

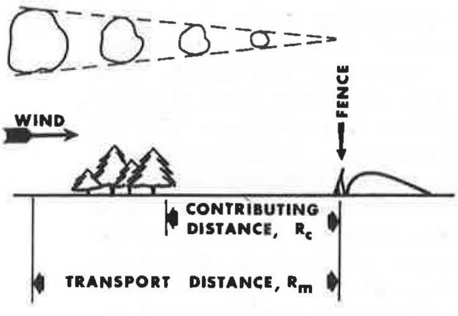


Table 1. Values for "equivalent transport distance" (θR_m) from 4 sites in Wyoming.

Site	Location	Elevation (m)	Vegetation	Year	Water-Equiv. Storage (m^3/m)	Precip. (mm)	θR_m (m)
I-80, system 1	S17, T18N, R77W	2370	Shortgrass	1971-72	85	184	925
				1972-73	116	236	979
I-80, system 12	S14, T19N, R79W	2380	Low-growing sagebrush	1971-72	138	249	1107
				1972-73	223	376	1185
Pole Mountain	S22, T15N, R71W	2440	Shortgrass	1969-70	44	171	481
				1970-71	56	195	574
				1971-72	22	81	538
				1972-73	68	239	570
Stratton Study Area (South Draw)	S25, T17N, R87W	2360	Sagebrush 0.2-0.6 m tall	1972-73	117	267	876

tance" (or fetch), R_o, upwind of a snow fence or natural barrier may be much less than R_m, depending on terrain and vegetation, but by definition cannot exceed R_m. If we assume steady, uniform flow across a smooth, horizontal surface of infinite extent (implying the absence of spatial and temporal gradients for factors affecting sublimation), then the rate of sublimation should be constant with respect to time and travel distance. Thus the amount of sublimation would be directly proportional to travel distance (R_o) so that, for a single event, as shown in an earlier paper (6),

$$Q_\ell = \frac{\theta P R_o^2}{2R_m}, \qquad R_o \le R_m \tag{1}$$

where Q_ℓ is sublimation loss over the distance R_o and θ is the ratio of the amount of snow that is relocated by the wind to the amount that falls as precipitation, P. For P, R_o, and R_m in metres, Q_ℓ is in units of cubic metres of water-equivalent per metre of width perpendicular to the wind. Average annual storage capacity, Q_c, required at a snow fence site can then be determined by subtracting sublimation loss (Eq. 1) from the total amount of relocating snow ($\theta P R_o$) at each site, using mean annual values for the variables:

$$Q_c = \theta P R_o\left(\frac{1 - R_o}{2R_m}\right), \qquad R_o \le R_m \tag{2}$$

Equation 2 was used to estimate the amount of snow storage required at each of the proposed fence sites on I-80. For this application, R_m was assumed to be 1 km (3,300 ft), based on previous studies at another location in southeastern Wyoming (6, 7). The snow transfer coefficient, θ, for each site was estimated from preliminary measurements of snow remaining on the contributing areas after drifting events. R_o was measured from aerial photographs, but for most sites was found equal to R_m. Mean winter precipitation was estimated at 244 mm (9.6 in.) from data published by the National Weather Service for nearby stations. Thus, for the extreme case where θ = 1.0 and R_o = R_m, Eq. 2 predicts an average capacity requirement of about 120 m^3 water-equivalent per lineal metre of fence (about 1,300 ft^3/ft).

