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Canada

Handling Agricultural Materials

Storage and Conditioning of Grain and Forage

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Research Branch
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FOREWORD

Handling Agricultural Materials is produced in several parts as a guide to designers of materials-handling systems for farm and associated industries. Sections deal with selection and design of specific types of equipment for materials handling and processing. Items may be required to function independently or as components of a system. The design of a complete system may require information from several sections of the manual.

This section was prepared by UMA Engineering Ltd., Winnipeg, Man., for the Canada Committee on Agricultural Engineering Services of the Canadian Agricultural Services Coordinating Committee.

1 INTRODUCTION

The financial viability of farms depends, to a great extent, on how producers maintain the quantity and quality of crops—from harvest to the time the crops are sold to market or fed to livestock.

Grain that is free from insects and mold is more valuable than out-of-condition grain. Loss of dry matter or available nutrients from improperly stored forage means that greater production is necessary to achieve the same quantity of output in terms of meat, milk, or other products. Canada enjoys relatively favorable climatic conditions for storing grain and forage crops. Therefore producers here find it easier to maintain crop quality than do farmers in more temperate climates. Nonetheless, losses in storage can affect the net income of Canadian producers, so it is worthwhile to control crop storage conditions.

Storage systems operate under a wide range of variables including the weather, crop type, moisture content, product utilization or marketing scenario, and power availability. Use this manual to identify these variables in developing storage facilities.

1.1 Maintaining the quality of grain in storage

Deterioration of grain in storage generally results from infestation by:

- rodents
- insects and mites
- fungus and molds

Control infestations by limiting access to food and water supplies.

Construct storage buildings to prevent rodent entry. Use concrete floors and curbs under buildings and steel kick plates around the bottom joists of wood-frame buildings. As well, repair leaking faucets and insulate sweating pipes to prevent water from collecting in open pools.

Clean bins between fills to remove the out-of-condition grain that attracts rodents. Old grain also harbors insects and mold that may contaminate the bin. In cleaning the bin, spray insecticide where insects can hide, for example, in aeration ducts, wall-to-floor joints, and panel-interconnection seams.

Clean grain spills outside the bins to discourage rodents, insects, and molds from populating. Cleanliness is especially important in summer when insects are very mobile and mold spores are readily transported in the warm wind. Both pests can contaminate storage facilities in their vicinities.

1.2 Controlling rodents, insects, and molds

1.3 *Moisture control* Insects and molds can survive in dry grain but require moisture to propagate. Grain that becomes tough or damp in storage, however, is a prime target for infestation. Prevent moisture from collecting in the grain mass and block access of free water into the bin.

Natural convection within the bin concentrates moisture within the grain mass. Temperature gradients between the interior and exterior of the bin promote convection currents. Mix and redistribute the grain mass. Use aeration equipment or turn the grain by unloading the bin, then by reloading the grain into the same or a different bin. These actions prevent large temperature gradients from generating convection currents. Moisture migration patterns vary seasonally, as Fig. 1 illustrates.

Good design and maintenance of the granary prevents free moisture from building up in the grain mass. Close the inspection and access hatches, ensure waterproof connections of bins to their foundations, and provide weather seals where the bins connect roofs to the walls, to prevent access of snow.

Other moisture-control strategies involve using a vapor barrier under concrete bin floors and installing high-density concrete. Both these measures prevent moisture from migrating through the floor. To alleviate a floor moisture problem that already exists, insert a granular (nonwicking) material below the bin floor and raise the bin floor above adjacent grade.

Natural-air drying of grain can often cause water to condense on the underside of steel bin roofs during cool nights. This moisture can run down the underside of the roof to drip points, usually around the periphery, causing moisture to concentrate in the grain. Use relief air openings in the roof to reduce this condensation problem. In difficult cases, supplement this venting with positive overventilation of the air space above the grain: exhaust air from the space faster than the air moves through the grain. Insulating the roof may also help.

1.4 *Temperature control* The ability of insects and molds to propagate depends on grain temperature. Grain harvested on warm days is particularly susceptible to insect infestations and to mold formation, especially when adequate moisture is available. Reduce the

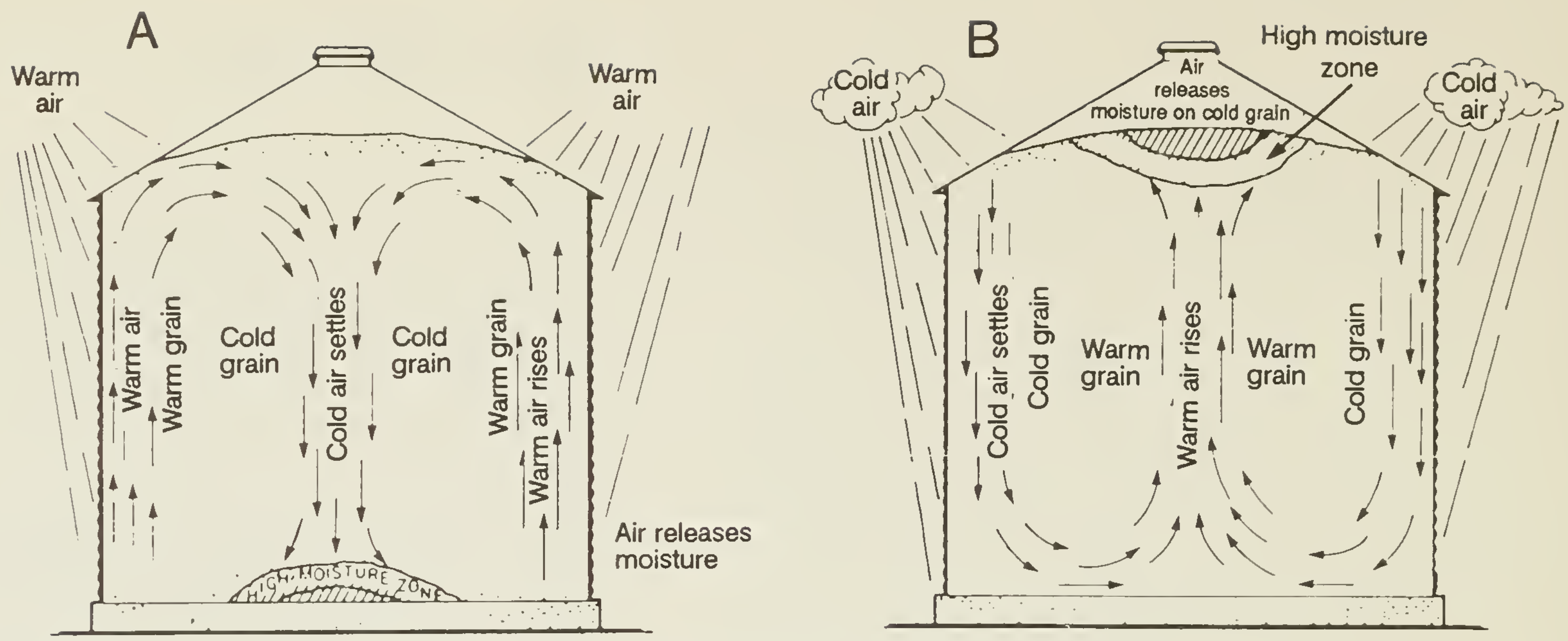


Fig. 1. Seasonal moisture migration patterns in (*A*) spring and summer, (*B*) fall and winter.

temperature of the grain to below 5°C as quickly as possible after harvest to prevent insect and mold growth. This action also reduces the temperature differential between the grain mass and the outside air which, in turn, limits natural convection currents.

Monitor grain temperature frequently to detect grain spoilage. Dry grain stored at a uniform temperature below 5°C does not deteriorate in storage.

1.5 *Chemical control* Pesticides also control rodents and insects. Two Agriculture Canada publications provide detailed information on selecting and using pesticides (Loschiavo 1976, *Control of rats and mice* 1979, Cessna 1988).

Using chemicals to control insects and mold presents a risk to the health of the user as well as to children, livestock, and pets. Limit the use of chemicals to situations where an infestation has developed and the grain has begun to lose quality. Use of advice in this manual, however, should help avoid either situation.

2 EFFECTS OF MOISTURE, TEMPERATURE, AND TIME ON GRAIN STORAGE

2.1 Moisture and temperature

The optimum conditions for reproduction and growth vary with each species of insect, mite, or mold. However, some generalizations can be made for pests that affect grain in storage. Table 1 presents the environmental conditions recommended for stored grain to prevent total loss (by other than chemical means).

Table 1 Environmental conditions associated with pests in grain storage

	Insects	Mites	Molds
Minimum temperature for reproduction	17°C	5°C	—
Minimum grain moisture content for reproduction	dry	dry	tough
Minimum temperature for activity	8°C	3°C	–8°C

Source: Sinha (1971), Loschiavo (1976).

Similarly, each species of grain exhibits a different ability to withstand storage conditions without loss, germination, or mold growth. Grains achieve stable storage moisture content when the relative humidity in the space between the kernels is less than the threshold humidity level for mold propagation. Table 2 lists moisture content designations for several grains.

To enhance the storage life of grain, control both the grain temperature and the moisture content. Figs. 2, 3, and 4 illustrate the length of time that grains at various moisture contents and temperatures can be stored.

As the temperature rises in heating grain, however, the rate of mold growth and insect infestation also increases to cause an exponential rate of temperature rise. In addition, storage without airflow causes a faster rate of decay and temperature rise than might be expected. Fig. 3 reflects storage of canola that is continuously ventilated.

Table 2 Moisture content designations for common species of grain

	% of weight		
Species	Dry	Tough	Damp
Wheat	14.5	14.6–17.0	>17.0
Barley	14.8	14.9–17.0	>17.0
Oats	14.0	14.1–17.0	>17.0
Rye	14.0	14.1–17.0	>17.0
Flax	10.5	10.6–13.5	>13.5
Canola	10.0	10.1–12.5	>12.5
Buckwheat	16.0	16.1–18.0	>18.0
Corn	15.5	15.6–17.5	17.6–21.0
Peas	16.0	16.1–18.0	>18.0
Sunflowers	9.5	9.6–13.5	13.6–17.0
Mustard	10.5	10.6–12.5	>12.5
Canary seed	12.0	—	—
Soybeans	14.0	14.1–16.0	16.1–18.0
Lentils	14.0	14.1–16.0	>16.0
Triticale	14.0	14.1–17.0	>17.0
White beans	18.0	18.1–21.5	>21.5

Note: Canola is considered safe for storage over winter at 8.5% moisture content. Other grains are considered safe for storage when they are dry.

