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Shelterbelt and Surface Barrier Effects on Wind Velocities, Evaporation, House Heating, Snowdrifting

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Shelterbelt and Surface Barrier Effects on Wind Velocities, Evaporation, House Heating, and Snowdrifting[1]

N. P. Woodruff[2]

SUMMARY

Models of shelterbelts, snow fences, and solid walls were tested in a wind tunnel to determine their effects on wind velocities, evaporation rates, snowdrifting, and house heating. Velocity patterns obtained in the vicinity of full-scale snow fences under atmospheric conditions also are presented to show the agreement between studies of the problem with wind tunnels and under field conditions.

The comparative velocity pattern about the single and successive snow fences indicates that wind tunnel approaches can be used to make reasonable estimates of the effects of full-scale surface barriers.

The snow fence surface barrier was shown to have the following effects on wind velocities:

1. The most substantial reductions in average velocity for a single fence occur in the zone extending from approximately 4 to 10 H. There is also a reduction in wind velocity of at least 20 percent extending a distance of 20 H aft of the single fence.
2. The successive fence data indicate that 4 fences are not sufficient to create an accumulative effect aft of the leeward fences, but reductions of at least 30 percent aft of each fence are obtained with the 15 H spacing used in this experiment.

Horizontal velocity measurements indicate a 5- to 6-H advantage for the leaved shelterbelt and the solid wall over the defoliated belt, as measured by ability to create 25 and 50 percent velocity reductions. The solid wall is also more effective than either of the two shelterbelts in creating 75, 50, end 25 percent velocity reductions. However, both the leaved belt and the solid wall cause a greater upward diversion of the flow lines in the zone above the barrier, resulting in increased eddy formation.

Surface reductions as indicated by shear patterns aft of the leaved and defoliated 10-row shelterbelts and the solid wall

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[1] Contribution 507, Department of Agronomy, Kansas Agricultural Experiment Station, Manhattan, and the U.S.D.A. Agricultural Research Service, Soil and Water Conservation Research Branch. Cooperative research in the mechanics of wind erosion.

[2] Agricultural Engineer, Western Section of Soil and Water Management, A.R.S., U.S.D.A.

Grateful acknowledgment is made to A. W. Zingg, former project supervisor, for many contributions and suggestions to this study and also to C. P. Davis, Agricultural Engineer, farm electrification division, A.R.S., U.S.D.A., for technical advice and lending electrical equipment used in the study.

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show the wall to be less effective at the ground surface than either the leaved or defoliated shelterbelt. The defoliated belt exceeds the leaved belt in apparent limit of influence and is equal in net zone of 25 percent reduction. The leaved belt, on the other hand, exceeds the defoliated belt in net distances to 50 percent reduction, index of protection, and effectiveness per tree.

The solid wall and the defoliated shelterbelt have similar effects on the evaporation rate. Points of maximum reduction (about 45 percent), apparent limits of influence, and average reduction in the zone from 0 to 18 H are the same for both the wall and the defoliated belt. Some differences exist in the zone from 2 to 10 H where the increased eddy effect caused by the plate is apparent in a lessened reduction in evaporation. The leaved belt has approximately 25 percent greater maximum reduction and a 19 percent greater average reduction than the solid wall or defoliated belt. A study of climatic data shows, however, that some of this seasonal advantage is offset by the lessened evaporation occurring naturally in winter months.

Relationships for house heating loads in terms of air temperature and wind velocities show that an unprotected house exposed to a 20 mph wind will use 2.4 times as many BTU per hour of heat as the same house exposed to a 5 mph wind under the same temperature conditions. Substantial reductions in the heating load are obtained by using a 10-row defoliated shelterbelt. Percentage reductions in the heating load decrease with distance aft of the belt. Maximum reductions occur with the higher wind velocities. The maximum measured reduction was 40.5 percent at 2 H with a 35 mph wind. The minimum measured reduction was 3.3 percent at 18 H with a 5 mph wind. Solution of a hypothetical problem using a house having a 95,000 BTU per hour demand and average design temperatures, wind velocities, and gas rates for Topeka, Kan., shows that a saving of 24,722 cu. ft. of gas or a dollar and cent saving of approximately $9.90 per season could be obtained if full protection from all winds were provided by placement of shelterbelts at 2 H distance from the house.

Measurements of "snow catch" using simulated sawdust snow indicated 4 fences spaced 12 H apart catch 4 times as much snow as a solid wall, 1.2 to 1.8 times as much as 2 fences with similar spacing, and approximately 2.5 times as much as a single fence. The model shelterbelts were all nearly the same; however, the 10-row belt caught slightly less material than the 5- or 2-row belts. The best shelterbelt evidently has a capacity approximately 3.6 times greater than the best snow fence combination. The drifts were located mostly within the boundaries of the trees for the 10- and 5-row belts, but did not begin to pile up for a distance of approximately 8 H aft of the 2-row belt.

DEFINITION AND INTRODUCTION

The movement of winds over the earth's surface is impeded in many ways—mountains and hills, forests, and even plains, all exert a frictional drag on the wind. This drag causes wind velocities to be less at the surface than at higher altitudes. Man, in an ever-continuing effort to improve his environment, has found that he can reduce wind velocities further by placing obstacles, such as windbreaks, snow fences, or solid walls, in the path of the wind. This practice is, in effect, a small-scale extension of the large-scale natural phenomenon.

Obstacles divert the air current upward and cause a drag on the wind at approximately the same height as the obstacle. This lessens the drag on the original ground surface, lowers the prevailing surface velocity, and creates a pool of relatively calm air within the zone the obstacle influences. In this sense, then, a surface barrier is any obstacle in the path of the wind that diverts some of the wind's force and accomplishes all or a part of the above.

Surface barriers in one form or another have been used for many years to protect humans, animals, and crops from the ravages of the wind. Recognition of their value in the United States dates from early pioneers who first settled the plains area. Most of the early settlers came from Europe where surface barriers in the form of trees were abundant. They were unaccustomed to the treeless plains and took immediate steps to alleviate the condition.

Trees planted as a windbreak are perhaps the best type of surface barrier. They have the advantages of being more or less permanent, economical, and have an aesthetic value. On the other hand, using trees as surface barriers suffers from the disadvantage of requiring many years to reach maturity. Trees also are susceptible to attacks of diseases and insects. These disadvantages have led to temporary types of surface barriers to reduce wind velocities, to control wind-driven snow, or to protect small areas of land from soil blowing. Some of the more common types of temporary barriers are various tall-growing crops planted in strips, snow fences, and solid walls constructed from wood or galvanized metal.

While many types of surface barriers have been and are being used, actual research on their individual merits has been sporadic and has led to variable conclusions in some instances. Actually, most of the scientific data available today was obtained in the 1930's after the government had promoted windbreak plantings on a large scale. As a result, there are many unsolved problems associated with surface barriers. This bulletin presents results of studies of some of these problems.

PROBLEMS ASSOCIATED WITH SURFACE BARRIERS

The comparative effectiveness of different types of barriers is one of the first problems requiring consideration. This effectiveness must be measured in terms of the function the barrier is to perform. Actually, the chief function of any surface barrier is to reduce the wind velocity; the consequences of this, however, are exerted in other ways. For example, a reduction in wind velocity will also reduce snow drifting, decrease the evaporation rate, and reduce house-heating loads. Of course each of the different barriers has certain advantages and disadvantages. A qualitative evaluation of these advantages and disadvantages is, therefore, of great value.

