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VENTILATION OF FARM BARNS
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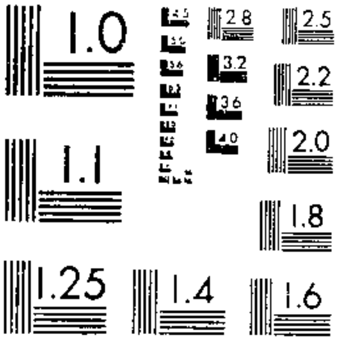

MICROCOPY RESOLUTION TEST CHART
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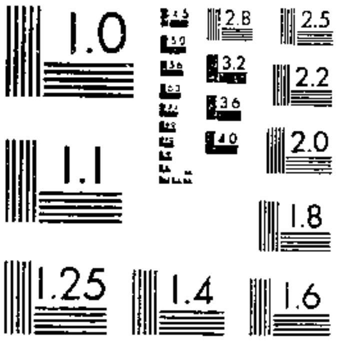

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NATIONAL BUREAU OF STANDARDS-1963-A

TECHNICAL BULLETIN No. 187 JUNE, 1930

UNITED STATES DEPARTMENT OF AGRICULTURE
WASHINGTON, D. C.

# VENTILATION OF FARM BARNS

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## INTRODUCTION

The ventilation of barns is an important consideration in the maintenance of the health of stock and in the preservation of hay, grain, and barn timbers. In the ventilation of dairy barns it is highly desirable to maintain a comfortable stable temperature with a proportionately low relative humidity. The limits of temperature and humidity should always be compatible with good ventilation. Good circulation with consequent dilution of the impurities in the air is the aim of all systems of ventilation, but the comfort of the animals must be considered as well as the purity of the air. However, it is better to have good ventilation than to attempt to maintain a high stable temperature without ventilation.

The success of a ventilation system depends upon its effectiveness in producing a movement of air which will be sufficient to supply the proper amount of oxygen to the stock, remove objectionable odors, afford satisfactory dilution of air and, at the same time, maintain a satisfactory degree of humidity and a comfortable temperature in the stable. The determination of the relationship of the factors affecting the ventilation of barns and having an important bearing upon the economic and efficient design of farm buildings was the object of investigations conducted by the Division of Agricultural Engineering in cooperation with the committee on farm building ventilation of the American Society of Agricultural Engineers and several State agricultural experiment stations.[1]

Altogether 27 tests were made, 3 in horse barns, 1 in a hog house, 5 in barns with mixed stock, and 18 in dairy barns. Five tests were made in North Dakota, 6 in Minnesota, 1 in South Dakota, 3 in the Upper Peninsula and 2 in the Lower Peninsula of Michigan, 2 in Massachusetts, 1 in Maine, and 7 in New York State. The tests were made in the localities indicated for the reason that the ventilation problem is of greater importance in cold sections than where winters are comparatively mild, both because of the atmospheric conditions and because the greater portion of the dairy cows of the country are located in the northern and northeastern States. The distribution of dairy cows is shown in Figure 4.

## CHARACTER OF TESTS

The first 19 tests were conducted for the purpose of making a general survey of the problem. In the later tests, studies of the factors affecting ventilation were made. The tests in the various barns were continuous, varying from 24 to 300 hours in duration. Regular readings were taken at intervals of 3 hours. Thus from 8 to 100 sets of readings were obtained in a single test. Observations taken from recording instruments show that this interval is satisfactory and affords readings representative of normal conditions. Additional readings, indicated in tables and text by the suffix a, were made for the purpose of noting the immediate effect of changed conditions. Two men assisted in taking the readings and the data were checked as recorded. The barns were kept closed as much as possible, and the same number of stock was retained in each barn throughout the test.

Most of the tests were made in barns where the principles of the King system of ventilation were employed. Three tests were made in barns in which windows are used for intakes, that is, the Sheringham valve principle, 4 tests in barns equipped with a modified King system, and 1 test in a barn in which a fan system of ventila-

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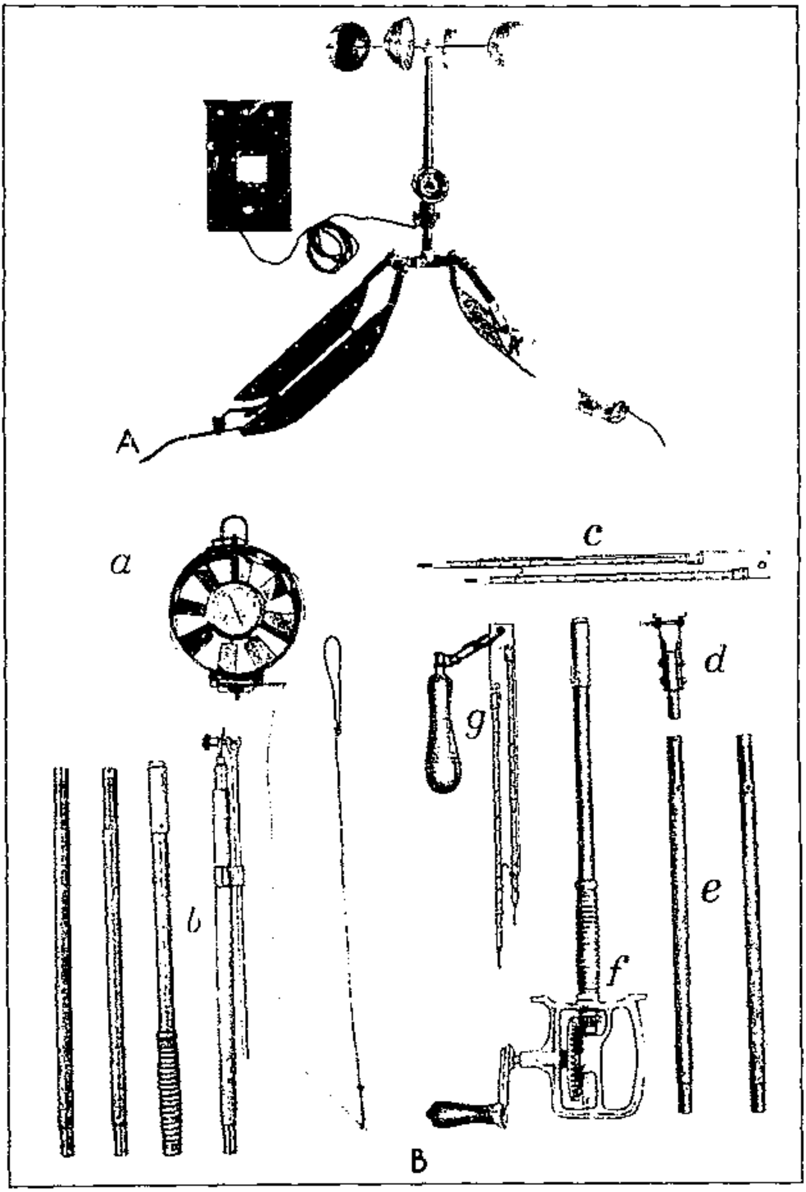
[1] Acknowledgement is made of the assistance rendered by W. D. Clarkson, Owatonna, Minn., chairman of the committee on farm building ventilation, in preparing for the work and in conducting some of the tests; C. S. Whitnah, Owatonna, Minn.; R. L. Patty, professor of agricultural engineering, South Dakota State College of Agriculture, Brookings, S. Dak.; and J. L. Strahan, assistant professor of rural engineering, Massachusetts Agricultural College, Amherst, Mass., members of the committee on ventilation, in conducting some of the tests; F. E. Fogle, assistant professor of agricultural engineering, and Walter Van Haitsma, of the Michigan State College of Agriculture, East Lansing, Mich.; F. L. Fairbanks, assistant professor of rural engineering, and A. M. Goodman, professor of extension, Cornell University, Ithaca, N. Y., in conducting tests made in their respective States.



A, Indicating anemometer, mounted on sled; and buzzer box. B, *a*, 5-inch anemometer or air meter, equipped with a spring release, used to measure the velocity of air through ventilating flues; *b*, jointed holder for anemometer which facilitated the taking of readings at high openings; *c*, psychrometer; *d*, special clamp, *e*, sectional gun cleaning rod; *f*, gear from small churn; parts *c*, *d*, and *f*, assembled, form a convenient means of taking humidity readings; *g*, ordinary sling psychrometer shown for comparison tion was installed (*25*).[2] Most of the barns were of frame construction with varying degrees of insulation. Concrete blocks were used in the construction of the walls in three barns.

### DESCRIPTION OF INSTRUMENTS

An indicating anemometer of the Weather Bureau type measuring one-sixtieth of a mile per hour was used to measure wind velocities. Plate 1, A, shows the details of the anemometer sled which, drawn upon the roof by means of a rope, was of great convenience in placing the instrument in position on the ridge. (Pl. 3, A.) Other instruments employed in the tests are illustrated in Plate 1, B.

In measuring outside temperature four thermometers are desirable, one on each side of the barn. Not less than four pairs of thermometers should be used within the barn. From 12 to 30 thermometers were used in these tests. The average of the floor and the ceiling readings was taken as the stable temperature.

In determining relative humidities it is desirable to use one or more hygrographs inside and one outside in order that variations between readings may be observed, but the best results are obtained with a sling psychrometer by means of which readings may be taken at different points in the barn. With the apparatus shown in Plate 1, B, it is possible quickly and evenly to obtain a large number of readings close to ceiling or floor. As the instrument is held firmly in position while being rotated there is less liability of its being broken than when held in the usual manner.

### EXPLANATION OF TERMS

Dilution of air per hour: The relation of the volume of air passed per hour through a room to the volume of the room. This term is preferred to "number of changes of air per hour," commonly employed, since the air in the stable is not completely replaced by fresh air. Part of the foul air is forced out and the incoming air, with a lower percentage of carbon dioxide ($CO_2$), is mixed with the stable air thus decreasing by dilution the carbon dioxide and other impurities.

Leakage: The difference between the volume of the measured air going out and that of the measured incoming air is considered as leakage. In order to maintain a balance of air pressure the amount of air passing out must be equivalent to that of the air entering by whatever means.

Estimated weight of stock: The weight of each animal in a barn was estimated, and these estimates were added to obtain the total weight.

Equivalent number of head of stock: The estimated heat production of the individual animals, determined by the application of Rameaux's law (p. 9), was added and the sum divided by the estimated heat production of an animal of average condition and weight. The average weight of cows was assumed as 1,000 pounds and that of farm horses as 1,350 pounds, the heat produced per hour being 3,000 B. t. u. (British thermal units) for the average cow and 2,200

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[2] Numbers in parentheses refer to "Literature cited," p. 72.

B. t. u. for the average horse. For example, in one barn there were 20 cows, 10 head of young stock, 1 bull, and 12 calves. The heat produced by these animals was found to be equivalent to that produced by 31.5 cows of average size.

Absolute humidity: The quantity of moisture in a given unit of atmosphere. It is usually expressed as "grains of water per pound of dry air" or in terms of "grains of moisture per cubic foot of dry air."

Relative humidity: The relation, expressed in percentage, between the actual amount of moisture in the air and the amount the air could hold, at the same temperature and pressure, without condensation. This relation is not a measure of the actual amount of moisture in the atmosphere, as the capacity of the air for water vapor is almost wholly a function of the temperature. It is the ratio of the absolute humidity of air of given condition to its absolute humidity at saturation.

The weight of the aqueous vapor per cubic foot of air at a temperature of 48° F. and saturated (100 per cent relative humidity) would be 3.800 grains; at 50 per cent relative humidity it would be one-half of this, or 1.900 grains; and for other percentages the weight would be proportionate. The drying or absorbing capacity of the air is therefore dependent upon its absolute humidity. Air having a relative humidity of 80 per cent is considered moist and that with a relative humidity of 30 per cent very dry. In the ventilation of structures for animals, where the comfort of the animals is essential, the relative humidity of the stable air is of greater importance than the absolute humidity; in the ventilation of structures for crop storage, where the removal of moisture is the prominent factor, absolute humidity must be considered also.

Dew point: The temperature at which air having a given weight of aqueous vapor becomes saturated. Unsaturated air becomes saturated when the temperature is lowered to the dew point or when sufficient moisture is added.

Heat used in ventilation: That portion of the heat given off by the stock that is used in producing ventilation. The heat produced was determined by the use of Rameaux's law (*43*). The heat loss from walls was estimated, coefficients secured from various sources being used. There is considerable variation in the coefficients of heat transmission given by different authorities for the same material, and those coefficients were selected which it was thought would give the most comparable data. No allowance was made for infiltration heat losses, as these depend chiefly upon how well the building is constructed, and allowance for such losses must be largely a matter of judgment.

## CORRELATION OF VARIABLE FACTORS

The analysis of some of the test data was made difficult by the number of factors that varied separately or collectively and were beyond control.

The best method of correlating such data appeared to be an application of the theory of correlation (*26*). By the use of this method it was possible to pick out the most dominant factors and those least important. In the case of some factors sufficient data were available to afford a quantitative measure. One of the most important results of the correlation studies is the establishment of the fact that low outside temperature has a greater effect in the ventilation of dairy barns than a high outside temperature with the same temperature difference (p. 48).

## SUMMARY

The following conclusions are based on data obtained in these tests and upon findings in related investigations, and should be of value in the designing and proper operation of ventilating systems.

The animal is the sole source of heat that is utilized in producing ventilation. Since the amount of heat given off and the ventilation requirements vary, the animal unit must be considered in the design of a ventilation system.

Carbon dioxide as ordinarily encountered in stable air does not settle. The evil effects of bad ventilation are not caused by carbon dioxide as found in the average stable.

There must be a constant removal of moisture from the occupied stable or the amount of moisture in the air will increase. Damp walls may be due to improper ventilation, poor construction, or insufficient production of heat or lack of conservation of heat.

A large volume of air space per head is not a substitute for ventilation, as purity of air is not dependent upon volume of air space. However, the volume allowance per head is important with regard to maintenance of stable temperature and varies according to climatic conditions.

Insulation requirements vary according to the temperatures to be expected in the different sections, amount of air space which the animal must heat, the amount of ventilation desired, and the method of securing it. The amount and choice of insulating material required will depend upon the relative efficiency and cost of the various materials available. Tight construction to prevent excessive leakage of air is essential to effective insulation.

Whenever barn walls are tightly built to save heat, ventilation becomes necessary. Storm sash, storm doors, vestibules, and feed rooms may be used as effective forms of protection against cold.

It is possible to maintain a comfortable temperature in a well-built barn and yet have an appreciable circulation of air. The temperature in a stable filled with stock can be controlled by temporarily or partly closing the ventilation system. Stable temperatures within certain limits appear to affect both the quantity and quality of milk.

Wind velocity and direction have an effect upon the amount of ventilation.

Back drafting may be due to poor design or poor position of ventilator or intake.

Outtakes near the floor are more favorable to the maintenance of desirable stable temperature than ceiling openings.

Under average conditions outside temperature is usually the dominant factor in barn ventilation.

The moisture-content of the air in a well-built stable is usually controlled by the amount of ventilation.

Horizontal runs and abrupt turns in outtake flues should be avoided. An air-tight flue with proper insulation is necessary to greatest efficiency. Lack of insulation may cause excessive drip from flues. This factor should be given consideration especially in the northern zone.

The bases of ventilator heads should be equipped with suitable doors, which may be opened or closed as required. The efficiency of an outtake flue is affected by an open base.

Windows as intakes require frequent adjustment and prevent uniform regulation of the ventilation. Their use for such purpose is undesirable in cold sections. However, during mild weather they are an advantage as they provide a large area of opening.

Warm-air furnace registers are unsuitable for use as intake valves in barn ventilation.

Open hay chutes interfere with ventilation, and should not be used as foul-air shafts.

Flue sizes proportioned to local temperatures may be obtained by a formula that has been developed as a result of these tests. (See "Development of formula," p. 54.)

## ANIMAL HEAT A PRIMARY FACTOR IN VENTILATION

The heat given off by animals must be employed in maintaining stable temperature and also as motive power in producing circulation of air. While good circulation of pure air is the chief aim in ventilation systems, the comfort of the animals must also be considered. A barn can not be kept warm if the allowance of air space per animal is too great or if the barn is but partially filled with stock. Furthermore, it is evident that a design suited to one section of the country may be only partly successful in another, since the loss of heat varies according to the construction of the barn and climatic conditions.[3]

In order that he may understand and properly employ animal heat in the ventilation of stock shelters, it is not necessary that the agricultural engineer study all the intricacies of animal nutrition, but it is desirable that he recognize those factors related to nutrition which have important bearing upon the proper ventilation of stables.

It is important that provision be made so that the dairy cow may be kept comfortable at all times as her condition affects milk production. Comfort of the body is dependent upon the cooling power of the air which, in turn, is dependent upon temperature, humidity and air movement—all factors affected by ventilation. These factors affect the cutaneous nerve endings which control the production of heat and maintain the balance between the temperature of the skin surface and that of the blood in the deeper tissues. For each degree of increase, within certain limits, in the cooling power of the surrounding atmosphere there is a definite increase in the loss of body heat which must be replaced by the heat regulating mechanism of the body (*1*, *3*, *10*, *37*, *45*.)

The animal is most efficient when not subjected to strains which tend to weaken the body resistance and make them more susceptible to disease germs. Continual breathing of damp stale air in ill-venti-

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[3] See Climatic Conditions Affecting Construction, p. 20.

lated stables lowers the vitality of the animal. In a stable without ventilation the air becomes stagnant, heat and moisture given off by the animals are not removed, and there is a consequent increase of temperature and humidity—a condition which interferes with the normal heat regulation of the body. Habitual exposure to such conditions leads to a lowered tone of the whole heat-regulating mechanism and an inability to respond to the demands which may be put on it, and in this way exerts a profound and important influence upon susceptibility to respiratory infection (*21*, *31*, *45*.)

The dairyman tries to induce his cows to eat as much feed as can be economically converted into milk; hence it seems desirable that the temperature should be low in order to maintain the appetite of the cow and yet not so low as to cause wasteful oxidation for simple heat production. Cows housed in cold barns utilize more food energy in maintaining normal body temperature but this may be at the expense of energy which might be used in milk production if the barn were comfortably warm. On the other hand, too warm a barn may induce loss of appetite and a consequent decrease in the amount of food energy available for milk production. Tests (*22*, *41*) have shown that milk yields are affected by sudden changes of temperature which may be avoided in a well-ventilated barn, since in such a barn a comfortable temperature may be maintained with an appreciable circulation of air.

There is an important relation between the amount of ventilation needed and the heat given off by the animal. Stable temperatures are dependent upon the amount of heat produced and that conserved. As it is not practical to determine either the heat production or the losses within the barn it is necessary to know how much heat is given off by each of the various farm animals and the most economical means of conserving this heat.

### FOOD, THE SOURCE OF ANIMAL HEAT

Alfalfa, when consumed by the dairy cow has a heat increment value of about 1,900 B. t. u. per pound of dry matter (*12*). In the conversion of fuel into steam for mechanical work about 6 per cent of the fuel energy is utilized; the rest is lost as heat. The dairy cow utilizes about 70 per cent (*3*, *15*) of the combustible food energy supplied. Thus the dairy cow is a very efficient converter of energy. The generation of heat and production of work in the body follow the same laws that govern these forces in motors such as steam and gas engines.

### HEAT LOSSES

Rubner, Armsby, and others (*1*, *24*, *37*, *38*, *46*) have proved that the body daily emits a quantity of heat equal to that which the oxidation of its reserves of fat and carbohydrates produces if the body is fasting, or the potential heat contained in the same elements supplied by the food. Hence it is possible to estimate the heat production of the animal if the calorific value of the food eaten is known (*43*). The calorific value of the food must equal the heat lost from the body in whatever manner plus the loss in manure, plus that used in body gain (flesh and fat), or in milk production.

Vierordt as quoted by Howell (*24*), estimates the loss of heat from the body as follows:

| | | |
|---|---|---|
| Urine and feces | per cent | 1.8 |
| Expired air (warming of air 3.5 per cent; vaporization of water from lungs, 7.2 per cent) | per cent | 10.7 |
| Evaporation from skin | do | 14.5 |
| Radiation and convection from skin | do | 73.0 |

The animal heat radiated from the skin is far greater in amount than that given off in other ways (p. 52). All the above factors, with the possible exception of the first, are affected by the environmental conditions which in turn may be modified by ventilation.

Rubner (*38*) concluded that basal metabolism is proportional to the surface of the skin and is approximately the same for our warm blooded animals per unit of surface. The maintenance requirement is the nutriment necessary for sustenance alone, under the living conditions of production. It is the basic food requirement to which must be added the food requirements for production. Under these conditions the food eaten produces no gain or loss in body weight and forms the basis for the determination of basal metabolism or heat production of the animal.

The food requirement of farm animals varies with the individual and as between species. Age, weight, temperament, sex, physical condition, digestive and physical activity, thermal surroundings, annoyances caused by insects, etc., all, theoretically at least, have a bearing on maintenance requirements. Weight and physical activity particularly are important factors in estimating heat production (*13, 14*.) Thermal environment has a definite influence upon heat emission and so on food requirements especially when below the critical temperature for the animal. The thermal environment may be modified by proper buildings and arrangements.

### EFFECT OF THERMAL ENVIRONMENT

Critical temperatures must not be confused with optimum stable temperatures as they are not coincident except under certain conditions. That point at which physical regulation of body temperature gives way to chemical regulation is not fixed and unvarying but is affected by the amount of food eaten. When the stable temperature falls below the critical temperature there must be an oxidation of more food or body tissue in order to maintain the body temperature. Hence the economic importance of maintaining desirable thermal conditions. It is apparent that the critical temperature for cows on heavy feed for maximum milk production would be less than for cows on a maintenance ration, since in the first case there would be more food energy available and oxidation of body tissues would not be necessary until a lower temperature was reached.

The best information available at present, places the critical temperature of the dairy cow on maintenance at approximately 50° F. (*2, 40*). For cows that produce large yields of milk and consequently consume large quantities of food, this critical thermal point must be lower and may be 40° or even less. There does not appear to be any direct data on the lower limits of critical temperature for dairy cows.

That the animal should produce more heat while standing than while lying is readily understandable because of the greater muscular activity in the standing position (*14*). In calorimeter or laboratory tests a correction factor of 29 calories per hour (approximately 7 B. t. u.) is added when the animal is standing. In the field tests it was observed that the increased heat production was sufficient to raise the stable temperature 1 to 2 degrees under average conditions. This was most noticeable when the cows stood up in the morning. The higher stable temperatures were reached in about one-half hour and continued until affected by other conditions.

Rameaux's Law (*43*), which states that in animals of the same kind the calorification is proportional to the cutaneous surface and to the cube root of the square of the weight of the body, together with the use of a suitable coefficient, provides a simple means of estimating the heat production of the various farm animals under average conditions.

It has been demonstrated by the tests in New York State that it is possible to maintain a temperature of 40° F. within a well-built barn, when the outside temperature is −30°. Armsby and Kriss (*2*) state that, when King's standard of air flow is taken as a minimum, the heat supplied by cows appears to become deficient for the maintenance of a stable temperature of 50° when the temperature outside is 15°. They base this statement upon the assumption of no heat loss through the walls, but it is obvious that such an assumption can not be made in actual practice.

In the test referred to there was a difference of 70° F. between the inside and the exceptionally low outside temperature with a good circulation of stable air, whereas the theoretical deduction would permit only 35° difference at a much higher outside temperature. This comparison makes apparent the need of finding the coefficient that will reconcile the theoretical with the practical. In order that more winter dairying may be successfully conducted in some sections of this country, and the greater part of the dairying is in those sections where some shelter is necessary during the winter, it is highly important that further study be given to heat production and losses.

The architect, in designing most types of structures, provides suitable space for the purposes for which the building is to be used and then calculates the size of the furnace or heater necessary to keep the occupants comfortable during cold weather. When he designs a dairy barn for a cold climate, however, he must first consider his furnace (the animals) and then provide a space that can be heated by the animals and still leave heat sufficient to produce good ventilation.

### COMPARISON OF HEAT PRODUCTION OF HORSES AND COWS

The application of Rameaux's law to available data appears to be satisfactory in estimating the heat production of cows, but the values obtained for horses seem to be too low. Evidence supporting this possibility was obtained in tests made in this investigation and is presented in the following pages.

The heat given off per square meter of surface is substantially the same in small and large animals and the extent of the surface appears as the determining factor in the amount of metabolism. The heat production of the hog, man, dog, and mouse per square meter of skin surface per 24 hours has been given by Rubner and reported by Grandeau (*16*) as 1,078, 1,042, 1,039, and 1,188 calories, respectively. The relation between the first three is remarkable and it would not seem unreasonable to suppose that a similar relation exists between the heat production of the horse and cow which are more comparable with respect to weight, food, and environment than are the animals mentioned above. Then may it not be assumed that, within the limits of their respective weights and surface areas, the heat given off by horses is more nearly that given off by cows than is suggested by Armsby and Kriss (*2*) especially as Armsby believed that the data upon which his conclusion [4] was based was of uncertain value and that his unit is too low.

The data secured in tests of two widely separated barns of different types of construction made under different atmospheric conditions appear to substantiate their belief. The evidence is based upon field tests, whereas the deductions by Armsby were based upon thermal energy. It is not possible, at this time, to place a definite value on the heat production of horses, but from all these data there may be drawn certain general conclusions which may be accepted, at least tentatively, and which may be considered as connecting links between the known facts.

The two barns are referred to as A–B and C–D. Both are general barns in which A and C were the respective dairy sections and B and D the horse stables. In these tests the weight of the average farm horse was taken as 1,350 pounds and that of the cow as 1,000 pounds.

Tables 1 and 2 have been prepared for convenient reference to the essential data of these tests. The tables should be studied together with Figures 1, 2, and 3, and Plate 2, A and B.