Source: *Grain grading handbook for western Canada.*

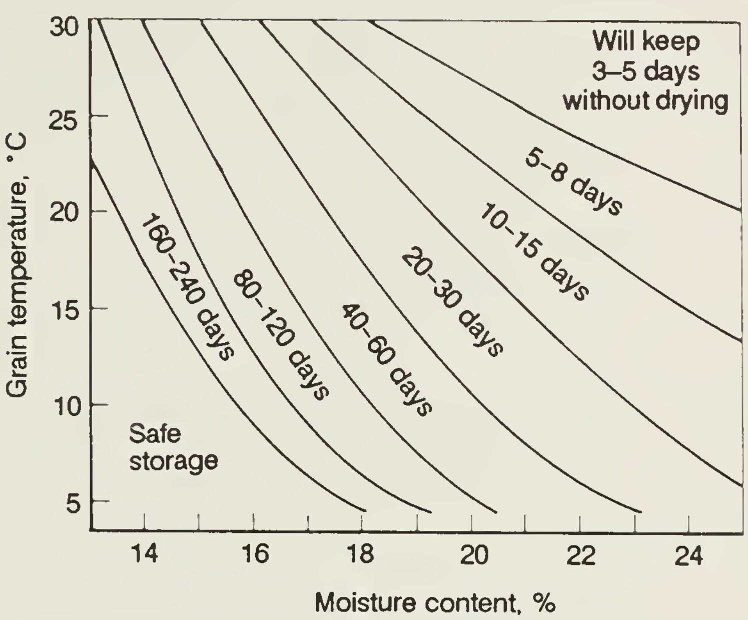


Fig. 2. Effect of temperature and moisture content on the allowable storage time for wheat, oats, and barley.

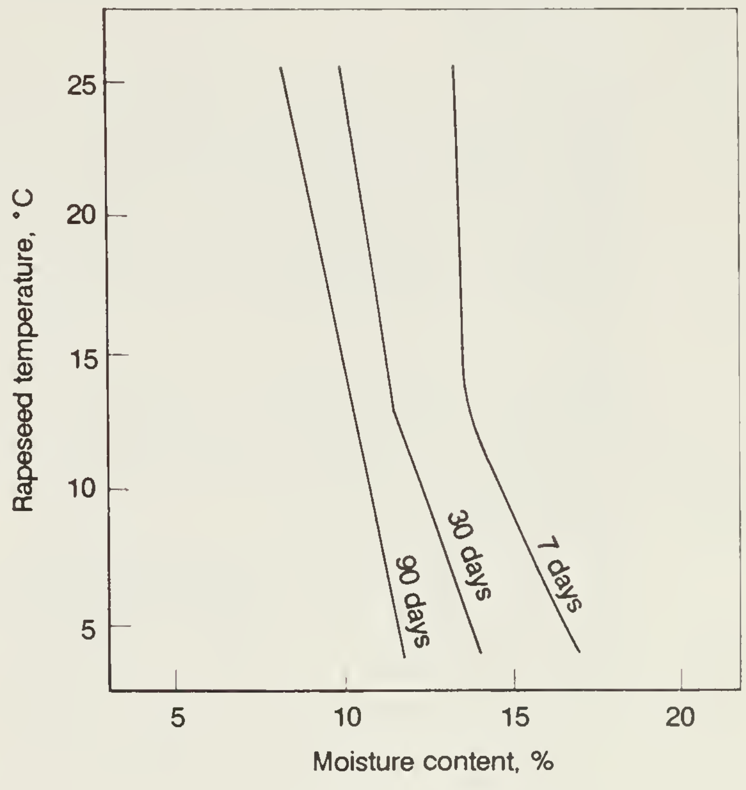


Fig. 3. Effect of temperature and moisture content on the allowable storage time for continuously ventilated canola.

Localized pockets of excess moisture in otherwise dry grain can result from insect infestation, concentrations of immature kernels, or moisture migration. Activity in these pockets generates heat in what is thought to be dry, cool grain.

Whenever possible, reduce the temperature of the grain mass below 5°C. Alternatively, reduce the moisture content of the grain mass to prevent insect or mite infestation, which can cause the temperature of the grain to rise (Table 1; Figs. 2, 3, and 4).

Because insects and mites reproduce rapidly, cool grain as soon as possible after harvest, especially on warm days when the ambient temperature reaches 15°C or more. Grain does not cool quickly in storage without air flow and retains the harvest temperature for long periods.

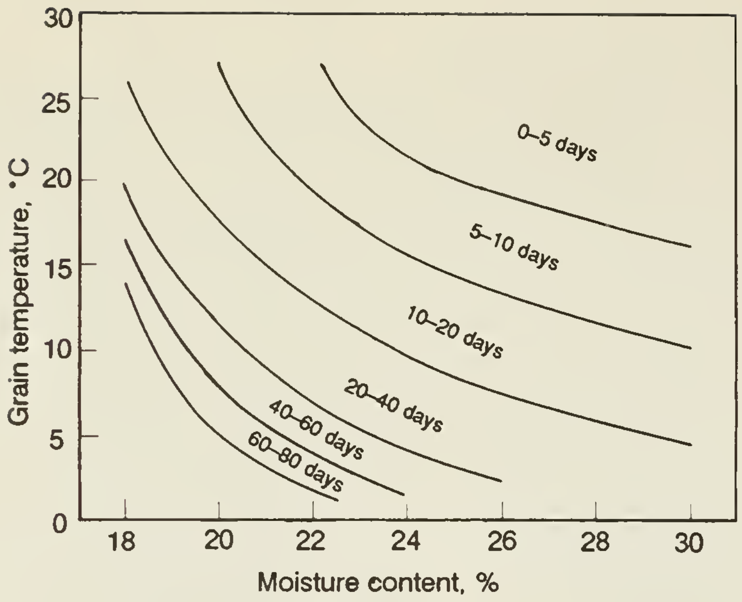


Fig. 4. Effect of temperature and moisture content on the allowable storage time for corn.

In summary, these factors predispose grain to spoilage:

- presence of immature kernels
- presence of mature grain having a higher moisture content than average
- presence of grain containing above-average quantities of damaged kernels and fine material

Immature kernels have a higher moisture content and a higher heat of respiration than mature kernels. Prevent pockets of immature grain from forming in storage bins by turning the grain. In addition, use a grain spreader during bin filling and satisfy appropriate moisture and temperature conditions.

Rewetting the grain, poor drying procedures, or moisture transfer within the bin can cause pockets of moist grain to form. Use control procedures similar to those for dealing with immature grain pockets.

Insects readily attack damaged kernels and fine grain because the feedstock inside the kernels is easily accessible. These damaged kernels and fines, called dockage, are also more difficult to cool because of their high airflow resistance. Turn the grain in storage and use a grain spreader during filling to distribute the dockage uniformly. Check the bin-loading method to avoid creating the same problem during turning. Filling devices often fail to distribute particles uniformly. However, if uniform distribution of this material in the bin is impossible, clean the grain to remove excessive dockage.

2.2 *Equilibrium moisture content* The equilibrium moisture content of grain occurs when the partial pressure of the water vapor in the grain equals the partial pressure of the water vapor in the air. The relative humidity (RH) of the air at equilibrium with material of a given moisture content is known as the equilibrium relative humidity. Grain gives up moisture to air (i.e., dries) when the relative humidity of the air is less than the equilibrium relative humidity. Conversely, grain takes on moisture if the relative humidity of the air exceeds the equilibrium relative humidity. The point of equilibrium varies with temperature and grain type.

When moving ambient air through grain, the grain either gives up moisture to the air, or takes it from the air, depending on the relative humidity of the air, moisture content of the grain, and temperature of both air and grain.

Fig. 5 illustrates two important notes about drying grain. As the grain dries, the drying rate slows significantly once the vapor pressures of the air and the grain begin to equalize. In addition, the ability of ambient air to dry grain declines as temperatures decrease. Consequently, the potential for removing moisture from grain by ambient air relates directly to the net evaporation in any given geographical area.

2.3 *Determining moisture content* For quick moisture content determinations, rely on electrical resistance testers. Use testers that demonstrate good accuracy for most grains over a wide range of moisture contents. Remember to recalibrate the electrical resistance testers, however, for each type of material.

When using a heated-air grain dryer, allow for the moisture rebound effect that occurs as the moisture in the grain restabilizes after a period of drying. Moisture rebound results because the moisture tester measures only the moisture in the surface layers of the kernels. These layers dry much faster than does the centre of the kernel. Thus, the tester reflects a low moisture reading immediately after drying.

Moisture rebound is negligible when only a small amount of moisture is removed from the grain. However, rebound frequently reaches 1–1.5% when 10% or more of the moisture in the grain must be removed.

To accommodate moisture rebound and accurately measure the moisture content, allow the grain to reach temperature equilibrium throughout the kernels before using the moisture tester.

Another way of overcoming the problem of moisture rebound is to overdry the grain by about 1%. Alternatively, before testing the sample for moisture content, grind it, seal it in a plastic bag to prevent moisture loss, and allow it to cool to ambient temperature.