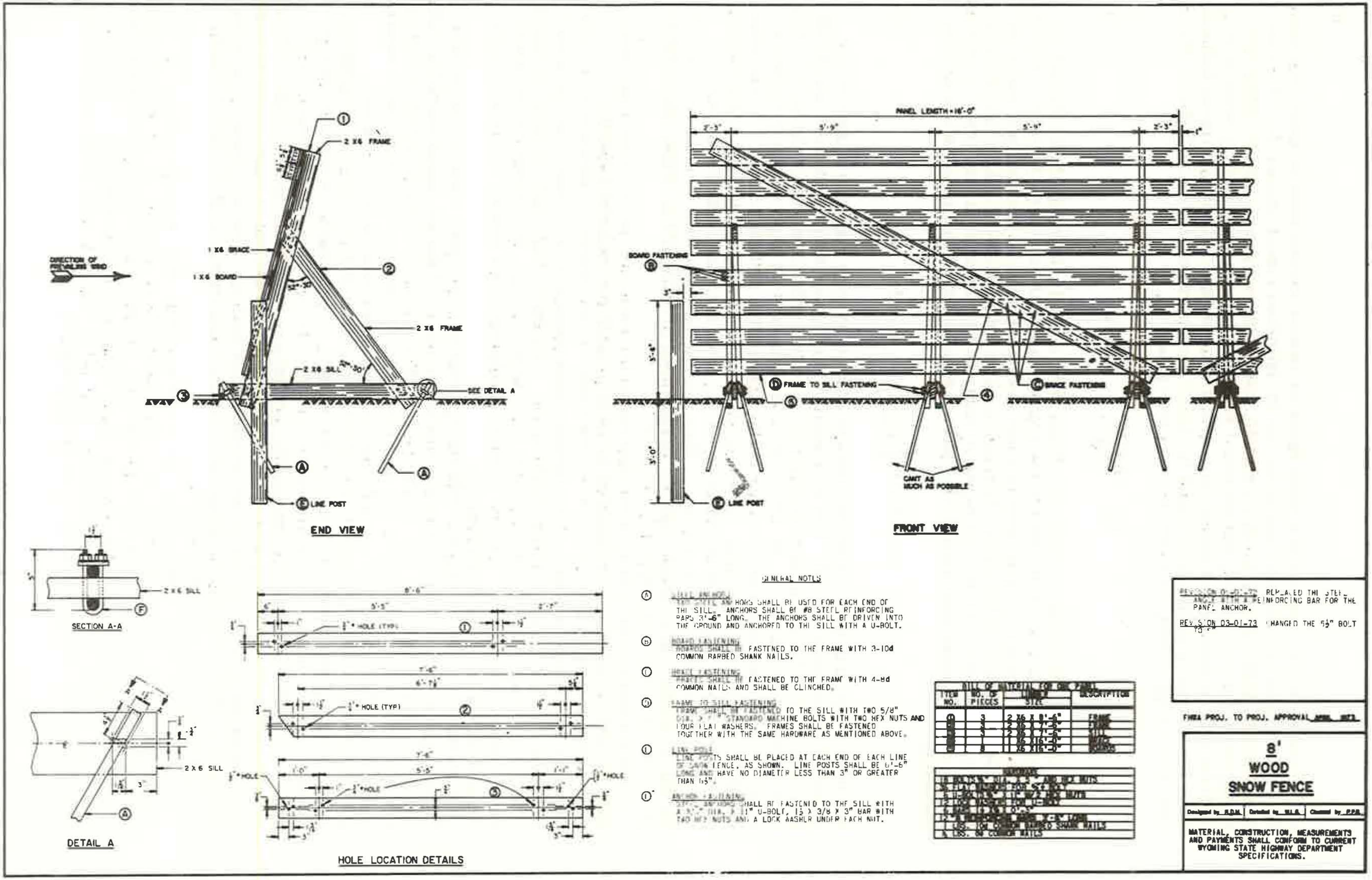
Once the quantity of blowing snow was known for each site, fence heights and numbers of rows of fencing were selected so as to provide the required capacity.

Because the initial estimates for R_m and θ were to be revised, if necessary, for the design of subsequent systems, these factors were measured at 2 sites over the winter following the first phase of fence construction. Results of that study verified the utility of Eq. 2; although the original estimates for θ were too high, they about compensated for an underestimate in R_m, and the original prediction of the amount of snow storage requirement was within 10 percent (9).

A recent model describing the sublimation rate of wind-blown snow (3) shows that R_m will depend on the relative humidity and temperature of the air, solar radiation, wind speed, and diameter of the snow particles (7). The transport distance would therefore be expected to vary from site to site and from year to year in response to these weather conditions. This variability is confirmed by our measurements of snow water-equivalent storage behind natural and artificial barriers of large capacity at different sites. Knowing the snow water-equivalent storage, in combination with precipitation measurements, permits calculation of the product θR_m (the "equivalent transport distance"). In effect, this factor represents the distance over which all the winter precipitation would have to be relocated in order to provide the amount of snow observed behind an efficient barrier by the end of the accumulation season. This combined term is introduced to allow comparison among sites where measurements of the snow transfer coefficient (and R_m) are not available.

From Table 1, which summarizes all of our available data, average values for θR_m range from about 1100 m (3,600 ft) on I-80 to about 550 m (1,800 ft) at the Pole Mountain study site. Unfortunately, the effect of elevation cannot be determined from these data because all study sites in Table 1 are at about 2400 m (7,800 ft) elevation. However, data from Straight Creek Pass (elevation 3800 m) in Colorado give a θR_m value of about 800 m (2,600 ft) averaged over 3 years of observations.

Figure 2. Wyoming Highway Department standard-plan fence, 2.4-m height.



FENCE DESIGN

The Wyoming Highway Department developed a new snow fence design in response to the need for tall fences on the I-80 project. Design features for the 2.4-m (8-ft) and 3.8-m (12.5-ft) fences are detailed in Figures 2 and 3. The basic features of this design include (a) use of horizontal slats 15 cm (6 in.) wide, spaced at 15 cm; (b) a leeward inclination of 0.26 rad (15 degrees); and (c) a bottom gap of 0.3 to 0.4 m (10 to 14 in.). The 1.8-m (6-ft) and 2.4-m (8-ft) fences are secured to the ground by metal stakes, while the 3.3-m (10.5-ft) and 3.8-m (12.5-ft) heights are guyed to anchors buried 1 m (3 ft) in the ground. A 45 m/s (100 mph) wind loading with an additional 30 percent gust factor was used in the design, and the completed structures have successfully withstood measured wind gusts up to 50 m/s (110 mph).

Our studies of this new fence show cross-sectional area A (m^2) of the lee drifts on level terrain to be proportional to fence height H (m) according to

$$A = 18\ H^2 \tag{3}$$

Using a typical snow density (at peak accumulation) of 500 kg/m^3, water-equivalent capacities of fences 1.8 m, 2.4 m, 3.2 m, and 3.8 m tall are 30, 54, 90, and 129 m^3 per lineal metre of fence (325, 575, 975, and 1,385 ft^3/ft).