TABLE 1.—*Comparison of conditions in stables A, B, C, and D*

| Stable | Equivalent number of stock [a] | Estimated weight | Volume of stable | Air space | | Air circulation | | | Stable temperature | Average estimated animal heat [b] |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Per equivalent head | Per 1,000 pounds live weight | Total per minute | Per equivalent head per hour | Per 1,000 pounds weight per hour | | |
| | | *Pounds* | *Cubic feet* | *Cubic feet* | *Cubic feet* | *Cubic feet* | *Cubic feet* | *Cubic feet* | *° F.* | *B. t. u. per hour* |
| A (cows) | 31.5 | 30,075 | 20,690 | 657 | 688 | 1,866 | 3,554 | 3,722 | 41.0 | 94,500 |
| B (horses) | 21.0 | 28,550 | 18,137 | 864 | 635 | 1,755 | 5,014 | 3,688 | 42.8 | 46,300 |
| Difference | | 1,525 | 2,553 | | | 111 | | | 1.8 | 48,200 |
| Per cent difference [c] | | 5.1 | 12.3 | | | 5.9 | | | 4.0 | 51.0 |
| C (cows) | 13.3 | 12,380 | 11,468 | 864 | 926 | 1,206 | 5,441 | 5,845 | 42.6 | 40,180 |
| D (horses) | 12.0 | 14,100 | 11,081 | 923 | 786 | 833 | 4,165 | 3,545 | 43.4 | 26,480 |
| Difference | | 1,720 | 387 | | | 373 | | | 0.8 | 13,700 |
| Per cent difference [d] | | 13.99 | 3.4 | | | 30.9 | | | 1.8 | 34.1 |

[a] Equivalent number of head of stock is based on the heat production from maximum number of stock in respective barns during test.
[b] The last three digits are of questionable value, since the figures are based on estimated weight, average conditions of feed and care of the animals being assumed.
[c] Data for A used as base.
[d] Data for C used as base.

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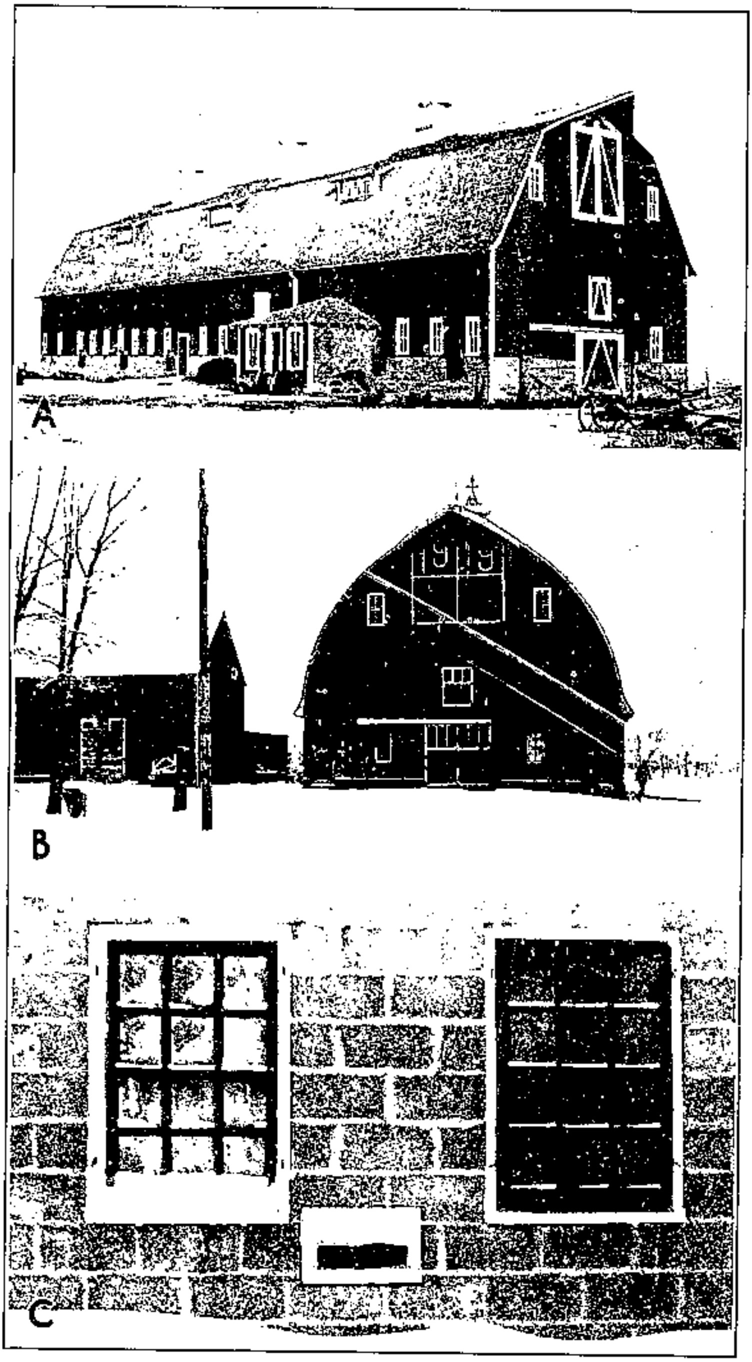
[4] No calorimeter experiments for direct determination of heat production of horses have been made. The unit is the result of an indirect method of computation which involved many estimates and calculations.



A, View of test barn A-B from the southwest; B, view of test barn C-D from south; C, barn windows with and without storm sash. The window on the right is equipped with storm sash

TABLE 2.—*Approximate percentage of various estimated heat losses and balances for stables A, B, C, and D*

| Stable | Loss by ventilation | Loss by radiation | Total loss | Balance available |
|---|---|---|---|---|
| | *Per cent* | *Per cent* | *Per cent* | *Per cent* |
| A (cows) | 53.5 | 15.3 | 68.8 | 31.2 |
| B (horses) | 97.3 | 22.4 | 119.7 | −19.7 |
| C (cows) | 74.7 | 21.3 | 96.0 | 4.0 |
| D (horses) | 94.1 | 67.7 | 161.8 | −61.8 |

Table 1 presents the conditions recorded in the four stables. From this table it may be seen that, although the estimated heat produced in stable B was 51 per cent less than in stable A, there was an average difference of only 1.8° in the temperature of the two stables during the entire test. A somewhat similar condition is found when stables C and D are compared. Stable B had 12 per cent less volume than stable A. The difference between the amounts of ventilation in A and B was small and much less than that in C and D. It also happened that the differences in the weight of livestock in the two stables of each barn were small. Other factors, such as construction and atmospheric conditions, were essentially the same in the two stables.

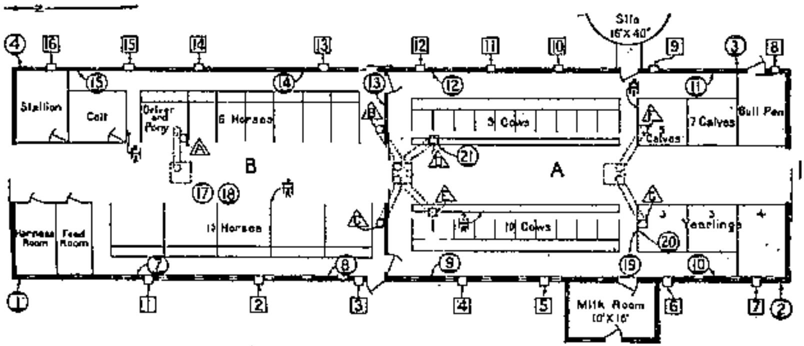


FIGURE 1.—Plan of test barn A–B

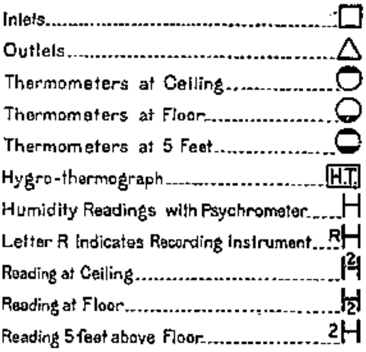


FIGURE 2.—Symbols used on floor plans to designate the positions of instrument readings

Stable B was in the north end of the barn and was partly protected by a grove and buildings, but it is not thought that this shelter caused a material difference in this case; if so, it would be in favor of stable B.

If this be true it follows that the actual amount of heat given off in each barn was approximately the same, since there was very little difference in the temperature of the two stables under similar conditions, and that the estimated amount of heat given off in stable B must have been too low. With the same amount of heat generated in the two portions of the barn, one would expect stable B to be cooler than stable A, because of a somewhat greater exposure and larger amount of ventilation per equivalent head. Hence, there must be a constant error in the estimate of heat generated in the two barns as this same condition is found when the temperatures of stables C and D are compared. It is believed that the estimated amount of heat produced by the horses is too low. The estimated heat production of the cows is probably more accurate since the calculation is based upon a larger amount of experimental data. As shown in Table 1 the volume of space to be heated by farm animals of average size is almost the same in stables C and D. This again indicates that the heat given off by the average farm horse and by the average cow are more nearly alike.

The average estimated heat losses in stables B and D (Table 2) were greater than the estimated heat generated. Since the amount of heat lost can not be greater than the amount produced there must be some explanation of this condition. It is obvious that the difference which can be maintained between the inside and outside temperature depends upon the heat supplied and the heat lost. Unfortunately, there is no means of accurately estimating the amount of heat lost by leakage.

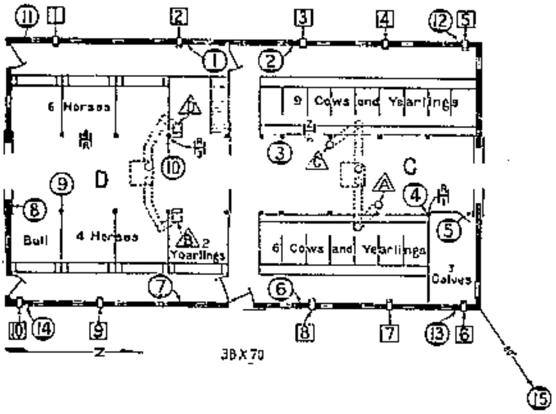


FIGURE 3.—Plan of test barn C–D

## CARBON DIOXIDE IN VENTILATION

The part played by $CO_2$ in barn ventilation is of comparatively little importance because so little is known regarding its relation to the metabolism of animals. It is known, however, that bacilli of tuberculosis, pneumonia, abortion, meningitis, and other diseases grow more rapidly when large amounts of this gas are present. It is also known that $CO_2$ in quantity stimulates respiration with a consequent strain on the animal. For these reasons an undue quantity of $CO_2$ in the cow stable is not desirable.

For many years the presence of $CO_2$ has been used as an index of the contamination of air and because of this use misconceptions regarding it have arisen. Some of these are: (1) The evil effects of vitiated air are due to its toxic properties; (2) the symptoms experienced in a badly ventilated room are caused by a deficiency of oxygen and an excess of carbon dioxide; (3) the presence of more than 1 per cent of $CO_2$ in stable air is fatal to animals; (4) expired air is heavier than fresh air because of the increased $CO_2$ content.

Professor Lee as quoted by Winslow (*45*) states "the problem of ventilation is physical, not chemical, cutaneous not respiratory," that is, the vitiation of stable air is of little importance so long as the animals are kept in good physical condition which necessitates the removal of excess heat and moisture given off through the skin.

Hill (*21*) after many experiments and careful weighing of previous evidence states that the

> Carbon dioxide content up to 1 per cent or even higher produces no deleterious effects or stresses on the human system—there is no evidence of organic toxins in the exhaled air.

Flügge, as reported by Winslow (*45*) after a number of years of careful search failed to find the obnoxious and injurious substance said to be in respired air. Priestly first discovered oxygen in 1774 and three years later Lavoisier (*45*) showed by animal experiments that the symptoms experienced in a badly ventilated room could not be attributed to oxygen deficiency. Recent experiments by Hill with eight students shut up inside a glass cage substantiate this assertion. It was found that when the oxygen had fallen to 10 per cent and the carbon dioxide risen to 4 per cent and the wet bulb read 85° F., the students began to suffer extreme discomfort and were astonished to find that they could not light their cigarettes. When the air within the cage was circulated by means of electric fans, the discomfort rapidly diminished.

The generally accepted view is that of Billings and his coworkers (*6*) and Haldane (*17*). Carbon dioxide and possibly other fatigue products are the normal stimulants of the respiratory centers. Thus a rise of 0.2 per cent in carbon dioxide in the alveolar air doubles the pulmonary ventilation, whereas oxygen deficiency does not increase the respiratory rate until the atmospheric oxygen falls below 13 per cent. Lumsden (*31*) further shows that very large amounts (20 to 30 per cent) of carbon dioxide can be breathed for several hours without danger to life. No further evidence is necessary to disprove the statement that "the presence of more than 1 per cent of $CO_2$ in stable air is fatal to animals." One per cent is rarely exceeded, even in poorly ventilated barns, and the injurious effects of poorly ventilated stables can be traced neither to reduced oxygen and increased carbon dioxide nor to hypothetical organic poisons.

Thus three of the general beliefs concerning $CO_2$ in stable air are shown to be erroneous. The relative weights of expired and fresh air have a bearing on the use of $CO_2$ analysis as an index of contamination and circulation. The impression regarding their relative weights is shown to be erroneous in later paragraphs (p. 15).

## COMPOSITION OF PURE AIR

Reliable sources of information (*40*) give the average composition of the air at 75° north latitude, 0° C. and 760 millimeters pressure as 77.87 per cent nitrogen, 20.94 per cent oxygen, 0.94 per cent argon, 0.03 per cent carbon dioxide, and 0.22 per cent water vapor. Water vapor is variable, depending upon the temperature, and is usually omitted. Gases such as krypton and helium occur in small amounts, but since they are not known to have any physiological significance they may be included with the nitrogen.

The normal amount of carbon dioxide in free air commonly has been assumed to be 0.04 per cent, or 4 parts in 10,000, although recent observations show an average content not exceeding 0.0317 and a general mean of 0.0308 per cent. Benedict (*5*) states that this holds true irrespective of weather conditions, temperature, or season, and that the chemical composition of outdoor air is very constant over practically the whole surface of the earth. Since country air is apt to be free from contamination the smaller percentage of $CO_2$ (0.03 per cent) should be used.

### WEIGHT OF AIR

The weight of 1 cubic meter of normal air, of the above composition, at 0° C. is 1,290.5 grams. The weight of a cubic meter of dry air at 0° C. and at 760 millimeters pressure is 1,293.3 grams or 2.8 grams heavier than moist air. This is explained by the fact that if the water vapor of the air is extracted, the other gases will completely fill the space previously occupied by the water vapor. Since the density of water vapor is much less than that of the other gases it is obvious that the weight of the air must necessarily be increased.

### COMPOSITION OF EXPIRED AIR

The composition of expired air varies with the conditions of respiration and nutrition. According to experiments by Paechtner (*34*) with a steer in a respiration chamber, and under varied conditions of nutrition expired air contains 5.53 per cent carbon dioxide and 14.29 per cent oxygen, there being an oxygen deficiency of 6.65 per cent. On this basis dry, expired air contains 5.53 per cent $CO_2$ 14.29 per cent $O_2$ and 80.18 per cent of $N_2$ and other gases with a temperature slightly less than body temperature of cows or 38° C. (100.4° F.). Expired air is practically saturated. The tension or pressure of the water vapor at 38° C. and saturation is 49.75 millimeters of mercury. Standard atmospheric pressure is equivalent to 760 millimeters of mercury. Hence the volume of water vapor in a saturated gas at this temperature, is $\frac{49.75}{760}\times 100=6.55$ per cent, and the volume of all the other gases together is 93.45 per cent. The density of expired air at 38° C. and of the above composition is found to be 1,126.0 grams per cubic meter. Since stable air is much cooler than the expired air it will be heavier by amounts proportional to the respective absolute temperatures and differences in composition.

### PRODUCTION OF CARBON DIOXIDE IN THE STABLE

There is no simple test for air conditions and the determination of $CO_2$ is of value as indicating the rate of diffusion or replacement of the air in the stable and of estimating the amount of air leakage.

Meissl (*33*) found that of the total daily $CO_2$ production of hogs 56 per cent was given off by day and 44 per cent by night. Closely agreeing are the findings of Henneberg (*32*) with sheep, namely, 54 per cent by day and 46 per cent by night. In the Vienna experiments (*33*) with horses similar data were obtained. Existing data relating to $CO_2$ production (*7*) by the dairy cow has not yet been summarized but, since neither assimilation of food nor generation of energy can take place without the consumption of a proportional amount of air, it is obvious that nutritional requirements may cause a wide variation in the oxygen consumption and carbon dioxide production.

Analysis of stable air affords a means of determining the amount of air leakage. The sampling of air must be very carefully done in order to obtain representative conditions, since chance contamination may result by reason of the too close proximity of stock. When this method is employed it is necessary to assume a standard production of carbon dioxide, which may or may not be within 10 to 25 per cent of the actual production.

### COMPOSITION OF BARN AIR

Numerous analyses of stable air have been made and a summary of the data shows that variation in $CO_2$ content may be expected under different conditions: Pettenkofer (*20*) found a range of 0.105 to 0.21 per cent of $CO_2$. Two hundred analyses made by Schultze (*32*) showed an average of 0.435 per cent of $CO_2$ with a maximum of 0.594 per cent. Märcker (*32*) concluded that in a ventilated stable the $CO_2$ should not exceed 0.25 to 0.30 per cent. Hendry and Johnson (*20*) found a variation of 0.089 to 0.228 per cent in a modern barn. Clarkson (*9*) found as high as 1.231 per cent in a poorly ventilated barn. Lipp (*36*) under experimental conditions obtained a percentage of 2.7 per cent of $CO_2$. Hendrick (*19*) concluded that the $CO_2$ content of the air had no relation to the amount of air space per animal and that a large air space gives no assurance of pure air.

The weight of pure carbon dioxide gas is approximately one and one-half times that of oxygen. This fact has led many to believe that respired air is more dense than fresh air because part of the oxygen is replaced by carbon dioxide in the lungs; consequently it has been assumed that since respired air contains a greatly increased amount of carbon dioxide, it is heavier than fresh air and tends to fall, accumulating at the stable floor.

This reasoning is at fault in that some of the oxygen in the lungs is replaced by water vapor which is much lighter than oxygen. Also, as expired air is usually of a higher temperature than inspired air it is, on this account, less dense than the stable air. Expired air is actually lighter per unit than fresh air under ordinary conditions of ventilation and therefore tends to rise. This holds true at all stable temperatures below 80° F. and may under certain conditions be true at higher temperatures. In Table 3 amounts of carbon dioxide and average humidities, similar to those found in practice, have been used in calculating the densities of stable air of different composition at 50°.

It is obvious from Table 3 that expired air, being lighter, will rise. It is also evident that the change in weight per unit of volume due to the increase in carbon dioxide is largely offset by the increase in the moisture content up to the saturation point. Since in most cases the expired air will be warmer than the stable air it will rise and generally, although not always, the air at the ceiling will have a higher content of carbon dioxide.

TABLE 3.—*Comparison of air conditions in stable*

| $CO_2$ parts in 10,000 | Assumed relative humidity | Air conditions at 50° F. | Weight per thousand cubic meters |
|---|---|---|---|
| | *Per cent* | | *Grams* [1] |
| 6 or less | 60–70 | Very good | 1,239.27 |
| 10 or less | 65–75 | Fair | 1,239.52 |
| 20 or more | 75–85 | Little close | 1,239.10 |
| 40 or more | 90–100 | Rather close | 1,239.25 |
| 100 or more | 100 | Foul | 1,242.27 |
| 250 or more | 100 | Very bad | 1,250.08 |
| 3 or more | 70 | Normal | 1,238.84 |
| 3 or more | 100 | Saturated | 1,237.19 |
| 3 or more | 0 | Dry | 1,242.83 |
| 517 or more | 100 | Expired air 100.4° | 1,126.04 |

[1] Argon and other inert gases are disregarded but the weights given are sufficiently accurate for the purpose of comparison.

A high $CO_2$ content of the stable air is usually associated with high temperatures and high humidities, but it is often an unreliable guide to the hygienic conditions although frequently so used. The data in Table 4 obtained at three stations during one of the tests made in this investigation show the condition that existed in one barn.

TABLE 4.—*Analyses of air in one barn*

| Station | $CO_2$ | Temperature | Relative humidity | Weight per thousand cubic meters |
|---|---|---|---|---|
| | *Per cent* | ° *F.* | *Per cent* | *Grams* [1] |
| Feed alley, ceiling | 0.0031 | 52 | 81 | 1,234.42 |
| Feed alley, floor | .0015 | 47 | 93 | 1,246.10 |
| Litter alley, ceiling | .0020 | 49 | 87 | 1,241.42 |
| Litter alley, floor | .0022 | 44 | 86 | 1,254.49 |
| Feed alley, ceiling | .0016 | 52 | 93 | 1,232.08 |
| Feed alley, floor | .0018 | 44 | 86 | 1,254.23 |

[1] Calculated.

The first two analyses show that the amount of carbon dioxide at the ceiling was more than double that at the floor. By comparing the fourth and sixth it is found that the air in the latter case is slightly lighter owing to a decrease in the carbon dioxide content, the temperature and humidity being the same. In the last two the carbon dioxide content is higher at the floor. The third and fourth analyses indicate that the temperature plays an important part in the weight of the air. The evidence leads to the conclusion that carbon dioxide, as ordinarily encountered, does not settle. Numerous samples taken by the author and data of other writers involving more than 3,000 samples show that the $CO_2$ content of stable air is higher at the ceiling than at the floor.

The manifestations of the evil effects of bad ventilation may be slow and are often difficult to measure. Although life may be sustained in a poorly ventilated barn (*30*, *36*) the products of respiration, excess heat, and moisture and odors should be removed in the interest of animal health. It is not a question of how little ventilation is required but the maintenance of air conditions most conducive to the health and maximum production of the animal.

## MOISTURE IN VENTILATION

Moisture is present in the air as a gas and is perhaps the most important factor to be considered in barn ventilation. It diffuses into the air almost twice as rapidly as carbon dioxide (*40*). The moisture content is not uniform throughout stable air, but the degree of variation is less than that of carbon dioxide diffusion. Air contains varying amounts of moisture, and the amount present depends upon the temperature, pressure, and composition of the air, but mainly upon the temperature. There must be a constant removal of moisture from the occupied stable or the amount of moisture in the air will increase. The efficiency of a ventilation system is often judged by the amount of visible moisture on the walls and ceiling, but this may not always be a true test of the effectiveness of the system. The presence of moisture may be due to improper operation or faulty construction.

### PRODUCTION OF MOISTURE

A milk cow of average weight gives off 12 to 18 pounds of moisture per day, or an average of 4.375 grains per hour (*2*). One ordinary breath of a cow is sufficient to cover with dew the entire glass area usually allotted to her—approximately 4 square feet. If the daily production of vapor were condensed and placed on her stall floor it would cover the surface to an approximate depth of three-sixteenths of an inch. The daily production of moisture is affected by the amount and condition of feed, size of animal, environmental conditions, etc.

### MOISTURE CONTENT OF AIR

Table 5 gives the number of degrees temperature drop before the dew point or saturation is reached under different conditions of stable air. It illustrates the importance of the warm stable temperatures in the prevention of condensation on the wall.

TABLE 5.—*Number of degrees drop in temperature before the dew point is reached under different conditions of stable air*

| Relative humidity (per cent) | Degrees temperature drop to dew point at stable temperature of— | | | |
|---|---|---|---|---|
| | 32° F. | 45° F. | 50° F. | 60° F. |
| | *Degrees* | *Degrees* | *Degrees* | *Degrees* |
| 100 | 0.1 | 0.1 | 0.1 | 0.1 |
| 90 | 2.4 | 2.8 | 2.9 | 2.9 |
| 80 | 4.9 | 5.8 | 5.9 | 6.3 |
| 70 | 7.9 | 9.2 | 9.4 | 9.9 |
| 60 | 11.0 | 13.0 | 13.3 | 13.9 |
| 50 | 14.9 | 17.0 | 17.9 | 18.7 |
| 40 | 19.4 | 22.0 | 22.7 | 24.3 |

At a stable temperature of 60° F. and a relative humidity of 70 per cent the temperature drop to the dew point is almost 10°, while at a temperature of 32° and the same relative humidity the drop is but 8°. If the humidity be increased to 80 per cent at this temperature a drop of but 5° would be necessary to reach the dew point. In order that the temperatures of inner surfaces of outside walls may be maintained above the dew point of the stable air it is necessary that the walls be sufficiently insulated.

It will be seen from Table 5 that the capacity of air for holding vapor in suspension, i. e., the number of degrees drop in temperature before saturation is reached, increases as the stable temperature increases. As cold air enters the barn it may be saturated, yet contain but a small amount of moisture per unit. Air entering at − 20° F. and saturated contains 0.166 grain of water per cubic foot. Each cubic foot that enters displaces 1 cubic foot of the air within the barn, but the air leaving at a stable temperature of 45°, if saturated, is capable of carrying off 3.414 grains of water per cubic foot, i. e., its moisture-holding capacity has increased more than 20 times. If the air enters at 0° it holds 0.418 grain of water when saturated, and at a stable temperature of 45° its moisture-holding capacity would be increased more than 8 times. This illustrates the importance of maintaining circulation within the barn, even if it is very slow.

That outtake flues actually do remove moisture may be shown by lowering the temperature of the air within the flue and condensing the water in the air column. In a trial an outtake was opened and the warm saturated air permitted to rise into the cold flue. The air was chilled to a temperature below the dew point, and 3 pounds of water were obtained in 6 minutes. The flue walls became warm in a short time, five minutes in one instance, and the drip from the flue decreased and finally stopped.

### CAUSES OF DAMP WALLS

Dampness in a barn may result from any one of four conditions, namely, lack of ventilation, lack of heat production, failure to conserve heat, and poor construction, or from a combination of two or more of these conditions. Condensation may be prevented (1) By lowering the moisture content of the stable air by ventilation, thus permitting a greater temperature drop before condensation takes place; (2) by increasing the temperature of the stable air by keeping the barn well filled or by substituting larger animals, thus increasing the capacity of the air for holding moisture without condensation; (3) by providing insulation so that the wall resistance to the transmission of heat is increased to a point where the inside surface temperature will not fall below the dew point of the stable air; (4) by avoiding any construction which will retard the circulation of air currents over the wall surfaces; (5) by any combination of the above methods.

### EFFECT ON ANIMAL LIFE

The effect of humidity upon human health has been studied and the present conception is that temperature, humidity, and motion of the air have a decided influence upon personal comfort (*7*, *21*, *41*, *45*). Information with respect to the effect on animals is very meager, but such data as are available indicate that farm animals are similarly affected (*2*, *6*, *13*). Data on page 8 show that of the total heat lost from the body 7.2 per cent is lost through vaporization of water from the lungs and 14.5 per cent by evaporation from the skin. The latter, upon which the comfort of the animal depends, is greatly affected by the relative humidity of the stable air. It is obvious that evaporation takes place more readily when the atmosphere is dry than when it is damp or saturated. Hence, when the air is very moist, the heat ordinarily lost by evaporation must find some other channel of dissipation, possibly causing discomfort to the animal.