In addition to the problem of selecting the particular type of barrier to fit the purpose, there are also problems associated with the respective barriers. The use of snow fences, for example, presents the problem of determining the proper location of the fence with respect to the object or area which is to be protected. When multiple fences are used there is also the problem of obtaining the most effective spacing interval between fences. Solid walls also present a problem for they are expensive to construct; it is imperative, therefore, that their effectiveness will be great enough to offset additional costs.

Where shelterbelts are used there is not only the problem of obtaining the most effective number of rows for the space available, but also the most effective combination of rows of trees and shrubs within the belt. Seasonal influences on the density of shelterbelts must also be considered. Since most shelterbelts are composed of several rows of deciduous trees and perhaps two or three rows of evergreen species, the density of the shelterbelt varies seasonally.

The preceding problems are associated with the use of surface barriers. Another problem concerns methods of experimental research. The most obvious approach, of course, would be field studies of actual barriers. However, this type of research lacks control of the many variables. It also presents a tremendous physical task in obtaining data throughout the zone of influence of a full-scale surface barrier. For these reasons models and a wind tunnel have been used to analyze problems of this nature. This type of research has the advantage of control over some of the variables while measuring others, i.e., velocities can be held constant to allow time for making complete traverses of areas of influence. Again, data may be taken at any desired time independent of the whims of the weather, and the cost is low. However, interpreting and applying the data to full-scale atmospheric conditions are inherent problems. A previous study (6) showed that these problems are not insurmountable. If modeling techniques and rules are followed, wind tunnel data give reasonable estimates of the effects of actual full-scale barriers under natural conditions.

SCOPE OF STUDY

This bulletin presents the results of wind tunnel studies on the following phases of surface barrier effects: (a) wind velocities about foliated and defoliated 10-row shelterbelts, solid walls, and single and successive snow fences; (b) evaporation rates aft of solid walls and foliated and defoliated shelterbelts; (c) the house-heating load aft of defoliated 10-row shelterbelts; and (d) snowdrift control using 10-row, 5-row, and 2-row defoliated shelterbelts, and single and successive snow fences. Included also in the section on wind velocity effects of snow fences is a presentation of comparative data taken under atmospheric conditions to give authenticity to the tunnel results.

DESCRIPTION OF MODELS

The model shelterbelts used in these experiments were fabricated from spiraea and cedar boughs placed in short lengths of ¼-inch aluminum tubing. The "trees" were oriented in a series of holes drilled in a 20- by 36-inch plywood base. Eight rows of spiraea "trees" and "shrubs" and two rows of cedar "trees" were prepared. The two rows of cedars were placed as the second and third rows on the windward side in a conventional 10-row belt. The trees could be moved in any manner desired, and 10-, 5-, and 2-row belts were assembled. The scale used for the models was 1 inch equals 5 feet. Thus, in terms of the prototype conditions, the shortest shrubs in a 10-row belt were 7.5 feet, the tallest trees were 30 feet, and the remainder were graduated upward in 2.5-foot increments from 7.5 to 30 feet. Spacing between the rows of trees was 2 inches on the model, corresponding to 10 feet for field conditions. Spacing within the rows for the shrubs was 1 inch, or 5 feet. This spacing provided 36 trees and shrubs in a 10-row belt, 21 trees and shrubs in a 5-row belt, and 8 trees only in a 2-row belt for each unit H.[3] The 10-row foliated belt was constructed first and tested, the leaves were then removed and 10-, 5-, and 2-row versions of the defoliated or "winter" condition were used in conjunction with the various phases of the study. Figure 1 is a view of the leaved and nonleaved 10-row shelterbelt oriented in the wind tunnel.

The solid wall used in the study was constructed from 1/16-inch aluminum sheeting. The vertical wall was 4 inches high and 36 inches long and was mounted in the center of a 6- by 36-inch, 1/16-inch aluminum base. Orientation in the tunnel of this movable, self-supporting unit is shown in Figure 2.

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[3] H=6 inches in the model, or 30 feet in an actual belt, and is the tallest tree in a given belt.

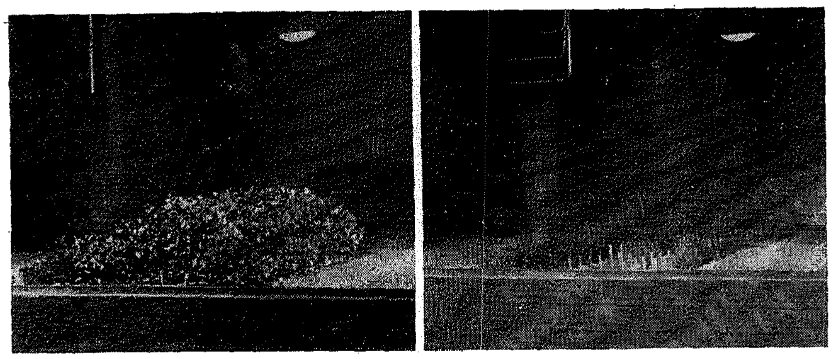

Fig. 1.—The leaved "summer" shelterbelt and the defoliated "winter" shelterbelt oriented in the wind tunnel.

The model snow fences used in the experiments were fabricated from galvanized tin. They were constructed on a scale of 1 inch equals 1 foot; thus, the model fence was 4 inches high, the slats 1/8-inch wide, and the openings between slats 3/16-inch. The length of the fences was 3 feet. Four such "fences" were constructed. Figure 3 shows one of the fences oriented in the tunnel.

The model house was constructed from 1/4-inch plywood on a scale of 1 inch equals 5 feet. The dimensions of the model were 5 by 5 by 5 inches, or in prototype measurements this

Fig. 2.—Solid wall and evaporation pan oriented in tunnel (right). Laboratory equipment for evaporation study also is shown.

would be 25 by 25 by 25 feet. There were 6 windows and 2 doors in the house. The windows were Plexiglass sealed to the walls. The doors each had a definite crack space proportional to that in a rather poorly constructed home. There was also a chimney equipped with a controlled vent to allow some similarity to chimney losses of heat in homes. The house was heated by an electrical heating coil placed in the floor. Temperatures were maintained at 76° F. by a thermostat. The house as it was oriented in the tunnel is shown in Figure 4.

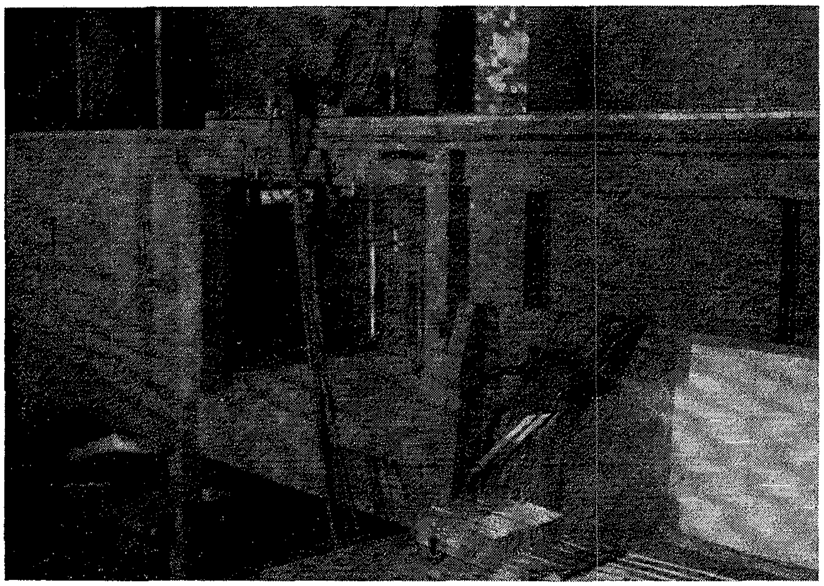

Fig. 3.—Laboratory set-up showing manometer and Pitot tubes and one of the model fences oriented in wind tunnel (behind tubes at left).