Other characteristics of the lee drifts at saturation (when the fence is filled) include a length of about 24H, a maximum depth of about 1.2H located 5H to 6H downwind of the fence, and a uniform tail slope of about 8.3 percent. There is reason to believe that the exceptional snow depths (and thus capacity) behind the new fences are due to the 0.26-rad inclination to leeward.

A mathematical description of the drift profile allows us to predict the capacity of these fences in irregular terrain. For this application we have found the lemniscate equation (in polar coordinates)

$$r^2 = L^2 \cos n\phi, \qquad (0 < n\phi < 90 \text{ degrees}) \tag{4}$$

to give a reasonable approximation of drift shape, where L is drift length, r is vector distance from the tail end of the drift, and the coefficient n for the vector angle ϕ is 16. The value for n is obtained by integrating for an element of area under Eq. 4 (which gives $A = L^2/2n$) and substituting Eq. 3 for A and 24H for L.

In rectangular coordinates, snow depth y at distance x from the fence is given by

$$y = L\ (\sin \phi)\ (\cos n\phi)^{1/2} \tag{5}$$

and

$$x = L\left[1 - \cos \phi\ (\cos n\phi)^{1/2}\right] \tag{6}$$

Equations 5 and 6 tend to underestimate depths in the drift nose and slightly exaggerate depths in the tail (Figure 4). This tendency is less pronounced, however, than with the rose equation ($r = L \cos n\phi$) proposed by Price (2).

FENCE HEIGHT

Data from one of our earlier experiments showed tall fences to be more efficient than shorter ones in trapping snow (Figure 5). Water-equivalent storage behind fences of different heights at various stages of snow storage prior to saturation suggests that trapping efficiency increases with increasing fence height, even at the earliest stages of accumulation. A similar conclusion was reached by Schneider (4), citing Croce's data. Since more than 95 percent of the wind-blown snow in the lowest 4 or 5 m is transported in the first metre above the ground (1), the difference in catch between fence heights of H and ($H + \Delta H$) seems to result from more than just the capture of the additional snow transported in the ΔH layer. Mean wind speed reduction behind fences has also been found to increase with increasing fence height (5), which supports the theory that collection efficiency increases with fence height.

Figure 3. Wyoming Highway Department standard-plan fence, 3.8-m height.