### EFFECT ON STRUCTURES

The proper ventilation of a stable is not a simple matter, with the weather changing from hot to cold, calm to stormy, and with a varying amount of stock in the stalls. It is more difficult to control humidity than temperature. It is possible to specify the temperature and humidity essential to a desirable air condition, but to obtain the amount of circulation required to produce and maintain them is not so easy.

The effects of too much moisture on the barn and contents are more readily apparent and are evidenced by rotted timbers, rafters, ceiling boards, sills, etc., and by spoilage of hay and feed. Indirect losses are due to illness caused by decomposed or mouldy feed and by the softening and destruction of plaster and paint. These are economic losses which can be measured. In many barns, rotting due to moisture within is much more rapid than outside deterioration caused by the elements.

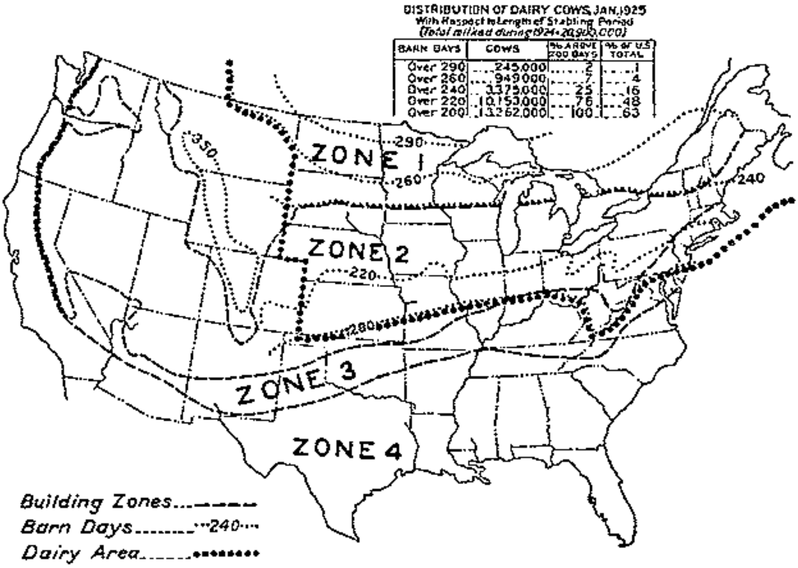
Moisture in the air will be deposited on a surface whenever the temperature of that surface falls to the dew point of the air. The walls of the barn when colder than the air may act as a condensing surface which, by removing moisture from the air as it circulates, lowers the moisture content of the stable air. If the temperature of the wall surface is below freezing frost is formed.

Heat is transmitted to the wall surface both by radiation and convection or air movement. The temperatures of the wall surface and of the air in contact with it are not the same, and the lowering of air temperature, which may cause deposition of moisture, occurs within a thin film of air very close to the surface and can not be measured with the ordinary thermometer. However, the desired stable temperature being known and the minimum expected outside temperature being obtainable from the Weather Bureau records, the amount of insulation required may be determined as described later.

Condensation on a wall surface may be due to a leakage of air through joints or cracks in the insulation, as well as to the lack of insulation. But regardless of how well the wall may be insulated there will always be some heat loss. In providing against condensation the greatest thickness of insulation is required under conditions of highest humidity, lowest air circulation, and low temperature.

Wind on the outside of a warm wall increases heat losses and condensation. Deposition of moisture on the wall surface is also affected by the air currents within the stable. The rate of circulation of these currents is in turn greatly affected by the amount of ventilation, and the higher the velocity the less the chance for deposition. Moisture may gather on ceiling surfaces where girders, beams, or other obstructions sometimes interfere with these currents and form pockets of uncirculated air. The paths of convection currents are often indicated on the walls, around corners and at ventilating flues by the pattern formed by frost or deposition of moisture where there is insufficient air movement. These slow-moving air currents prevent the deposition of moisture and emphasize the need of maintaining a circulation of air even if it is at a slow rate.

The absence of "air stoppings" at the ribbon where joists and studs meet is a common cause of moisture on the ceiling. This omission permits cold-air currents to circulate between the joists, chilling the ceiling boards and causing the temperature of warm, moist stable air in contact with this cold surface to drop to or below the dew point.



DISTRIBUTION OF DAIRY COWS, JAN. 1925
With Respect to Length of Stabling Period
(Total milked during 1924 = 20,900,000)

| BARN DAYS | COWS | % ABOVE 200 DAYS | % OF U.S. TOTAL |
|---|---|---|---|
| Over 290 | 245,000 | 2 | 1 |
| Over 260 | 949,000 | 7 | 4 |
| Over 240 | 3,375,000 | 25 | 16 |
| Over 220 | 10,153,000 | 76 | 48 |
| Over 200 | 13,262,000 | 100 | 63 |

FIGURE 4.—Map showing zoning of the United States with respect to temperature and barn days and the principal dairy area, the location of which makes evident the need of comfortable shelter for dairy cows

## CLIMATIC CONDITIONS AFFECTING CONSTRUCTION

Variations in climatic conditions in different localities affect the requirements of a ventilation system. The probability of low temperatures and the range of the expected temperatures determine the need and amount of insulation necessary to the maintenance of desirable stable temperatures under given local conditions. The accompanying map, Figure 4, and Tables 6 and 7 are of value in choosing the construction best adapted to a particular locality. The average temperatures for the months of January and February over a period of 30 years at 100 selected stations were used in determining the boundaries of the several zones shown on the map.

TABLE 6.—*Temperatures for January and February at selected stations*

| Item | Temperature in zone— | | | |
|---|---|---|---|---|
| | 1 | 2 | 3 | 4 |
| | *° F.* | *° F.* | *° F.* | *° F.* |
| Daily mean at 8 a. m | 5 | 17 | 27 | 36 |
| Mean monthly | 11 | 22 | 30 | Above 32 |

TABLE 7.—*Number of days annually when temperature at 8 a. m. was below 50°, 32°, and 20° F., respectively*

| Temperature (° F.) | Item | Days in which temperature was below the point stated in zone— | | |
|---|---|---|---|---|
| | | 1 | 2 | 3 |
| Below 50 | Range | 225-350 | 117-290 | 160-240 |
| | Average | 266 | 225 | 193 |
| | Per cent of annual | 72.9 | 61.6 | 52.9 |
| Below 32 | Range | 130-175 | 45-140 | 30-90 |
| | Average | 154 | 107 | 64 |
| Below 20 | Range | 37-153 | 0-80 | 0 |
| | Average | 8 | 21 | 0 |

According to Table 7 the temperature at 8 a. m. was below 50° F. during 72.9 per cent of the year in the first zone, 61.6 per cent in the second zone and 52.9 per cent in the third zone. This makes clear the relative importance of the temperature factor in barn ventilation in the various zones and the number of days that the full capacity of the ventilation system will be required. It also shows that about 58 per cent of the average number of days, on which the temperature was below 50°, were below freezing during the night in the first zone, 48 per cent in the second zone and 33 per cent in the third zone, and that of the number of days below freezing in the first zone 52 per cent were below 20°. These average temperatures should be considered in determining the amount of insulation required in a given locality and the capacity of the ventilation system best suited to the conditions.

### LENGTH OF STABLING SEASON

The map also shows the length of the stabling season in the northern zones. Because of the variable conditions this factor is omitted in the southern zones. Tables 6 and 7 may be used to supplement the map. The number of days that cows are kept in the barn varies widely in different sections of the country because of differences in practice. In most parts of Maine the cows are kept in the barn nearly every night, whereas in the semiarid regions, where the same temperature prevails, cows are permitted to run out.

Available information indicates that milk yields are affected by temperatures below 50° F. Turner, as quoted by Hays (*18*) concludes that temperature is a major factor in the seasonal variation of the percentage of fat in cow's milk. In most sections it is desirable to house the cows at night when temperatures below 50° are expected. This temperature may then be used as a basis for the determination of the number of days during which ventilation will be required. When the outside temperature is above freezing the windows and doors may be kept open a greater part of the time. At such times the amount of ventilation obtained is not solely dependent upon the flues. When the temperature drops below freezing the doors and windows should be closed and the ventilation system operated at full capacity. It is seldom necessary, under average conditions, to restrict the ventilation until the outside temperature drops below 20°. With good construction this point may be lowered considerably. Windows, as aids to ventilation, may be used in sections where the temperature is above 32° on a large percentage of the days on which ventilation is necessary. In sections where the temperature on a large number of days is below 20°, greater attention must be given to insulation and to the design of the ventilation system in order that the maximum use may be made of the system.

Although it is recognized that there are many factors which may affect the annual number of days that the stock is housed in a particular locality, nevertheless these data, which are based upon the best information available, are thought to be representative of average conditions for dairy cattle and are valuable in coordinating the several factors affecting the design of a ventilation system.

## VOLUME OF AIR SPACE PER HEAD OF STOCK

### RELATION OF VOLUME TO PURITY OF AIR

Purity of stable air is not dependent upon a large volume of air space. The air within a barn is vitiated by emanations from the stock, particularly the products of respiration. Expired air does not necessarily mix with the whole air of the room even with moderate circulation. If the ventilation is bad because of either poor circulation or distribution, diffusion will not be uniform and theoretically there is no limit, except that of saturation, to the extent of contamination that may exist at a given point within the stable, however large the air space.

Repeated analyses (*35*, *39*) have shown that bacteria in the stable air have relatively small effect upon the bacteria count in the milk. Milk readily absorbs odors from the stable air, and if certain of the common feeds are present at milking time the milk may become unfit for sale or use as food. The flavor and odor of such plants as garlic, cabbage, turnips, green cowpeas, and silage, if fed before milking, may be detected in the milk. Garlic may be detected in milk 1 minute after feeding or in 2 minutes after the milk is drawn when the cow has been permitted to inhale the garlic odor for 10 minutes (*4*). Contamination can best be avoided by removal of the source of odor and by providing for adequate ventilation and the removal of milk from the stable as soon as drawn. If feeds having odors that affect the milk are given after milking, the effects of their ingestion and the odor-laden stable air will have been removed by the time of the next milking.

In a stable having the largest practical unit of volume per head and with no ventilation, the air is contaminated (assuming complete diffusion) beyond the point of desirable purity within a few minutes. The standard developed by King (*29*) requires that the degree of purity of air in the stable should not be lower than

96.7 per cent, i. e., that the air in the stable shall not contain more than 3.3 per cent of air once breathed. On this basis 3,542 cubic feet of air per hour is required for the average cow. The amount of air space is of great importance in controlling stable temperatures and in economy of construction, but as previously stated a large volume per head gives no assurance of pure stable air. In the ventilation of barns the degree of contamination of the air is dependent upon the rate of production and the rate of removal of the units of contamination and not upon the unit volume of air space. Hence ventilation must be a continuous process when the animals are in the barn.

That the statement regarding the relation of volume to air purity holds true in practice as well as theory is shown by analyses of air in stables wherein the volume of air space per head differed widely. I. Frick (*19*) after more than 200 analyses of stable air found that there was no relation of air space to carbon dioxide content and that high $CO_2$ content was usually associated with the higher stable temperatures and humidities. Comparing the samples taken at approximately the same stable temperatures, he found 4 to 41 parts of $CO_2$ in 10,000 in a stable having 510 cubic feet of air space per head. In a stable with 1,145 cubic feet per head he found 14 to 49 parts and in another, having 2,578 cubic feet per head, 14 to 16 parts.

Regulations of a number of cities specify a certain amount of air space for each animal. The successful laws or regulations of one section are often adopted verbatim in others without consideration of the climatic conditions and this often leads to the adoption of rules which are not applicable, and which are frequently impractical.

### DETERMINATION OF VOLUME PER HEAD

In designing a barn for a given locality the three factors which have the greatest bearing on the determination of the air space to be provided are (1), the desirability of controlling stable temperature; (2), economy of construction; and (3), convenience and economy in caring for the stock.

The volume of air space generally may be approximated as the product of the length, width, and height—usually at the platform—divided by the number of head. But this method should not be used in a ventilation test where greater accuracy is necessary. Heat production and losses are often of more importance than circulation of air, and in an investigation involving a large number of tests these factors can not be compared unless the space per head has been accurately determined. It is advisable that deductions be made for large columns, girders, and joists where the stable is not ceiled. The height of the ceiling as measured at the feed and litter alleys must sometimes be considered separately and not averaged as is often done.

The physical comfort of confined animals is dependent upon the three factors of temperature, humidity, and air circulation. Lipp (*30*) in discussing experiments states that—

> It was observed that after the stall temperature had reached 80° F. there was an unmistakable evidence of discomfort. When the temperature had climbed to 85° F. the discomfort had increased to actual distress and at 90° F.

there was danger of collapse and death.' When the air of the unventilated stall was suddenly cooled and its moisture content lowered, after having reached 90° F., and full saturation respectively, all symptoms of collapse and distress disappeared in a very short time.

Since excessive stable temperature and humidity interfere with elimination of heat from the body and water from the respiratory organs, the importance of temperature control is obvious. Theoretically it is possible to provide sufficient insulation to save all the heat, but practically the cost would not be warranted. Hence, in determining the proper volume of air space per head, the comfort of the animal at least cost must be sought.

In a warm barn there is more heat available for inducing ventilation and circulation of air with the resultant elimination or reduction of odors and excess moisture. Many farmers provide warm barns to prevent freezing of drinking cups, but fail to ventilate properly. Comfortable stable temperatures and ventilation are inseparable and the one must follow the other.

If the temperature of a stable is to be kept comfortable a sufficient number of cows must be provided to heat the air space. An 800-pound cow has approximately 48 square feet of radiating surface and one weighing 1,200 pounds, 61 square feet (*3*, *44*). Since their body temperatures are the same and their capacity of heat production varies according to their weight, it is obvious that the smaller cow can not heat or maintain the temperature of as large a volume of air space as the larger cow. Hence the size of the cows must be considered in determining the proper volume of space per head.

The amount of heat produced bears a definite relation to the weight of the stock and in turn to the amount of ventilation required. This relationship permits of tests being compared on a basis of heat production of the actual stock in terms of an equivalent number of average size as described on page 3. In this manner the several factors are made proportional to the size of the individual equivalent animal, and proper credit may be given to each according to its capacity. This method also permits of the comparison of barns full of stock with those that are but partly filled. Many ventilation installations have been unjustly criticized because of lack of consideration of this factor. Stable temperature depends upon the amount of animal heat produced and that saved. If a barn is designed for 20 head, allowing a space of 600 cubic feet per head, and if there are but 15 head in the barn, the actual volume per head is 800 cubic feet. In the northern zones this may be the limit of the heating capacity of the animal.

Yapp (*47*) has found that the volume of air space occupied by cattle is approximately 29 cubic inches per pound of live weight. On this basis a cow weighing 1,200 pounds and allotted 1,000 cubic feet of space occupies approximately 20 cubic feet, or 2 per cent, of the space. On the same basis an 800-pound cow would need but about 670 cubic feet in order that she might occupy proportionately the same amount of space as the larger cow. But the heating capacities of cows vary as the two-thirds power of their weights, and hence the smaller cow may be allowed a somewhat larger space than that given above. This relationship is given consideration in the formula found on page 26.

The volume of air space in well-designed barns is seldom less than 500 or more than 1,000 cubic feet per head. The average cow requires a stall 3.5 feet wide and in addition an allowance must be made for cross alleys. The necessary clearance for litter carriers fixes the minimum height of ceiling at a little less than 8 feet, and to secure 1,000 cubic feet per head in a 2-story barn would require an unnecessary expenditure of money in the colder sections.[5]

### COMPARISON WITH TEST DATA

A study of available data shows that under average conditions the volume per head is not important when the outside temperature is above 32° F. At 20° conservation of heat is important, and volume per head is a factor to be considered. As the temperature decreases the importance of volume per head increases. Hence the proper allowance of volume per head will be relatively greater in the first and second zones than in the third. The data from tests in Table 8 show what may be accomplished under average working conditions. The table affords a comparison of the stable temperatures, with a given volume per head, with outside temperatures of 0°, 10°, 20°, 32°; also the minimum outside temperatures at which stable temperatures above 32° were maintained. The table also serves as a valuable check on the practicability of the formula given subsequently, page 26.

TABLE 8.—*Comparison of volume per head and observed stable and outside temperatures*

| Number of barns | Actual volume per head | Outside temperature | | | | Stable 32° F. or above at outside temperature of— |
|---|---|---|---|---|---|---|
| | | 0° F. | 10° F. | 20° F. | 32° F. | |
| | | Stable temperature maintained at— | | | | |
| | *Cubic feet* | *° F.* | *° F.* | *° F.* | *° F.* | *° F.* |
| 5 | 600–690 | 40–46 | 42–52 | 41–54 | 47–58 | −32–0 |
| 2 | 700–790 | 37 | 37–39 | 30–47 | 51 | −7 |
| 5 | 800–890 | 32–38 | 36–46 | 37–47 | 40–48 | −10–4 |
| 6 | 900–960 | 34 | 34–44 | 41–46 | 44–52 | −5 |

It has been shown how the several factors affect the selection of the volume of air space per head. Cost of construction, available heat, expected temperatures, and convenience in handling the stock are factors which must be considered in choosing the proper volume of air space for each cow. The following empirical formula,[6] which serves as a check in determining the desirable air space per cow in various localities, takes into consideration the two most important factors affecting the design of a barn for cold sections, namely, heat production and its relation to expected temperatures.

From Figure 4 the average annual number of days that the cow may be kept in the barn in a given locality is obtained (*27*). This

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[5] A barn housing 20 cows in two rows of 3.5-foot stalls with one 5-foot cross alley would be 40 feet long. If the barn is 36 feet wide, which is recommended practice, it would require a height of approximately 14 feet to provide 1,000 cubic feet per head. This is unnecessarily costly and impractical in a 2-story barn. It might be practical in a 1-story barn, or a 2-story pen barn, or one but partly filled with stock.

bears a direct relation to the expected temperatures for the locality and makes it possible, as shown in the following paragraph, to introduce the temperature factor into the formula indirctly. In the formula, $V=\frac{H\times k}{D}$, $H$ represents the heat in British thermal units per hour produced by an animal equal in size to the average of those within the barn. The constant $k$ has a value of 60 for the dairy cow kept under average conditions in a well-built barn. Where it is certain that the barn will always be filled with mature stock during cold weather, which is seldom the case, a constant of 70 may be used. $D$ represents the average annual number of days that the cows are kept in the barn. $V$ is the desirable allowance of cubic feet of air space per head. If more space than that obtained from this formula is allowed greater consideration must be given to insulation.

There are many stations within a zone which have mean temperatures above or below the average for the zone. It has been found that the factor $D$ may be expressed in terms of approximate outside temperature by the quantity $(300-5T)$ in which $T$ represents the mean temperature for the month of January. Results which are compatible with good practice are obtained when the proper values for this expression are substituted in the above formula. When air-space volumes obtained by use of the formula are used, the heat available is sufficient to permit an average of 3.5 dilutions of air per hour when the outside temperature is at zero or above. Hence the formula provides a practical rule for the determination of the desirable volume per head in a dairy barn, either by reference to the mean temperature for January or to the number of barn days.

## WALL CONSTRUCTION AND INSULATION

The comfortable housing of stock is of interest to all stockmen but especially to dairymen since the majority of the milk cows of the United States are found in the colder sections. (Fig. 4.) The farmer desires a comfortable barn for four reasons: (1) Comfort of the stock with consequent saving of feed; (2) comfort of the workmen; (3) prevention of the freezing of water pipes; and (4) prevention of dampness in the barn.

Experience has shown that it pays to keep cows comfortable. There is little information with regard to the physiological reaction of cows to low environmental temperatures and the consequent saving of feed. However, the Institute of Animal Nutrition of Pennsylvania (*13*) found that under the usual conditions of intensive cattle feeding, for each degree that the temperature falls below the point at which the animal begins to feel cold, the cost of maintenance increases 1.4 per cent.

Feeding, milking, and other routine operations are more efficiently accomplished in a barn of comfortable temperature than under conditions that arouse an instinctive desire on the part of the workmen to slight the work in order to get it done quickly.

Water systems with individual drinking cups have been installed in many barns in order to save labor as well as to provide the stock with ready access to water. Warm structures are necessary to prevent the freezing of water pipes and the consequent inconvenience in caring for the stock.

## FUNCTION OF INSULATION

The function of insulation in barn walls is to retard the flow of heat. Heat is transmitted in three ways: (1) By radiation from a warm to a colder body, (2) by conduction from one molecule to another, or (3) by convection currents passing over a warm surface. The effect of wind is to increase both conduction and convection losses.

Insulation provided to insure warm structures lessens the likelihood of condensation of moisture and consequent damp walls. As stated elsewhere a damp barn may be the result of lack of ventilation, lack of production of heat, or lack of conservation of heat. The last is generally the result of insufficient use of insulation materials. Whenever barn walls are tightly built to save heat, ventilation becomes necessary as the leakage through walls and windows is not sufficient for the air requirements of the animals.

The maintenance of a comfortable temperature within the stable, when the outside temperature is low, depends upon the amount of heat given off by the animals and the total heat lost. It is evident that after the temperature in the barn has reached the desired point, the amount of heat added per unit of time must equal the amount of heat lost in order to maintain that temperature. Until the desired temperature is reached, there must be generated sufficient heat not only to raise the temperature of the air within the barn but to replace the heat lost by radiation, conduction, and convection to the walls and contents of the stable. The amount of heat absorbed depends upon the specific heat of the building materials and the contents of the building. Since the heat produced by the animal can be controlled only to a limited extent, it is evident that more insulation is required in the cold sections than in warmer regions in order to conserve the heat produced. The amount of insulation required for a given locality must be proportioned to the expected temperature.

In a structure heated by coal it is possible, within a limit, to raise the room temperature by heavier firing of the furnace, and to measure the saving of fuel effected by the application of different amounts of insulation. In a barn more heat can be obtained to a limited extent from the animals by heavier feeding, but it is more difficult to estimate the saving in feed due to added insulation since little is known about the physiological reaction of the cow to low temperature, a factor which has a bearing on the economics of insulation. Increasing the stable temperature by means of expensive feeds is uneconomical if the extra annual feed cost exceeds the investment charges incident to the added insulation.

## SELECTION OF MATERIALS

In selecting an insulating material suitable for barn construction consideration must be given to the following points: Its efficiency as an insulator, whether or not it will retain its efficiency indefinitely, its structural strength, the effect of moisture on the material, harborage afforded rodents and vermin, whether it is fire retardent, the cost of the material, and the cost of installation and upkeep.

Next to a perfect vacuum the most effective insulation against the flow of heat is air confined in minute spaces. Because of this property of air, there is a common misconception with respect to the insulating value of so-called dead-air space, and its practical value is often exaggerated. Dead air is almost unknown in structures except in porous materials where the air cells or spaces are microscopic. It is this entrapped air which adds insulating value to porous materials.

The air space between studs does not possess the insulating properties commonly attributed to it. The air currents rise on the warm side and descend on the cold side, thus transmitting heat from one surface to the other. It is not until the space is broken at short intervals by headers that it becomes at all effective. Stud spaces are sometimes filled with commercial insulating materials, packed mill shavings, sawdust, gravel, or even straw, all of which are effective if kept dry. Sawdust and straw are apt to deteriorate and settle down in the wall. Gravel, in itself a fair conductor of heat, would be effective because of its value in breaking up the convection circulation within the wall but is not desirable because of its weight.

Metal conducts heat quite rapidly, even more rapidly than the surrounding air can absorb it, provided the air is still. Hence any air current or wind blowing against the surface will increase the rate of heat loss. Farm structures in which the walls and roof are built of metal will be cold in winter and warm in summer, unless the metal is combined with other materials having insulating properties.

Masonry walls are sometimes preferred for barn construction because of their qualities of fire resistance, durability, low cost of upkeep, and structural strength, but their use in northern sections has been objected to as they lack insulating value. There is greater loss of heat and more frost and dampness in masonry barns than in comparable frame structures. One-half inch of good insulating material added to a masonry wall may decrease the heat loss by as much as 50 per cent. Although costing considerably less, this amount of insulation may be equivalent in insulating value to 8 or 10 inches of concrete or brick. A combination of masonry and insulating materials, which are now available in most sections at reasonable cost, will often produce a more economical, stronger, more durable and warmer structure than if a single material were used. One barn tested (pl. 6, B) had a double wall constructed of air-cell concrete blocks, 4 and 8 inches thick with a 2-inch air space between. This construction did not afford insulation sufficient to prevent deposition of moisture on the wall at temperatures near zero. Another barn wall (pl. 3, A) constructed of 8-inch blocks of the same kind with one-half inch of good insulating material showed no moisture at subzero temperatures. The two walls are of similar outward appearance but under like conditions of construction the latter and better wall probably could be erected at less cost.

Next in importance to the selection of materials is the way they are assembled in the wall. Each new surface that is placed in the path of heat flow offers considerable resistance not only because it breaks the continuity of heat flow but also because it holds confined a thin film of air. Two ½-inch layers of a material therefore have greater heat resistance than a 1-inch layer of the same material. Insulation placed on the inner or warm side of the barn wall is more efficient than if placed on the outer side. The object in the use of insulation is to stop the flow of heat outward, as heat flows from the warmer to the colder object or surface, and the sooner the heat flow is stopped the greater the conservation. Since heated air tends to rise and barn ceilings generally offer less resistance to heat flow than do the walls, insulation placed on the ceiling is more effective in maintaining stable temperature than is the same amount placed in the walls. This is especially true in a 1-story barn, since in a 2-story structure the hay in the mow above affords very good insulation. When part of the mow is empty the floor should not be allowed to become bare as frost and moisture may collect on the ceiling below. Less heat will be lost through the ceiling if 6 to 8 inches of hay or chaff are left on the mow floor during the cold months. Moisture on the stable ceiling is sometimes caused by the circulation of cold air between the joists. Precautions should be taken to prevent this.

### AIR-TIGHTNESS

Air-tightness in construction helps to cut down heat losses. There is always some leakage of air through the walls themselves, through cracks, mortar joints, etc., the amount varying with the permeability of material and quality of workmanship. Whenever a strong wind blows against the surface this leakage is increased. Building paper, plaster, and even paint are of value in reducing air leakage through walls. Recent tests (*23*) of a brick wall 8½ inches thick show that infiltration of more than 9 cubic feet per hour per square foot of surface may be obtained with a pressure against the wall equivalent to a 15-mile wind. Other tests show that infiltration losses account for as much as 25 per cent of the heat supplied in dwellings of average construction. It is therefore evident that air tightness of construction is essential to the conservation of heat in barns.