METHODS OF STUDY

The studies of the problems covered in this bulletin were carried out in the laboratory tunnel shown in Figure 5. The working section used for these particular experiments consisted of a 16-foot horizontal length beginning 42 feet downwind from the blower. The top of the tunnel for this section was constructed to facilitate horizontal movement of a staff of Pitot tubes through the entire 16-foot length. The floor consisted of sieved gravel 2.0-6.4 mm., thus assuring development of a turbulent boundary layer similar to atmospheric conditions.

Horizontal velocity measurements were made with the group of 4 Pitot tubes and an alcohol manometer shown in Figure 3. The Pitot tubes are mounted on a rack and gear carriage to

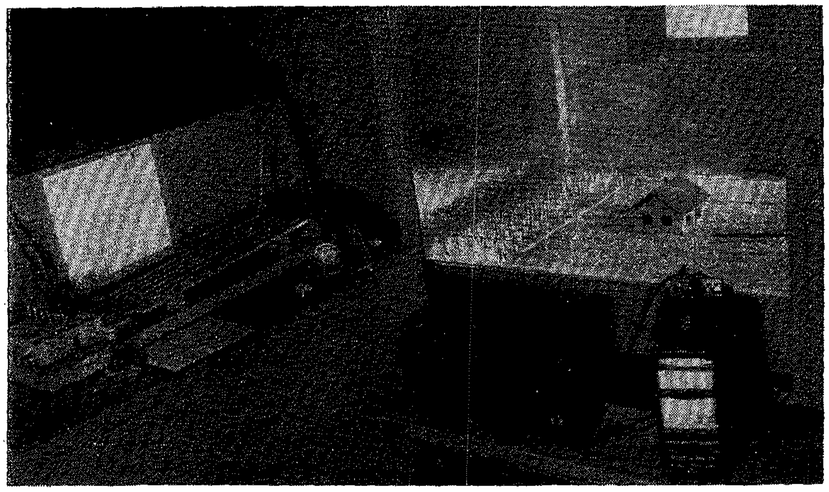

Fig. 4.—The model house oriented in the wind tunnel aft of the 10-row defoliated shelterbelt. The recording ammeter used to measure electrical current required to heat the house and the alcohol manometer used to measure velocity also are shown.

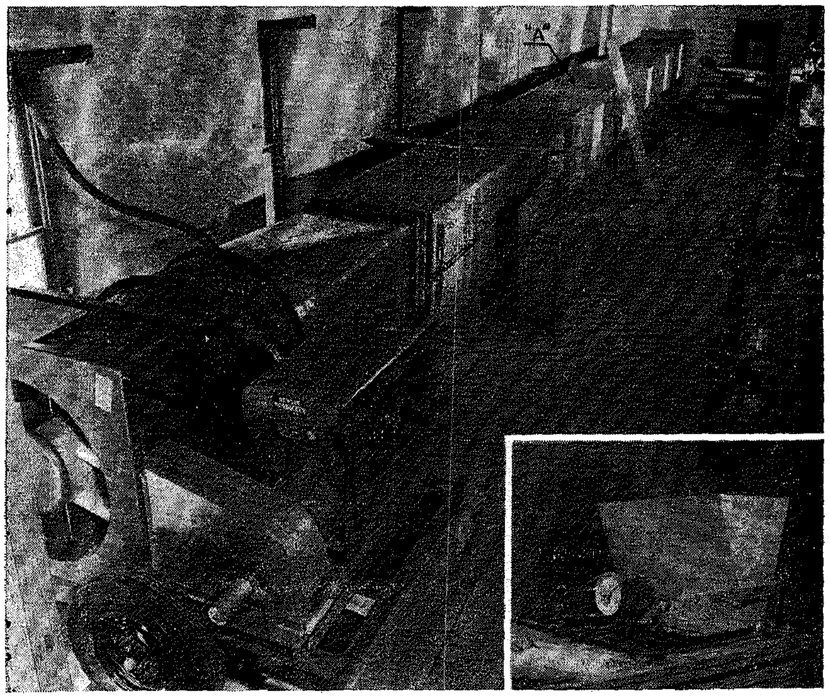

Fig. 5.—Panoramic view of laboratory wind tunnel and sawdust feeder mechanism for simulating snowfall (inset) used in this study. The location of feeder on tunnel is indicated at point "A."

facilitate horizontal movement and on a staff gage equipped with a vernier scale for accurate vertical movement. All tests in the tunnel were run in duplicate or triplicate at the following wind speeds measured in the center of the tunnel:

Barrier	Wind speed in mph
Snow fences	17.5 & 27.6
Shelterbelts	17.5 & 27.6
Solid wall	16.9, 25.2, & 29.5

The atmospheric wind velocity data used in comparing wind tunnel and atmospheric horizontal airflow patterns about the snow fences are averages of 6 trials with the wind speed ranging from 13.1 to 24.1 mph measured 1 H above the ground. Previous study (5) has shown that the ratio of the velocity aft of a given barrier to the velocity at the same location in the clear tunnel is constant irrespective of the level of wind movement. The flow pattern in terms of this ratio, therefore, is not affected by the magnitude of the velocities used.

The effect of the wind on the ground surface to the lee of the shelterbelts and the vertical plate also was investigated by a method of shear patterns. Procedures for this method have been described in detail previously (5); therefore, only a brief summary will be given here. It is based on the concept that the velocity ratio $\frac{u}{u_0}$ is related to levels of shear as follows:

$$\frac{u}{u_0} = \sqrt{\frac{\tau}{\tau_0}}$$

where u_0 is the threshold velocity for a given erodible material in a clear tunnel, u is a velocity of known magnitude greater than the threshold also measured in a clear tunnel, τ_0 is the threshold shear, and τ is a shear of known magnitude greater than threshold. Dune sand of size 0.30-0.42 mm was used as an experimental vehicle. Four levels of wind, each yielding values of $\frac{u}{u_0}$ greater than 1, were passed over the trees and sand, and boundary of sand remaining at the end of each test denoted the approximate location at which the belt reduced the shear at bed level to τ_0. This is the equivalent of reducing the value of $\frac{u}{u_0}$ to unity at the same location. This reduction is termed the "effective velocity reduction." Expressed as a percentage, it is equal to $100 \left(1 - \frac{u}{u_0}\right)$. When data obtained in this manner are plotted they yield dimensionless curves that describe the effect of the wind on the ground to the lee of each of the barriers. Benefits may be expressed in terms of apparent limits of influence, effective percentage velocity reduction at any distance from the belt, effectiveness per tree, and indexes of protection (area under the curve), irrespective of the velocity of the wind.