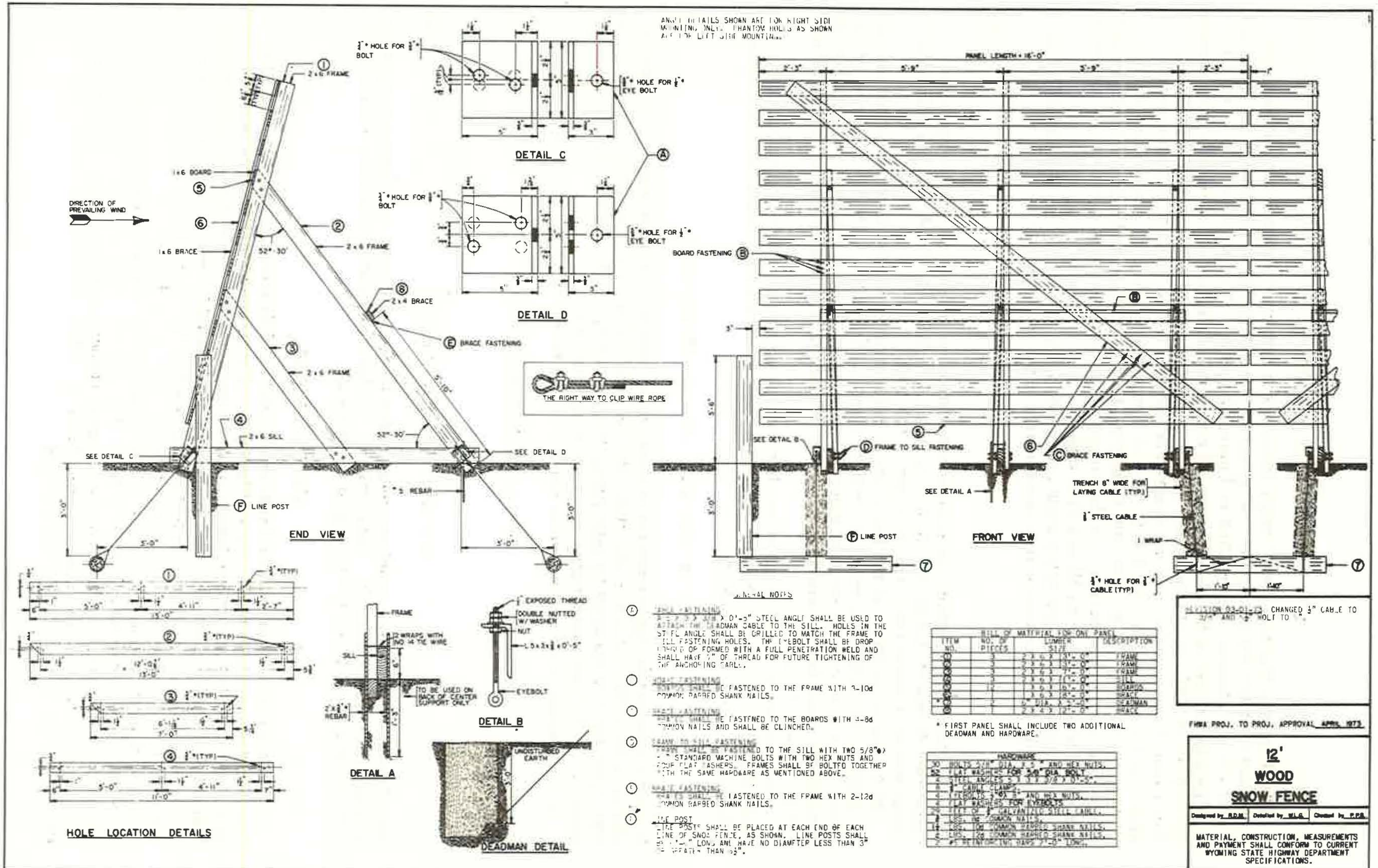


Figure 4. Average drift profile measured behind the 3.8-m fence at saturation compared with the lemniscate equation r = L cos½ (16 ϕ).

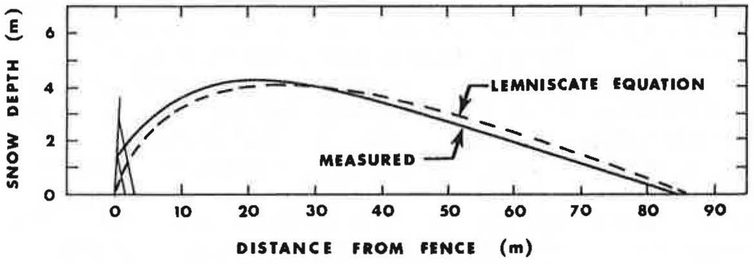


Figure 5. Lee drift water-equivalent per metre of fence (Q) as a function of fence height (H), from an earlier study in southeast Wyoming. The saturation values shown for the vertical-slat fences used in this study are considerably less than for the Wyoming Highway Department fences described in this report. Each point is the average of 4 fences.

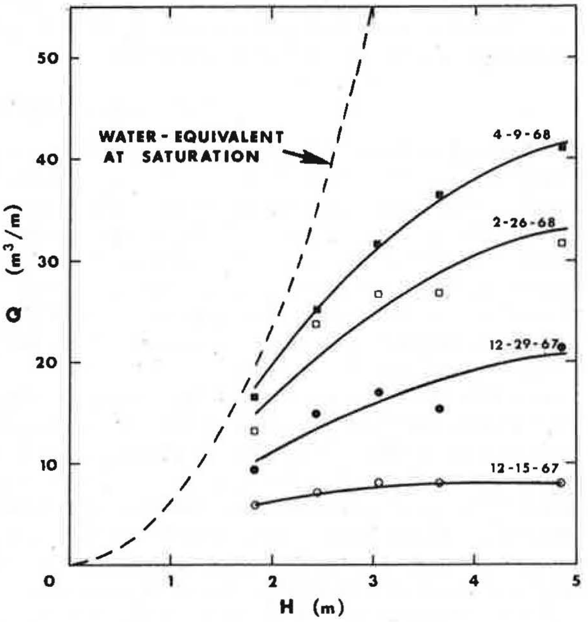
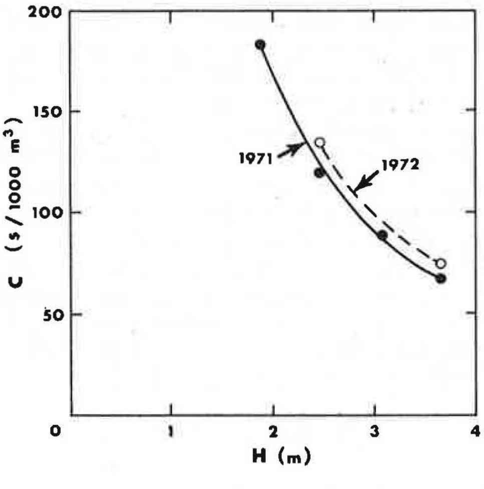


Figure 6. Construction costs (C) per 1000 m^3 of water-equivalent storage as a function of fence height (H) for the two I-80 contracts.



We believe the greater trapping efficiency of the 3.8-m fences on I-80 is an important factor in the dramatic improvement in visibility (8). However, perhaps the most important reason for using tall fences is the economy of construction. Construction costs per 1000 m^3 of water-equivalent storage using a 3.8-m fence are about one-third those for a system of four 1.8-m fences of equal storage capacity (Figure 6). Costs used for this analysis are from the two I-80 snow fence contracts over the last 2 years, each totaling about $500,000. Figure 6 also suggests that the 3.8-m fence may be near the maximum height with respect to minimum costs per unit of storage.