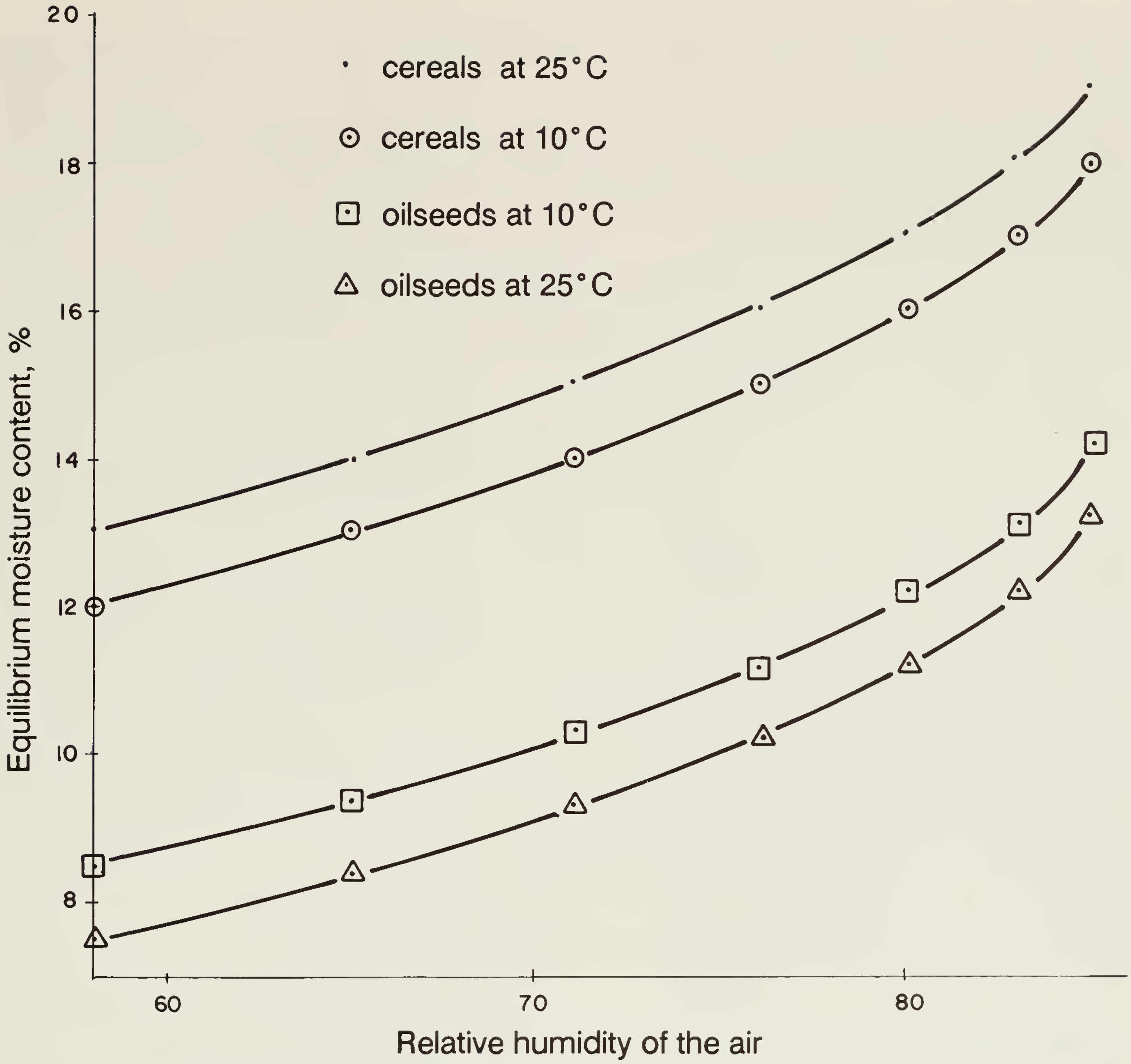


Fig. 5. Equilibrium moisture content of cereal grains and oilseeds.

Several publications from the American Society of Agricultural Engineers (ASAE) offer standard methods for determining the moisture content of grains, seeds, and forages. In fact, the accuracy of all types of moisture testers are measured against the ASAE oven dryers.

2.4 *Temperature-monitoring devices* Monitoring temperature is the easiest and most convenient means of checking the condition of stored grain. Temperature measurements indicate whether any heating is taking place or whether the propagation of insects and mites threatens the quality of the grain mass.

Minor increases in temperature indicate a need for closer examination. Maintain good records of temperatures so that even minor temperature changes can be detected and evaluated.

Locate temperature sensors in at least three places within the grain to adequately reflect the temperature of the storage mass. Good locations in the storage bin include the top centre (0.5–1 m below the surface), bottom centre (0.5–1 m above the floor), and on the south side (half-way up the bin about 0.1–0.5 m from the exterior wall).

Because moisture migrates within the bin, the top and bottom centre locations are most susceptible to moisture accumulation from internal convection. Monitoring the temperature differential from the outside to the centre reflects changing temperatures within the grain mass and provides an early clue to the presence of moisture within the grain. Uniform temperature throughout the storage mass ensures the best storage conditions.

The most common temperature-sensing devices include thermocouples, thermistors, and gas-filled thermometers. Thermocouples and thermistors are relatively low-cost sensors but they require high-cost meters to interpret the signals. Gas-filled thermometers are often low-cost devices but function best as probes or when in fixed locations.

Use thermocouples or thermistors when several bins must be monitored on a regular basis. These devices can remain enclosed in the bins since they generate temperature signals to exterior meters.

Equip all bins over 300 m^3 with devices to monitor temperature. However, bins of any size can benefit from temperature-monitoring equipment, particularly if the stored grain is tough or is susceptible to heating, such as canola.

2.5 Time

Time of storage is the most frequently underutilized factor in alleviating grain storage problems.

Design storage systems to handle wide-ranging demands for time variability. With the appropriate system, an operator can take advantage of the time variable and use it to economic advantage.

Consider the scenario involving a harvest of No. 2 wheat at 18% moisture content on 5 September. The operator faces these questions:

- Should the grain be dried?
- Should the grain be cooled for possible sale as No. 2 tough?
- Should the grain be cooled for future sale as feed wheat?
- Should the grain be cooled for future consumption by the operator's own livestock?
- Should the wheat dry in the field prior to harvest? In this case it may no longer be No. 2.

The operator can only answer these questions with a full knowledge of the following:

- grain stocks available
- feed requirements
- tax position
- market conditions
- risk-taking ability

The design of the storage facility should not add additional constraints.

3 SYSTEMS TO CONTROL MOISTURE AND TEMPERATURE

Air moving through the grain mass controls its moisture content and temperature. The necessary quantity, temperature, and humidity of the air depend on the objectives of the drying operation.

The four basic systems for drying grain are

- aeration
- natural-air drying
- heated-air drying
- combination drying

Aeration maintains the quality of dry grain and eliminates temperature and moisture differences throughout the bin.

Natural-air (or unheated-air) drying dries grain using ambient air. This process removes limited quantities of excess moisture.

Heated-air drying dries grain using supplementary heat. Adding heat to the drying air increases the vapor pressure differential between the grain and the air and reduces drying time.

Combination drying uses aeration, natural-air, or heated-air drying to dry the grain. Such methods are normally referred to as dryeration, cooleration, and modified cooleration. Use them during cooling to remove the last 1–6% of moisture from the grain.

3.1 Aeration systems

Use aeration to

- cool dry grain for storage at the lowest practical temperature
- establish and maintain temperature and moisture uniformity throughout the grain mass

Aerating grain in storage requires a minimum airflow of 1 (L/s)/m^3. At this rate, grain cools uniformly to near ambient temperature within 150–200 h. It cools in half this time with double the rate of airflow.

Airflow rates above the minimum recommendations increase storage options. Aerate at 2–6 (L/s) per cubic metre of grain to reduce the fan-operation time. At this rate, the grain cools well and attains uniform temperature. At the same time, aeration reduces the risk of moisture accumulating in the stored tough grain.

The ideal grain temperature is within 5°C of the average ambient temperature. Realistically, however, maintain grain below 5°C during winter and rewarm it to 10°C in the spring.

Monitor the grain temperature in the bin to determine temperature uniformity within the grain mass. If temperature differentials develop, moisture may migrate within the bin and reduce the safe storage time. Adequate fan operation times ensure uniform temperatures.

Moisture migration within a storage bin causes liquid to deposit in the top centre of a bin during winter and the bottom centre during summer. Monitor these locations frequently. Since it is relatively inaccessible, the bottom centre of the bin can be effectively monitored only by measuring the temperature. Aerating the bottom of the storage bin, however, makes it less important to monitor the bottom of the bin.

Do not expect aeration to dry tough grain, although under ideal conditions some moisture may be removed. Avoid overdrying the grain, which reduces the amount of marketable product.

Taking advantage of increased airflow rates, faster cooling, or holding tough grain requires that the aeration system be properly designed and that the operator understand the influence of ambient conditions on the ability of grains to be stored.

3.2 *Fan operation* During harvest, the primary objective is to cool the grain. Operate the fan continuously while filling a bin and afterward for as long as the exhaust air temperature measures 5°C above the maximum daily temperature. Cooling the grain to below 5°C generally requires several periods of continuous fan operation as the ambient temperature decreases. Ignore the relative humidity of the ambient air when the grain is cooling. Continue operating the fan, even during wet weather, because cooling the grain is much more important than any rewetting that may take place. Operate the fan for a day or two after the wet weather to remove excess humidity from the storage bin.

The top centre of the bin cools last if air moves upward through the bin. With a downward airflow, the bottom centre cools last. Cooling is complete when the temperature of these locations reaches 5°C or lower.

During the winter, maintain uniform temperatures by operating the aeration fan 1 or 2 days when the ambient temperature approaches that of the grain in storage. Extreme cold reduces the temperature uniformity in the bin and increases the tendency for moisture migration. Winter cold also causes condensation to occur on grain near the air ducts.

When the fan is not operating, keep a cover over the aeration fan or duct. This cover

- prevents the grain near the duct from cooling excessively because of severe winter conditions
- prevents rain or snow from entering the bin
- reduces the accessibility of the bin to rodents

Rewarm the grain in the spring, especially if the grain is to be stored through the summer and if the grain temperature measures 0°C or less. Begin warming in the spring when average daily ambient temperature reaches 5°C above the grain temperature. Warm in several stages, eventually bringing the temperature to 10°C, and select periods when the relative humidity is below 70%. Warming under these conditions reduces the risk of condensation forming on the grain and rewetting if the grain absorbs the moisture.

Operate the fan continuously during rewarming to ensure the temperature remains uniform in the bin. Condensation and spoilage may occur within a few days if the fan is shut off prior to grain achieving uniform temperature.

During the summer, take advantage of fair weather when the temperature dips to 15°C or lower to reestablish temperature uniformity. Do not run the fan when the ambient temperature is above the grain temperature, except to complete the period necessary to establish temperature uniformity.

3.3 *Direction of airflow* The decision to direct the air through the grain—from top to bottom, or the reverse—depends on several factors. Use the following information to decide which method to use in designing airflow drying systems.

Exhausting air through the bottom of the storage bin has one important advantage. It eliminates condensation on the underside of the roof while cooling warm grain during cold weather.

On the negative side, however, exhausting air through the bottom of the bin can cause moisture to accumulate at the bottom centre of the bin where accessibility for quality monitoring is most difficult. To avoid this situation, fix a temperature sensor in the spoilage location and periodically remove a small quantity of grain from the bottom centre of the bin to monitor for potential spoilage.

Additionally, exhausting air through the bottom poses a problem since it rewarms cooled grain at the bottom of the bin if warm grain is added at the top or if solar heat gain raises the air temperature under the bin roof during cooling.

Exhausting air at the top of the storage bin has four important advantages. It offers easy access to check the condition of the area most susceptible to spoilage (the top centre). It also simplifies temperature measurement to determine when aeration is complete.

Air exhausting at the top of the bin helps in keeping perforations clean during bin filling, especially when the fan begins operating prior to filling. And finally, it prevents the solar heat gain from the roof and space above the grain in storage from warming the grain in storage, a particular advantage during spring and summer.