Rates of evaporation were measured by placing three thicknesses of filter paper in a 4- by 18-inch rectangular pan and saturating it with distilled water. The pan was 1/8-inch deep. The sides of the pan were rounded and streamlined to reduce edge effects. It was exposed for a 5-minute period at a given location in the clear tunnel; then, immediately following, it was exposed for another 5 minutes with the barrier in position. These measurements were made in triplicate under a varying wet and dry bulb temperature difference but with a constant wind velocity of 27.3 mph measured at the center of the tunnel. The pan was weighed on a laboratory balance before being placed in the wind and again immediately following a given test, thus giving evaporation in terms of weight loss. The humidity of the airstream was determined for each test by using a sling psychrometer. Figure 2 shows the experimental equipment and the orientation of the evaporation pan aft of one of the snow fence barriers in the tunnel.

Barrier effects on house heating were measured using the model house placed at distances of 2, 6, 10, 14, and 18 H aft of the 10-row defoliated shelterbelt. Electrical energy required to maintain the house at a constant temperature was measured with a recording ammeter. Reductions in heating load caused by the belt were determined by measuring first without belt protection, then immediately following with protection. Length of time for a given test varied, depending upon the existing air temperatures and wind velocities. The outside air temperature ranged from 9° to 59° F.; the wind speed from 4.7 to 29.2 mph. Air temperature variation was obtained by opening doors at the end of the wind tunnel and drawing in air at the prevailing temperature. Figure 4 shows the equipment and the house as it was oriented in the wind tunnel.

Barrier effects on snowdrift control were measured using a single snow fence; two fences spaced 3, 6, 12, and 24 H apart; 4 snow fences spaced 3, 6, and 12 H apart; 10-, 5-, and 2-row shelterbelts; and solid wall. Snowfall was simulated with fine sawdust. A feeder mechanism, shown in the inset on Figure 5, allowed the sawdust to enter the airstream at the top of the tunnel at the rate of 3 pounds per minute. The feeder mechanism was located at point A (see Fig. 5) so that the sawdust fell to the windward and over the barrier in a manner similar to actual snowfall. The wind velocity was held constant at 15.9 mph measured 5 inches above the tunnel floor. Extent, depth, and density of "snow catch" in the vicinity of the various barriers were measured at the end of the 15-minute test period.

BARRIER EFFECTS ON WIND VELOCITIES

Single and Successive Snow Fences

A comparison of atmospheric and wind tunnel results.—This portion of the bulletin includes not only wind tunnel results, but also some comparative measurements of wind velocity patterns about snow fences under atmospheric conditions. Atmospheric wind studies were made in the spring of 1953 to obtain some definite measures of the correlation between wind tunnel model and prototype results. Figures 6 and 7 show comparative wind patterns obtained in the tunnel and under atmospheric conditions for both single and successive snow fences. These profiles are expressed in terms of the dimensionless ratio $\frac{z}{H}$ and $\frac{U_b}{U_o}$, where

z = elevation above surface at which velocity is measured.
H = height of barrier (4 or 6 inches in models, 4 feet in snow fence prototype).
U_b = velocity aft of barrier.
U_o = velocity in open tunnel or unobstructed atmospheric wind.

Percentage reductions in velocity are equal to $100\ (1 - \frac{U_b}{U_o})$. Vertical and horizontal distance on the profile maps is shown in terms of barrier heights H.

In general, the wind tunnel and atmospheric profiles are nearly the same behind both single and successive barriers. The extent of influence of the snow fences at a height of 0.1 H is similar in the model and prototype. Furthermore, statistical standard error of differences between means tests applied to tunnel ratios and to atmospheric ratios for both single and successive fences showed no significant difference between means of the entire pattern in either case. The over-all similarity of these results is vitally important as it demonstrates rather close correspondence of behavior between model and prototype; hence reasonable estimates of full-scale surface barrier effects may be made from wind tunnel results.

In addition to showing the correlation between tunnel and atmosphere, Figures 6 and 7 also indicate that snow fences are quite effective in reducing wind velocities. Substantial reductions in average velocities for a single snow fence occur in a zone extending from approximately 4 to 10 H. There is also a reduction in wind velocity of at least 20 percent extending to a distance 20 H aft of the single fence, and some influence is exerted to distances of 30 to 35 H. The successive fence data indicate that 4 fences are not sufficient to create an accumulative effect aft of the leeward fences, but reductions of at least 30 percent aft of each fence are obtained with the 15 H or 60-foot spacing used in this experiment. A more detailed discussion of this type of barrier's effectiveness in reducing wind velocities is given in another publication (6).

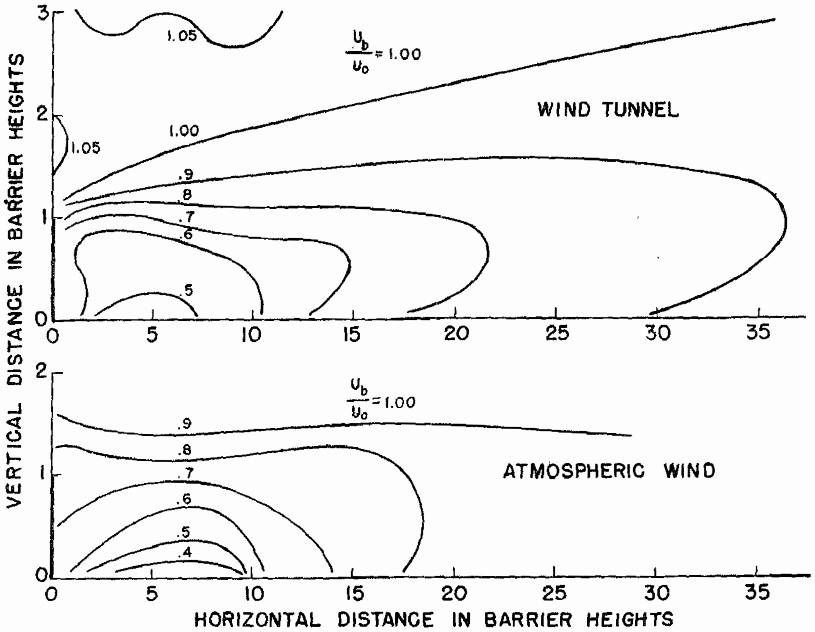

Fig. 6.—Velocity ratios $\frac{U_b}{U_o}$ obtained in vicinity of a single snow fence placed in the wind tunnel and in atmospheric winds.

10-Row Foliated and Defoliated Shelterbelts and Solid Wall

Horizontal velocity measurements.—Velocity patterns for the leaved and defoliated 10-row shelterbelts and the solid wall are shown in Figure 8. Consideration of the zone above these barriers indicates that both the solid wall and denser foliated shelterbelt cause a more abrupt diversion of the airstream up over the barriers than does the less dense, defoliated belt. This sharp upward diversion causes a higher level of increased velocity over these barriers, with maximum ratio values being 1.18 and 1.15 for the wall and the leaved belt, respectively, compared with 1.05 for the defoliated belt. The general shape of the contour lines also indicates a higher degree of eddying formation for the leaved belt and the wall, whereas the rather straight, level contour for the defoliated condition indicates less eddying and merely an increased forward velocity.