A study of the relationship of back drafting in outtakes to wind direction and velocity shows that infiltration was probably a contributing cause of back drafting in the flues of one barn.

### AMOUNT OF INSULATION

The heat coefficients of insulating materials are expressed in various ways, but most commonly in British thermal units per square foot per inch of thickness per hour per degree difference in temperature. It is sometimes expressed in daily loss instead of hourly. Tables of coefficients of heat losses for different materials are found in standard handbooks. Most of the data available are from laboratory tests, very few tests having been made of the common types of construction under field conditions. In making use of tables of coefficients consideration should be given to the conditions under which the data were obtained.

Insulation is employed for the conservation of heat given off by the stock and the prevention of damp walls and ceiling. The limitation of its use for the first purpose is the economic relation between the cost of construction and the amount of heat saving necessary to the maintenance of the temperature desired. The extent of its use for the second purpose is determined by the temperature and relative humidity that it is desired to maintain since these factors determine the number of degrees drop in temperature that must take place before the dew point is reached (p. 4). The latter is the more important consideration in the determination of insulation requirements for barns. Although at times it may not be sufficient to insure as high a temperature as desired, the insulation necessary to prevent condensation under normal conditions will usually be economically justified and will serve as a measure of the minimum requirements for local conditions.

The curve in Figure 5 suggests the minimum insulation for different localities. The coefficients of heat transmission are used as ordinates and indirectly represent the amount of insulation required to prevent damp walls under average conditions of weather and good ventilation. The abscissas are the mean temperatures for the month of January. This curve is a great convenience in determining the amount of insulation required in a given locality when the mean January temperature is known. Knowing the amount required, one is able to choose from a number of available materials the most desirable construction.

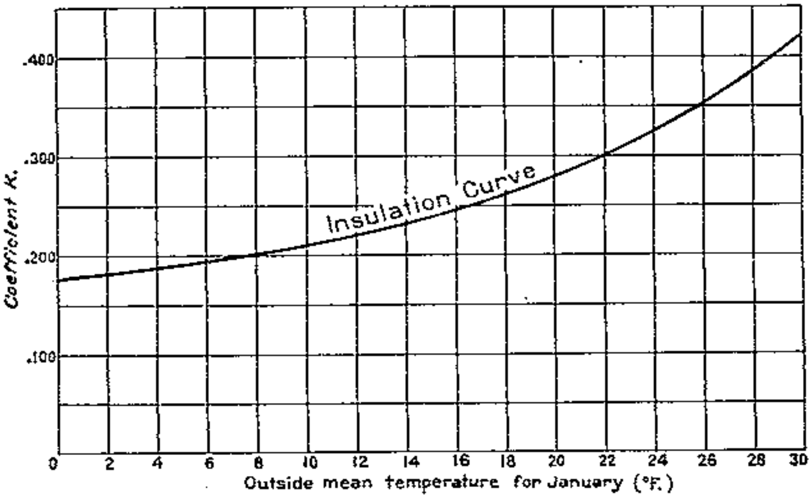
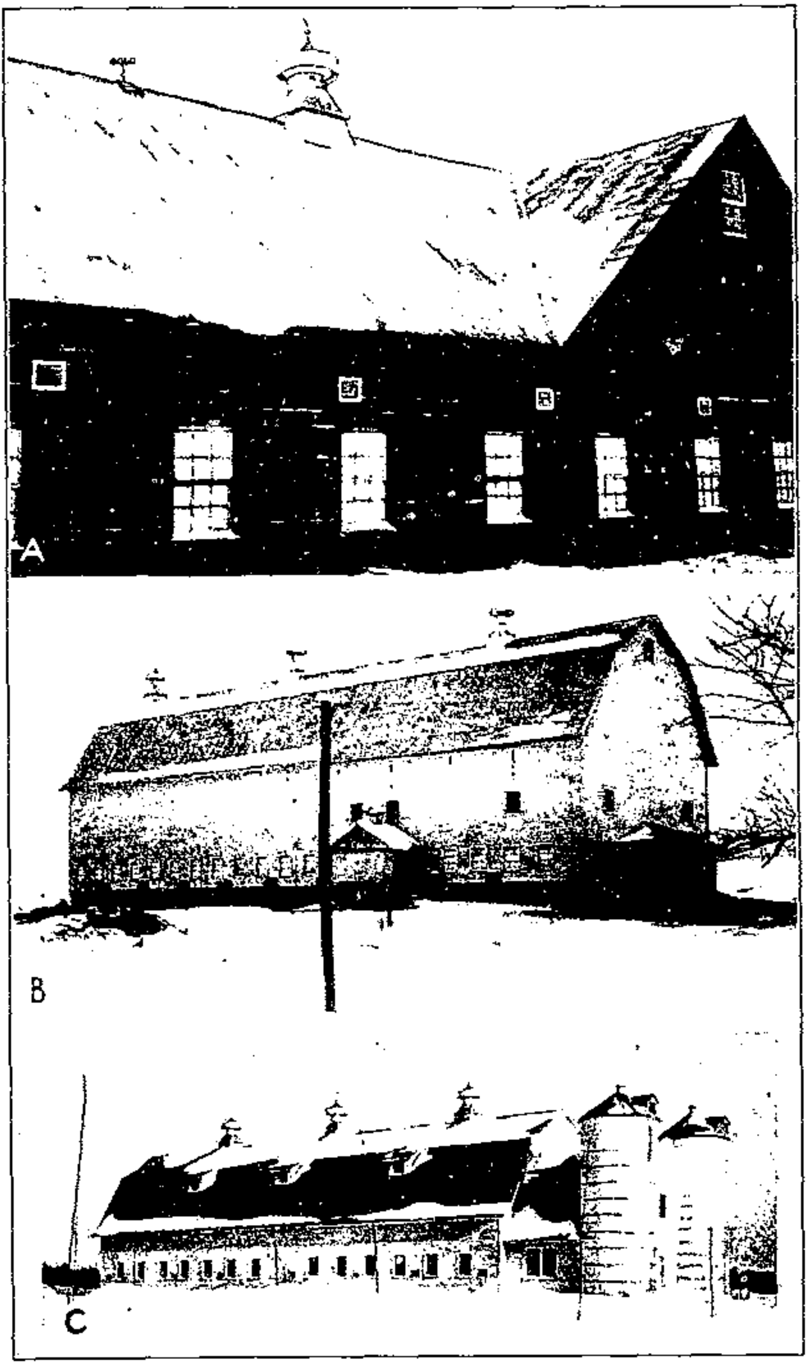


FIGURE 5.—Insulation curve. Coefficient *k* equals British thermal units loss per square foot per degree difference in temperature per hour

The heat saving effected by an insulating material is in proportion to the difference between the heat transfer coefficients of the insulated and uninsulated construction. The saving of heat by good insulation is continuous and is reflected in decreased annual cost of feed and in the comfort of the animal with the consequent greater production.

The selection of an insulating material will depend upon consideration of the characteristics previously mentioned and to a large extent upon the cost and availability. It may be more economical to use twice the amount of a material locally available but of low insulating value, than a more efficient insulating material shipped from a distance. The amount of insulation required will vary with the normal temperature expected. The coldest months of the year



A, View of barn showing wall construction, frost covered windows, and position of inlets. Note anemometer on roof; B, view of barn with vestibules; C, view of test barn T from the west are January and February, and temperatures for these months may be used in determining insulation requirements for a given locality. Average conditions may be obtained by referring to the zone map, Figure 4 or Tables 6 and 7, or for more detailed information, to Weather Bureau data.

### STORM SASH AND VESTIBULES

Infiltration of cold air through cracks around doors and windows is an important consideration especially in windy sections. Tests have shown that there may be a leakage of air around a window, as ordinarily fitted, amounting to as much as 2 cubic feet per hour for each lineal foot of crack for each mile per hour of wind velocity. The use of storm windows and storm doors helps to reduce such heat losses.

The disadvantages and limitations of windows for ventilation purposes are explained elsewhere. Their relation to heat loss is also of importance. Glass surfaces radiate heat rapidly. A single thickness of glass offers little resistance to the transmission of heat and, since it is desirable that there be approximately 4 square feet of glass for each cow, the total heat loss through the glass alone may be very great in some barns. The use of double or triple sash, or even double-glazed sash, decreases the heat loss through windows. If frost collects on the windows, the light is retarded, and any condensed moisture running down the sash hastens deterioration of the sash, sills, and other woodwork. Sunlight on the stable floor is a sanitation requisite, and it also adds many heat units to the stable air. An illustration of the value of storm sash in preventing frost formation is presented in Plate 2, C. Plate 3, A, is a view of windows without storm sashes. During zero weather frost formed on these windows to a depth of 1 inch.

Separate storm sash outside of the regular sash are preferable to single, double-glazed sash. The loss by breakage is usually less, and the glass can be more easily cleaned. When the putty of a double-glazed sash becomes loose, dirt sifts in between the panes and the glass can not be cleaned without removal. Air leakage around a stationary storm sash can be more effectively stopped than that around a sliding or hinged sash that is used the year around. Observations have shown that there is less tendency to frost formation where separate storm sashes are used than where single, double-glazed sashes are installed.

Sliding barn doors are a great convenience, but it is difficult to keep them tight enough to prevent leakage of air. If provided with hooks they may be drawn close to the frame. Hinged doors can be closed more tightly. Because the leakage around barn doors is apt to be very large, storm doors are often desirable. They may be installed in one of several ways, but most commonly they are placed on the inside and hinged. The presence of a litter-carrier track often determines the type of door construction. A vestibule entrance decreases heat losses through and around barn doors. Such a vestibule is illustrated in Plate 3, B.

Vestibules are no doubt an advantage in regions where deep snow is frequent, but it is believed that greater warmth can be provided and more economically by a judicious use of storm doors and storm sash. The vestibule shown in Plate 3, B, covered almost one-half the end of the first story of the barn. During the test made in this barn, the vestibule temperatures were found to be from 2° to 4° higher than the outside temperatures.

In one of the barns tested, a feed room across the north end reduced the exposure of the stable wall from 5 to 10 degrees. Table 9 of selected readings is interesting, as it shows the protection afforded by a feed room to prevent rapid fluctuations of temperature. These data show that the feed room provided a very effective protection to the stable on the north. The variation in stable temperature was small, whereas, that in the outside temperature was very marked. The temperature in the feed room was slow to respond to the increase or decrease of outside temperature.

TABLE 9.—*Comparison of outside, feed room, and stable temperatures*

| Reading No. | Outside temperature | Feed-room temperature | Average stable temperature |
|---|---|---|---|
| | *° F.* | *° F.* | *° F.* |
| 1 | 5.0 | 18.0 | 41.7 |
| 5 | 15.0 | 18.0 | 43.0 |
| 6 | 16.5 | 20.0 | 44.0 |
| 8 | 12.0 | 20.0 | 41.5 |
| 12 | 8.5 | 18.0 | 44.2 |
| 13 | 20.0 | 22.0 | 45.5 |
| 14 | 23.5 | 23.0 | 47.2 |
| 15 | 22.0 | 23.0 | 47.5 |
| 16 | 22.0 | 21.0 | 46.7 |
| 19 | 29.0 | 26.0 | 47.1 |
| 21 | 32.5 | 28.0 | 43.3 |
| 22 | 42.0 | 32.0 | 46.0 |
| 26 | 29.0 | 32.0 | 44.7 |
| 29 | 24.0 | 29.0 | 43.2 |

Windbreaks and tight board fences around the barn lot afford protection to the barn and help to decrease the heat losses incident to strong winds.

## REPRESENTATIVE TEST

### DESCRIPTION OF PHYSICAL CONDITIONS

The limited space precludes the presentation in this bulletin of all the data of the many tests made. A single representative test is reported with such data as is necessary to the discussion, in order that the nature of the studies and the method employed may be better understood. This test, continuous for almost 200 hours, was selected because of its length, and because it was made under a wide range of weather conditions. It is of particular value in studying the effects of weather on the ventilation of barns. It shows the effect of some factors that were not evident in other tests and afforded opportunity for studying some that could not be analyzed to the same extent in shorter tests.

The barn in which the test was made in located in Piscataquis County, Me., and is one of the few modern barns in that section. It is an example of what may be accomplished in designing barns suited to local climatic conditions. Plate 3, C, is an exterior view of the structure, the arrangement being shown in Figure 6.

Thirty-six head of stock were housed in the stable, which was not filled to capacity as will be seen by reference to the floor plan.

The stock consisted of 1 bull, 4 calves, 10 heifers, and 21 cows which, upon the basis of the aggregate heat production of the individuals, were equivalent to 34.6 average-size animals. The volume of air space per animal was 838 cubic feet. Had the barn been filled there would have been approximately 600 cubic feet per head.

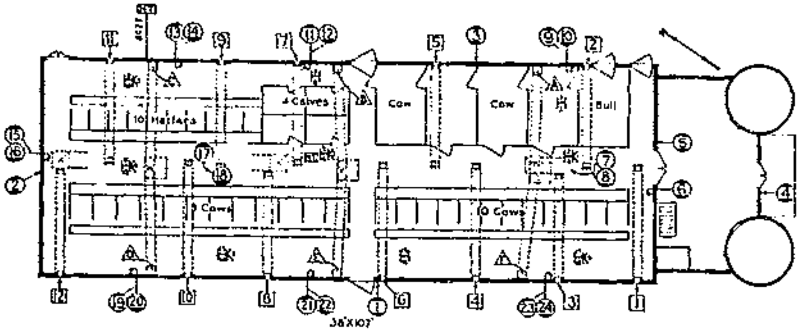


FIGURE 6.—Floor plan of test barn T

The mow floor was double-boarded and was well covered with hay. The stable was ceiled with matched lumber. The walls were of beveled siding and sheathing, with paper between, on the outside of 2 by 6 studs and paper with 6-inch flooring on the inside. The hay chutes were closed with doors of 1-inch boards which were too thin to prevent frost from collecting on them at times.

The windows were tightly fitted and provided with storm sashes. The doors to the pens were provided with storm doors and were never opened during the test.

The ridge of the roof was 33 feet above the stable floor. There were six metal outtake flues insulated with one-half inch of commercial insulation. A pair of flues entered each ventilator at the ridge.

The ventilators were closed at the base. The flues were fitted with a metal collar which closed one half of the base, while the other half was closed by means of two hinged doors operated by means of ropes and pulleys. (Fig. 7.)

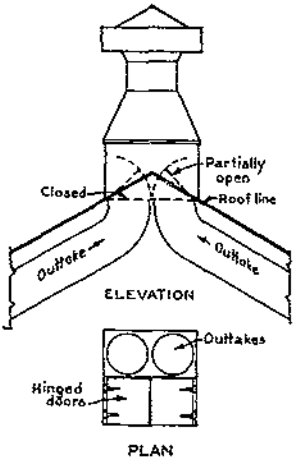


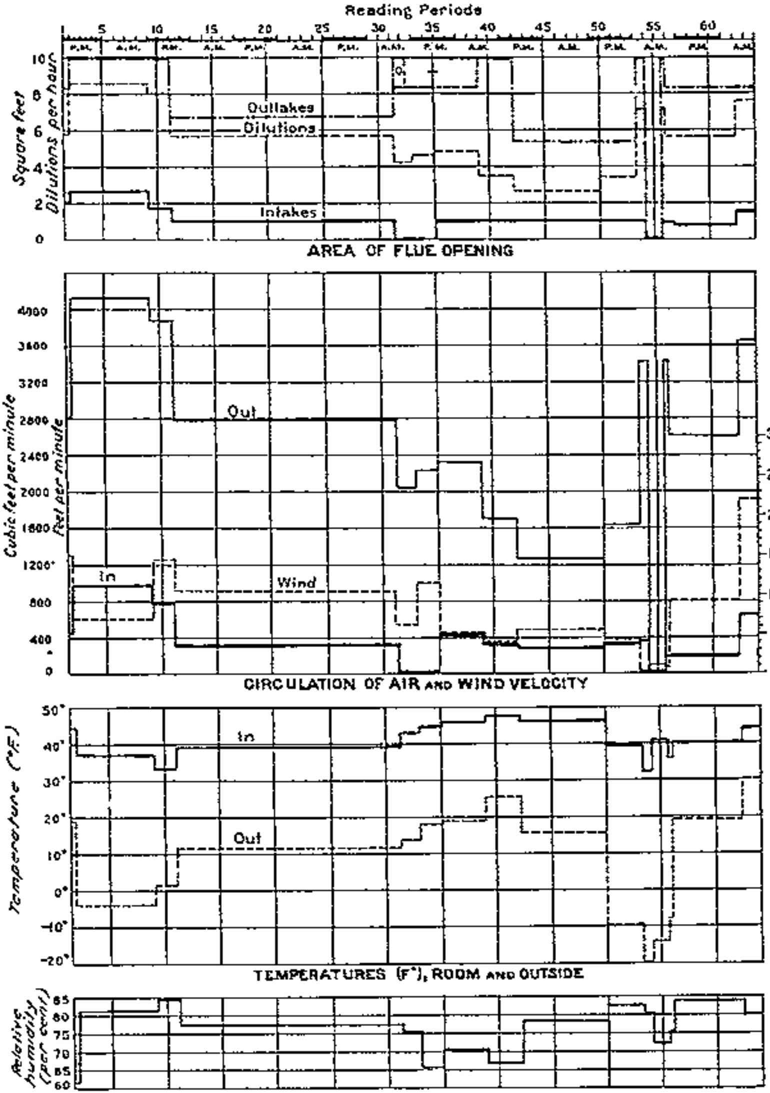
FIGURE 7.—Diagram showing the operation of doors in ventilator base

### DESCRIPTION OF TEST

Trials were made with the ventilation system wide open, partly open, and closed; with ceiling openings and floor openings; and with the ventilator base open and closed. Altogether 11 different combinations of intake and outtake adjustments were used during the test with seven changes in the setting of the outtakes. It was planned to make as few adjustments as possible in order that the effects of climatic changes upon the ventilation might be studied.

### ADJUSTMENT OF OUTTAKES

At the first reading all outtakes except B were open and the damper in D was half closed. (Figs. 6, 7, and 8.) Outtakes B and D were opened after the first reading and remained open until reading 11a,



AREA OF FLUE OPENING

CIRCULATION OF AIR AND WIND VELOCITY

TEMPERATURES (F°), ROOM AND OUTSIDE

RELATIVE HUMIDITY OF ROOM

FIGURE 8.—Summarization of averaged ventilation data obtained with different settings of intakes and outtakes in test barn T

when they were closed and remained so until reading 31a. After reading 32 the doors in the ventilator base were opened and remained open until reading 50a. After reading 42 the dampers in the outtake flues were closed, and the heat doors at the ceiling were opened, remaining so until reading 53a. The entire ventilation system was closed at 3.30 a. m., after reading 54 and remained closed until 7.45 a. m. at reading 55a during which time the stable air developed considerable odor and seemed stuffy. Flue A was closed at reading 56 and remained closed to the end of the test.

### ADJUSTMENT OF INTAKES

The intake openings at the first reading varied from 1 to 4¾ inches. After the first or preliminary reading all the intakes were adjusted to a 3-inch opening, this setting being maintained until after reading 9 when all the intakes were changed to 2 inches. After reading 11, intakes Nos. 3, 8, and 12 were closed and all others reduced to 1½-inch openings. This setting was used until after reading 31, when all the intakes were closed and remained so until after reading 35. After reading 35 all the intakes were opened 1½ inches except Nos. 3, 8, and 12 and no further change was made until after reading 54 when all intakes were closed. After reading 55a all the intakes were opened to 1 inch with the exception of No. 3. Intake No. 12 was closed after reading 57. After reading 62 all the intakes except Nos. 3 and 12 were opened to 2 inches and remained in this position.

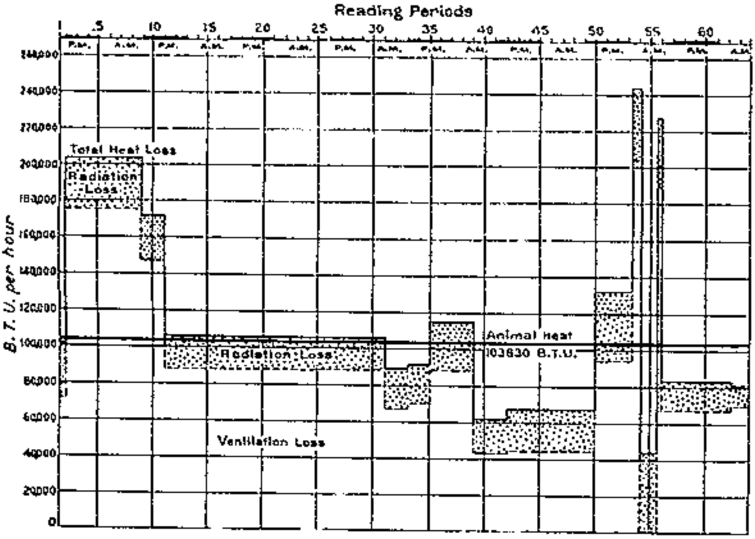


FIGURE 9.—Average estimated amounts of heat produced and heat lost in test barn T

### AMOUNT OF VENTILATION

During most of the time the ventilation in this barn was very satisfactory. There was an average of 5.5 dilutions per hour for the entire test although at reading 64 there were 12.1 dilutions per hour. Table 10 compares the amounts of ventilation obtained with different settings of intakes and outtakes. The readings for the same settings of intakes and outtakes are averaged and arranged according to sequence of decreasing amounts of ventilation. In Figures 8 and 9 the averaged results are shown graphically in the sequence of the test.

TABLE 10.—*Average amount of ventilation obtained with different settings of intakes and outtakes in test barn T* [1]

| No. | Readings | Areas of flues |  | Dilutions per hour | Temperature |  |  | Wind velocity |
|---|---|---|---|---|---|---|---|---|
|  |  | In | Out |  | Stable | Outside | Difference |  |
|  |  | *Square feet* | *Square feet* | *Number* | *° F.* | *° F.* | *° F.* | *Miles per hour* |
| 1 | 2 to 9 | 2.647 | 9.072 | 8.6 | 37.1 | −0.5 | 37.6 | 0.8 |
| 2 | 9a to 11 | 1.764 | 9.072 | 8.0 | 33.2 | .7 | 32.5 | 14.2 |
| 3 | 62a to 64 | 1.469 | 8.333 | 7.6 | 44.3 | 30.2 | 14.1 | 22.0 |
| 4 | 55a to 56 | .809 | 9.152 | 7.1 | 36.0 | −8.1 | 44.1 | 1.0 |
| 5 | 53a to 54 | .987 | 9.072 | 7.0 | 32.4 | −20.1 | 52.5 | .4 |
| 6 | 1 | 2.167 | 8.333 | 5.8 | 44.5 | 18.8 | 25.7 | 14.6 |
| 7 | 11a to 31 | .987 | 6.694 | 5.7 | 39.6 | 11.5 | 28.1 | 10.3 |
| 8 | 57 to 62 | .748 | 8.333 | 5.6 | 40.4 | 19.2 | 21.2 | 9.3 |
| 9 | 35a to 39 | .987 | 9.072 | 4.8 | 46.0 | 18.9 | 27.1 | 5.3 |
| 10 | 33a to 35 | (2) | 9.072 | 4.6 | 44.9 | 18.0 | 26.9 | 11.4 |
| 11 | 31a to 33 | (2) | 9.072 | 4.2 | 43.0 | 13.7 | 29.3 | 6.1 |
| 12 | 40 to 42 | .987 | 9.072 | 3.5 | 47.7 | 25.4 | 22.3 | 4.0 |
| 13 | 52a to 53 | .987 | [3] 5.244 | 3.4 | 30.4 | −9.7 | 40.1 | 4.4 |
| 14 | 42a to 50 | .987 | [3] 5.244 | 2.6 | 46.3 | 15.6 | 30.7 | 5.6 |
| 15 | 54a to 55 | (2) | (2) |  | 41.1 | −14.1 | 55.2 | 1.2 |

[1] Data for readings indicated are averaged. [2] Closed. [3] Dampers closed, heat doors open.

At reading 54 when the outside temperature was −22.2° F. with 7.2 dilutions per hour, the stable temperature was 31°. This is more than twice as great a circulation of air as was necessary for good ventilation, and had it been desired to keep the stable warmer it could easily have been accomplished by restricting the ventilation. This was not done as the object was to study the effect of low outside temperatures on the ventilation and to determine how much it would lower the stable temperature. The data show that it is possible to keep the ventilation system open even at low temperatures if the barn is properly insulated. While the system was closed between readings 54 and 55, the temperature rose from 31° to 41.6°, indicating that there was sufficient heat available for warming the stable although it was but partly filled.

When the doors at the base of the ventilators were open the suction on the flues was decreased, a smaller amount of air being withdrawn from the stable while air was withdrawn from the mow also. When they were closed after reading 50 air was removed from the stable only. A comparison of individual readings shows that closing the mow opening at the bottom of the ventilator apparently increased the amount of air leaving the stable about 10 per cent.

At reading 32 the air movement through flue A was neutral and from reading 32 to 38, inclusive, back drafting was observed. Flue A probably would have back drafted after reading 56 had it remained open as this flue was located in an empty pen (Fig. 6), and the reversed action in the outtake was undoubtedly caused by the lack of heat.

The effect that the various changes in the ventilation system had on the amount of ventilation can be readily seen by reference to Figure 8 which shows the average conditions resulting from the different adjustments.

One of the important developments of this test is the relationship of the outside temperature to the amount of ventilation obtained (p. 48). It is important in its relation to the design of the ventilation system. From data presented herein (Fig. 4) one may learn what the expected outside temperature may be in the locality under consideration and, knowing the relation of the outside temperature to the ventilation which may be obtained, he may design the system accordingly. Heretofore designs have been based on an assumed difference between the inside and outside temperatures because definite information as to the difference that might be maintained under ordinary conditions has not been available (p. 64).

The relationship of ventilation to the temperature difference is closer in this test than in others because for the most part no attempt was made to keep the stable temperature high, it being permitted to fluctuate with the atmospheric conditions. However, the stable temperature was satisfactory except at a few periods.