As a disadvantage, though, exhaust air exiting the bin through the top may allow condensation forming on the bin roof to drip onto the grain.

3.4 Natural-air drying

Unheated ambient air can dry stored grain provided the equilibrium relative humidity corresponding to the moisture content of the grain exceeds the relative humidity of the ambient air. The drying rate must surpass the rate at which spoilage develops. The drying rate increases with increasing ambient temperature, but remember, this change in conditions also promotes spoilage. On the other hand, the equilibrium moisture content increases as the grain temperature decreases, further restricting the drying rate already reduced by the lower enthalpy of cooler air.

3.5 *Design and operation* Air forced through grain in storage first dries the grain it initially contacts. As it passes through the grain it takes on moisture until it reaches the equilibrium relative humidity, which corresponds to the moisture content of the wet grain. Subsequently, the air passes through the remaining grain with essentially no drying effect.

The depth of grain that correlates with the moisture uptake by air is known as the drying zone. The thickness and rate of travel of the drying zone varies with the airflow rate, ambient conditions, and the moisture content of the grain. To prevent spoilage, the drying zone must pass through the entire grain mass within the allowable storage time. Natural-air drying, then, is a race to dry the grain before it spoils.

Normally, a fan blows the air upward through the bin so the top layer of grain dries last. During drying, closely monitor the grain in this location to detect any signs of heating and to determine when a drying zone has moved through. If the grain begins to heat, remove it to a heated-air dryer as quickly as possible to reduce the chances of spoilage.

In a natural-air drying system the operator can control only the rate of airflow. Higher airflow rates move a wider drying zone through the grain faster. A drying zone, once developed, moves through grain as long as the fan operates. Therefore, operate the fan continuously until the zone has moved through the entire grain mass, or until the grain reaches a temperature for safe storage. Expect grain nearest the air supply to overdry during good weather and rewet during adverse conditions.

Continue operating the fan until either the grain dries or it reaches a safe storage temperature (see Figs. 2, 3, and 4). Store cereal grains and corn at 15–18% moisture content and at temperatures from 0 to −5°C. No further drying is required if the grain is to be used as feed during the winter. Otherwise completely dry the grain or corn by operating the fan continuously during the spring as soon as ambient temperature permits. Moisture removal proceeds quickly in the spring when ambient conditions normally favor drying.

3.6 *Airflow rate* Select airflow rates depending on:

- grain type and moisture content
- date of harvest
- normal autumn weather conditions for the area

Tables 3–8 list airflow rates for a variety of conditions.

3.7 *Operational aids* Several factors can influence the efficiency of grain drying.

First, the concentration of fines and broken material can have a significant detrimental effect on airflow. Reduce this effect by removing some of the grain through the centre unloading port after filling the storage bin. Alternatively, use a grain spreader during filling. Hand leveling the grain surface may also encourage uniform airflow through the bin.

Start the fan as soon as there is enough load on the perforated area of the bin floor to prevent uplifting. Continue operating the fan until the grain is dry or cool enough to prevent spoilage.

During storage, monitor the temperature and moisture content of the grain in at least the top metre of the bin.

During the winter, operate the fan for 6–8 h if the ambient temperature rises or following periods when the ambient temperature exceeds 0°C.

Finally, use the fan in the spring to rewarm dry grain to 10°C, especially when storing the grain past the end of June.

Table 3 **Recommended minimum airflow for a storage bin with a fully perforated floor and a level grain surface in Manitoba**

Crop and harvest date	Dry date	% time dried in fall	Initial moisture content (%) 16	17	18	19	20	22	24	26	28
			Airflow (L/s·m³)								
Seed wheat											
15 August	Fall	100	9	9	10	15	27	**	—	—	—
		97	6	7	10*	15	27	**	—	—	—
		94	6	6	10*	15*	27*	**	—	—	—
		90	5	5	10*	15*	27*	**	—	—	—
	Spring		6	7	10	15	27	**	—	—	—
	% time dried in fall		97	97	100	100	100	**	—	—	—
1 September	Fall	100	10	11	12	13	17	40	—	—	—
		97	8	10	10	13*	17	40	—	—	—
		94	7	9	10	13*	17	40*	—	—	—
		90	7	8	9	13*	17	40*	—	—	—
	Spring		7	8	8	13	17	40	—	—	—
	% time dried in fall		94	91	88	100	100	100	—	—	—
15 September	Fall	100	19	23	28	30	32	37	—	—	—
		97	17	22	23	24	25	27	—	—	—
		94	13	13	16	17	20	27	—	—	—
		90	10	12	15	16	17	26	—	—	—
	Spring		8	8	8	8	14	26	—	—	—
	% time dried in fall		76	73	52	33	82	88	—	—	—
1 October	Spring		8	8	8	9	13	23	—	—	—
	% time dried in fall		33	15	3	3	39	61	—	—	—
15 October	Spring		8	8	8	11	15	24	—	—	—
	% time dried in fall		0	0	0	3	9	30	—	—	—
Commercial wheat											
15 August	Fall	100	9	9	10	10	17	34	—	—	—
		97	6	7	8	9	17*	34*	—	—	—
		94	5	6	7	9*	17*	34*	—	—	—
		90	5	5	6	9*	17*	34*	—	—	—
	Spring		6	6	7	9	17	34	—	—	—
	% time dried in fall		97	94	94	97	100	100	—	—	—

(continued)

Table 3 Recommended minimum airflow for a storage bin with a fully perforated floor and a level grain surface in Manitoba (*continued*)

Crop and harvest date	Dry date	% time dried in fall	16	17	18	19	20	22	24	26	28
			Initial moisture content (%)								
			Airflow (L/s·m³)								
1 September	Fall	100	10	11	12	13	15	21	—	—	—
		97	8	10	10	12	13	21	—	—	—
		94	7	9	10	11	13*	21	—	—	—
		90	7	8	9	10	13*	21*	—	—	—
	Spring		7	8	8	8	13	21	—	—	—
	% time dried in fall		94	91	88	76	97	100	—	—	—
15 September	Fall	100	19	23	28	30	32	37	—	—	—
		97	17	22	23	24	25	27	—	—	—
		94	13	13	16	17	20	27	—	—	—
		90	10	12	15	16	17	26	—	—	—
	Spring		8	8	8	8	9	18	—	—	—
	% time dried in fall		76	73	52	33	15	88	—	—	—
1 October	Spring		8	8	8	8	8	15	—	—	—
	% time dried in fall		33	15	3	3	0	48	—	—	—
15 October	Spring		8	8	8	8	8	16	—	—	—
	% time dried in fall		3	0	0	0	0	0	—	—	—
Barley											
15 August	Fall	100	16	—	16	—	18	40	—	—	—
		97	9	—	12	—	18*	40*	—	—	—
		94	8	—	10	—	18*	40*	—	—	—
		90	7	—	9	—	18*	40*	—	—	—
	Spring		7	—	9	—	18	40	—	—	—
	% time dried in fall		88	—	88	—	100	100	—	—	—
1 September	Fall	100	19	—	19	—	24	30	—	—	—
		97	16	—	19	—	19	27	—	—	—
		94	14	—	17	—	18	27	—	—	—
		90	13	—	16	—	17	27*	—	—	—
	Spring		13	—	13	—	13	27	—	—	—
	% time dried in fall		91	—	85	—	85	97	—	—	—

(continued)

Table 3 Recommended minimum airflow for a storage bin with a fully perforated floor and a level grain surface in Manitoba (*concluded*)

Crop and harvest date	Dry date	% time dried in fall	Initial moisture content (%) 16	17	18	19	20	22	24	26	28
			Airflow (L/s·m³)								
15 September	Fall	100	35	—	45	—	50	**	—	—	—
		97	29	—	39	—	45	47	—	—	—
		94	24	—	30	—	31	37	—	—	—
		90	20	—	25	—	30	35	—	—	—
	Spring		13	—	13	—	13	17	—	—	—
	% time dried in fall		73	—	64	—	45	55	—	—	—
1 October	Spring		13	—	13	—	13	17	—	—	—
	% time dried in fall		45	—	24	—	6	15	—	—	—
Corn†											
15 September			—	—	—	—	10	—	29	—	117
1 October			—	—	—	—	8	—	22	—	49
15 October			—	—	—	—	8	13	20	25	52
1 November			—	—	—	—	8	—	12	—	20

* Lower airflows are possible for this condition, but a risk of spoilage would be introduced. See your local agricultural engineer for details.
** Airflow rates would be excessive for this condition.
† Data are based on computerized drying simulations using Winnipeg weather data for the years 1961–1970. The final moisture content was 15.5%. The airflow rates given would complete drying in the spring following the harvest year.

3.8 *General discussion* Natural-air drying systems usually provide 10–30 (L/s) of air for each cubic metre of grain. This rate is sufficient to dry tough grain, or at least store it through the winter. It may even be suitable for damp grain. However, this sort of drying system demands attention from a knowledgeable operator.

Drying systems using natural air usually require less capital investment and less materials-handling equipment than do heated-air dryers. Natural-air drying systems also consume less energy than any other means of drying. This fact is especially notable in areas having a low relative humidity in the autumn and where only small amounts of moisture are removed from the grains.

In fact, natural-air systems work particularly well in areas with low relative humidity during the autumn. In such locations, though, pay attention to controlling the costs associated with overdrying; they can be significant.

In areas where the ambient relative humidity approximates the equilibrium humidity levels for dry grain, energy costs escalate rapidly. Systems in these areas require high airflow rates to prevent spoilage and extended fan operation to remove the moisture.

In designing natural-air drying systems use wide and short bins. For economical operation, select a fan that maintains static pressure as low as possible. These fans are particularly necessary in facilities storing small-seed crops (e.g. flax, canola) because pressure loss through grain increases considerably with grain depth and air speed. This configuration of bin and fan reduces the cost of the bin marginally; however, it increases the cost of the foundation and perforated floor.

3.9 Heated-air drying

As grain dries it releases moisture to the air at a rate dictated by two factors: the difference between the partial pressure of water vapor (VPD) between the kernels and the air, and the permeability of the kernels. Excessive VPD causes physical damage.

Table 4 Recommended airflow for natural-air drying of wheat in Edmonton, Alta.

Harvest date	Year	Initial moisture content (%) 16	18	20	22	24
		Airflow (L/s·m³)				
15 August	2nd worst	—	5.0	20.0	35.0	—
	Worst	—	6.3	22.5	41.3	—
1 September	2nd worst	—	4.4	12.5	28.8	—
	Worst	—	4.4	16.3	28.8	—
15 September	2nd worst	2.5	3.8	7.5	17.5	40.0
	Worst	2.5	4.4	7.5	18.8	41.3
1 October	2nd worst	—	3.8	6.3	10.0	—
	Worst	—	4.4	6.3	11.3	—
15 October	2nd worst	—	3.8	5.6	8.8	—
	Worst	—	4.4	5.6	8.8	—

The data in this table are based on simulated drying results for the years 1967–1976.