The effect of each of the barriers at an elevation of 0.1 H is summarized below:

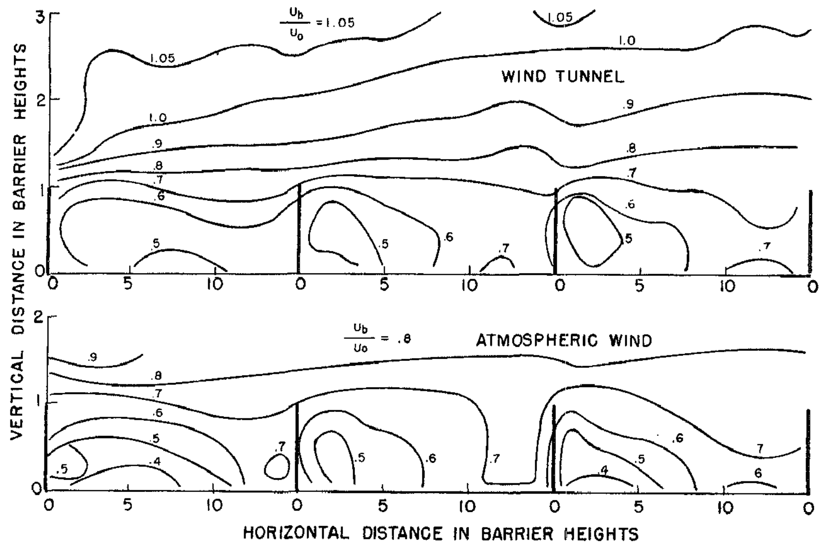

Fig. 7.—Velocity ratios $\frac{U_b}{U_0}$ obtained in vicinity of four successive snow fences placed in the wind tunnel and in atmospheric wind.

Barrier	Distance at 0.1 H elevation to: 75% reduction	50% reduction	25% reduction
Solid wall	13.0 H	15.5 H	21.5 H
10-row belt, leaved	10.6 H	14.0 H	19.8 H
10-row belt, defoliated	....[1]	8.0 H	14.8 H

[1] No point of 75% reduction due to jetting of air through trees.

Ground surface velocity measurements.—The effect of the two 10-row belts and the solid wall on wind velocities at the ground surface to the lee of the barrier, determined by the shear pattern method, is shown in Figure 9. Maximum reductions for both shelterbelts occur close to the leeward row of the belt. The solid wall, however, shows two zones of maximum reduction, one close to the leeward edge of the wall, the second at about 10.5 H from the wall. Apparently the increased eddy currents caused by the sharp-edged plate greatly reduce the effectiveness at points between the two maximums. The leaved belt indicates a substantially higher percentage reduction from 14.5 H to 30 H. From this point on leeward the defoliated condition causes a larger velocity reduction extending for a greater distance. A summary of pertinent data from Figure 9 is given in the following table:

Barrier	Apparent limit of zone of influence[1]	Zone of effective velocity reduction[2] 50% H units	Zone of effective velocity reduction[2] 25% H units	Index of protection (area under curve)	Effectiveness per tree[3]
10-row belt, leaved	50 H	14.3	30.0	19.4	0.54
10-row belt, defoliated	59 H	11.0	30.0	17.5	0.49
Solid wall	49 H	10.2	23.5	15.0	....

1. Apparent limit of zone of influence = point of zero effective velocity reduction as determined by extrapolation of the curves of Figure 9.

2. Zone of effective velocity reduction = net distances to points of 25% and 50% reductions after allowance for zones of less reductions caused by jetting of air through trees.

3. Effectiveness per tree $= \frac{\text{Index of protection}}{\text{Number of trees per unit H length of belt}}$

BARRIER EFFECTS ON EVAPORATION RATES

Evaporation reduction curves for the solid wall and the leaved and defoliated shelterbelt are shown in Figure 10. Values of the curve at a given location are expressed in terms of the ratio $\frac{E_b}{E_c}$, where E_b is the evaporation rate aft of the barrier and E_c is the rate at the same location in a clear tunnel, and as a percentage reduction in evaporation. The curves for the wall and for the defoliated shelterbelt are similar. Maximum measured reductions for both the wall and defoliated belt (approximately 45 percent) occur at 2 H aft of the barrier. However, the reduction in evaporation rate caused by these barriers is substantially less than for the leaved belt. While the curves for both shelterbelts show a gradual decrease in reduction to the limit of influence, the wall has a varied effect with a 13 percent reduction at 6.5 H and 22 percent at 12 H. The decreased effect at 6.5 H apparently is due to eddy formations striking the surface. Pertinent data are summarized in the following table:

Barrier	Average reduction aft of barrier to 18 H	Average windward reduction	Apparent limit of influence	Maximum measured reduction
	%	H distance	H distance	%
10-row belt, leaved	45.5	6.6	30.0	70.0
10-row belt, defoliated	26.4	3.6	32.0	45.5
Solid wall	26.2	Not measured	29.0	46.0

The evaporation rate data show some rather significant advantages for one barrier over another. There are, however, certain aspects of this study which should be considered. First of all, the evaporation was measured from a point source. The rate would not be the same if the wind were passing over a great length of saturated material—whether it be soil or filter paper. There is also the fact that a soil will dry out in a short time and the evaporation rates would not be so great. Bates (1) concluded that shelterbelts more probably benefit crops when moisture is abundant in the early growing season. This study does not consider the above mentioned variables, but it does provide a good relative comparison of the two shelterbelts and the solid plate.

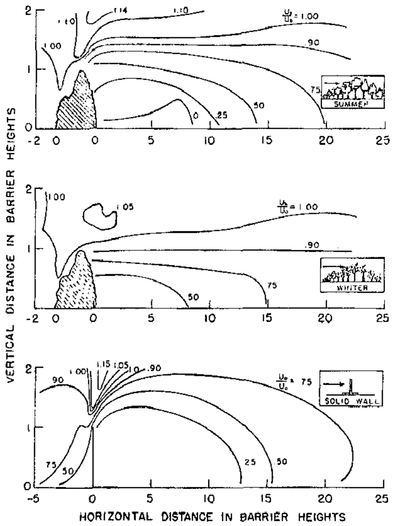

Fig. 8.—Velocity ratios $\frac{U_b}{U_o}$ obtained in the vicinity of a leaved and a defoliated 10-row shelterbelt and a solid wall.

The other aspect of the study that should be mentioned concerns the difference in evaporation rates shown between the leaved and defoliated belt. Evaporation rates are much less in winter than in summer because of lower prevailing temperatures. Mead (3) has used Weather Bureau data to show this. His data for evaporation from a free water surface at Topeka, Kan., indicate the average monthly evaporation occurring during October through March to be 1.8 inches, whereas for April through September it is 4.2 inches. This would indicate that

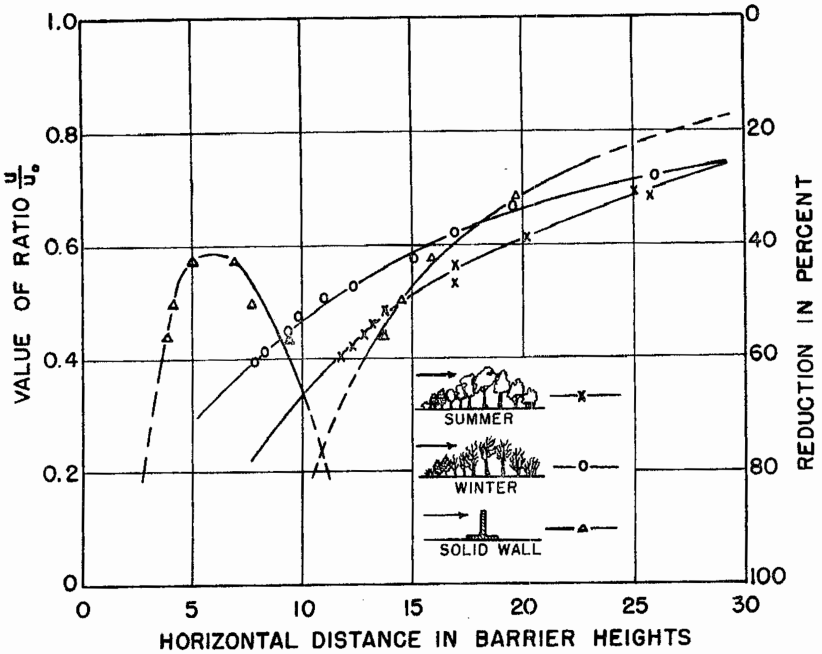

Fig. 9.—Dimensionless curves showing effective velocity reduction at ground level to the lee of a leaved and defoliated 10-row shelterbelt and a solid wall. Velocity reduction applies irrespective of wind velocity.