The greatest amount of ventilation at any individual reading (12.1 dilutions per hour) occurred at the sixty-fourth, when there was almost the least temperature difference of the test (15.1°) and the least temperature difference (9.1°) occurred at the sixtieth reading, when the ventilation was almost 5 dilutions per hour. With wide variations in temperature difference almost the same amount of ventilation was obtained. This with the results of other tests is evidence that low outside temperature is more effective than high outside temperature with the same temperature difference. In the past, temperature difference only has been considered whereas the amount of ventilation produced is dependent upon the weights of the warm and cold columns of air (p. 48).

### COMPARISON OF CEILING AND FLOOR OUTLETS

The effect of the use of ceiling outlets is shown by data given in Table 10. By comparing No. 12 with No. 13 it is seen that the stable temperature in the former is higher than in the latter, yet the ventilation is about the same and the wind velocity is practically the same. The intake flue areas were the same in each case. The outtake area in No. 13 is that of the heat doors at the ceiling and was approximately 50 per cent of the cross-sectional area of the flue when the floor openings were used in No. 12. If the outside temperature in No. 13 had been the same as in No. 12 the stable temperature in the former possibly would have been equal to that in No. 12, but the ventilation would have been less.

If these were the only data available to show the advantage of floor outlets in securing higher stable temperatures with equal ventilation, the evidence would not be conclusive. The readings of No. 5 and No. 14 may also be compared. In the first the outside temperature is much lower and the stable temperature is also lower, but there was almost three times as much ventilation as in No. 14. By restricting the ventilation, the stable temperature in No. 5 could easily have been raised to a point more comparable with that of No. 14 and with a lower outside temperature. Again, No. 14 shows lower stable temperature and with less ventilation than does No. 12.

The latter comparison is more typical of conditions found in other tests.

In these comparisons the area of the intakes was the same in each case while the area of the outtakes in the one was 9.97 and in the other (ceiling openings) 5.24 square feet. There was very little change in the wind velocity. The velocity of the incoming air decreased immediately when the heat doors were opened and increased after they were closed. Because the total area of intake openings in square feet was small (Table 10) the change in volume of incoming air was not great. When the heat doors were opened there was a reduction of almost one-half in the outtake area and a proportionate reduction in the volume of outgoing air. From the results of this test it does not appear that ceiling openings are more effective in producing ventilation than floor openings of equal area.

The control of the stable temperature is important, and it is interesting to note what occurred in this barn when ceiling openings were used as compared with floor openings.

TABLE 11.—*Comparison of stable temperatures, humidities, and ventilation in test barn T*

| Reading | Temperature | | | | Relative humidity | | | | Dilutions per hour | Wind velocity |
|---|---|---|---|---|---|---|---|---|---|---|
| | Ceiling | Floor | Stable | Outside | Ceiling | Floor | Stable | Outside | | |
| | *° F.* | *° F.* | *° F.* | *° F.* | *Per cent* | *Per cent* | *Per cent* | *Per cent* | | *Miles per hour* |
| 35a to 39 | 45.7 | 42.9 | 46.0 | 18.9 | 70.2 | 70.7 | 70.4 | -------- | 4.8 | 5.3 |
| 40 to 42 | 50.1 | 44.5 | 47.7 | 25.4 | 66.6 | 67.2 | 66.9 | -------- | 3.5 | 4.0 |
| 42 [1] | 50.9 | 44.9 | 48.1 | 24.4 | 55.3 | 56.4 | 55.8 | -------- | 5.1 | 5.4 |
| 42a | 51.2 | 45.4 | 49.0 | 19.2 | 70.9 | 73.8 | 72.4 | -------- | 2.0 | 1.1 |
| 43 | 50.9 | 45.7 | 48.9 | 15.5 | 78.9 | 78.9 | 78.9 | 74 | 2.1 | .8 |
| 44 | 50.3 | 45.2 | 48.2 | 17.8 | 79.1 | 79.6 | 79.4 | 57 | 2.7 | 6.5 |
| 45 | 49.1 | 44.1 | 46.7 | 16.6 | 79.6 | 79.9 | 79.8 | 53 | 2.8 | 5.7 |
| 46 | 47.3 | 42.7 | 45.0 | 12.1 | 84.2 | 84.3 | 84.2 | 50 | 2.7 | 9.6 |
| 47 | 46.8 | 42.2 | 44.7 | 6.4 | 75.8 | 76.1 | 76.0 | 59 | 2.8 | 4.2 |
| 48 | 46.0 | 41.3 | 44.3 | 12.6 | 80.3 | 80.3 | 80.3 | 61 | 2.5 | 2.8 |
| 49 | 46.2 | 41.2 | 44.5 | 22.5 | 76.8 | 77.4 | 77.1 | 40 | 3.4 | 13.9 |
| 50 [2] | 47.1 | 42.1 | 45.4 | 17.6 | 75.7 | 75.2 | 75.4 | 36 | 2.7 | 5.5 |
| 51 | 44.8 | 40.5 | 43.3 | −1.0 | 66.8 | 67.6 | 67.2 | 68 | 3.4 | 5.9 |
| 52 | 41.2 | 38.2 | 39.8 | −10.2 | 91.2 | 92.7 | 92.0 | 69 | 3.6 | 5.0 |
| 53 [3] | 36.1 | 34.1 | 35.1 | −18.0 | 86.2 | 90.0 | 88.1 | 66 | 3.4 | 2.4 |
| 53a | 34.5 | 33.1 | 33.9 | −18.0 | -------- | -------- | -------- | -------- | 6.9 | 0.0 |
| 53a to 54 | 32.9 | 31.9 | 32.4 | −20.1 | -------- | -------- | 80.0 | -------- | 7.0 | .4 |
| 42a to 53 | 44.5 | 40.4 | 42.8 | 2.9 | 79.6 | 80.9 | 80.3 | -------- | 3.0 | 5.0 |

[1] Heat doors at ceiling opened after reading.
[2] Doors in base of ventilator closed after reading.
[3] Heat doors closed after reading.

Table 11 shows temperature, humidity, number of dilutions, and wind velocity. Reading 42 was taken just before, and 42a immediately after, the change from floor to ceiling outlets. The table shows that between the two readings, that is, within one-half hour, the temperature rose a little less than 1°—the increase was uniform at all stations—and the stable humidity increased 17 per cent and at the same time the amount of ventilation was reduced more than one-half. The heat doors were closed and the dampers opened after reading 53, the effect being a slightly lowered temperature with doubled ventilation. Similar effects have been observed in other barns. After the heat doors were opened the air became noticeably warm and oppressively stagnant, a condition attributable to increased relative humidity and slight increase in temperature, because of restricted ventilation and slowing up of circulation incident to change in direction of air currents. This condition prevailed for approximately one-half hour, after which the effect passed off. The slight increase of temperature must be attributed to the decrease in the amount of ventilation as the outside temperature fell at this time.

The difference between the relative humidity at the ceiling and at the floor remained practically the same regardless of whether the floor outlets or ceiling outlets were used. The relative humidity subsequent to the opening of the heat doors was not excessively high although the lower humidity would be preferable as the stable temperature could then drop about 3° more before the dew point would be reached.

It is desirable to secure the greatest amount of ventilation compatible with the maintenance of a high stable temperature and a low relative humidity. This test (Table 11) shows that approximately 50 per cent more ventilation may be maintained with floor outlets than with ceiling outlets with approximately the same stable temperature. These results agree with those of other tests and show that floor outlets are a decided advantage in the colder sections.

### DRIP AND CONDENSATION

The objectionable drip from outtake flues appears to have some relationship to the amount of ventilation, outside temperatures, the sun, and the wind, or to a combination of any of these factors, but the main cause is not made sufficiently clear by the data obtained to warrant a definite conclusion.

No practical means of preventing the formation of frost in flues is known. Small outtake flues have been frozen solid with ice. The probability of this happening may be lessened by the use of outtake flues more than 12 inches in diameter.

Advocates of wood flues contend that where they are used there is less drip, but there is no comparative data available. Plate 4, B, shows evidence that wood flues are not free from condensation. Alternate wetting and drying causes the wood to rot quickly. This condition is more prevalent in cold sections, particularly where the roof sheathing and shingles are permitted to form one side of the flue. Flues should be well insulated in order to minimize condensation. Flues other than of wood should be of rust-resisting metal or waterproof material. Black iron rusts out quickly when exposed to moisture.

Condensation of moisture on the ceiling of the stable was observed at several periods. The mow floor was double and the joists were ceiled on the underside, but there were no headers or air stoppings between the joists at the studding line. This omission permitted leakage of cold air between the joists which chilled the ceiling surface and caused the deposition of moisture. When strong wind augmented this leakage there was an appreciable difference in the amount of moisture deposited on the ceiling.

It is common practice to make the girders under the mow continuous from one end of the barn to the other and to support the joists above them. Structurally this method has advantages, but in this barn an air pocket was formed between the girders where moisture appeared to gather more readily than it would have gathered had the air circulation been free to sweep the entire ceiling. This condition could have been improved by making the ceiling flush with the bottom of the girders or providing coved corners between ceiling and girder.

### WIND EFFECTS

The wind velocities varied during this test from a calm to more than 26 miles per hour, the highest wind occurring near the end of the test.

This and other tests made under field conditions show that the wind has little effect on the amount of ventilation at velocities below 4 miles per hour and that it is not often a dominant factor until it exceeds 10 miles. At velocities greater than this the effect is noticeable, but its full effect is seldom obtained in field tests during cold weather, as the ventilation is then generally restricted as the velocity of the wind increases. The maintenance of ventilation during periods of calm is of greater importance.

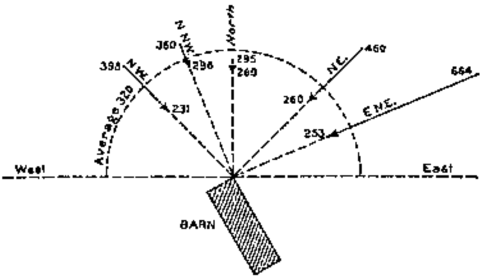


FIGURE 10.—Influence of wind direction on the velocity of air passing through intakes. The figures are velocities in feet per minute

The weather conditions were so variable that opportunity was afforded for a study of the effect of the direction of the wind on flue velocities, especially with respect to the velocity of incoming air. A study of the effect of wind direction is valuable because of its relationship to flue velocities and its influence on the location of intakes with respect to corners and adjacent buildings. It is difficult to trace the effect of wind direction on the passage of air through outtakes, but that there is an appreciable effect is evident from the data.

Table 12 and the chart (fig. 10) show the influence of wind direction on the velocity of air passing through the intakes as observed over a continuous period of eight days.

TABLE 12.—*Influence of wind direction on intake velocities in test barn T*

| Wind direction | Wind velocity | | Intake velocities | |
|---|---|---|---|---|
| | | | Windward | Leeward |
| | *Miles per hour* | *Feet per minute* | *Feet per minute* | *Feet per minute* |
| East-northeast | 12.2 | 1,074 | 664 | 253 |
| Northeast | 14.3 | 1,258 | 460 | 260 |
| North | 7.0 | 616 | 295 | 260 |
| North-northwest | 10.6 | 933 | 360 | 296 |
| Northwest | 13.1 | 1,153 | 398 | 231 |
| Calm | 0 | 0 | 296 | 296 |

Table 12 shows that the velocity of the incoming air was the same on both sides of the barn when not influenced by wind. The intake velocity at the first reading (664) is high as compared with the other readings, since the ventilation system was wide open at the time. The wind was almost directly against the side of the barn at the first and second readings, hence high intake readings on the windward side were to be expected. It will be observed that there was not much variation in the readings on the leeward side. The circular dotted line in Figure 10 represents the average intake velocities for the entire test.

### HEAT BALANCE

The amount of heat produced must balance the amount of heat lost through walls, etc., plus the amount used in producing ventilation. There is no direct measure of the heat produced within the barn so that the amount produced and the amount lost can only be estimated. The total estimated heat produced by the 36 head of stock in this barn was 103,830 B. t. u. per hour which is equivalent to that given off by 34.6 average-size animals. It should be remembered that the barn was not filled with stock. In Figure 9 the estimated amount of heat produced and the estimated total heat lost are shown, the stable temperatures being shown in Figure 8. When the estimated heat lost was greater than the estimated heat produced the stable temperature decreased and vice versa. Since the heat lost can not exceed that produced, it is evident that the estimates of production and losses are at fault or that the stock responded to the lowering of the stable temperature by giving off more than the average amount of heat. In other tests the tendency of the cows to do this was observed (p. 43). There is need of research in the methods of estimating or determining heat production and loss.

The cows in this barn were large producers and were fed in proportion to their milking capacity. The stable temperature was slightly higher in those sections of the barn where the cows were on the heaviest feed. This, to a certain extent, offsets the lack of heat in unoccupied sections. Consideration of this factor should be made in planning the arrangement of the barn.

An outside temperature of approximately 20° appears to be the point below which the conservation of heat becomes necessary. The possibility of raising the stable temperature by closing the system for a short time is clearly shown by Table 10, Nos. 5 (open) and 15 (closed), and Figures 8 and 9.

During this test there appeared to be sufficient heat given off by the animals to maintain a stable temperature of approximately 40° under normal conditions with good ventilation. During the interval between readings 2 to 9 (Table 10, No. 1), the ventilation appeared to be a little too liberal for the maintenance of a warm stable with the low temperature outside. The ventilation could have been restricted by partly closing the intakes, resulting in a higher stable temperature with ample ventilation.

This test also afforded evidence that the milk production varies with the stable temperature, but the length of the test was too short to warrant a quantitative analysis. The eight cows which were milked gave about 400 pounds of milk daily, seven of them being milked four times and one twice a day. The variations in milk yield followed fluctuations in the night temperatures more closely than those of the day. Variations in the morning temperatures appeared to have the least effect. This emphasizes the importance of controlling stable temperatures at night. The results of this test are in accord with data of other investigators (*23*, *18*, *28*, *41*).

## FACTORS AFFECTING OPERATION OF VENTILATION SYSTEM

Progress has been made in the development of partly automatic systems, but no mechanical devices yet offered can entirely replace personal attention and the exercise of common sense and good judgment.

### MAINTENANCE OF STABLE TEMPERATURE

Briefly, the maintenance of the desired temperature involves consideration of the insulation, the amount of which will vary according to the temperatures to be expected in different sections of the country; the efficiency of the materials available; the amount of air space that the animals must heat; the amount of ventilation desired; and the method of securing it. Tightness of construction is necessary to prevent excessive leakage of air. The actual amount and choice of insulating material will depend upon the relative efficiency and cost of the various kinds available.

High temperature is not necessary for comfort. It is suggested that a temperature between 40° and 45° F. is satisfactory for the average dairy barn in the northern sections of the country, while from 45° to 50° may be easily obtained in the central sections. In barns where the hind quarters of the cows are washed before milking a temperature of from 55° to 60° may be desirable.

The desirability of maintaining a relatively high stable temperature is shown by comparison of the moisture-holding capacity of air at two ordinary stable temperatures, 48° and 44° F. If air saturated at 44° be raised to 48° it would have a relative humidity of 86.7 per cent. If 800 cubic feet of air, a common volume of air space per cow, at 48° and a relative humidity of 100 per cent is reduced to a temperature of 44°, it would require 923 cubic feet of air to hold the same amount of moisture without deposition. If it is desired to obtain a relative humidity of 86.7 per cent, with the same amount of moisture and at a temperature of 44°, 1.064 cubic feet would be required. As the volume can not be changed the maintenance of the higher temperature is desirable as it permits of a greater drop in temperature before the dew point is reached.

The tests under discussion were made under a range of outside temperatures of from 45° to −40° F. The greatest difference between inside and outside temperature was 71°. It was found that even with extreme variations a satisfactory temperature may be maintained in a well-built stable if the ventilation system is intelligently operated.

The temperature in a stable filled with stock or where the volume per head is not excessive can be controlled by temporarily or partially closing the ventilation system. Tightness of construction permits of the control of stable temperature by proper operation, but ventilation is necessary in barns so constructed. The curves from two tests shown in Figure 11 illustrate the possibility of control in a well-constructed barn and lack of control where there was excessive leakage.

Figure 11, A, represents stable and outside temperatures in a well-built barn where the ventilation system was operated so as to maintain a uniform stable temperature. This barn was not entirely filled, there being 832 cubic feet of air space per head. The stable temperature was a little subnormal, but the ventilation was more than was necessary to secure good air condition, being slightly more than six dilutions per hour.

In the second stable, Figure 11, B, there were approximately eight dilutions of air per hour. Although there were only 713 cubic feet per head it was impossible to control the stable temperature.

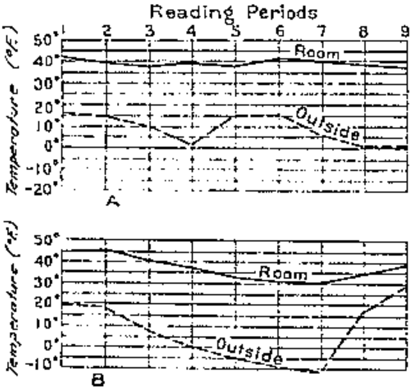


FIGURE 11.—Controlled (A) versus uncontrolled (B) ventilation

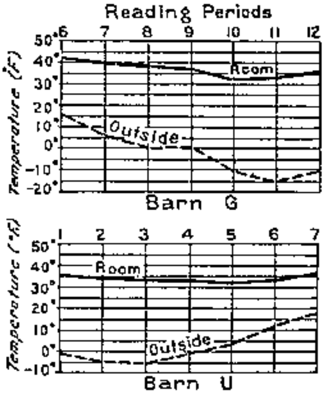


FIGURE 12.—Stimulating influence of low temperatures on heat production

Because of excessive leakage the stable temperature dropped below freezing when the outside temperature was about —12° F. In another barn (fig. 6) it was possible to keep the stable temperature above freezing with an outside temperature of −20° and with seven dilutions of air per hour.

Since the ventilation of dairy barns during cold weather is of major importance, heat losses should be reduced to a minimum in order that as much as possible of the heat generated may be available for producing the maximum amount of ventilation. This is best accomplished by tightness of construction and the use of the maximum amount of insulation that can be economically provided.

That low temperature stimulates metabolism of cows is apparent in the data from two tests. It appears that the stock resisted the tendency of the stable temperature to drop below freezing by increased metabolism. But food energy which is used in keeping the body warm and in warming the stable is not available for milk production. Figure 12 illustrates instances in which the maintenance of a fairly even stable temperature was obviously caused by increased heat production, since no change was made in the ventilating system although there was a wide variation in outside temperature. In barn G an expected drop in stable temperature was apparently counteracted by an increase in the heat production of the animals. In barn U the same effect was observed, it being evident that as the outside temperature rose the production of heat returned to normal.

In barn G, although the stable temperature approached freezing, the decrease in stable temperature was not proportional to the decrease in the outside temperature which fell to −15° F. Had the heat production remained constant there would have been a closer relationship between the inside and outside temperature drop.

In barn U there appeared to be an increase of almost 28 per cent in the heat production of the stock above that occurring under average conditions. The volume of air space per head, 944 cubic feet, was so large that a comfortable stable temperature was not to be expected. Yet it is apparent that more than the average amount of heat was generated, or the stable temperature would have dropped when the temperature outside was as much as −5° F.

Stable temperatures, within certain limits, appear to affect milk production in both quantity and quality (*13*, *15*, *18*, *22*, *41*). Investigations[6] tend to show that increased milk production in the spring is not caused by pasture feed but by optimum environmental temperatures ranging from 50° to 80° F. When the temperature exceeds the upper limit milk yields tend to decrease. In these tests stable temperatures of approximately 32° appeared to stimulate the metabolism of the animal.

The area of intake openings has an important bearing upon the maintenance of stable temperature. It was found possible to control the temperature by varying the amount of intake area, a reduction in area resulting in a decrease of the amount of outgoing air but not always in the same proportion.

In these tests, with a few exceptions in which conditions were unusual, the amount of measured outgoing air was greater than that of the incoming air, the difference being due to leakage. In one barn, when the outside temperature was −11° F., the intakes and the dampers in the outtakes were closed, yet there was a measured leakage around the dampers sufficient to produce 1.4 dilutions of air per hour. In another test, with the system wide open, there was less than 1 measured dilution per hour. In these tests the number of dilutions of air ranged from 0 to 13 per hour, and in several barns the full capacity of the system was not used.

The outtake area has usually a greater influence on the amount of ventilation secured than the intake area, and floor outtakes are more favorable to the maintenance of stable temperature than ceiling openings. This was found to be especially true during cold weather. Reduction of the outtake area appeared to produce a proportional decrease in the amount of ventilation. In one test, by temporarily closing the system it was possible to raise the stable temperature 10° during a period of unusually low outside temperature.

### EFFECT OF CHANGES IN INTAKES AND OUTTAKES

There are many factors which affect the amount of ventilation obtained by varying the effective area of intakes and outtakes. It is

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[6] Unpublished data of department of animal industry, University of Maine.

impossible under practical working conditions to isolate these factors so that their individual effects may be determined. However, the experience afforded by a large number of tests and the method of analysis employed makes it possible to partly determine the effects and the natural tendencies of many of these factors.

In the test of one barn the largest amount of ventilation was obtained during the first two groups of readings (Table 10, and fig. 8) when the intakes were open approximately 3 inches (readings 2 to 9) and 2 inches (readings 9a to 11). The data show that with an outside temperature of approximately 0° F. it was possible to keep the temperature in the stable above freezing and still have a very large circulation of air (eight dilutions per hour) within the barn. This is much greater than necessary for maintaining the standard minimum purity of air.

The data also show that a reduction of approximately one-third in the intake area offset the effect on ventilation that would be expected of a more than doubled wind velocity. The effect on the amount of ventilation of closing the intakes is uncertain because of the leakage, but the possibility of compensating for the effect of wind by decreasing the intake openings is evident. The velocity of the incoming air increased but that of the outgoing air decreased which would indicate that the reducton in intake area did have an appreciable effect. It is interesting to note what happened when the intakes were closed. (Table 10, Nos. 10 and 11.) The data show that ample ventilation was secured with the intakes closed and with an effective wind velocity. In No. 4, with small intake area, low outside temperature, and no effective wind more than ample ventilation was obtained.

No. 15 of Table 10 presents data obtained with the ventilation system closed and shows the effect and the value of insulation in obtaining a stable temperature above 41° with an outside temperature of −14°, a difference of more than 55°. The data in Nos. 1 to 5 inclusive, taken during low outside temperatures, show the possibility of maintaining the stable temperature above freezing in a well-insulated barn together with an abundance of ventilation. It is believed that ventilating systems are often closed down more than is necessary when low outside temperatures are anticipated. In this connection the temperature existing prior to an anticipated drop must be taken into consideration. If, during a prolonged period of low temperature, it is found that the stable temperature drops too low, the system can be closed temporarily and reopened when the temperature has been raised. In one test, with an outside temperature of −22°, the stable temperature was raised more than 10° in less than three hours by closing the system. In another test the temperature of the barn was raised from 40° to 50° with an outside temperature of from −12° to −15°.

In reducing the amount of ventilation in order to raise the temperature, it is better to entirely close one or more of the outtakes rather than to partly close all. Partial closing reduces the velocity of the outgoing air which may become chilled, thus increasing the tendency to condensation and drip.

### CEILING AND FLOOR OUTTAKES

Ventilation may be obtained with either the ceiling or floor type of outtake. Each has its advantages and limitations which vary according to local conditions and results desired.

The following comparison is based upon data obtained in a number of tests made under widely varying conditions. In some cases the comparison was made between permanent heat doors and floor outlets and in others between existing ceiling outlets and temporary floor flues that were built for the purpose. This method was used so as to limit the number of variables that would be encountered in comparing two different barns. Some of these tests were continuous for 300 hours; hence it is impractical to present much of the test data. Representative data are included, and the discussion is based on the summation of all data available.

In these tests the difference between floor and ceiling temperatures ranged from less than 1° to 10°. In the barn used in the tests the average ceiling temperature was 46° dry bulb and 41° F. wet bulb, and the floor temperature was 41° dry bulb and 36° wet bulb, a condition which is common. The ceiling air contained 15.8 B. t. u. per pound of dry air and the floor 13.5 B. t. u., or a difference of 2.3 B. t. u. Hence the ceiling air in cooling to the floor temperature gave up 2.3 B. t. u. per pound of air which were available for warming 123 cubic feet of air 1° at stable temperature. It is obvious that air withdrawn at the floor will remove less heat from the stable, other conditions being equal.

In all localities there are a number of warm days during the stabling season. Hence all floor flues should be provided with heat doors of approximately the same effective area as that of the flue—auxiliary or secondary ceiling openings are sometimes used. The heat doors should be placed near the ceiling and operated in accordance with the temperature conditions. When the outside temperature is 32° F. or more it is advantageous to open the heat doors for the ready removal of heat from the stable. Practical experience and results obtained from the tests show that under ordinary conditions it is desirable to close these doors when the outside temperature drops to approximately 20°. This point will be somewhat affected by the velocity and direction of the wind. Hence the extent of the use of heat doors in a given locality will vary according to the frequency of warm days. In sections having a large number of warm days ceiling openings only may be used.

Other conditions being comparable, a larger circulation of air may be maintained with floor outlets than with ceiling outlets with equal resultant stable temperatures. In Table 13, which gives data from one of these tests, the stable temperatures are practically the same in both cases, but there is a much larger amount of ventilation with the floor outlets.

TABLE 13.—*Comparison of floor and ceiling outlets in a dairy stable*

| Vents open at— | Dilutions per hour | Humidity |  |  |  |  | Temperature |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|
|  |  | Relative at— |  |  | Water per cubic foot of air— |  | Ceiling | Floor | Stable[1] | Outside |
|  |  | Ceiling | Floor | Stable | In stable | Outside |  |  |  |  |
|  |  | *Per cent* | *Per cent* | *Per cent* | *Grains* | *Grains* | ° *F.* | ° *F.* | ° *F.* | ° *F.* |
| Floor | 4.1 | 68.6 | 69.2 | 68.0 | 2.491 | .783 | 49.2 | 43.5 | 46.6 | 21.3 |
| Ceiling | 2.6 | 77.9 | 78.4 | 75.2 | 2.797 | .520 | 48.3 | 43.3 | 46.3 | 15.6 |

[1] Stable temperature is the average of the stable temperatures for the period involved and not the average of floor and ceiling temperatures.