For the extreme case on I-80 where the snow storage requirement is about 120 m^3 per lineal metre, a single row of 3.8-m fencing would provide the desired capacity (using the average year as the design criterion). However, because the efficiency of a snow fence declines as the fence fills (as will be shown in the next section), an additional row of 2.4-m fence would be prescribed, particularly in critical locations where roadway cuts have a small storage capacity or in situations where visibility improvement is the primary objective. Although there is good reason to question the practice of engineering snow control systems for the average year, an economic assessment of the problem must await more experience.

FENCE EFFICIENCY

Trapping efficiency is here defined as the percent of incoming snow that is trapped behind a barrier. When a fence is empty (at the beginning of winter), efficiency will be relatively high; once the fence is filled to capacity (or "saturated"), the efficiency must be zero. Absolute efficiency over a given interval is difficult to determine because it requires that total snow transport be known. Relative efficiency, however, may be determined by comparing performances among fences with different degrees of saturation. This comparison provides at least a preliminary idea of how much snow escapes a single fence over the course of a season and the additional fencing necessary to compensate for this escape.

For this study we compared the capture of snow among 3 tandem fences with a very large combined capacity relative to the average annual snow transport. This system is about 490 m (1,600 ft) long and consists of a 2.4-m lead fence followed by two 3.8-m fences spaced 61 m (200 ft) and 152 m (500 ft) behind the lead fence. Snow depth and water-equivalent were sampled behind the fences after each major drifting event over 2 winters. Snow depths were probed at 3-m (10-ft) intervals along 4 permanent transects, and water-equivalent was sampled with a Mount Rose sampler at 3-m intervals along 1 randomly selected transect at each fence.

A double-mass plot (Figure 7) of the change in water-equivalent storage behind the 3 fences provides some insight into how efficiency changes as a fence fills. In 1972-73, for example, the relationship between the lead 2.4-m fence and the 3.8-m fence immediately downwind was relatively constant up to the time the lead fence was about 80 percent filled. The preceding winter, this relationship showed noticeable curvature somewhat earlier (when the lead fence was about 50 to 60 percent full), probably reflecting the effect of stronger winds.

To derive a curve for this relationship, let us assume the second and third fences to be 100 percent efficient over the period of study. Of course, this assumption is not strictly true, but it is consistent with the objective of expressing efficiency of the lead fence relative to that of the second. The assumption is not too unreasonable since the second fence was only about 20 percent full by the end of the first season and only 30 percent filled by the end of the second; the third fence contained only about 10 percent of its capacity during both years, and the catch was about what would be expected from the relocation of precipitation between the last 2 fences. Using the third fence catch to estimate that portion of the second fence catch contributed by precipitation relocated between the first 2 fences, we obtain

$$\text{Efficiency of lead fence} = \frac{\Delta Q_1}{\Delta Q_1 + \Delta Q_2 - (2/3)\Delta Q_3} \tag{7}$$

where ΔQ_1, ΔQ_2, and ΔQ_3 are the changes in water-equivalent storage over a measure-

Figure 7. Double-mass plot of the change in water-equivalent storage (ΔQ) behind 3 tandem fences at system 1, I-80.

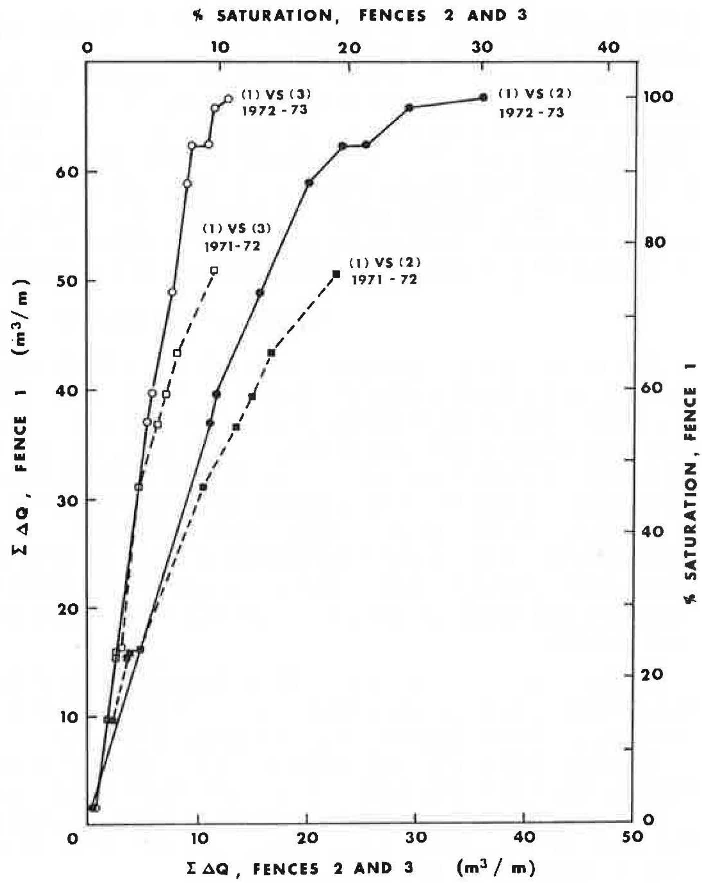
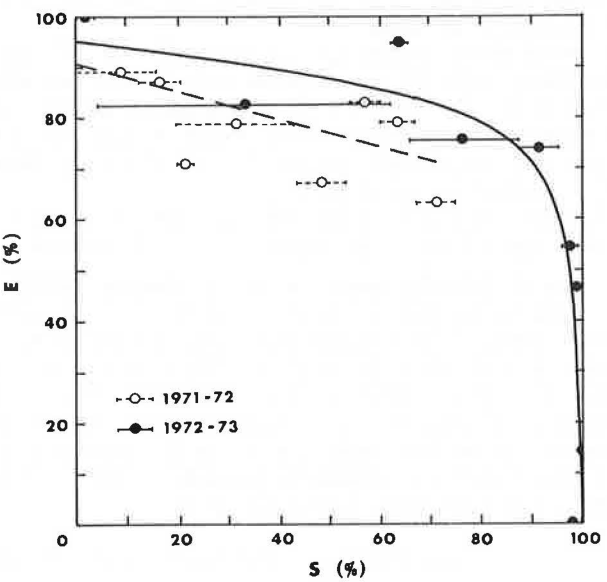