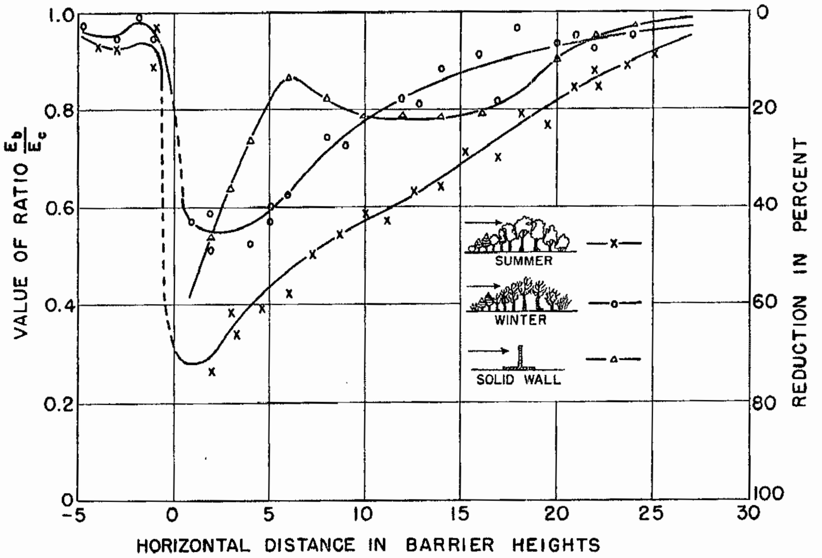

Fig. 10.—Evaporation reduction curves for a leaved and defoliated 10-row shelterbelt and a solid wall. Wind velocity was 27.3 mph measured at center of tunnel.

the evaporation occurring during October through March, or when the trees are defoliated, is approximately 57 percent less than that occurring in April through September, or when the trees are leaved. The effect of this natural seasonal variation in evaporation rates on the relative efficiency of a summer leaved belt as compared with a defoliated winter belt can be illustrated by the following hypothetical projection of the wind tunnel results:

> Assume that the evaporation rate from a soil is 4.2 inches in summer without the belt, then, as shown in Figure 10 for the summer condition, at 10 H aft of the belt the reduction would be 43 percent or the net evaporation would be 2.4 inches. On the other hand, if the comparable evaporation in winter were 1.8 inches and the winter belt reduced the evaporation at 10 H by 22 percent (Fig. 10), the net evaporation would be 1.4 inches.

Thus, even though the summer belt reduced evaporation some 20 percent more than the winter belt, the net evaporation would be more in summer than in winter. This would tend to minimize the need and effectiveness of a shelterbelt in reducing evaporation rates in winter. However, in areas of limited rainfall even the small amount of the potential moisture saved during the winter would benefit crops the following year.

This example serves only as an illustration of the relative effectiveness of leaved and defoliated shelterbelts. Actual savings of moisture under field conditions would vary with the moisture content of the soils and would not necessarily be equal to amounts reported in this study.

BARRIER EFFECTS ON HOUSE HEATING

The general functional relationship for the heating load, the wind velocity, and the temperature difference for the house unprotected and at locations aft of the belt is expressed graphically in Figure 11. The general equation of the curve for no protection is

$$\frac{Q}{T_{\Delta}} = 1.3\ (10^{0.025\ u})$$

The curves for the various locations aft of the belt approximate a family of lines and, therefore, may be expressed in the following 3-variable equation:

$$\frac{Q}{T_{\Delta}} = 1.3\ (10^{0.018\ L^{0.07}\ u})$$

Symbols in these two equations are defined as follows:

Q = heating load in BTU per hour.
T_{Δ} = difference between inside and outside temperature in °F.
L = distance from belt to house in barrier heights H.
u = wind velocity in mph.

The unprotected house function indicates that the heating load with a 20 mph wind is approximately 2.4 times as great as that for a 5 mph wind under the same temperature conditions. The heating load for the protected house exposed to a 20 mph wind was approximately twice as great as that for a 5 mph wind, thus indicating the belt to be slightly more effective at higher wind velocities.

Figure 12 shows reductions in heating load at various distances aft of the belt for wind velocities ranging from 5 to 35 mph in 5 mph increments. It is noted that the amount of reduction in heating load decreased with distance aft of the belt and that the largest percentage reductions occur for the higher wind speeds. This analysis also shows that the percentage reduction in heating load is not a function of temperature, i.e., for a given temperature the reduction changes only with wind velocity. This is probably explained by data of Bates (1) where he shows only a 1° F. difference in air temperature behind a belt compared with the open. This does not mean, how-

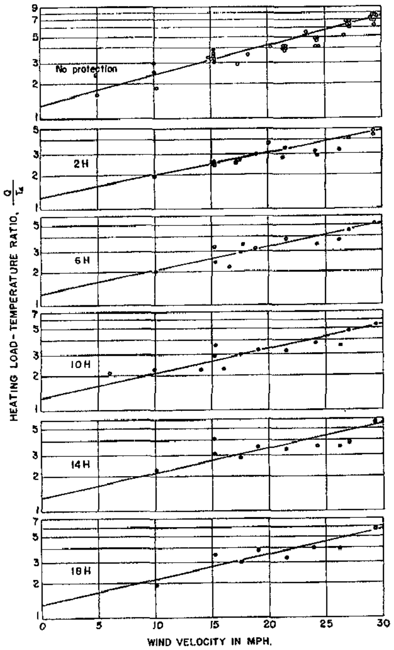

Fig. 11.—Relationship between house heating load Q, temperature difference T_Δ, and wind velocity u for protected and unprotected house. All points are averages of 2 trials.

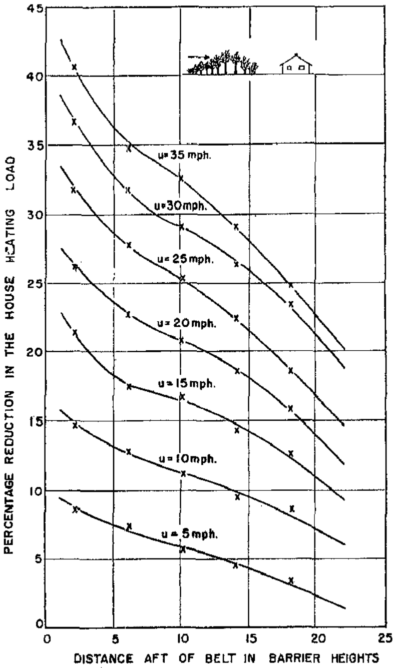

Fig. 12.—Percentage reduction in heating load for house at various distances aft of 10-row defoliated shelterbelt for velocities ranging from 5 to 35 mph.

ever, that temperature is not important. Since the total heating load Q is a function of the temperature difference, it follows that as the temperature difference increases Q will increase. For example, assume a 32° F. outside temperature, a 30 mph wind and a house with a 76° F. inside temperature located 2 H aft of a shelterbelt. According to Figure 11, Q would equal 211 BTU per hour; but if the outside temperature dropped to 0° F. and the wind speed and location remained the same, Q would equal 365 BTU per hour. For these conditions a drop in temperature of 32° F. increased the heating load 154 BTU per hour, or 73 percent.