At the same outside temperature the stable temperature will be lower when the heat doors or ceiling outlets are open. Figure 13 represents a hygrometer chart obtained during one of the tests. It is of particular interest in that it shows the drop in stable temperature after the heat doors were opened. This change was made at 2.45 a. m., as shown on the chart at point A. It will also be noticed that the difference between the wet-bulb and dry-bulb temperatures was less, indicating a higher percentage of relative humidity.

The difference in the relative humidities at the ceiling and floor was practically the same when the floor outlets were used as when the ceiling outlets were open. (Table 13.) The readings at the different stations in this barn reveal no significant difference at any point for the two conditions. At the same stable temperature the relative humidity of the stable was almost 10 per cent higher when the ceiling outlets were used. In neither case was the relative humidity harmfully high. However, the lower relative humidity was to be preferred as the stable temperature could have dropped about 3° lower before the dew point would have been reached.

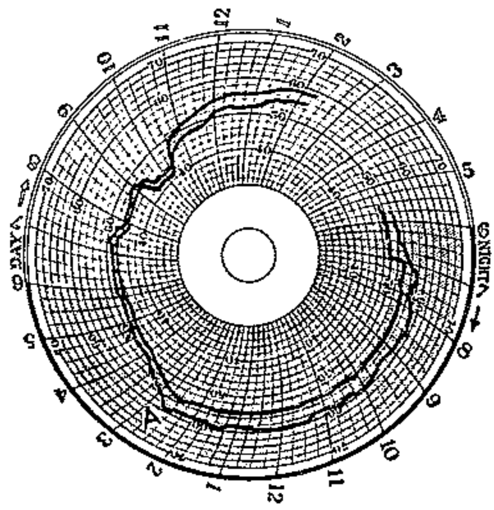


FIGURE 13.—Hygrometer chart showing effect of the opening of heat doors upon stable temperature and humidity

A comparison of the actual amounts of moisture in the stable and in the outside air under the two conditions given in Table 13 shows that the air removed at the ceiling contained 2.797 grains of moisture per cubic foot, while that removed at the floor contained 2.491 grains. However, more moisture was removed from the stable through the floor openings because of the larger circulation of air, notwithstanding the fact that the entering air was of a higher moisture content. The stable temperature being practically the same in both cases, the higher stable humidity was largely due to decreased air circulation.

With equal amounts of ventilation, other conditions being comparable, a higher stable temperature may be obtained with floor outlets than with ceiling outlets, and the floor outlets may be kept open at a lower outside temperature without unduly lowering the stable temperature. Reference to Table 10 shows that the floor outlets were open when the average outside temperature was −20.1° F. (No. 5), and the stable temperature approached freezing, and that the heat doors were open at −9.7° (No. 13) with an average stable temperature of 39.4° but with less than half as much air circulation as in the former case. Had the amount of ventilation been decreased in the first case, a higher stable temperature would have resulted.

On the basis of approximately equal stable temperature, the ventilation was approximately 50 per cent less and the humidity was higher when ceiling outlets were used, the latter being the natural consequence of restricted ventilation. It is then apparent that in order to maintain the same stable temperature with ceiling outlets as may be had with floor outlets there must be less ventilation. In order to obtain with open ceiling outlets stable temperatures comparable with those obtained with open floor outlets, the ceiling flues would need to be reduced in size, but while smaller flues may provide sufficient ventilation during cold weather, in warm periods when abundant ventilation is desired, the small flues would not have the desired capacity.

### EFFECTS OF OUTSIDE TEMPERATURES

Temperatures have an important bearing on the adjustment of the ventilation system. The outside temperature is usually the most dominant of the factors producing variations in outtake flue velocities at all temperatures below 20° F. Under average conditions of barn ventilation low outside temperature has a greater influence on flue velocities than has the difference between the stable and outside temperatures. When the outside temperature falls or rises the system is adjusted to control the amount of ventilation. The adjustment of the ventilation system causes a variation in flue velocities proportionate to the increase or decrease in resistance of air circulation but not necessarily to the change in the area of the intake openings because of the leakage that usually exists. Without regard to the wind, the passage of air through the flue is dependent on the difference in weights of the column of air in the flue and the outside air. The weight of air is determined by the amount of moisture it contains as well as by the temperature and pressure. The lower the outside temperature, the drier and heavier the air. The rate of change in the weight of air is more rapid at low temperatures than at high temperatures, as will be seen by reference to Table 14. Under average conditions of barn ventilation, the effect of a given difference between inside and outside air temperatures on flue velocities will vary with the outside temperature—the lower the temperature, the greater the influence.

TABLE 14.—*Weight of dry air in grams per thousand cubic meters*

| Temperature | Weight | Decrease | Temperature | Weight | Decrease | Temperature | Weight | Decrease |
|---|---|---|---|---|---|---|---|---|
| *° F.* | *Grams* | *Grams* | *° F.* | *Grams* | *Grams* | *° F.* | *Grams* | *Grams* |
| −20 | 1,446.4 | ---------- | 4 | 1,371.3 | 12.0 | 28 | 1,303.7 | 10.8 |
| −16 | 1,433.3 | 13.1 | 8 | 1,359.6 | 11.7 | 32 | 1,293.1 | 10.6 |
| −12 | 1,420.5 | 12.8 | 12 | 1,348.0 | 11.6 | 36 | 1,282.6 | 10.5 |
| −8 | 1,407.9 | 12.6 | 16 | 1,336.7 | 11.3 | 40 | 1,272.3 | 10.3 |
| −4 | 1,395.5 | 12.4 | 20 | 1,325.5 | 11.2 | 44 | 1,262.2 | 10.1 |
| 0 | 1,383.3 | 12.2 | 24 | 1,314.5 | 11.0 | 48 | 1,252.2 | 10.0 |

A study of available data shows that there is a close relationship between temperature difference and flue velocities when the ventilation is unrestricted and unaffected by the wind, but when the ventilation is restricted and other variable factors are introduced there may be wide variance in this relationship. Test data, taken at random and presented in Table 15, illustrate this relationship.

TABLE 15.—*Effect of temperature on flue velocity*

| Temperature | | | Flue velocity | Wind velocity |
|---|---|---|---|---|
| Stable | Outside | Difference | | |
| *° F.* | *° F.* | *° F.* | *Feet per minute* | *Miles per hour* |
| 56 | 27 | 29 | 234 | 16.3 |
| 37 | 8 | 29 | 373 | 16.7 |
| 49 | 8 | 41 | 288 | 0.8 |
| 45 | −13 | 58 | 392 | 7.0 |

The meager data do not represent average conditions, but they do indicate variations that are common. The first two readings were taken when the ventilation was free, the last two when the ventilation system was partly closed. The temperature difference in the first two readings is the same, yet there is an appreciable difference between the flue velocities and there is a considerable difference in the outside temperatures. The lower outside temperature is coincident with the higher flue velocity which is in accord with the tendency shown by existing data. In the second and third readings the outside temperatures are the same, the temperature difference is greater in the third reading and the flue velocity is greater in the second reading. The greater flue velocity of the second reading is but partly accounted for by the higher wind velocity. The higher stable temperature of the third reading was because of the restricted ventilation. Had the system been fully open a smaller temperature difference and a greater flue velocity would have been expected. This again shows that temperature difference alone has less effect on flue velocities than low outside temperatures have.

Flue velocities vary with the difference between the weights of the air within and without the flue. These weights are affected principally by change in temperature, the low temperatures being most effective as will be seen by reference to Table 14. A decrease of 4°

in air temperature produces a change in weight of 10, 11, 12, and 13 grams per cubic meter, respectively, at temperatures of 48°, 24°, 4°, and −16° F. With these outside temperatures and an assumed stable temperature of 48°, the respective differences in weight of the air in the stable and outside would be 0, 62, 119, and 181 grams per cubic meter. With a constant difference between inside and outside temperature of 20°, a difference commonly assumed in ventilation design, there would be a difference in weight of 52 grams at 48° stable temperature, 53 grams at 40°, 58 grams at 20° and 63 grams at 0°.

The two curves shown in Figure 14 represent the average results of test data relating to flue heights that are commonly used in barn ventilation. The straight line is the result of the assumption of a uniform rate of increase or decrease in the variables throughout the range; this is more nearly true when the flue velocities are compared on the basis of outside temperature than when compared with temperature difference. The assumption introduces no error of consequence and may be used within the range of temperatures herein considered.

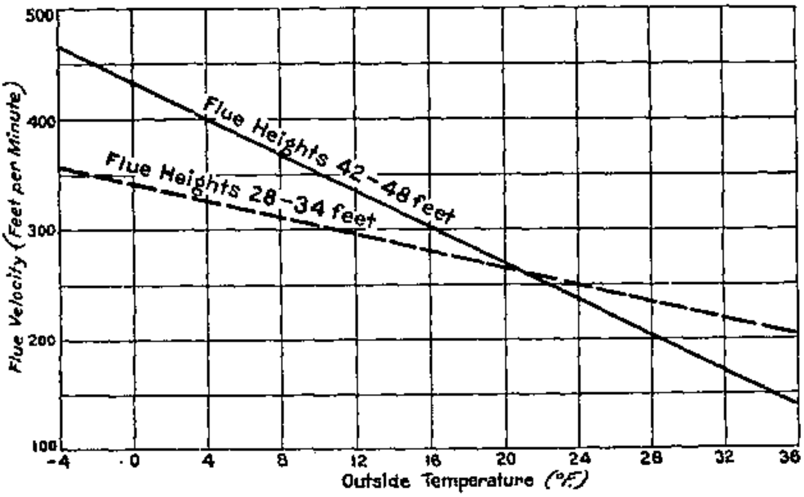


FIGURE 14.—Effect of outside temperature upon flue velocity

### STABLE HUMIDITY

The temperature of, and percentage of moisture in, the outside air have a great influence upon the percentage of moisture in the stable air, greater perhaps, in the average farm barn that is not well insulated than that due to restriction of the ventilating system.

The optimum percentage of humidity in stable air has not been determined. There are so many variable factors that must be taken into consideration that it is difficult to set a standard, but it is suggested that at a stable temperature of 45° F. an average relative humidity of 80 per cent is satisfactory. The tests show that it is not difficult to obtain this degree of moisture when other conditions are favorable. In the majority of the tests the relative humidity at the ceiling was less than that near the floor. In one stable a relative humidity as low as 61 per cent was recorded.

Theoretically the actual amount of moisture, or the absolute humidity, of the stable air should vary in proportion to the amount of ventilation and production of moisture. In a tightly constructed barn this relationship can be obtained by intelligent operation of the ventilation system as will be shown by reference to Figure 15.

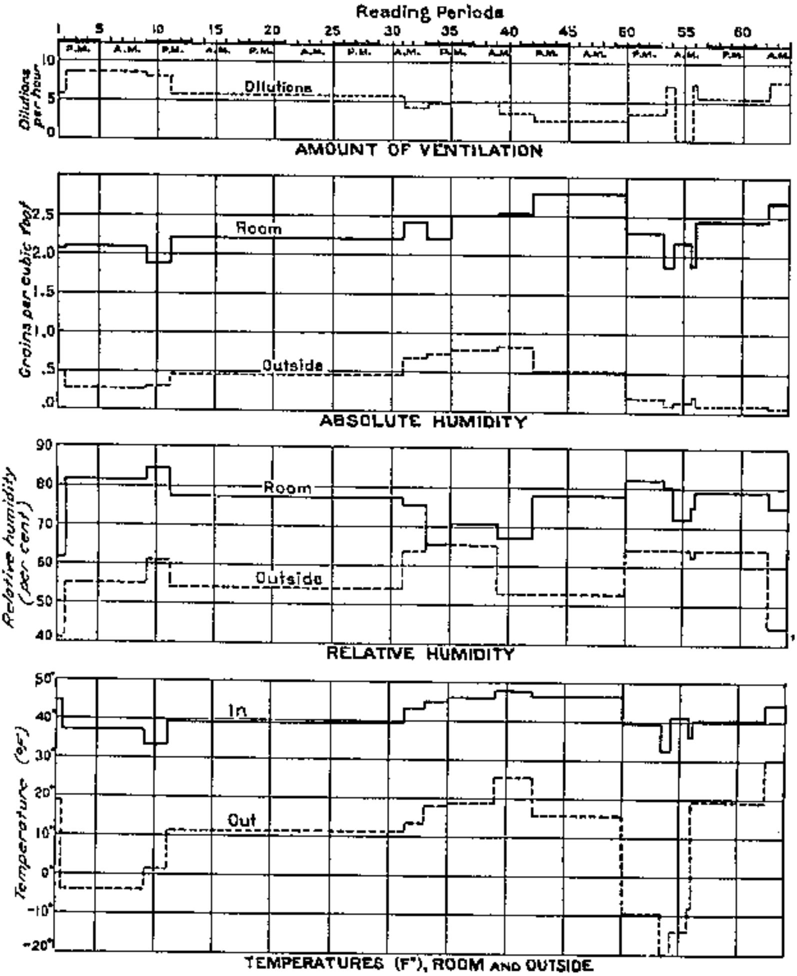


FIGURE 15.—Relation of absolute humidity to ventilation in test barn T

The chart shows the amount of ventilation as measured in dilutions per hour, the absolute and relative humidity of stable and outside air, and the temperature of stable air. That there was considerable variation in the temperature of outside air may be seen by referring to Figure 8 or Table 10. In actual practice there will not always be a close relationship between the moisture in the stable air and the amount of measured ventilation because of the varying and unaccountable leakage in most barns.

Figure 15 shows that with but few exceptions, mainly at readings 9 to 11 and 62 to 64, an increase in the ventilation produced a decrease in the amount of moisture in the stable air. In the first instance the condition may have been because of some temperature effect as the stable temperature was but little above freezing. There may have been more moisture condensed on the stable walls and also a change in the moisture production owing to environmental influence on the metabolism of the animals. The moisture content of the outside air was never very high. It was very low after the fiftieth reading, when the temperature ranged from −1° to −20° F., and remained exceptionally low until the last of the test. Notwithstanding this condition the moisture in the stable air increased unaccountably.

Further, it is evident that a high relative humidity outside does not necessarily mean a high relative humidity in the stable or vice versa. The data show that, although the air outside is saturated, it may be possible to use it in removing moisture from the stable if its temperature is lower than the stable temperature.

TABLE 16.—*Influence of temperature on the manner of daily heat loss from two steers*

| Hair of animal | Test No. | Temperature of chamber | Heat lost— | | | Percentage of total heat lost— | |
|---|---|---|---|---|---|---|---|
| | | | By radiation and conduction | By evaporation of water | Total | By radiation and conduction | As latent heat of water vapor |
| | | ° *F.* | *Calories* | *Calories* | *Calories* | *Per cent* | *Per cent* |
| Sheared | 1 | 56.7 | 6,764 | 1,411 | 8,174 | 82.7 | 17.3 |
| Do | 2 | 60.3 | 6,309 | 1,475 | 7,784 | 81.0 | 19.0 |
| Do | 3 | 64.0 | 5,945 | 1,551 | 7,496 | 79.3 | 20.7 |
| Do | 4 | 71.7 | 4,933 | 1,776 | 6,709 | 73.5 | 26.5 |
| Full coat | 1 | 59.9 | 4,604 | 1,581 | 6,185 | 74.4 | 25.6 |
| Do | 2 | 65.3 | 4,081 | 2,186 | 6,268 | 65.1 | 34.9 |
| Do | 3 | 70.7 | 3,531 | 2,791 | 6,322 | 55.8 | 44.2 |
| Do | 4 | 57.5 | 4,468 | 1,544 | 6,012 | 74.3 | 25.7 |

Variations in air temperature affect the amount of moisture produced by the average cow kept under ordinary stable conditions. Table 16 which presents data obtained by calorimeter test on two steers (*13*) affords evidence of this and indicates the need for data obtained under temperatures more comparable to those of a stable and for much lower temperatures. The higher the temperature the greater the loss of heat by evaporation, and the smaller the loss by radiation and conduction. With both steers a decrease in the heat lost by radiation and conduction was accompanied by an increase in the heat lost by evaporation of water and vice versa.

A pronounced difference is noticeable in the response of the two steers to similar temperatures. The steer having a full coat gave off 25.6 per cent to 44.2 per cent of the heat production as latent heat of water vapor, whereas the shorn steer eliminated but 17.3 per cent to 26.5 per cent of the heat in this manner.

A, View of test barn O from southwest; B, view of flue C above mow floor in test barn O

The production of heat and of carbon dioxide are directly related under all conditions of production, but this is not necessarily true with respect to moisture, which varies according to environmental conditions. The loss of heat by evaporation is also influenced by the relative humidity of the air. Hence animal comfort is dependent upon a combination of temperature, relative humidity, and air circulation as evaporation increases with an increase in movement of air currents. Thus ventilation may not only affect the rate of removal of moisture from the air but also its rate of production.

## FACTORS AFFECTING EFFICIENCY OF SYSTEM

### HEIGHT AND CONSTRUCTION OF FLUE

Much of the foregoing discussion has been based on the assumption that the ventilation system has been properly designed for the local conditions and that it has been properly installed. It has been shown that a change in the air conditions or setting of the outtakes or intakes may vary the amount of ventilation obtained. These factors have but a temporary effect on the amount of ventilation secured. There are many construction features that may permanently affect the efficiency of the ventilation system.

The design and position of flues affect their efficiency. Intake and outtake flues should be so placed as to provide for the best distribution and circulation of air within the stable. In order that a desired amount of ventilation may be obtained it is necessary that those factors that affect the amount of outgoing air be known so that flue areas may be made sufficient to permit the passage of the required amount of air. Flue area will vary with the temperatures expected and with the height of the flue, as explained later. Under the same conditions of temperature and vertical height one flue may be less efficient than another. Horizontal or inclined runs add resistance without increasing vertical height; crooked flues and abrupt turns also add to the frictional air resistance. Abrupt turns may decrease the efficiency of the flue by more than 50 per cent.

Figure 16 presents the floor plan of the barn shown in Plate 4, A, in which there is a rather unusual and inefficient arrangement of flues. The ventilator shown by dotted lines on the floor plan, in the cross-drive alley, is on the higher part of the barn. By tracing the path of the air through this ventilator, it will be seen that the air left the stable through ceiling openings A and B, passed to the right and left between the joists, turned at right angles for another horizontal run of about 4 feet, then up through the risers A and B following the roof line to the ventilator. The risers A and B were separated so as to give clear floor space in the mow and not interfere with hay storage. These flues would have been more efficient had the openings been directly below the risers, and the cost of construction would have been less. These flues were found to be less efficient than those in another barn in which the conditions were comparable.

There are also horizontal runs in flues C and D with connecting flues from floor openings. The latter are offset (pl. 4, B) in order to avoid the windows. The dark streaks on the flue show incipient rot caused by condensation of moisture inside the flue.

An instance of unnecessarily long, inclined flues with high frictional resistance is shown in Figure 17 which represents the floor plan of a 1-story barn 136 feet in length with but two ventilators. Three could have been used to advantage and would have decreased the length of the connecting flues. Efficiency was sacrificed in this case for the sake of appearance.

Ventilating flues and ducts, in the conventional arrangement, are placed so that the fresh air enters in front of the cows and is removed at the rear. With cows facing in, the outtakes would be placed next to the outer wall and the intake openings at the center feed alley. When the cows face out the position of outtakes and intakes are usually reversed. However, it is sometimes difficult and inconvenient, especially in long barns with the cows facing out, to obtain this arrangement. In such cases the arrangement commonly used when the cows face in may be employed. Tests in several barns showed that such an arrangement was satisfactory with respect to the ventilation secured.

For best results intakes and outtakes should not both be placed on the outer wall. Plate 5, A, illustrates one example wherein the intakes and outtakes were adjacent and, during the time that the heat door was open as shown in the cut, the air came in through the intake and passed out through the outtake, mixing but little with the stable air.

When it is possible without the sacrifice of too much space in the alleys, outtakes should be kept away from the outer wall, that is, they should not be built between the studs. If they are built between the studs, without proper insulation of the outward side, the paint is apt to peel off the barn siding next to the flue because of

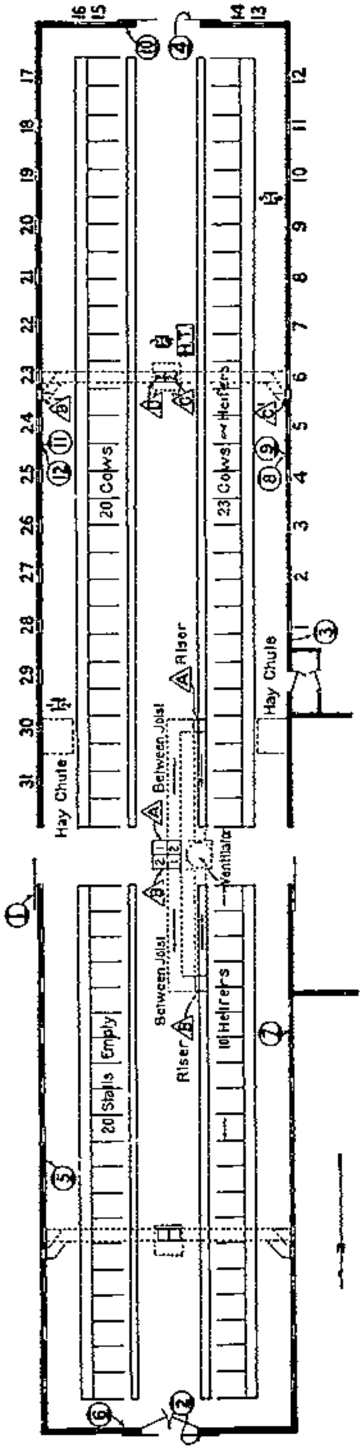
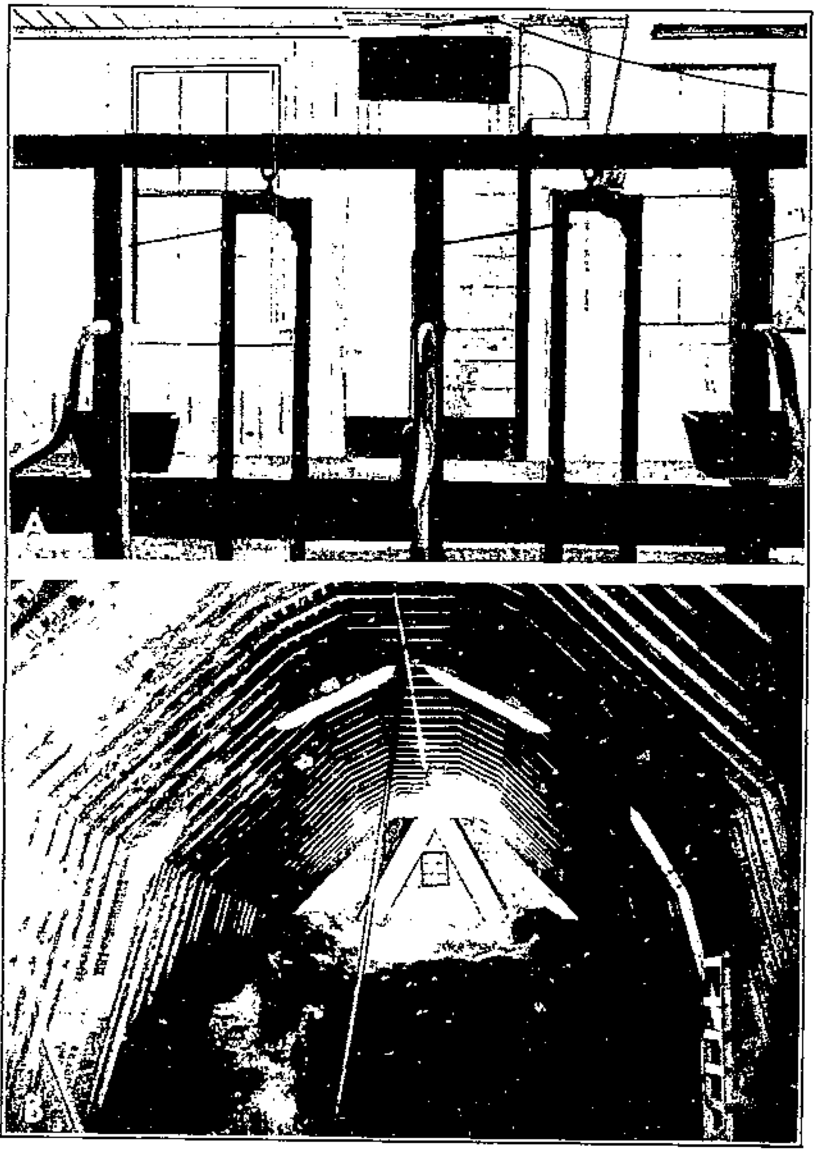
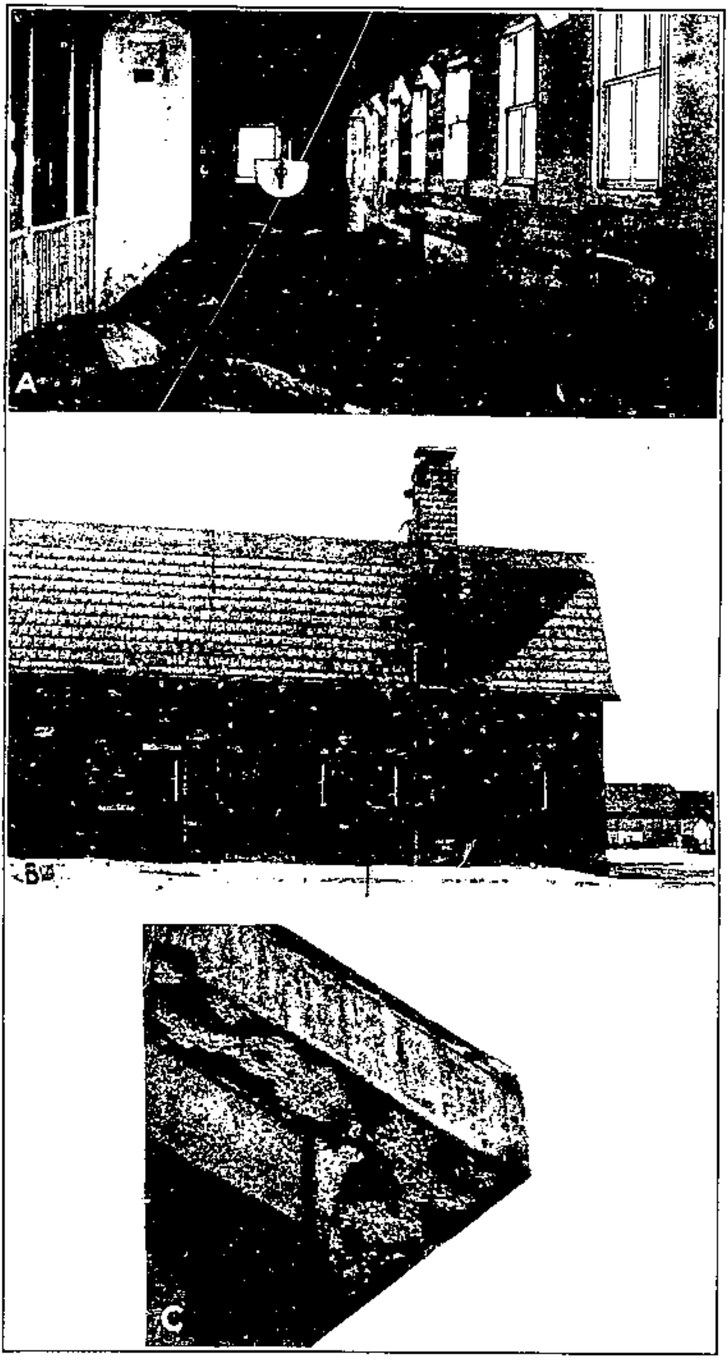


FIGURE 16.—Floor plan of test barn O



A, Improper relation of intake and outtake; B, view of outtake flue built between rafters



A, Outtake flue beveled at the bottom; B, concrete block intakes and outtake; C, section of ventilator screen closed with ice the condensation of moisture. When flues are placed between the studs or rafters, as shown in Plate 5, B, the exposure is greater and there is more heat loss. The flues shown in this picture were built between the studs down to the mow floor then, in order to avoid the stone wall in the stable below, they were offset horizontally 1 foot. These flues were much less efficient than the two neighboring flues which were straight at this point. The two right-angle turns could easily have been avoided.