Table 5 Recommended airflow for natural-air drying of wheat in Swift Current, Sask.

Harvest date	Year	Initial moisture content (%) 16	18	20	22	24
		Airflow (L/s·m³)				
15 August	2nd worst	—	5.0	13.8	26.3	—
	Worst	—	5.0	15.0	35.0	—
1 September	2nd worst	—	5.0	11.3	21.3	—
	Worst	—	5.6	12.5	25.0	—
15 September	2nd worst	2.5	3.8	8.8	17.5	33.8
	Worst	3.1	4.4	11.3	18.8	35.0
1 October	2nd worst	—	3.8	7.5	12.5	—
	Worst	—	4.4	7.5	15.0	—
15 October	2nd worst	—	3.8	6.3	10.0	—
	Worst	—	4.4	6.3	11.3	—

The data in this table are based on simulated drying results for the years 1960–1974.

Table 6 Recommended airflow for natural-air drying of wheat in London, Ont.

Harvest date	Year	Initial moisture content (%) 20	22	24	26	28
		Airflow (L/s·m³)				
15 September	2nd worst	21.0	35.0	69.0	113.0	175.0
	Worst	26.8	51.3	72.3	128.0	187.0
1 October	2nd worst	11.7	25.6	49.0	87.5	111.0
	Worst	15.2	30.3	66.5	128.0	163.0
15 September	2nd worst	7.7	17.5	39.6	70.0	140.0
	Worst	11.7	24.5	73.5	128.0	152.0
1 November	2nd worst	8.2	12.8	21.0	40.8	67.5
	Worst	9.3	12.8	23.3	42.0	80.5
15 November	2nd worst	8.2	7.7	15.2	22.1	39.6
	Worst	8.2	7.7	16.3	26.8	45.5

The data in this table are based on simulated drying results for the years 1962–1973.

Table 7 Predicted minimum airflow for drying canola in Manitoba

Harvest date	Dry date	% time dried in fall	Initial moisture content (%) 10	11	12	13	14	15
			Airflow (L/s·m³)					
15 August	Fall	100	16	16	16	16	17	28
		97	13	13	13	13	15	28*
		94	10	10	11	13*	15*	28*
		90	7	8	9	13*	15*	28*
	Spring		7	7	7	13	15	28
	% time dried in fall		88	85	76	97	97	100
1 September	Fall	100	26	26	26	27	27	30
		97	19	19	19	19	19	20
		94	13	17	17	17	17	20*
		90	13	14	15	16	17	20*
	Spring		12	12	12	12	16	20
	% time dried in fall		85	82	79	70	85	97
15 September	Spring		12	12	12	12	12	14
	% time dried in fall		55	39	39	33	30	36
1 October	Spring		12	12	12	12	12	12
	% time dried in fall		24	24	15	15	9	6

* Lower airflows are possible for this condition, but a risk of spoilage would be introduced. See your local agricultural engineer for details.

Table 8 Effect of harvest date, climatic condition, and initial moisture content on airflow rates for low-temperature drying of corn in Toronto, Ont.

Harvest date**	Climatic condition (year)				
	1971 (poor)	1972	1975	1969	1976 (good)
	Airflow (L/s·m³)				
1 October	28.1	23.9	23.5	21.2	12.8
15 October	26.1	23.8	21.5	16.4	12.4
1 November	18.7	20.8	20.0	19.7	13.1
15 November	24.4	27.2	26.6	18.3	12.7
Initial moisture content (%)†					
22	26.1	23.8	21.5	16.5	12.4
24	42.3*	25.3	28.1	21.8	18.9
26	46.1*	29.8	47.4*	28.9	21.2

* These airflow rates may not be feasible unless a high-speed centrifugal fan or shallow depths of grain are used.
** Initial moisture content of 22%.
† Harvest date 15 October.

Source: Mittal and Otten (1982).

During initial drying, the grain is still relatively cool and takes some time to warm, because of low thermal conductivity. As the grain dries, the moisture at or near the surface of the grain evaporates, which further controls the warming rate because the kernels lose heat to evaporation. As the grain approaches dry, the moisture near the surface depletes so the rate at which moisture can move from the centre of the kernel through the hull dictates the rate at which further drying can occur. The kernel permeability and the VPD affect how moisture moves through the grain. Rapid moisture removal from the surface of the kernel causes the exterior layers to overdry.

Expect some overdrying in high-temperature drying; but excessively high temperatures and accelerated drying cause two compounding problems:

- brittle hulls with lower-than-normal moisture permeability
- high vapor pressure within the kernels

Together these problems result in stress cracking of the grain hulls. They also lead to increased damage to the grain during handling.

Tough grain normally dries before the grain temperature and internal vapor pressure reach levels likely to cause stress cracking. Damp or wet grain, on the other hand, is very sensitive to the drying rate. For wet grain, select a dryer or drying system that yields a slow drying rate, particularly for the final drying stages. Such a system substantially reduces damage to the grain, as well as limits the possibility for damage in handling.

Rapid removal of moisture in the final drying stages requires a great deal of energy. Two factors account for the increase in energy demand. First, instead of drying the grain, the energy increases the sensible heat of the grain. Second, the slower release of moisture from grain that is almost dry results in exhaust air with a low relative humidity. The net effect is a lower dryer efficiency.

Excessive grain temperature reduces the ability of the seeds to germinate. Both drying time and temperature are correlated; however, the short time involved in heated-air drying generally reduces its impact on the quality of the grain.

Extremely high temperatures cause the grain kernels to discolor and disfigure. Controlling the drying process to prevent these distortions, however, results in temperatures higher than required for complete drying. Consequently this approach proves an undesirable control strategy.

Refer to the temperatures listed in Table 9 as a guide to safe air temperatures. However, do not overlook safe grain temperatures when planning grain-drying systems.

Grain dryers vary in design and operation. They provide a wide range of conditions that affect the safe drying temperature. In particular, two aspects of dryer design most strongly influence safe drying temperature:

- temperature uniformity in the supply air
- moisture content uniformity in the grain being dried

The design of the air supply system, the burner type, the shape of air plenum, and the mode of operation each affect the temperature of the supply air at different locations within a grain dryer. Temperature variations within a dryer generally remain constant for each type of grain, but change significantly from one grain to another because of changes in airflow rate.

For grain with a nonuniform moisture content, the maximum temperature that the driest kernels can be exposed to without damage represents the safe drying temperature for that batch. A nonrecirculating batch dryer requires a lower safe drying temperature than a recirculating batch dryer. The difference occurs because in a nonrecirculating dryer the hottest, driest air continuously contacts the same kernels first throughout the drying process. Consequently these kernels overdry by the time the entire batch is dry.

The temperatures given in Table 9 depend on drying to not more than 1% below dry (as designated in Table 2), and on removing not more than 6% of the moisture in one pass through a high-speed dryer. To remove more than 6% moisture on the first pass, the initial drying temperature can exceed the temperatures shown in Table 9 because evaporation cools the grain kernels during this drying stage. However, as the grain gets close to being dry, maintain the air temperature at the levels given in Table 9.

Operate nonrecirculating batch dryers at 5–10°C below the temperatures indicated for commercial use, particularly when drying oilseeds. Prolonged exposure to high temperatures affects the oil quality in oilseed grains.

Table 9 Maximum drying temperatures

	Maximum temperature (°C)		
Crop	Seed or malting	Commercial use	Feed
Wheat	60	65	80–100
Oats	50	60	80–100
Barley	45	55	80–100
Rye	45	60	80–100
Corn	45	60	90–100
Flax	45	80	80–100
Canola	45	65	—
Peas	45	70	80–100
Mustard	45	60	—
Sunflowers	45	50	—
Buckwheat	45	45	—

For damp grain (see Table 2), air temperatures 20°C above those given (Table 9) can be used safely in the early stages of drying.

3.10 *Dryer types* There are three main types of heated-air dryers:

- nonrecirculating batch dryers, in which the grain remains static during drying and is then removed
- recirculating batch dryers, in which the grain constantly mixes during drying
- continuous flow dryers, in which the grain feeds into the dryer wet and exits dry on a continuous basis

Each of these types can supplement round steel storage bins or exist as single-purpose machines. Select a dryer that permits drying in 24 h only the amount of grain normally harvested in a day.

3.11 *Nonrecirculating batch dryers* Wet grain is loaded into a batch dryer and heated air is passed through it until the average moisture content reaches the dry point. The grain then cools and is unloaded. Fig. 6 shows a sectional view of a nonrecirculating batch dryer.

Since the grain remains stationary during drying, the grain closest to the hot air plenum dries before grain located further away. Achieving a dry average requires fairly severe overdrying of the interior grain. To avoid grain damage, reduce the operating temperature of the dryer during the final drying stages.

3.12 *Batch bin dryers* A batch bin dryer (Fig. 7) consists of a perforated floor, one or more fans and heat sources, plus controls to regulate temperature. Supplementary equipment often

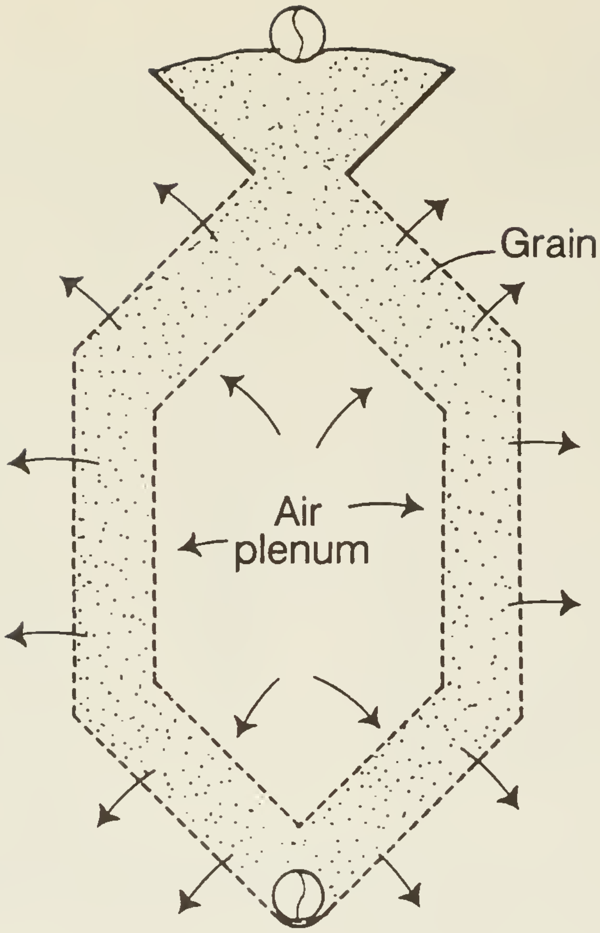


Fig. 6. Nonrecirculating batch dryer.

includes timers to aid in temperature regulation, a manometer to correlate grain depth with fan capacity, and a bin spreader to level the grain and to achieve more uniform distribution of fines and foreign material.