Some idea of the savings in fuel consumption for house heating which may be obtained by using shelterbelts can be given by considering a hypothetical problem:

Problem: Assume the following:

Heating load on average home = 95,000 BTU per hr.
Inside temperature = 76° F.
Type of heating unit = gas furnace.
The house has shelterbelt protection from all winds.

Using design temperatures, average wind velocities, and degree days of heating for Topeka, Kan., as given in the Air conditioning manufacturers Interim Code (2) and the Degree Day Handbook by Strock and Hotchkiss (4), determine the savings in cu. ft. of gas for the heating season if a house were placed at 2 H aft of a shelterbelt.

Information Required:

Design temperature for Topeka, Kan. = - 10° F.
Degree days of heating = 5,037.
Heating value of natural gas = 900 BTU per cu. ft.
Efficiency of gas burning furnace = 90%.
Average winter wind velocity = 10 mph.
Percentage saving in heating load at 2 H aft of belt with 10 mph wind = 15.0.

Solution:

Heating load for season for unprotected house (BTU per season) $= \dfrac{(95{,}000)(24)(5{,}037)}{76 - (-10)} = 133.5\ (10^6)$

Cu. ft. of gas consumed per season $= \dfrac{133.5\ (10^6)}{900(0.90)} = 164{,}815$

Cu. ft. of gas saved per season for protected house at 2 H leeward of belt $= 164{,}815\ (0.15) = 24{,}722$

By assuming that the rate of consumption can be divided into 5 equal increments and the fuel bill is paid 5 times during the season, the dollar and cent saving for the season would be approximately $9.90 at present Topeka, Kan., gas rates.

These computations, of course, are only averages based on design recommendations for home heating; they serve only as guides for procedures in making calculations of this type.

BARRIER EFFECTS ON SNOWDRIFT CONTROL

Barrier effects on snowdrift control are shown in Figures 13 through 16. The depth and extent of catch about each of the various barriers are indicated in terms of barrier heights. The area under these curves can be used as an index of effectiveness for the various barriers. Values of this index in terms of both

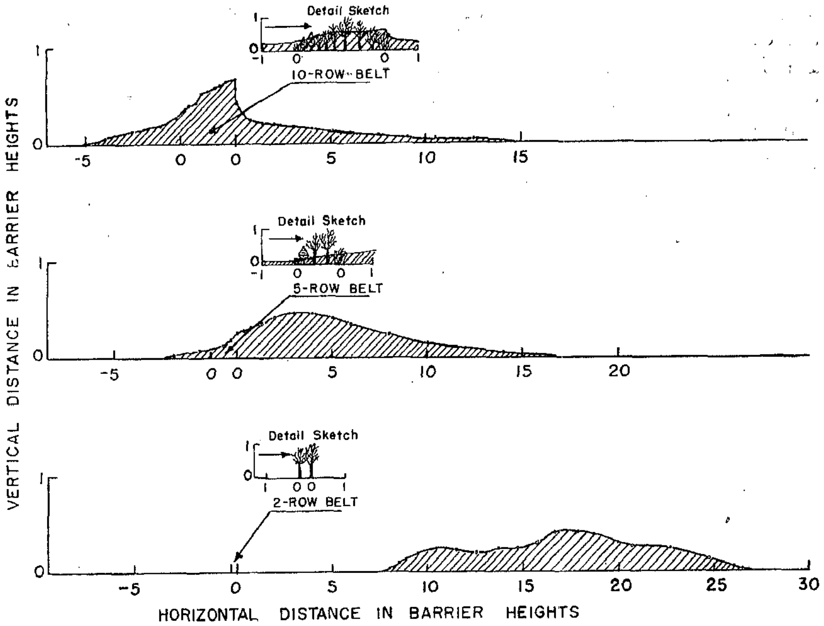

Fig. 13.—"Snow catch" profiles developed by 2-, 5-, and 10-row defoliated shelterbelts. Wind velocity constant at 15.9 mph measured 5 inches above tunnel floor.

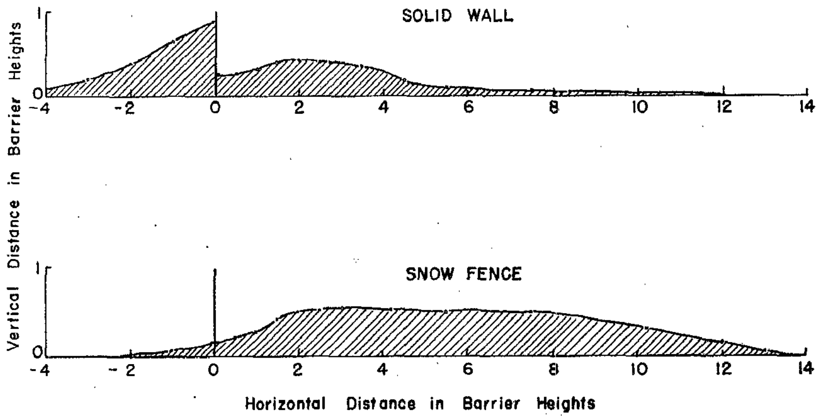

Fig. 14.—"Snow catch" profiles developed by a single snow fence and a solid wall. Wind velocity constant at 15.9 mph measured 5 inches above tunnel floor.

the model and prototype conditions are given in the following table:

Rank	Barrier	Index of effectiveness (area under curve) Model	Prototype[1]
		sq. H	sq. ft.
Snow fences and solid wall			
1	4 snow fences, 12 H spacing	41.1	3,295
2	2 snow fences, 24 H spacing	32.9	2,635
3	4 snow fences, 6 H spacing	27.8	2,225
4	4 snow fences, 3 H spacing	24.2	1,934
5	2 snow fences, 12 H spacing	22.7	1,818
6	2 snow fences, 6 H spacing	20.9	1,676
7	1 snow fence	16.8	1,345
8	2 snow fences, 3 H spacing	15.6	1,245
9	1 solid wall	10.0	800
Shelterbelts			
1	5-row shelterbelt, defoliated	26.6	119,500
2	2-row shelterbelt, defoliated	25.6	115,000
3	10-row shelterbelt, defoliated	24.0	108,000

1. Prototype snow fence is 4 feet high; prototype shelterbelt is 30 feet high.

For the 8 snow fence combinations and the solid wall, the index of effectiveness ranges from 41.1 to 10.0, or 4 fences spaced 12 H apart will catch 4 times as much material as a solid wall. Apparently 4 fences will catch 1.2 to 1.8 times more material than 2 fences with similar spacing.

There is little difference in the performance of the various shelterbelts; however, the 10-row belt caught slightly less drift material than the 5- or 2-row belts.

A direct comparison of the snow catch capacity of the snow fences and the shelterbelts cannot be made due to the difference in scale of the models. However, since the amount trapped by the barriers in these experiments constituted a maximum for the 15.9 mph wind, some idea of the difference in capacity can be obtained from the indicated index of effectiveness in terms of prototype conditions. Here it is noted that the best shelterbelt barrier has a capacity approximately 3.6 times greater than the best snow fence combination. The poorest shelterbelt has a capacity approximately 135 times greater than the solid wall.