Figure 8. Efficiency (E) of a 2.4-m lead fence relative to a 3.8-m fence downwind as a function of degree of saturation (S) of the lead fence. Bars denote range of saturation over each measurement interval.



ment period, and the ⅔ factor accounts for the relative spacing between the 2 pairs of fences (61 and 91 m respectively).

Results from Eq. 7 were plotted against degree of saturation (Figure 8); average curves show that efficiency decreases slowly as a fence fills, with between 70 and 80 percent of the incoming snow still being trapped by the time the fence is 75 percent full. This result agrees with our observations that fences markedly improve visibility on the roadway even when fences are filled to 60 percent or more of capacity (8).

For the 1972-73 data, average efficiency of the fence, from onset of accumulation to time of saturation, is about 85 percent. We therefore recommend that storage capacity be at least 20 percent greater than the amount of blowing snow estimated from Eq. 2.

TERRAIN INTERACTIONS

The scope of this paper precludes a detailed discussion of the complex relationships between terrain and fence performance. A few general rules have contributed substantially to the success of the I-80 system, however, and so are briefly outlined here. Our applications have been limited to rolling topography with slopes of 20 percent or less, and our guidelines are not necessarily applicable for steeper terrain or for fences other than the new Wyoming Highway Department design (Figures 2 and 3).

Terrain can be used to greatly increase the storage capacity of a snow fence, making it possible for a short fence to contain as much snow as a much taller (and thus more expensive) structure. Conversely, certain terrain situations detract from fence performance and should be avoided. The following rules condense some of the more common situations:

1. For gently rolling topography with gentle to moderate slopes, fence performance is affected by the terrain extending from about 45 m (150 ft) upwind (approach zone) to about 90 m (300 ft) leeward (exhaust zone) of the snow fence.
2. On uniform slopes of less than 10 percent, either upward or downward with respect to the prevailing wind, a fence will store as much snow as on level terrain.
3. Depressions in the lee drift zone serve to augment snow storage capacity. The increase can be estimated by plotting Eqs. 5 and 6 relative to a horizontal surface extended leeward from the fence.
4. Downward slopes in the exhaust zone increase storage capacity; as a preliminary guide, capacity is increased by 15 to 20 percent for each 0.017 rad (1 degree) of slope up to 0.17 rad (10 degrees).
5. Upward slopes in the approach zone (up to 0.17 rad) have also been observed to increase fence capacity. As a preliminary guide, effective fence height increases about 0.15 m (0.5 ft), with a resulting capacity increase of about 15 percent, for each 0.017-rad increase in slope. Drift length is also increased according to this rule. This effect has been confirmed only for the new Wyoming Highway Department fence design described earlier in this report.
6. Upslopes and hills in the exhaust zone generally decrease fence capacity, except as noted in rules 2 and 5 above, and should be avoided.

The largest drift we have observed behind any of the I-80 fences (Figure 9) demonstrates some of the guidelines given above. In this example, a 3.8-m fence is located on a ridge crest. The upslope approach, approximately 0.061 rad (3½ degrees), has resulted in a drift about 0.6 m (2 ft) deeper than would be expected with a level approach (rule 5). Storage capacity is further enhanced by the 0.15-rad (6-degree) downslope in the exhaust zone (rule 4). The cross section of this drift was 445 m^2 (4,800 ft^2), or about twice that expected behind a 3.8-m fence on level terrain. The capacity of the fence at this location is estimated to be about 320 m^3/m water-equivalent and would be expected to fill only about 1 year out of 100.

END EFFECT, OVERLAP, AND MINIMUM LENGTH

Criteria for overlapping staggered fences, as well as for minimum length, must be developed from a knowledge of how the trapping efficiency of a snow fence varies as a function of distance from the end of the fence. For a fence oriented exactly normal to

Figure 9. Cross section of the largest drift yet measured behind the I-80 fences, showing the effects of terrain on storage capacity of a 3.8-m barrier at system 14A. A saturated drift on level terrain is shown for comparison.