Additionally, wet and dry grain surge bins reduce the time and supplementary equipment required to load and unload the dryer. A second bin dryer using the same heating device and fan as the primary dryer can function as a wet surge bin. An airflow diverter shares the heated air between the two bins.

The airflow rate used in bin dryers varies widely. However, most systems operate at 125 (L/s) per cubic metre of grain. Increasing the airflow, either by increasing the fan capacity or decreasing the grain depth, dries the grain faster.

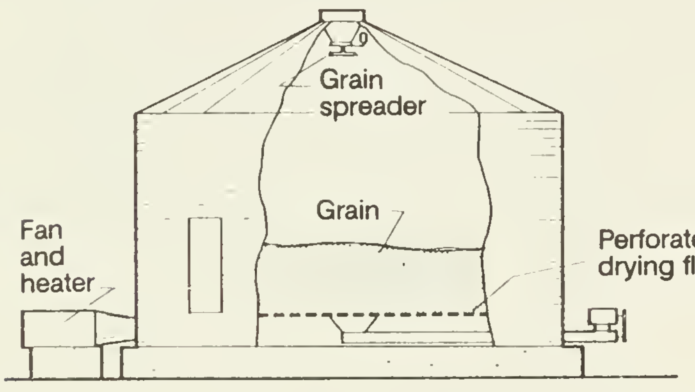


Fig. 7. Batch bin dryer.

Control condensation on the underside of the bin roof using techniques similar to those used for natural-air drying (see section 3.4).

For all batch dryers, consider carefully the time required to load and unload the dryers and design a drying system to match the harvest system. Because of their high resistance to airflow, small-seeded crops like canola and flax greatly influence the choice of dryer and the design of the drying system.

3.13 *Portable batch dryers* The term portable describes batch dryers that are not the bin type. These portable dryers pose design constraints similar to batch and batch-bin dryers. Most notably, the grain nearest the plenum dries long before the rest of the batch. To avoid this problem, maintain the operating temperature for portable dryers lower than dryers that provide a greater degree of mixing.

Portable batch dryers differ from bin dryers in two important ways. Portable batch dryers are generally smaller in volume and they have a higher airflow rate per unit volume than bin dryers. Together these characteristics reduce the time the grain must remain in the dryer. Yet at the same time they decrease fuel efficiency.

Locate a wet surge bin ahead of the dryer and use it to top up the grain during drying. As it dries, the grain shrinks. Air escapes through the area above the grain at the top of the dryer, rather than passing uniformly through the entire grain mass. Avoid this problem by ensuring the dryer is full for drying.

Batch dryers usually come with high-capacity unloading conveyors. These conveyors are designed to minimize unloading times and increase dryer capacity.

Drying very wet grain in cold weather can be difficult with a stationary batch dryer. This situation is particularly relevant to small-seeded crops, which have a higher resistance to airflow. As the warm air moves through grain layers, it picks up moisture and cools very quickly. If the relative humidity exceeds the dew point of the grain temperature before leaving the grain mass, water condenses in the exterior layers of grain and results in a nearly impenetrable barrier in the grain column.

Recirculating batch dryers (see section 3.14) and rack-type continuous-flow dryers (see section 3.15) can contend with such adverse conditions by constantly mixing the grain. Mixing leads to a more uniform grain moisture content throughout the grain mass being dried.

3.14 *Recirculating batch dryers* Recirculating batch dryers (Figs. 8 and 9) continuously mix grain during drying. Mixing essentially eliminates most of the operational constraints associated with batch dryers. It allows high operating temperatures, thereby increasing the drying rate. As well, it removes the problem of severe overdrying of grain adjacent to the air plenum. Mixing also reduces airflow resistance; the grain moves continuously so larger batches can be dried. However, if the grain is very wet, the continuous recirculation may damage it.

Depending on the type of dryer, two sorts of equipment generally recirculate grain. Bin dryers use stirring augers; portable dryers use vertical screws discharging at the top centre of the bin. Fig. 9 shows a portable recirculating batch dryer.

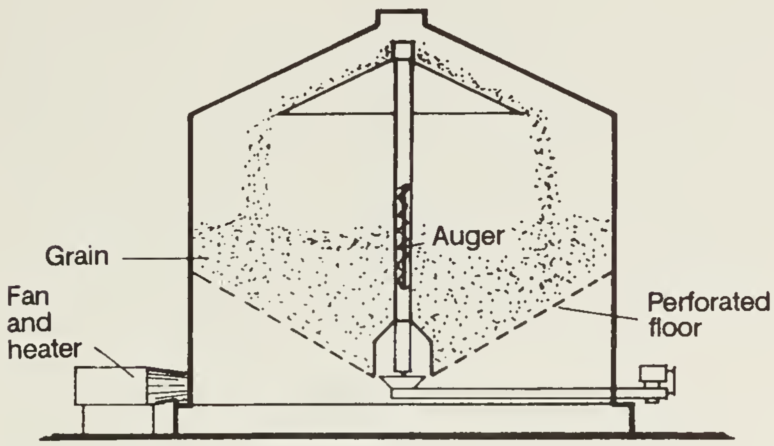


Fig. 8. Recirculating batch bin dryer.

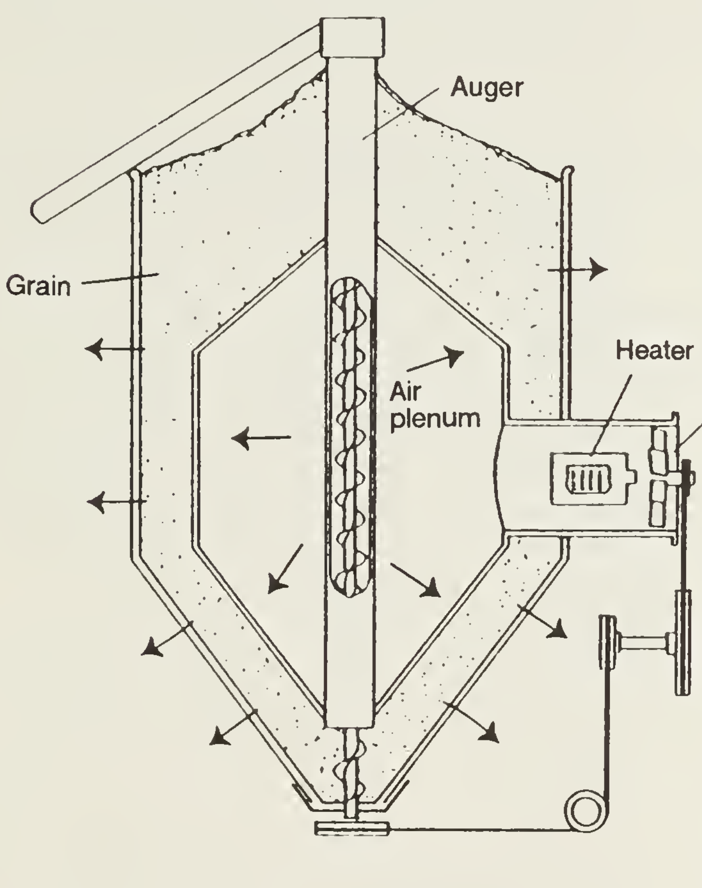


Fig. 9. Portable recirculating batch dryer.

Bin dryers, whether recirculating or not, generally rely on much lower airflow rates than other types of dryers. This trait makes bin dryers more fuel efficient. Yet, because of the lower airflow rates, the grain remains longer in the bin.

3.15 *Continuous-flow dryers* A variety of equipment allows bin dryers to dry grain on a continuous-flow basis. The most common—a tapered sweep auger—removes a layer of grain from the bottom of the drying bed and discharges it through a central hopper and unloading auger (Fig. 10). Generally, hot grain moves from the dryer to secondary cooling bins, although variations of this system permit cooling in the dryer as well.

Portable continuous-flow dryers (Fig. 11) are generally either cross-flow or rack types. Grain loads at the top of the dryer and flows down in columns around the central air supply plenum to discharge at the bottom. A temperature sensor, located in the grain column near the bottom of the drying section, regulates the flow. The operator correlates the temperature of the grain with its moisture content.

The grain cools in the lower portions of the dryer, just ahead of the discharge. Some dryer designs permit adjustment of the cooling-to-heating area to accommodate more readily conditions such as grain moisture, ambient temperature, and cooling method.

As in stationary or portable batch dryers, cross-flow batch dryers rely on an airflow perpendicular to the grain column. Very little grain mixes in the grain column so it dries from the inside out.

Rack—or parallel-flow—dryers (Fig. 12) direct the airflow through the grain parallel to the grain column. As a result, the temperature

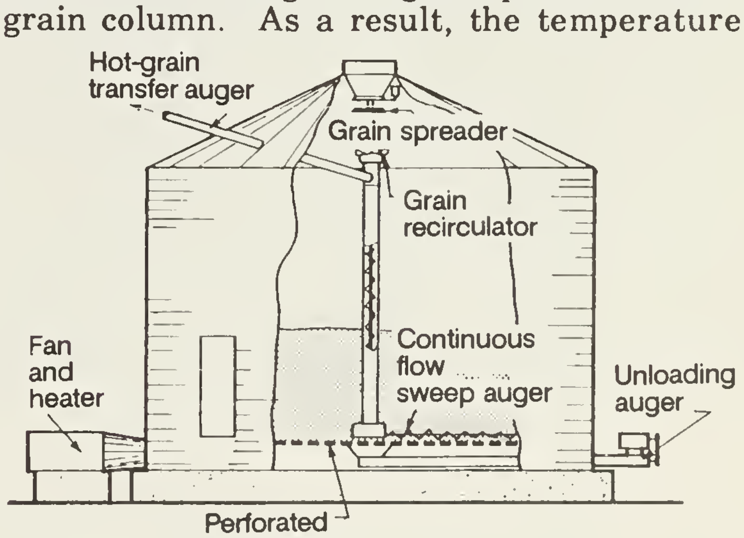


Fig. 10. Continuous-flow in-bin dryer.