The location of the drifts with respect to the barriers is also an important consideration. The 10- and 5-row shelterbelts trap part of the snow in the belt while the open 2-row belt piles the drift at a considerable distance aft of the barrier. All the snow fences trap the snow immediately aft of the fence.

The area utilized by the barriers and the drifts might also be an important consideration. For example, the 4 fences with the 12 H spacing trap a large amount of the material, but they would require a 200-foot length. Areas this large might not be available for all utilizations of the barriers. A com-

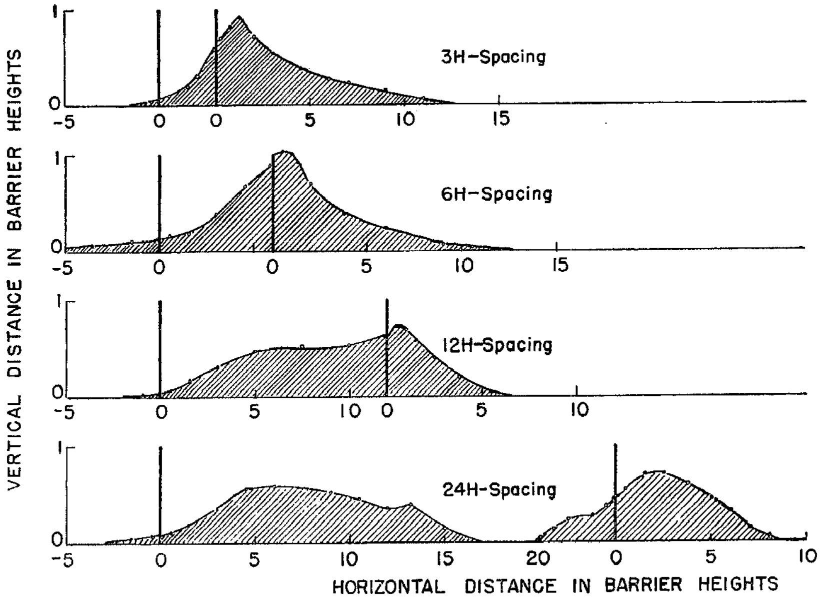

Fig. 15.—"Snow catch" profiles developed by 2 snow fences with 3-, 6-, 12-, and 24-H spacing. Wind velocity constant at 15.9 mph measured 5 inches above tunnel floor.

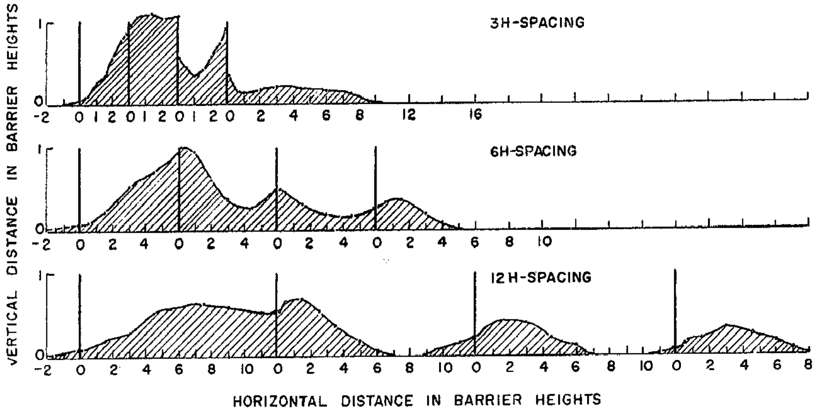

Fig. 16.—"Snow catch" profiles developed by 4 fences with 3-, 6-, and 12-H spacing. Wind velocity constant at 15.9 mph measured 5 inches above tunnel floor.

promise barrier fitting the available space and providing the maximum protection should be used in these cases.

In developing the profiles obtained in this study, all barriers were treated alike and were exposed to the same total amount of material at the same wind speed. This method of study provides a good evaluation of the merits of single or groups of barriers having similar dimensions and characteristics; it cannot, however, provide a true evaluation of the snow profile for each barrier. A different tunnel, a change in wind speeds, or even a change in material, no doubt, would give different profiles. The profile developed under unsteady atmospheric conditions would also vary with other factors. The results, therefore, serve only as a relative evaluation of the merits of the individual barrier.

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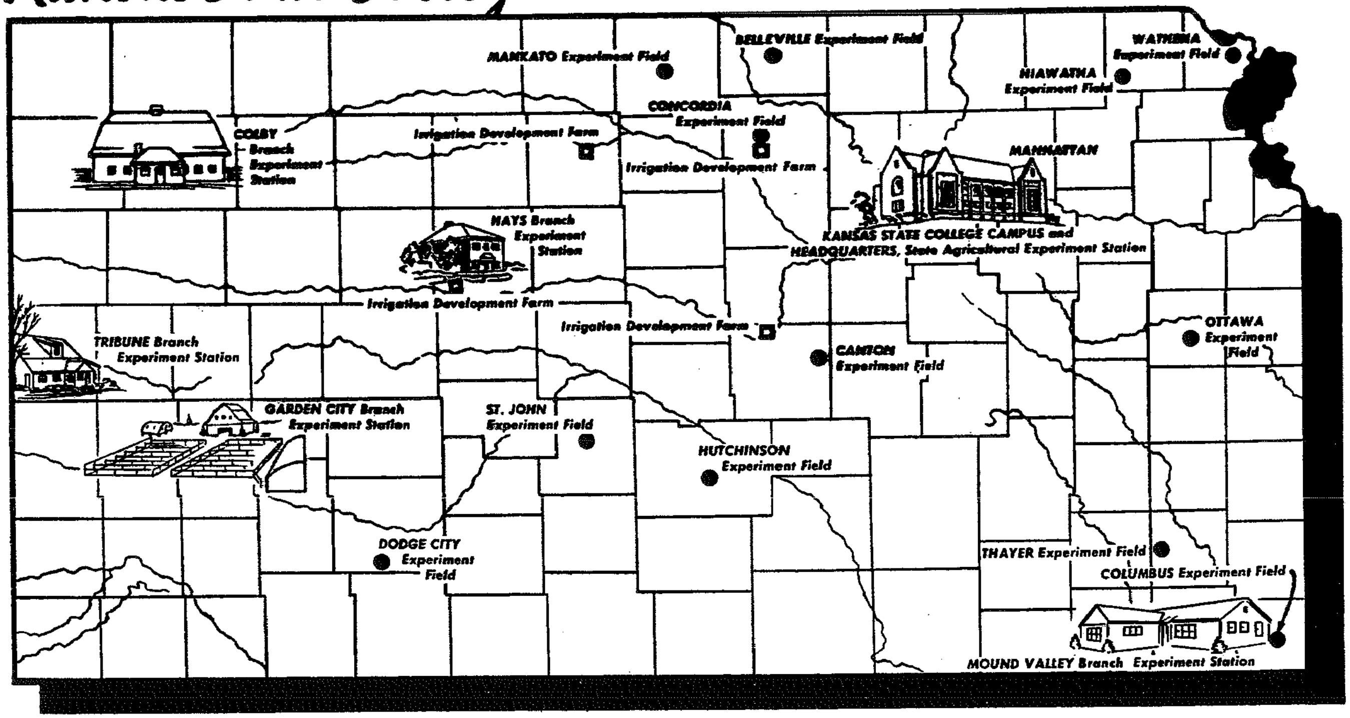

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