Plate 6, A, shows the construction of an outtake flue opening into the feed alley of a hog house. It was found that beveling the bottom of the flue added to its efficiency and provided more room in the pen with less need for protection against injury than would be required had the flue been extended squarely to the floor.

Insulation and air-tightness are requisites of greatest flue efficiency. The drop in temperature of the gases during their passage from the bottom to the top may be but 1° or 2° in a properly insulated flue, whereas in one lacking in insulation this may be more than five or six times as much. This factor has an important bearing on the amount of moisture that will be removed from the stable. (Table 5 and p. 18.) One installation was found where the leakage of air was so great that it was impossible to detect any circulation of air through the flue except at high wind velocities.

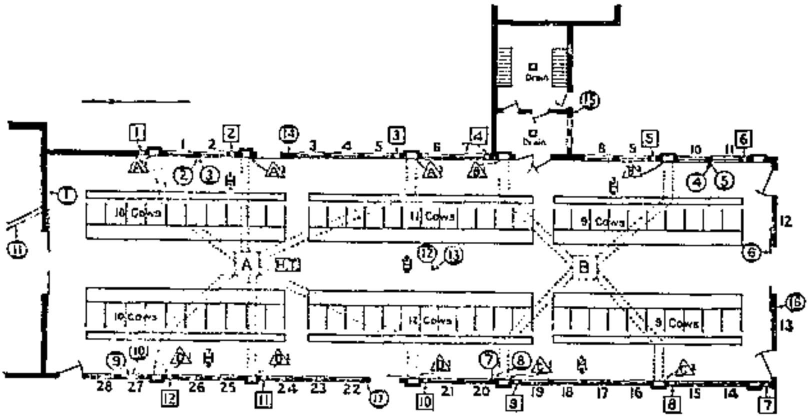


FIGURE 17.—Floor plan of test barn R

Lack of insulation may cause a large amount of troublesome drip. There does not at this time appear to be any means of altogether overcoming this condition in the colder sections. All flues should be air-tight, and insulation is necessary particularly on metal flues. This is of greater relative importance in the colder sections. In one test it was evident that, while there were several contributing factors which must be considered in the prevention of drip, proper insulation of the flues was most important.

Consideration should be given to the probability of drip in locating the outtake flues. Installations were found where the flue opening was directly over a cow stall and the drip fell on the cow's back. In the better installations of metal flues a small trough with a drainage pipe is provided.

The chimney flue shown in Plate 6, B, was made of 4-inch concrete block, which did not afford sufficient insulation to prevent a rapid cooling of the outgoing air. The blocks were made by the dry-mix method and were more or less porous. The pore leakage through these blocks was considerable, especially under high wind pressure. The ventilator shown on the top of the flue was homemade and very inefficient. A wire screen of ¼-inch mesh was used to prevent entrance of birds through the ventilator—a useless precaution, as they usually find other entrances. Small-mesh wire should not be used in a ventilator as the openings soon become stopped by ice or trash as in the case of the one illustrated. Plate 6, C, is a view of a section of this ventilator and shows how the ice formed on the screen and greatly reduced the air circulation.

### EFFECT OF OPEN VENTILATOR BASE

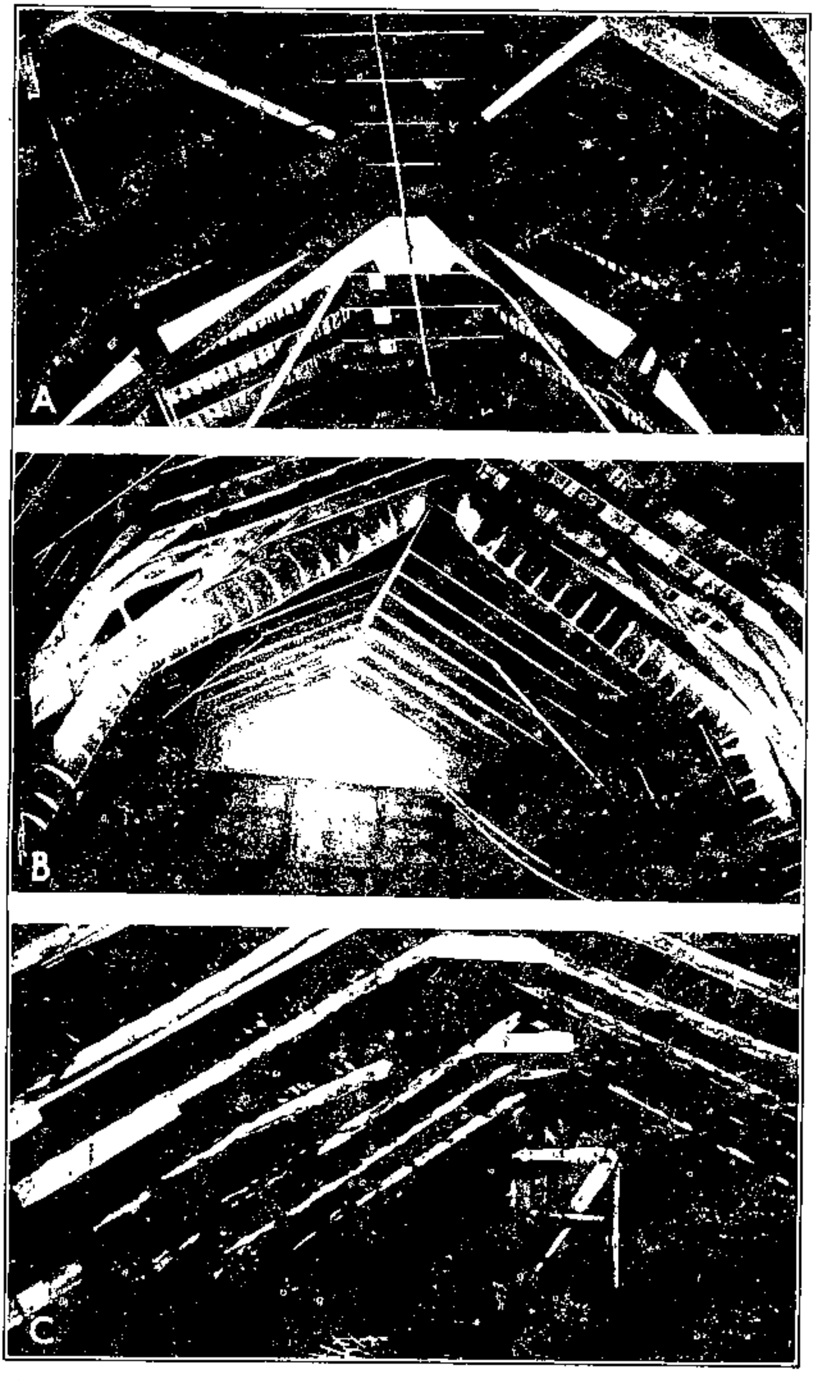
It is generally considered best to place the ventilator at the highest point, usually the ridge of the roof, but there has been some question as to whether the base of the ventilator should be closed at the ridge as shown in Figure 7 and Plate 7, A, or left open as shown in Plate 7, B. Both methods have been used for a number of years.

When the base of the ventilator is open at the ridge, part of the air passing through the ventilator head is withdrawn from the mow and part from the stable. When the base is closed the entire pressure head is utilized in removing air from the stable. Results of tests show that the opening of the ventilator base may reduce the amount withdrawn from the stable by from 10 to 30 per cent.

If the question is considered solely with respect to the ventilation of the stable, the ventilator base should be closed. However, ventilation of the hay mow during the warm summer months and just after the crop is stored is desirable and if the ventilator is open to the mow it provides a ready exit for the mow gases. During the winter months ventilation of the mow is not necessary and, if the ventilator base is left open during cold weather, eddy currents, formed by the warm air coming through the stable outtake and the colder air from the mow, may cause formation of frost on the roof timbers around the base of the ventilator and shorten the life of the roof timbers. (Pl. 7, C.) It is believed that the open base tends to produce greater condensation in the flues since the cold air from the mow meets the warm air coming through the flue and chills it. It was also noted during the tests that strong winds had less effect on the amount of stable ventilation when the ventilator base was open. If doors with convenient means of operation were provided it would be possible, without closing the outtakes at the lower end, to counteract the effects of high wind velocities which otherwise would cause too much ventilation and a consequent lowering of stable temperature. One attempt to provide this convenience is illustrated in Figure 7. There is opporunity for improvement in the construction and operation of such a device.

### WINDOWS AS INTAKES

The amount of incoming air is affected by several factors which vary according to the type of intake used. The three principal types of intakes are windows, wall ducts, and automatic intakes. The



A, Ventilator with a closed base; B, ventilator with an open base; C, rotting of roof boards and rafters due to condensation limitations of window intakes are clearly shown by tests made in this investigation, but that they are not widely known is evident from the frequent use of windows in unsuitable places. It is not the intention to imply that ventilation through window openings is impossible, nor to advise against their use in mild weather or in southern zones. Windows may be used when the outside temperature is above freezing and when the circulation of a large quantity of air does not cause harmful drafts on the animals; but their use should be restricted during cold weather, since it is obviously impossible to supply sufficient fresh air to remote sections of the barn without chilling the animals near the windows. Although windows, when provided with side shields, direct the incoming air toward the ceiling, the currents of air drop almost immediately and under most temperature conditions reach the floor within 6 feet of the wall. These currents are also affected by the wind pressure.

If windows are used as intakes the formation of frost can not be avoided during cold weather, and if the temperature is not quite low enough to form frost the moisture that condenses on the panes runs down the sash, rusts bottom hinges, and rots the sills and frames. Under such conditions the sash itself swells and sticks in the frame, and often panes are broken in attempting to open the windows. In one barn the sash swelled to such an extent that the muntins were broken out.

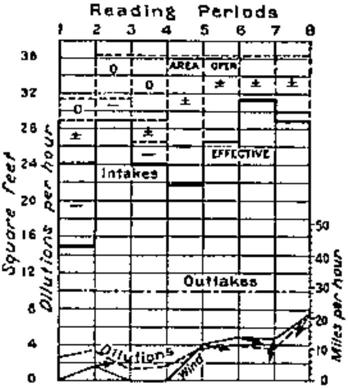


FIGURE 18.—Effect of window intakes in test barn O. Arrows show direction of wind

The most serious objection to the use of windows as intakes is that it is difficult to control the temperature and the amount of ventilation because of the variation in the direction of the wind, which makes frequent adjustment of the windows necessary.

Particularly during periods of high wind velocity, the volume of air passing outward through the windows was more than twice that through the regular outlets, the air taking the path of least resistance. At such times the air is apt to come in at high velocity on the windward side and, practically unchecked, pass out on the leeward side. The motive power furnished by the difference in the temperatures of the inside and outside air in a well-designed system is sufficient in cool weather to induce ample circulation without the aid of a strong wind. Although undesirable as intakes in cold sections windows are an advantage during mild weather, as they provide a large area of opening.

Figures 18 and 19 represent data taken from two tests during parts of which windows were used. Floor plans of these two barns are shown in Figures 16 and 17, the windows being numbered for convenience in reference. The data, presented graphically, show the total area of window openings, those portions of the windows that were used for entering air and the portions used as outlets. There is considerable variation in the effectiveness of the openings at the different periods. During the tests both stable and outside temperatures varied less than 5°. The stable temperature in the first barn was 48° F. with an outside temperature of 30°. The average stable and outside temperatures in the second test were 55° and 43°, respectively. In the first test the average wind velocity was a little more than 8 miles per hour, although the velocity reached a maximum of 20 miles per hour as shown in Figure 18. In the second test the average velocity was a little over 6 miles per hour. In both tests the ventilation was satisfactory.

The variation in the stable temperature was greater when windows were used than when wall intakes were employed. In barn O the stable temperature dropped to almost 40° F., notwithstanding the fact that the outside temperature was not lower than 27°, which illustrates the difficulty of maintaining stable temperature with window intakes.

In barn R, 13 dilutions of air per hour were obtained at a period when the wind was comparatively low and the outside temperature was above 43° F., showing the value of window intakes during mild weather.

At the beginning of the test in barn O (fig. 16) all odd-numbered windows on the east side and all even numbered on the west side, except No. 30, were opened. The greater part of the ventilation was through windows on the east side. There was no circulation of air through No. 18 at any point of the opening, and very little air entered the other windows on that side of the barn. At the second reading the velocity of the incoming air through the windows on the east side increased but the air movement in No. 16 varied in and out as did that in No. 28. Windows Nos. 11, 18, 29, and 22 back drafted, while No. 24 was neutral. After the second reading all windows on the east side were closed and the odd-numbered windows on the west side were opened, no further changes being made.

Window No. 20 back drafted at the third reading and Nos. 28 and 29 were neutral. At the following reading the air movement through No. 24 was first in and then out; Nos. 22, 28, and 29 were neutral; the circulation of air through Nos. 25, 26, and 27 was barely detectable, while No. 30 back drafted. At the fifth reading the circulation of air through Nos. 25 to 30 was alternately in and out; similar conditions were recorded at the sixth reading. At the seventh reading the movement through Nos. 28 and 29 was alternately in and out, while in the others there was positive action. Nos. 16, 29, and 30 were recorded as in and out at the eighth reading. This shows the effects of wind currents upon the entering air and the variability of air circulation.

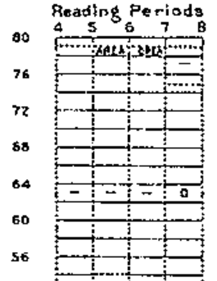


FIGURE 19.—Effect of window intakes in test barn R

The same effect was recorded in the second test in barn R. The efficiency of the various openings is apparent in Table 17 and Figure

19 which show that there was considerable variation in the amount of effective intake area during the time window intakes were used.

The fifth reading showed the greatest amount of effective area; at the eighth reading the effective area was equal to the area wherein no circulation of air was detectable. Although the wind was never high its effect was noticeable. Back drafting was obtained in some of these windows at a wind velocity of less than 1 mile per hour. From the data the influence of wind velocity and direction could be traced.

TABLE 17.—*Comparison of circulation of air in intakes*[1] *of barn R*

| Reading | Area open | Area effective | Area of intake in which readings were— | | |
|---|---|---|---|---|---|
| | | | Plus and minus | Minus | Zero |
| | *Square feet* | *Square feet* | *Square feet* | *Square feet* | *Square feet* |
| 5 | 79.04 | 45.76 | 4.16 | 29.12 | ---------- |
| 6 | 79.04 | 41.60 | 12.48 | 24.96 | ---------- |
| 7 | 79.04 | 37.44 | 12.48 | 29.12 | ---------- |
| 8 | 79.04 | 37.44 | 0 | 4.16 | 37.44 |

---

[1] Windows Nos. 1, 2, 4, 6, 8, 9, 11, 15, 16, 17, 18, 19, 20, 21, 22, 23, 25, 26, and 28 (fig. 17) were open. The efficiency of these openings varied as is apparent in the table. At reading 5 a plus and minus movement was recorded at No. 20 and Nos. 4, 6, 15, 16, 17, 18, and 19 back drafted. The action in all other windows was positive. At reading 6 the movements at Nos. 1, 2, and 20 were plus and minus, while Nos. 4, 6, 15, 16, 18, and 19 back drafted. At reading 7 there were plus and minus movements at Nos. 2, 20, and 28; Nos. 4, 6, 15, 16, 17, 18, and 19 back drafted. At reading 8 No. 26 back drafted and Nos. 4, 6, 8, 9, 11, 17, 18, 19, and 28 were neutral. The average velocity of air through windows Nos. 1 and 2 was approximately 150 feet per minute while the velocity through the others was very low. Through Nos. 15, 16, 21, 22, and 23 the average was a little more than 20 feet per minute and through Nos. 20 and 25 it was 54 feet per minute at this period.

The stable temperature and the amount of ventilation were very satisfactory throughout this test. Under the conditions existing at the time the variations in the air circulation through the windows could not be considered objectionable, but they make apparent the impossibility of controlling ventilation and stable temperature when window intakes are used.

### BACK DRAFTING

Back drafting in outtakes is usually because of poor design or of the position of the ventilator on the roof; in one outtake it was caused by the lack of heat in a portion of the stable (p. 36). Back drafting occurs in intake ducts installed in the wall but with less frequency than in the case of windows. Increasing the length of the intake ducts tends to decrease back drafting, but structural considerations do not permit sufficient length entirely to prevent its occurrence. Plate 2, A, shows an extension, built on the outside wall, that was effective to a certain degree in reducing the amount of back drafting. Back action at a velocity of more than 1,800 feet per minute, the highest noted during the series of tests, was recorded in intake No. 9, Figure 1, during a wind of 17 miles per hour. There are a number of records of back drafting at velocities between 400 and 600 feet per minute, but in most instances the velocity was between 150 and 400 feet per minute.

It is natural to expect that the velocity of the air would be greater through the intakes most exposed to the wind. In some of the tests the velocity of the air through intakes on the windward side was four times that on the leeward side. As the wind increases the velocity of the air entering on the leeward side gradually decreases and, if the wind is high enough, back drafting may occur. In one barn back drafting occurred in a wall intake at the center of the leeward side with a wind blowing from the opposite side at a velocity of 16 miles an hour. Back drafting is common at corners (pl. 8, A), and where milk houses, silos, or other near-by buildings deflect the currents of air. When whirls are formed the air sometimes goes in and sometimes out, and this reversal may take place very quickly. The tendency to back drafting and the velocity at which it occurs depend mainly upon the design and the position of the intakes. The lowest wind velocity that produced back drafting in wall intakes, 5 feet or more in length, was 6 miles per hour, but back drafting in window intakes occurred several times at a wind velocity of 3 miles per hour and once, as previously recorded, at a velocity of less than 1 mile per hour.

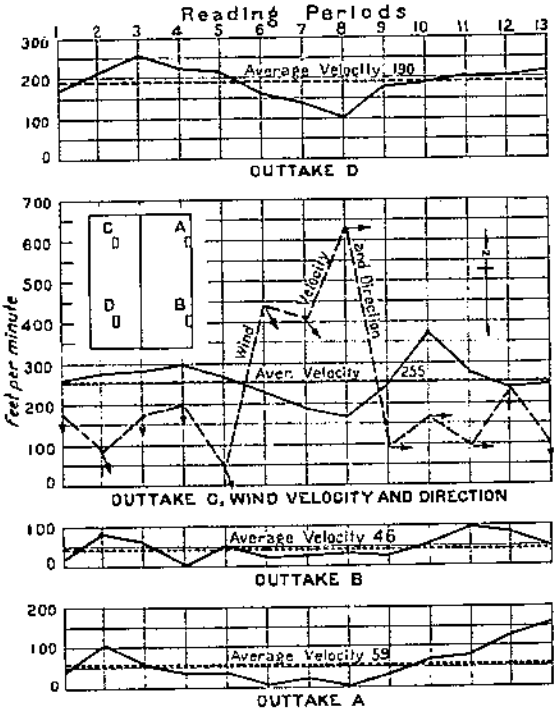
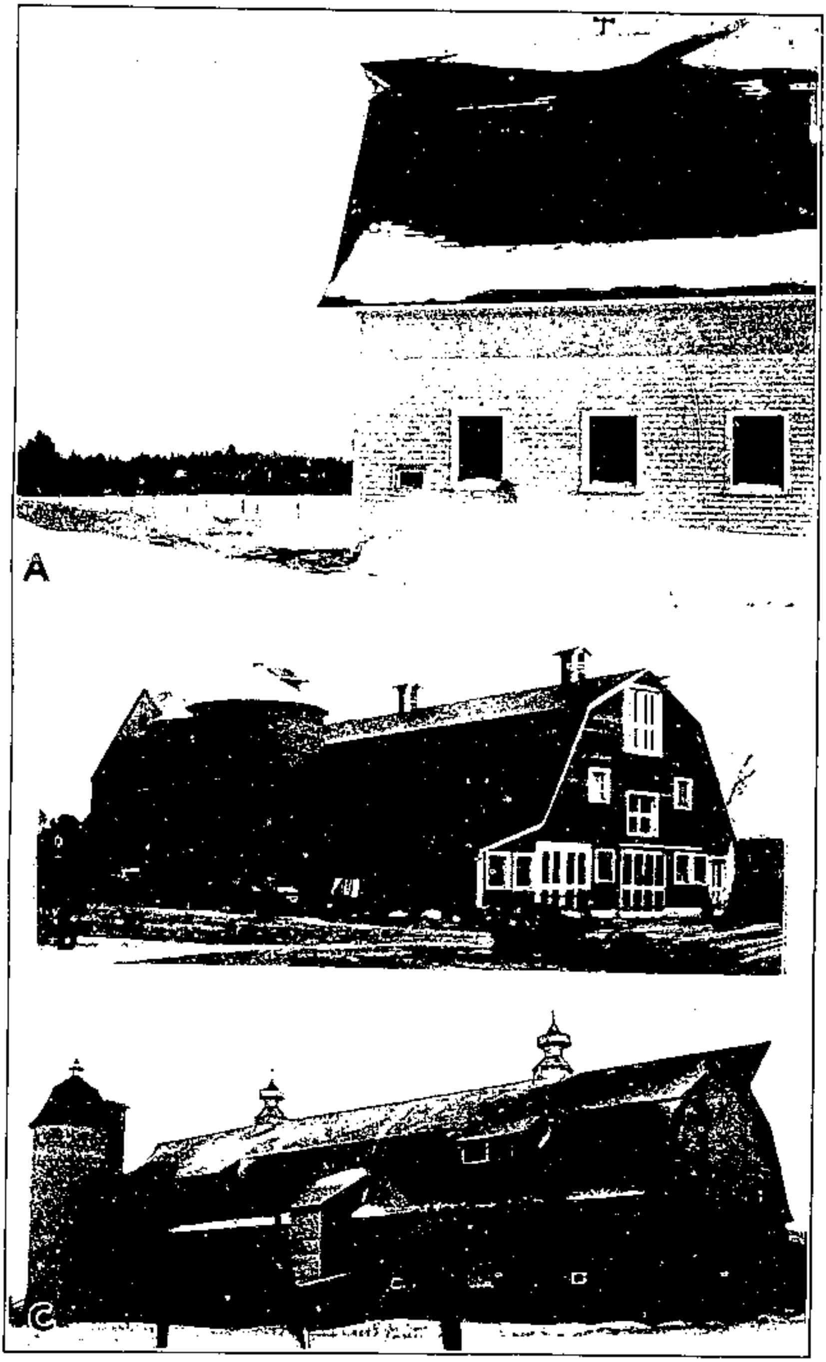


FIGURE 20.—Effect of wind velocity and direction upon flue velocity

## EFFECT OF WIND ON FLUE VELOCITY

One test with windows as intakes and cupola ventilators showed an interesting relation between flue velocities and the wind. Plate 8, B, shows an exterior view from the southwest. The openings in the two cupolas are filled with slats spaced 2¼ inches apart. The influence of wind velocity and direction upon the flue velocities, and in turn upon the ventilation secured, is shown graphically in Figure 20. The velocity of the air through outtakes A and B on the leeward side of the barn was very low, and the velocity in the windward flues was more than four times as great. At the period of greatest wind velocity the wind pressure had the greatest decremental influence on the flues which was contrary to the effect produced with other ventilators. The wind appeared more effective when blowing parallel to the ridge than when at right angles to it, which is characteristic of slatted cupolas. During periods of highest wind the veloc-



A, Effect of wind on roofs at corner of barn; B, view of barn 8 with slotted cupola; C, barn with outside hay chute ity of air through the outtakes was lower than the average for the test, and the velocity of the air through flues A, C, and D was lowest at this time. The velocity of the air through flues C and D was high, when there was a large difference between the inside and outside temperatures. This would indicate that temperature was the principal factor producing ventilation and that the wind impeded rather than assisted the movement of air through these flues.

### FURNACE REGISTERS

In a few of the barns tested warm-air furnace registers were used in the intakes and in some cases as heat doors in the outtakes. They are entirely unsuited to these purposes as the slats rust, become broken, collect dirt and cobwebs, and, during cold weather, collect frost, sometimes to the extent of complete closure. The grates and shutters retard the free passage of air. If no better means is available, a board, hinged or sliding in a slot, is superior to the furnace register. It is necessary to screen the outer opening in the inlet ducts to prevent entrance of trash and vermin, but the passage of air through the inner opening should be unobstructed except as it becomes necessary to restrict the amount of ventilation by partial closing of the opening. Wire screen of less than ½-inch mesh should not be used in a ventilator as it is easily closed by ice or trash.