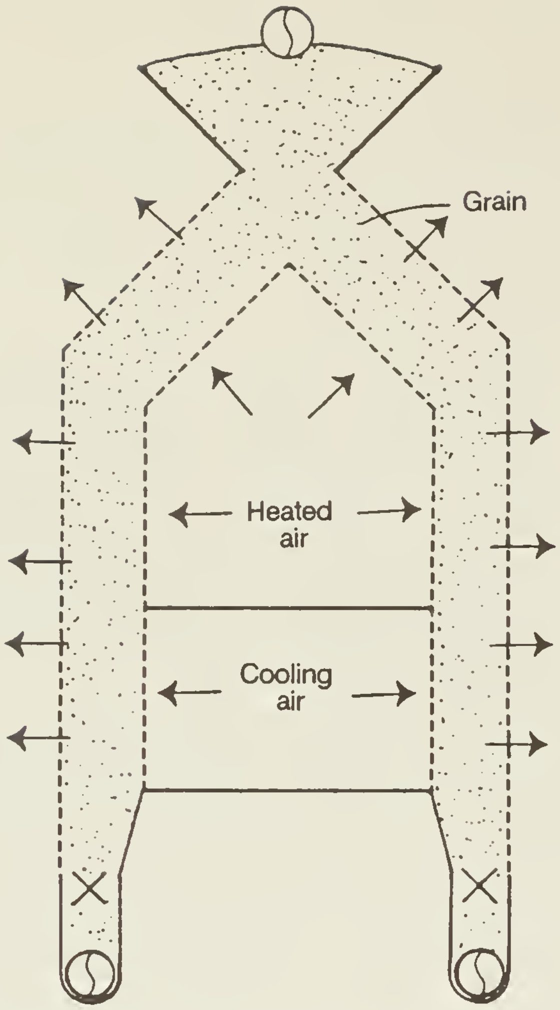


Fig. 11. Portable continuous cross-flow dryer.

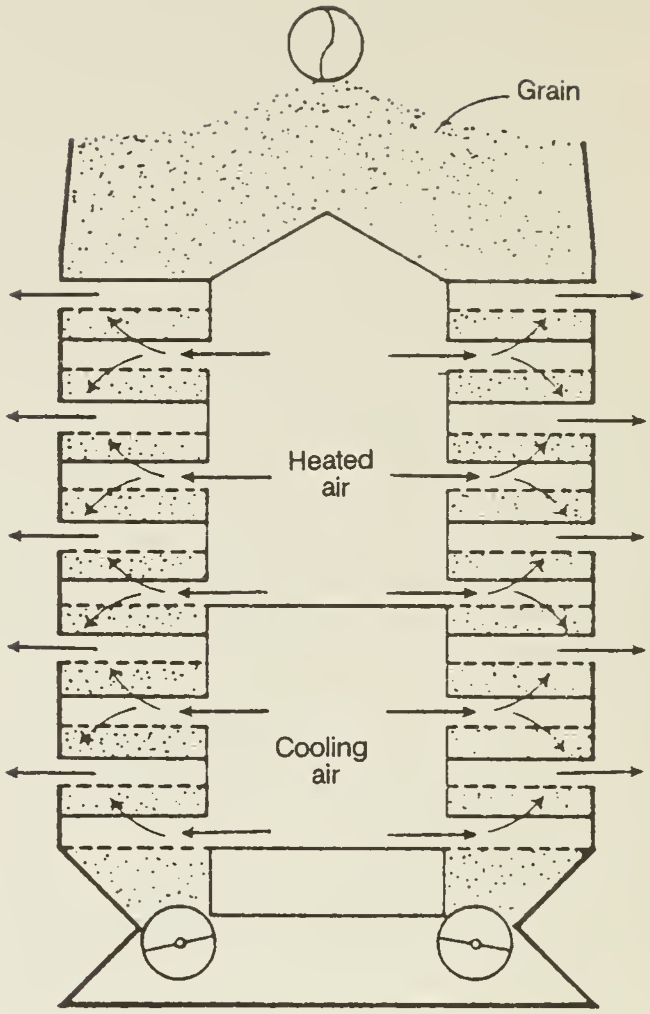


Fig. 12. Continuous parallel-flow portable dryer.

remains uniform across the column and contributes to uniform drying. The mixing grain that flows around the supply and discharge ducts also assures uniform drying. Consequently, the grain can withstand high drying temperatures in this type of dryer.

Rack dryers use no screens so they are suitable for both small and large grains.

3.16 Temperature control systems

For all dryers the air temperature varies from one location in the hot air plenum to another. This location differs for each grain type because of the changes in the airflow resistance for different grains. To prevent excessive drying, monitor the temperature at several places in the hot air plenum during the initial run of the equipment for each grain. This action allows the operator to locate the temperature sensor in the hottest area or to recalibrate the sensor so that it correlates with the higher temperatures known to exist elsewhere.

Design compromises made to maintain dryer portability or economy affect the temperature uniformity of the air supplied to the grain. These compromises include burner size and design, installation arrangement, opportunity for mixing the air before its entry into the hot air plenum, and temperature and pressure of the gas supplied to the burner.

The principles of fluid flow that dictate the use of transitions between fan discharges and large ducts are ignored, to some extent, in the design of many commercially available dryers. In most dryers the combustion device is mounted at the entrance to the hot air plenum. Thus, the heated air cannot adequately mix before it disperses in the plenum. So select burners to gain complete combustion of the gas as close as possible to the burner itself. Ideally, choose burners that yield complete combustion within about 1 m of the burner under full fire. This configuration enhances air mixing.

Duct velocities over 15 m/s allow for maximum burner output. At high duct velocities the effective capacity of the burner increases because of increased turbulence. Some models of grain dryers operate at duct velocities set to optimize performance of the burner at full fire. However, the fast-moving air passes directly into the much larger dryer plenum making uniform temperature and airflow throughout the dryer impossible to maintain. Reducing the operating temperature and mixing the dried grain counteract the problems associated with design inefficiency.

Typically, operators set the temperatures on dryers by manually adjusting modulating valves to regulate the flow of gas to the burner. The setting of the valve changes for each grain type, because of the different rates of airflow required. However, motorized valves for automatic adjustment can replace the fairly tedious, trial-and-error manual efforts. Motorized valve devices cost little and offer great time savings. Moreover, they provide more reliable control than do manual devices. For instance, motorized valves automatically allow for normal variation in ambient temperature during the day and for variation in tank pressure in propane-fired dryers.

The quality of the gas delivered to the modulating valves depends on the performance of the vaporizer being used. A vaporizer mounted inside the dryer plenum cannot compensate for the effects of fluctuations in ambient conditions. The vaporizer simply transfers heat to the gas to allow it to vaporize before it reaches the burner.

Choose an adjustable vaporizer to accommodate the widely fluctuating range of energy transfer requirements demanded by the dryer. For example, various grains require different dryer operating temperatures. As well, varying ambient conditions and tank pressures demand adjustments in the vaporizer operation.

Configuring a motorized modulator valve with an internal vaporizer or a manual modulator in conjunction with an external vaporizer offers superior temperature control for most dryers. However, an external vaporizer with a dedicated regulator for discharge gas temperature and pressure combined with a motorized modulator valve provides the best temperature control.

Ensure the gas supply line size is adequate enough to permit the necessary heat output from the burner. Smaller control components cost less and so initially appear advantageous. However, operating the system in cold weather soon reveals inadequate burner output and reduced effective tank volume in undersized units.

3.17 Temperature sensing

Most single-burner dryers rely on three temperature sensors:

- grain-temperature monitors
- low-limit sensors that shut off gas in case of flame failure
- air plenum sensors (see section 3.16)

The grain-temperature monitor, usually located in the grain near the exterior of the column, provides a grain temperature that the operator uses to estimate moisture content. On batch dryers, this monitor automatically terminates the heating cycle and initiates the cooling or unloading cycle. On some batch dryers, these monitors supplant timers that provide the same function. In continuous-flow dryers, temperature monitors control the discharge conveyors.

Because of its location, the grain-temperature monitor senses the temperature of the air moving past it, as well as the temperature of the grain. It may also sense solar heat or wind chill, depending on where the dryer is placed. Although the direct effects of the sun and wind negligibly affect the actual performance variation of a heated-air dryer, these climatic conditions seriously impair the performance of the control system. For consistent operation, shield the temperature monitors from both sun and wind.

Other electronic devices are available for use as grain-temperature monitors, but users report variations. Therefore, until the technology improves, use alternate devices cautiously.

Check and calibrate monitors annually, since reliable performance of the dryer depends on accurate temperature measurement. Ensure monitors are mounted in appropriate locations. The best location varies with both dryer and crop types. Temperature monitors can be fragile, so locate them where they are not likely to be damaged.

Monitor and adjust the dryer based on moisture and temperature measurements from grain samples removed from the dryer. Moisture meters generally do not accurately measure the moisture content of newly dried grain. So allow for a moisture rebound of 0–2%, depending on the drying rate and the initial moisture content of the grain. The moisture rebound reflects the average moisture content through the kernels after the grain is removed from the dryer. Check the rebound carefully for each condition to prevent overdrying or underdrying.

3.18 Fire prevention

Fires may occur while drying any crop with a direct-fired burner dryer. Excessively high temperatures in the hot air plenum may cause fires. Most commonly, however, fires occur because combustible materials such as chaff, dust, or straw accumulate in the burner area. The burner ignites these materials as they flow into the grain columns. To reduce the possibility of fires, prevent access of airborne combustible materials to the supply-air fan.

Oilseeds also pose fire risks because they tend to coat the interior surfaces of grain dryers with a combustible residue which, if ignited, burns very well. Clean daily any dryers used for oilseeds.

Other strategies for fire prevention include orienting the dryer relative to the prevailing wind, using a coarse filtration medium or a large filter to avoid seriously impeding airflow, and using an intake duct to relocate the intake away from hazardous material. As well, prior to drying, clean the grain to remove the fine materials prone to ignition. These strategies have been used with varying degrees of success.

Monitoring the dryer to ensure uniform grain flow, airflow, and temperature also reduces the risk of fires. Attention to these factors is especially important when drying sunflowers.

Sunflowers and canola both dry well with natural air. Take advantage of warm fall weather to remove moisture from these grains. Run the grain through the dryer without the burner operating. Besides preventing possible fires, this action also saves fuel and limits wear and tear on the dryer.

For other crops at risk of ignition during drying, constant attention is really the only means of preventing fire.