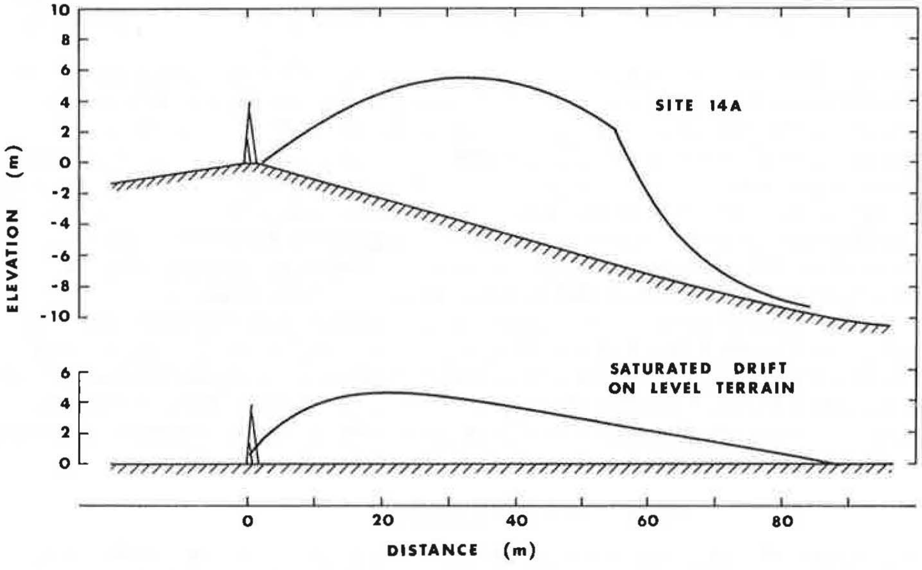
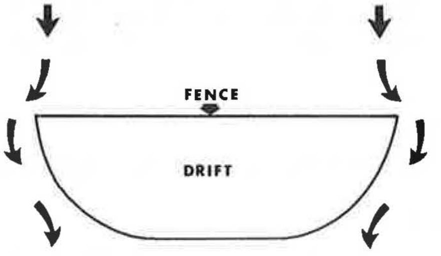


Figure 10. The ends of a drift rounded by wind sweeping around the ends of the fence: (A) plan view, (B) elevation.



A

B

the wind, the ends of the lee drift at saturation will be rounded by wind sweeping around the fence (Figure 10). This effect is due to the generation of turbulent eddies at the fence boundary, an acceleration of the converging air flow at the ends of the fence, and the response of the air flow to the lateral pressure gradients developed behind the barrier. Of course, oblique winds tend to accentuate this rounding on the end exposed to the wind.

Our data from 6 fences of different heights show this end effect to extend inward as far as 12H from the end of the fence (Figure 11); at a distance of 5H, the drift cross section is only about 80 percent of maximum. Based on this information, we recommend a minimum overlap in a series of staggered fences of about 8H, which will reduce the escape through the overlap section to less than 10 percent (Figure 12). This recommendation assumes drifting winds to be relatively constant in direction and also ignores the tendency of blowing snow to weave its way around staggered barriers. Overlap should be extended to 10H or more in cases where wind directions are variable or where terrain might tend to reinforce the snaking tendency of the wind.

By using the data from Figure 11, it is possible to compare capacities of different lengths of fences relative to a fence of infinite length. The end effect is a significant factor (Figure 13); for example, a fence 10H in length will be able to contain only about 60 percent of the snow trapped behind the center 10H of a very long fence. Based on this analysis, we recommend that all fences be at least 30H in length; shorter structures are obviously much more expensive in terms of cost per unit of storage.

CONCLUDING REMARKS

Although the length of this paper does not permit a discussion of other guidelines, such as those for optimizing fence configurations in instances where winds are oblique to highway alignment, the reader can develop these for himself from the basic concepts outlined.

Properly engineered snow fence systems are a powerful tool for snow control, and it is unfortunate that earlier applications of improperly designed fences have made some engineers skeptical of their potential. Indeed, the benefits of improved visibility and reduced ice formation have only now come to light with the I-80 installations. The criteria proposed here should help bring snow control technology up to date with today's standards of highway engineering.

ACKNOWLEDGMENT

Research reported here was supported in part by the Wyoming Highway Department.

REFERENCES

1. Komarov, A. A. Some Rules on the Migration and Deposition of Snow in Western Siberia and Their Application to Control Measures. Trudy Transportno-Energeticheskogo Instituta, Vol. 4, 1954, pp. 89-97. Nat. Res. Counc. of Canada Tech. Transl. 1094.
2. Price, W. I. J. The Effect of the Characteristics of Snow Fences on the Quantity and Shape of the Deposited Snow. General Assembly of Helsinki, Internat. Assoc. of Sci. Hydrol., Internat. Union of Geod. and Geophys., Pub. 4, 1961, pp. 89-98.
3. Schmidt, R. A., Jr. Sublimation of Wind-Transported Snow—A Model. USDA For. Serv. Res. Pap. RM-90, Rocky Mtn. For. and Range Exp. Stn., Fort Collins, Colo., 1972, 24 pp.
4. Schneider, T. R. Snowdrifts and Winter Ice on Roads. Eidgenossisches Institut Für Schnee- und Lawinenforschung, Interner Bericht Nr. 302, 1959, 141 pp. Nat. Res. Counc. of Canada Tech. Transl. 1038, 1962.
5. Tabler, R. D., and Veal, D. L. Effect of Snow Fence Height on Wind Speed. Bull. Internat. Assoc. of Sci. Hydrol., Vol. 16, No. 4, 1971, pp. 49-56.
6. Tabler, R. D. Design of a Watershed Snow Fence System, and First-Year Snow Accumulation. West. Snow Conf., Billings, Mont., Proc. Vol. 39, 1971, pp. 50-55.
7. Tabler, R. D., and Schmidt, R. A., Jr. Weather Conditions That Determine Snow

Figure 11. Cross-sectional area (A) of the lee drift at saturation (expressed as percent of maximum value in center of fence) as a function of distance (D) from the end of the fence (in multiples of fence height H).