### AUTOMATIC INTAKES

Wall intake ducts, having a vertical flue 5 feet or more in length may be installed readily in a frame structure, but when the walls are of masonry it is more difficult. Plate 2, A, illustrates a type of flue in a barn having a combination frame and masonry wall. Plate 6, B, shows intake ducts built on the outside of the barn wall. They are also sometimes built on the inside of the wall. In remodelling old barns having masonry walls the matter of intakes is often simplified by the use of intake valves (pl. 3, A), which automatically prevent back drafting and obviate the use of a flue with a vertical leg.

Since the intakes open at the ceiling in most barns, it is obvious that they would act as outtakes much of the time if provision were not made to prevent it. The vertical leg of an intake duct does not always overcome the tendency, in which case one of the automatic devices now on the market may be used. Automatic intakes were used in three of the barns tested.

These devices are provided with control dampers, which permit regulation of the amount of air entering the stable, as well as automatic valves, which prevent the escape of the warm air at the ceilings; in some the two are combined, in others they are separate. Such intakes should be set level and plumb to insure balanced movement of the valves, which are operated by the air currents only. The inclosing boxes should be well insulated to prevent condensation of moisture. These automatic valves operate either on a vertical or horizontal axis as illustrated in Figures 21, 22, and 23. There are a number of styles available, the exact construction being varied in accordance with the need of the individual installation.

### HAY CHUTES

Open hay chutes interfere with ventilation and should not be used as foul-air shafts. Plate 7, C, shows how roof boards and rafters were rotted and broken when moisture-laden air from the stable was permitted to rise through the hay opening and to condense on the roof

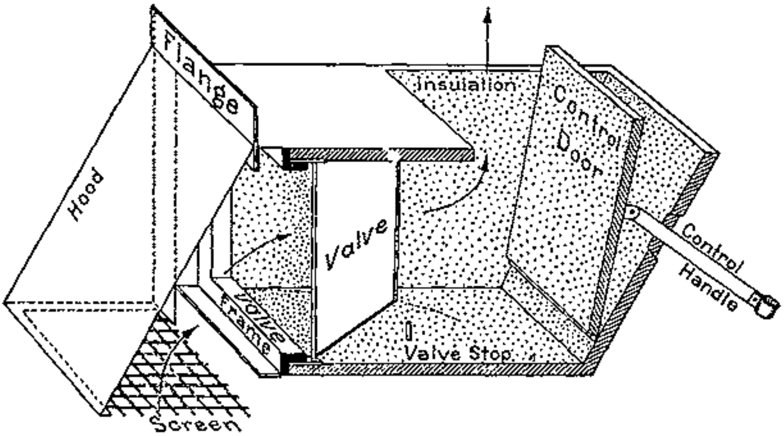


FIGURE 21.—Automatic intake with vertical-axle type of valve

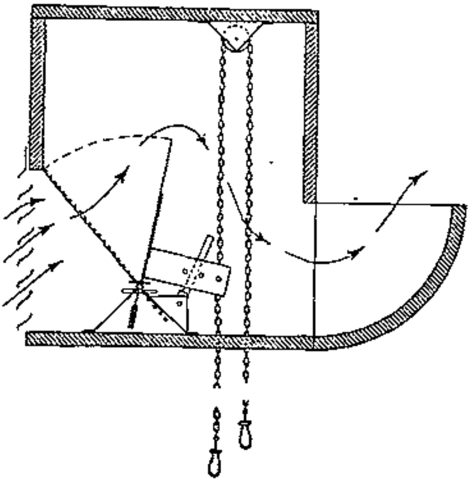


FIGURE 22.—Automatic intake with horizontal-axle type of valve

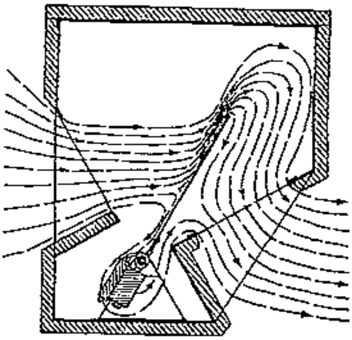


FIGURE 23.—Automatic intake with horizontal-axle type of valve

timbers. There were no ventilators in this barn. Metal cupolas were installed on the roofs of a number of barns visited, but no special ventilation flues were provided. The roof sheathing boards were found to be dripping with moisture, and the hay around the opening was damp and unfit for food.

It is obvious that the bottom of hay chutes can not be left open if the foul-air flues are to function properly. Air will seek the easiest passage, and a large opening in the mow floor provides a means of quick exit for the warm stable air. These openings should be closed by means of easily operated hinged or sliding doors.

Two of the barns tested had hay chutes built on the outside wall, as shown in Plate 8, C, a very convenient arrangement, saving labor and providing storage for the daily supply of hay. Covered passageways or doors over stairways should be well insulated to minimize condensation. The temperature in most mows is usually not more than 1° or 2° above the outside temperature.

## DETERMINATION OF FLUE SIZES

### CONSIDERATION OF BASIC FACTORS

The capacity of the ventilation system is determined by the amount of heat generated, the average mean outside temperature, and the size of outtakes and intakes. The total area of the intakes is usually the same as that of the outtakes, but they are of smaller size and greater number. It is important to so distribute the intakes as to insure a good circulation of air in all parts of the stable. The full capacity of the intakes will not be needed during cold weather. In cold climates therefore the total intake area may be made 10 per cent or more less than the total outtake area by reducing the size of each intake or the number of intakes. There is little economy with respect to cost in reducing the size of the intakes, and on the other hand it is often difficult to obtain good distribution if the spacing is in excess of 12 feet. There are many days when the larger area would be desirable.

The direction of the wind has an influence upon the amount of ventilation. Sloping roofs, projecting walls and adjacent buildings cause deflected air currents, which affect the functioning of the ventilators depending upon their design.

In only nine (approximately one-third) of the tests made did the average wind velocity exceed 8.5 miles per hour, but in some sections of the country the wind attains at times such high velocities that some provision must be made to offset its effect, especially during cold weather. In such sections the wind is likely to be extremely variable; this, and the fact that ventilation is particularly necessary during periods of calm are reasons for placing no dependence upon the wind in designing a ventilation system for a barn. In one of the tests the wind velocity varied in 48 hours from practically no movement at all to 40 miles per hour. Fortunately such variations are infrequent.

The outside temperature is usually the most dominant of the factors affecting outtake flue velocities at all temperatures below 20° (p. 48). There are but few localities in the United States where the mean monthly temperature for January is below 0° F. When the weather is above freezing doors and windows may be used as auxiliaries to the ventilation system. Hence 0° and 32° would appear to be the practical temperature limits to be considered in the determination of the capacity requirement of the system. It is desirable to maintain a stable temperature of not less than 45° when the outside temperature is 0°. In design, this stable temperature may be taken as the lower limit and 53° as the upper limit with an outside temperature of 32°, assuming a variation of 1° in stable temperature for each 4° variation outside. Such control can be readily obtained in good practice of ventilation and construction.

The number of days annually when ventilation normally will be required may be obtained from Table 7. It is obvious that greater consideration must be given to the temperature factor in the first zone, where ventilation is required about three-fourths of the year, than in the third zone where ventilation by means of flues is required but one-half the year.

### DEVELOPMENT OF FORMULA

Economy in construction demands that design be for neither the maximum nor minimum temperatures but that the capacity of the system meet the requirements during the greater part of the stabling period. In warm weather large flue area is required, whereas during cold weather small flues suffice. Thus the size of flues will vary from small to large according to the difference in climatic conditions in the several zones, the smallest flues being used in the first zone.

The quantity of air passing through the outtakes is determined by the size of the flue and the velocity of air movement. It has been common practice to assume the actual velocity of air passing through a flue as 50 per cent of the theoretical velocity. In these tests, made under a wide variety of conditions, it was found that this assumption gives higher values than will be obtained in ordinary practice.

The velocity of air passing through a flue is dependent upon the pressure inducing flow. Air has weight and exerts pressure as do liquids. The velocity with which a liquid will escape through an opening in the side of a vessel, when acted upon by the weight of the liquid alone, is expressed by the formula $V=\sqrt{2gh}$ in which $V$ is the velocity of escaping liquid in feet per second, $g$ the acceleration of gravity (32.2 feet per second) and $h$, the height in feet of the free surface of the liquid above the opening, or the pressure head. This relation holds true for the flow of gases. Substituting the value of $g$ and expressing $V$ in terms of feet per minute the equation becomes

$$V=60\times\sqrt{2\times32.2\times h}=60\times8.02\sqrt{h}$$

$$V \text{ in feet per minute}=481.2\sqrt{h} \qquad (1)$$

Also $Q=V\ A$ where $Q$ is the volume in cubic feet of air per minute, $V$ velocity of flow in feet per minute and $A$ the area of the flue in square feet. Where the volume is expressed in cubic feet per hour, $Q_1$ the area $A_1$, in square inches and $V$ in feet per minute

$$A_1=\frac{Q_1\times2.4}{V} \qquad (2)$$

It is known that when the temperature of a given weight of gas is maintained constant the volume and pressure vary inversely, and that when the pressure of a given weight of gas is maintained constant the volume increases in proportion to its change in absolute temperature. The absolute temperature, $T$, corresponding to any Fahrenheit temperature, $t$, is found by adding 460 to the latter, i. e., $T=460+t$.

In two flues of equal cross-sectional area the weights of the air columns within vary in proportion to the difference in heights if the temperatures are equal, or if the temperatures differ and the air columns are of equal weight, the heights of the flues will vary in proportion to the absolute temperatures. In a flue of any height, $H$ containing stable air of the same composition as the outside air there will be no movement when the flue temperature and the outside temperature, $t_o$, are equal as the air will have the same weight.

If the air in the flues is warmed to a given temperature, $t_s$, it will expand and an additional height of flue, $h_1$, will be required to balance the outside air column, assuming that the outside temperature, $t_o$, remains the same. The expansion of air is in proportion to the rise in absolute temperature. Since the height of the flue is fixed, this expansion must produce unbalanced air columns forcing air out of the flue and thus inducing movement in the flue in proportion to the change in temperature. This relationship may be expressed thus:

$$H : H+h_1=460+t_o : 460+t_s$$

combining, $h_1=\dfrac{H(t_s-t_o)}{460+t_o}$ (3)

substituting this value of $h_1$ in equation (1)

$$V=481.2\sqrt{\frac{H(t_s-t_o)}{460+t_o}} \tag{4}$$

This expression gives the theoretical flue velocity in a flue $H$ feet in height with a difference in temperature of $(t_s-t_o)$. But, due to friction and unaccountable losses, the actual velocity obtained in practice will be less.

The coefficient of velocity is a number by which the theoretical velocity of flow is to be multiplied in order to obtain the actual velocity. Thus if $k$ be the coefficient of velocity, $V$ the theoretical velocity and $V_1$ the actual velocity in the flue then

$$V_1=Vk. \tag{5}$$

The values for $k$ must be determined experimentally. A number of tests were made under widely varying conditions and with common types of construction. The average flue velocities obtained in these tests are given in Table 18 for various outside temperatures and at stable temperatures which may be obtained readily.

By substituting these temperature values in equation (4), theoretical velocities, as in Table 18, are obtained for the given range of temperatures. By comparing the theoretical velocities with the actual velocities obtained in tests it is found that the average coefficient of velocity is slightly less than 0.4. This figure may be used in determining the area of flues of heights commonly found in farm barns. Data permitting the determination of a coefficient for use in the design of shorter flues are not available.

TABLE 18.—*Coefficients of flue velocities*

| Temperature | | | Air velocity in flue heights of— | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | 42 to 48 feet (average 45 feet) | | | 28 to 34 feet (average 31 feet) | | |
| Outside | Stable | Difference | Theoretical | Test | Coefficient | Theoretical | Test | Coefficient |
| *° F.* | *° F.* | *° F.* | *Feet per minute* | *Feet per minute* | | *Feet per minute* | *Feet per minute* | |
| 0 | 45 | 45 | 1,011 | 430 | 0.425 | 834 | 340 | 0.408 |
| 4 | 46 | 42 | 972 | 400 | .412 | 807 | 325 | .403 |
| 8 | 47 | 39 | 933 | 365 | .391 | 775 | 310 | .400 |
| 12 | 48 | 36 | 891 | 335 | .376 | 740 | 295 | .399 |
| 16 | 49 | 33 | 849 | 300 | .353 | 705 | 280 | .397 |
| 20 | 50 | 30 | 807 | 270 | .335 | 670 | 265 | .396 |
| 24 | 51 | 27 | 762 | 235 | .308 | 633 | 250 | .395 |
| 28 | 52 | 24 | 717 | 200 | .279 | 595 | 235 | .395 |
| 32 | 53 | 21 | 667 | 170 | .255 | 555 | 220 | .396 |

Substituting this value of $k$ in equation (5) and combining with (4)

$$V_1 = 0.4 \times 481.2 \sqrt{\frac{H(t_s - t_0)}{460 + t_0}} = 192.5 \sqrt{\frac{H(t_s - t_0)}{460 + t_0}} \qquad (6)$$

It has been found that the temperature factor $\sqrt{\frac{t_s - t_0}{460 + t_0}}$ may be expressed in simpler form by substituting the value of $t_s$ and $t_0$, as given in Table 18, and plotting the values of the temperature factor, under the radical, on the $y$ axis and values of $t_0$ on the $x$ axis. The curve obtained in this manner is so nearly a straight line that the standard intercept form of expression may be used without introducing an appreciable error.

The general expression of the intercept form is as follows:

$$y - y_1 = \left(\frac{y_2 - y_1}{x_2 - x_1}\right)(x - x_1) \qquad (7)$$

By substituting the intercept values in equation (7) and simplifying, the temperature factor may be expressed as $(.313 - .0033t_0)$ and by substituting this value in (6) the equation becomes

$$V_1 = \sqrt{H}(60.2 - 0.64\,t_0) \qquad (8)$$

in which $V_1$ is the velocity in the outtake flue in feet per minute, $H$ the height of flue in feet, and $t_0$ the mean temperature of January for the locality. Thus is developed an expression of velocities that reasonably may be expected under practical working conditions in a given locality. Before substituting the value $V_1$ in equation (2), it is necessary to determine $Q_1$, the volume of air which will be required per hour per head, in order that the size of flue necessary to meet these requirements may be calculated.

The air circulation required to give the desired conditions may be determined upon the basis of air purity ($CO_2$ production), moisture removal, heat production, or a combination of these. In determining the size of flue necessary to meet the King standard (p. 22) a velocity equal to 50 per cent of the theoretical flue velocity and a temperature difference of 20° between the stable air at 50° F. and the outside air at 30° was assumed, no consideration being given the average temperature variations in the various zones. In assuming actual velocities to be 50 per cent of the theoretical, the values obtained are higher than those secured in practice. The use of this standard with its narrow limitations fails to give satisfactory results under many conditions.

Investigations by Armsby and Kriss (*2*) showed that King's assumption of $CO_2$ production is high, and they suggested that a flow of 3,452 cubic feet of air per hour per head was sufficient to maintain the desired purity of air within the stable. In both of these standards the ventilation requirements are based upon the $CO_2$ production, and little consideration is given to the temperature and moisture, factors which can not be disregarded.

The moisture content of the air varies according to its temperature and relative degree of saturation, hence the air required for the removal of the average production of moisture will vary under different stable conditions. The average rate of moisture production by a cow giving 20 pounds of milk daily is 15 pounds per day or 4,375 grains per hour (*2*). This amount must be removed hourly by ventilation to prevent an increase in the degree of saturation within the stable. Weather Bureau data (*11*) gives the relative humidity, under average weather conditions during January, as 85 per cent of saturation. At a stable temperature of 45° F. the stable humidity should not exceed 85 per cent and this percentage, or less, may be maintained with good ventilation. At a stable temperature of 53° a relative humidity of 75 per cent is obtainable in ordinary good practice. These limiting values are used in comparing the several standards with proportional values for the intermediate points.

By basing calculations upon these limits, it is found that to remove 4,375 grains per hour there would be required approximately 1,800 cubic feet of air per hour with the air entering at 0° F. temperature and normal degree of saturation, whereas at 32° outside temperature a little more than 2,700 cubic feet would be required.[7] These data, which are conservative, serve for the determination of flue sizes on the basis of moisture removal.

Another common method that has been used in estimating the capacity of the ventilation system is based upon obtaining a definite number of dilutions of air per hour, commonly three. It is readily seen that flue sizes determined upon this basis will vary widely since the volume of air space per head varies greatly according to the construction. However, it has been found that good stable temperatures with 3.5 dilutions per hour may be maintained in a well-constructed barn if the allowance of cubic air space per head is in accordance with the formula given on page 26.

No one size of flue will meet the requirements of all temperatures. Figure 14 shows that flue velocities vary inversely with the outside temperature. The maximum flue size need not exceed that required

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[7] Air at 32° F. and 85 per cent relative humidity contains 1.796 grains of moisture per cubic foot of dry air (8); at 53° and 75 per cent relative humidity it holds 3.394 grains and it would require about 2,700 [4375÷(3.394−1.796)=2,738] cubic feet of air per cow per hour to remove the average production of moisture.

at an outside temperature of 32° F. as the barn will seldom be closed tightly at higher temperatures. A proportionately smaller flue will be required in the colder localities in order to supply a given amount of air.

It is obvious that in localities having a mean January temperature of 32° F. or higher there will be a large proportion of warm days. Hence the maximum flue size would be required in such localities, and the total area of the flues would be needed during most of the time. In every locality there are a number of days, varying with the location, during which the full capacity of the system is needed. It is obvious that to provide for the maximum requirements would be uneconomical and that the size of flue should be determined upon the basis of the local weather conditions. This hypothesis is the basis for a new standard for the determination of flue sizes.

Figure 24 affords a means of comparing flue sizes based on the requirements of these different standards. A flue height of 31 feet, the average of the most common dimensions (28 to 34 feet) is used for the purpose of illustration and the comparison is made upon the basis of identical outside temperatures, other conditions being equal. The ordinates represent the flue area in square inches per head of average-size cow while the abscissas represent the mean monthly temperature for January. The chart shows the flue area required as determined by the various methods for given outside temperatures.

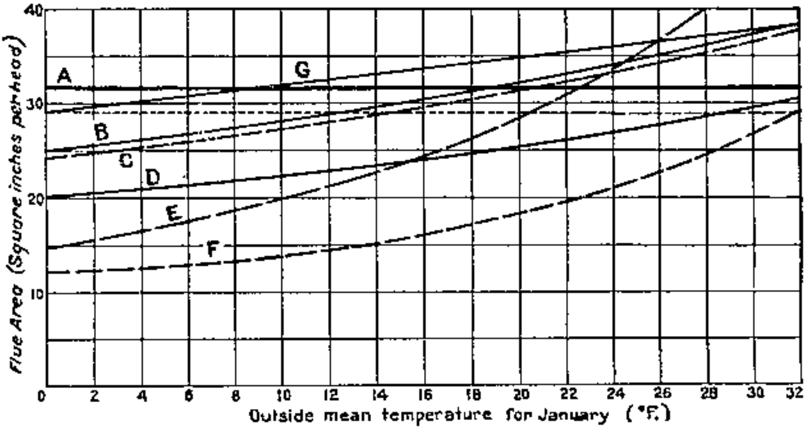

FIGURE 24.—Comparison of flue sizes, for dairy barns, as determined by various standards, with flue heights ranging from 28 to 34 feet

Curve A represents the flue size used in common practice for the stated flue height and is based upon King's standard of 20° difference in temperature (p. 66).[8] In this method no consideration is given to variation in requirements owing to local conditions. At low temperatures the sizes are larger than necessary while at warm temperatures they are too small.

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[8] The calculations necessary in the determination of flue sizes according to this standard may be simplified by the use of the formula suggested by J. L. Strahan (42).

Curve B is based on velocities obtained in tests (fig. 14) and the quantity of air (3,542 cubic feet per hour) required to remove the average production of $CO_2$, these values being substituted in equation (2). If 50 per cent of the theoretical velocities, as obtained by equation (4), and the above quantity of air as recommended by King are used curve D will be obtained.

Curve C is obtained as is curve B except that the air requirement suggested by Armsby, namely, 3,452 cubic feet, is used.

Curve E represents the flue sizes necessary if the velocities recorded in tests are used and 3.5 dilutions of air per hour are desired, the volume per head being based upon the formula $V=\frac{H\times k}{D}$ on page 26.

Curve F represents the flue sizes necessary to remove the average moisture production. The quantity of air required will vary between the limits given on page 67 in accordance with the variation of temperature and humidity.

Again referring to Figure 24 it will be noted that the largest flue areas are required at 32° F. At this temperature the full capacity of the system will be needed to remove the $CO_2$ and moisture as well as the heat produced by the animal. A flue area of 38 square inches will be required to remove the $CO_2$ (curve B) and 29 inches to remove the moisture (curve F). The larger size will meet all the requirements since, if the barn becomes too warm, the doors and windows may be opened. In a locality having a mean January temperature of 32° or more the entire flue area would be required frequently, whereas in colder sections warm days would be less frequent and a lesser flue area, proportioned to the lower temperatures, would be sufficient, thus making for economy of construction and convenience in regulating the system. To base the flue size upon a standard requirement per head irrespective of locality is uneconomical and unwise since too much restriction of unnecessarily large flues would result in inefficient operation during cold weather.

The sizes shown in curve A satisfy the $CO_2$ requirements (curve B) at all temperatures below 19° F., but are too small at higher temperatures. The size of flue required to remove the moisture at a temperature of 32° (curve F) is 29 square inches. Curve B gives sizes less than 29 inches at temperatures below 13°. Since periods of this temperature occur in all localities, it would appear that the flues should be made of sufficient size to remove at least the average amount of moisture produced, one of the important functions of the ventilation system. The dotted line at 29 inches shows the temperature below which the size of flues, determined by the several methods, will not satisfy the moisture-removal requirements. However, this size is too small at temperatures above 13° to remove $CO_2$ produced and keep the air of desired purity. In the warm sections the flue should be of sufficient area to remove the $CO_2$, and in the cold localities the flue should not be made so small as to prevent the removal of moisture during the warm days. It appears reasonable that the flue sizes should vary between the limits of 29 and 38 inches per head according to the intermediate temperatures, and these flue sizes would satisfy the requirements of $CO_2$ and moisture removal at all times.

These sizes are represented by curve G and make for greater economy in construction than the sizes obtained by curve A, present practice, in all localities having a mean January temperature of 9° or less. In the warmer sections their use would result in better ventilation.

It was found by trial, using Weather Bureau temperature data for several stations selected at random, that the sizes obtained from curve G conform to the average of the flue areas which would be used most frequently in a given locality. The daily outside temperatures were studied and the flue area for these days obtained by curve G. When the total of the areas for each day was divided by the total number of days on which the temperature was below 32° F. it was found that the average area was nearly the same as that obtained by the use of curve G with the average January temperature of that locality. Hence the use of the average January temperature as a basis for the determination of flue sizes appears to be justified. It is obvious that the flue sizes obtained by this method would be in agreement with average climatic conditions and would be most efficient as they would be proportioned to the length of ventilating season. When these sizes are compared with the amount of ventilation obtained during tests made under various weather conditions and in accordance with common practice in operation, they are shown to be practical. They may be varied according to the size of the animal by basing the calculations upon the requirements of the equivalent amount of stock of average size.

The graphic comparison shown in Figure 24 is of value in comparing the different standards, and from it may be obtained flue sizes determined by any of the methods just described. The flue sizes may also be determined by means of an easily remembered formula that for curve G in terms of outside temperature and flue heights, has been developed as follows:

The minimum flue size ($A_0$) obtained by the new method, curve G, is based upon the quantity of air required to remove the average amount of moisture, or 2,700 cubic feet per hour, at 32° F. while the maximum flue size ($A_{32}$), is based on the King standard for the removal of $CO_2$ produced or 3,542 cubic feet of air per hour. By substituting these values in equations (2) and (5)

$$A_0 = \frac{Q_1 \times 2.4}{V_1} = \frac{2{,}700 \times 2.4}{V_1} = \frac{6{,}480}{V_1} \qquad (9)$$

$$A_{32} = \frac{Q_1 \times 2.4}{V_1} = \frac{3{,}542 \times 2.4}{V_1} = \frac{8{,}500}{V_1} \qquad (10)$$

The values of $V_1$ at a temperature of 32° F. may now be substituted in equation (8) and combined with (9) and (10), then

$$A_0 = \frac{6{,}480}{\sqrt{H}(60.2 - .64t_0)} = \frac{6{,}480}{\sqrt{H}(60.2 - .64 \times 32)} = \frac{6{,}480}{39.7\sqrt{H}} = \frac{163}{\sqrt{H}} \qquad (11)$$

$$A_{32} = \frac{8{,}500}{\sqrt{H}(60.2 - .64t_0)} = \frac{8{,}500}{\sqrt{H}(60.2 - .64 \times 32)} = \frac{8{,}500}{39.7\sqrt{H}} = \frac{214}{\sqrt{H}} \qquad (12)$$

According to the original hypothesis a flue in a locality in which the mean January temperature is 0° F. must be of sufficient area to permit removal of the moisture when the temperature warms to 32°. By using the values $A_0=\frac{163}{\sqrt{H}}$ and $A_{32}=\frac{214}{\sqrt{H}}$ as the minimum and maximum flue areas and substituting in (7) the expression for curve G may be obtained.

Then the area, $A$, for any outside temperature, $t_0$, may be obtained as follows:

$$y-\frac{163}{\sqrt{H}}=\frac{\left(\frac{214}{\sqrt{H}}-\frac{163}{\sqrt{H}}\right)}{32-0}(x-0)$$

Simplifying

$$y=\frac{163+1.6x}{\sqrt{H}}$$

or

$$A=\frac{163+1.6t_0}{\sqrt{H}} \tag{13}$$

This general expression may be used in determining flue sizes for a locality where the mean January temperature is known. If the mean January temperature is not available its approximate value may be obtained from the zone map (fig. 4) and the formula on page 26.

Flue sizes obtained by this method are conservative and are in accord with the average climatic conditions and length of ventilating season in any locality. By comparing them with sizes tested in practical operation under various weather conditions, they are found to be satisfactory. Flue sizes, based upon present practice in design, as represented in curve A, are too small in the warmer sections and larger than necessary in cold sections. Since it is obviously unwise and uneconomical to provide for extreme conditions flue design should be based on local conditions so that the farmer may obtain the maximum circulation of air and at the same time maintain comfortable conditions within the stable.

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