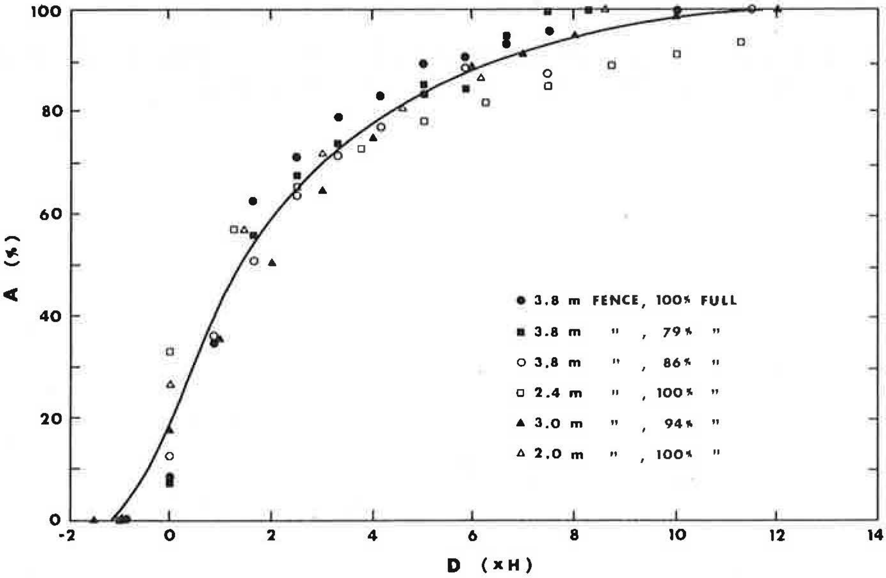


Figure 12. Escape of blowing snow through an overlap section (in percent of total ambient transport) in relation to amount of overlap and distance from center (in multiples of fence height H).

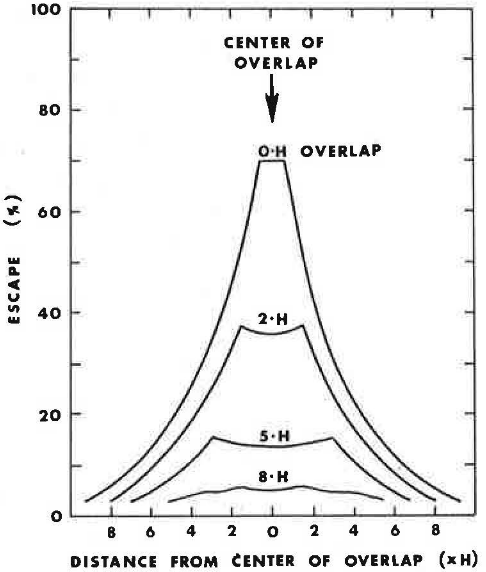
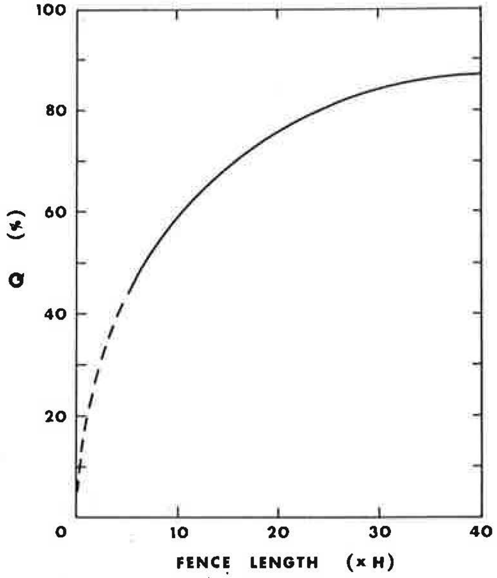


Figure 13. Total storage capacity Q (in percent of maximum possible) as a function of fence length (in multiples of fence height H).



Transport Distances at a Site in Wyoming. UNESCO/WMO/IAHS Internat. Symp. on Role of Snow and Ice in Hydrol., Banff, Alberta, Canada, Sept. 1972, Proc. (In press.)
8. Tabler, R. D. New Snow Fence Design Controls Drifts, Improves Visibility, Reduces Road Ice. 46th Ann. Transport. Engin. Conf., Denver, Colo., Feb. 1973, Proc. pp. 16-27.
9. Tabler, R. D. Evaporation Losses of Windblown Snow, and the Potential for Recovery. West. Snow Conf., Grand Junction, Colo., Proc. Vol. 41, 1973, pp. 75-79.