If a fire starts, close the air supply. This action may snuff out the fire if it is caught early enough. Alternatively, use a water-spray or chemical extinguisher. Keep this fire-fighting equipment within easy reach of the dryer.

3.19 Energy sources for dryers

Essentially any combustible material or energy source can be used to dry grain. For most applications in Canada, however, natural gas, propane, and electricity are the only feasible energy sources.

If using nongaseous fuels, production of combustion by-products requires that a heat exchanger be installed between the combustion chamber and the air supply. This configuration reduces fuel efficiency and increases the capital cost of the dryer.

Table 10 compares the relative fuel consumption and dryer capacities with various drying methods for corn. Notice that high-temperature drying requires a tremendous amount of energy. This situation makes electrical energy feasible only for low-temperature drying. The cost of installing electrical power at farm sites and the demand charges levied by the utility for high-power requirements also limit the use of electricity.

3.20 Low-temperature drying

Low-temperature drying entails the addition of a small amount of sensible heat to air flowing through grain. Normally the grain is situated in a bin that has a totally perforated floor.

Locating the fan-drive motor in the air stream achieves a temperature rise of 1–4°C across the fan. Alternatively, installing an electric or gas-fired heater in the supply air stream raises the temperature further and increases the drying rate. This second option suits areas where the average ambient relative humidity in autumn exceeds 75%. In most areas, however, adding small amounts of supplementary heat this way is less efficient than high-temperature drying (Mittal and Otten 1982).

As discussed in section 3.4, the increase in the rate of grain spoilage due to minor increases in temperature surpasses the increase in drying rate. Therefore, adding supplementary heat requires an increased airflow rate to speed the drying rate further. Natural-air drying consumes less energy than low-temperature drying in areas where the equilibrium relative humidity of air in contact with the drying grain exceeds the average relative humidity.

Table 10 Impact on fuel consumption and dryer capacity of various drying methods for corn dried from 25% to 15% moisture content

Method	Propane per tonne of corn at 5°C (L)	Electricity per tonne (kWh)	Relative dryer capacity
Heated-air drying	30	4.0	1.0
In-bin cooling	26	3.2	1.35
Dryeration	22	2.8	1.6
In-bin cooling and drying	12	28.0	3.0

Source: Cloud and Morey (unpublished).

Low-temperature drying incurs two significant costs:

- the cost of energy
- the cost of overdrying the grain

Low-temperature drying uses more energy than natural-air drying where natural-air drying can be used effectively. For cost effectiveness, increase the airflow to achieve a faster drying rate rather than adding supplementary heat. Increasing the airflow rate also reduces the risk of spoilage in storage and enhances the opportunity to hold tough grain over the winter for final drying in the spring.

The cost of overdrying grain is realized in a loss of saleable material.

3.21 Combination drying

The combination drying sequence includes all the functions between harvest of the tough, wet grain through to production of cool, dry grain suitable for safe storage.

The series of drying functions selected for a given operation depends on the space available, the economics of each function, the crops to be handled and their volumes, and the climatic conditions in the area.

Field conditioning of grain is the most common drying option for most grains in western Canada where the climatic conditions usually allow rapid field drying of grain before harvest. The real cost of this approach is paid in years with unusually wet weather. At these times, significant grade reduction as well as weight loss can occur when grain is rewetted by rain or poor drying. Research into the use of desiccants to speed field drying rates has shown some positive initial results.

Farm operators in eastern Canada depend on dryers for many crops, such as corn, beans, and sunflowers. As well, dryers serve as backup support in the harvest of small grains.

Ensure that all grain-handling systems can accommodate damp grain off the field. A common technique to handle damp grain involves a simple device to turn or mix grain in storage. However, if the entire volume is damp or if long storage periods are necessary, turning the grain offers only a short-term solution.

As a minimum, farm systems require an ability to move air through the grain in sufficient volume to prevent spoilage. Depending on the climatic conditions and crops grown, the air-moving system may also provide the necessary drying facilities.

Other applications require high-temperature dryers, raising the question of how to use the drying system to best advantage. Consider these observations in answering this question.

- Relatively safe storage conditions exist when the grain is both dry and cool.
- Energy costs and the risk of grain damage are highest when a high-temperature dryer is used to remove the last few points of moisture from grain that was initially wet.
- Higher temperatures, better fuel efficiency, and higher capacity for the dryer are achieved when the grain is not dried exclusively in a high-temperature dryer.
- The maximum drying capacity of a high-temperature dryer is achieved when the dryer is not expected to both dry and cool the grain. Instead, add a separate burner to the cooling section of the system. Or for batch dryers, eliminate the cooling cycle.

In line with these points, numerous combinations of methods are available to complete the drying process and cool the grain outside the high-temperature dryer. These methods are described as combination drying.

Combination drying entails the transfer of hot grain from a high-temperature dryer into storage for cooling. The methods in combination drying include

- in-bin cooling
- in-bin steeping and cooling (dryeration)
- in-bin cooling and drying

For in-bin cooling, hot grain with a moisture content of 15–16.5% is transferred to a long-term storage unit. Up to 40% of the floor space in the bin is perforated and air flows through the bin at a rate of 5–10 (L/s) per cubic metre.

For in-bin steeping and cooling, hot grain with a moisture content of 16.5–18% is transferred to a temporary storage unit where the entire floor is perforated. Air flows through the bin at a rate of 5–10 (L/s) per cubic metre.

For in-bin cooling and drying, hot grain with a moisture content of 20–22% is transferred to a long-term storage unit where the entire floor of the bin is perforated. Air flows through the bin at a rate of 5–20 (L/s) per cubic metre (Tables 3–8) for natural-air or low-temperature drying.

3.22 In-bin cooling

Run the cooling fan continuously during and after the drying until the last of the grain is cooled to ambient temperature. Cooled grain does not need to be transferred to a long-term storage bin. Expect a reduction in grain moisture content of 1% for most crops and 2%

for corn. The system efficiently uses the sensible heat in the grain to aid cooling.

To avoid condensation on the bin walls, start the cooling fan as soon as hot grain enters the bin. A fully perforated floor and sufficient airflow also help to eliminate condensation problems. Otherwise, the grain must be transferred to long-term storage.

Completely cool the grain to 0°C. See section 3.1 for details on cooling.

3.23 In-bin steeping and cooling (dryeration)

Hot grain enters the dryeration bin from the heated-air dryer. In the bin the grain steeps without airflow for at least 4–6 h before being slowly cooled.

The useful capacity of the heated-air dryer increases when it is not used for cooling. Add a separate burner to the cooling section of a continuous-flow dryer system to convert the dryer column to full heat. In a batch dryer, eliminate the cooling time entirely.

Immediately after heated-air drying, the outside of the kernels are drier than the centres. During the steeping process, moisture equalizes throughout the kernel. The slow cooling process that follows the steeping period removes two to three percentage points of moisture. The actual amount of moisture removed while cooling is proportional to the difference between the initial grain temperature and the ambient air temperature. In contrast, little water is removed during rapid in-dryer cooling.

Because less moisture needs to be removed in the high-speed dryer with dryeration, more dryer capacity is realized. Dryeration uses the heat contained in the grain to remove water during cooling. As a result, the system requires less fuel for the heated-air dryer.

Dryeration minimizes the kernel stresses developed in the final stages of heated-air drying and cooling. It also reduces stress cracking and kernel damage. The improved kernel quality yields grain less susceptible to damage during subsequent handling operations.

When using dryeration, increase the drying air temperature in heated-air dryers since the grain discharges at a higher moisture content and resides in the dryer a shorter time than it would with other methods of combination drying. Increasing the air temperature increases dryer capacity and improves the fuel efficiency of the heated-air dryer. However, if the drying-air temperature is increased, carefully monitor the grain quality. Assess the weight and milling quality and inspect for germination or stress cracking. This routine helps ensure satisfactory grain quality is maintained.

The magnitude of fuel savings and increased dryer capacity with dryeration depend on weather conditions, grain temperatures, and moisture contents. Typically, an energy savings of 20–40% and a drying capacity increase of 50–75% result. Larger increases occur when drying low-moisture grain.

For dryeration cooling, set the airflow rate at 5–10 (L/s) per cubic metre of grain. Lower rates of airflow remove more moisture but increase the risk of spoilage.

After cooling is completed, the grain is moved from the dryeration bin to aerated storage for steeping. During steeping, condensation may build up in the grain next to the bin wall. To avoid this problem, do not leave the grain in the dryeration bins for storage unless the bins have fully perforated floors. Fig. 13 illustrates the dryeration process.

3.24 *Managing dryeration systems* Dryeration systems require at least one separate cooling bin. Arrange the dryer and the cooling bins to facilitate switching grain from one bin to another and for transferring cooled grain to storage. Ideally, two or more cooling bins should be available, each holding a minimum 24-h dryer capacity.

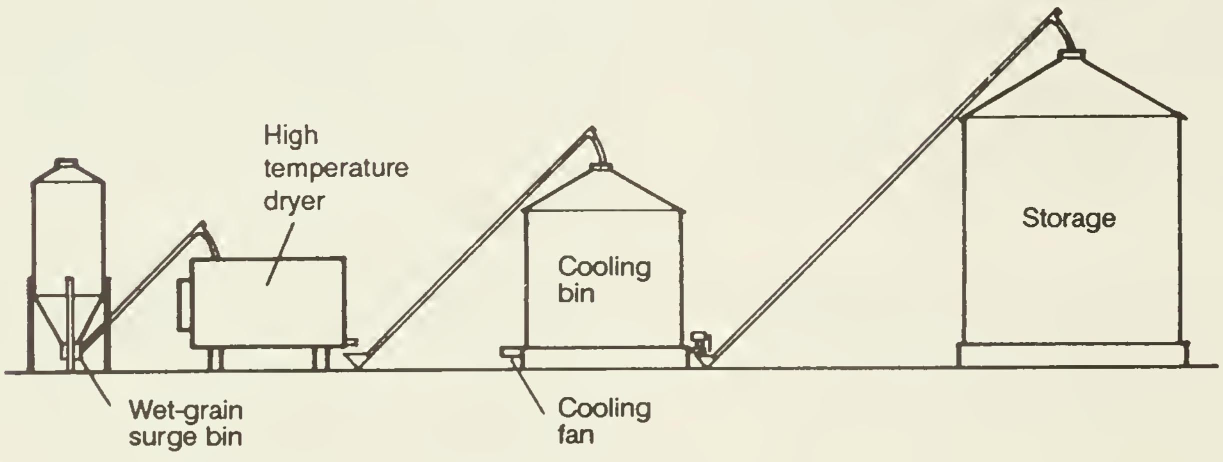


Fig. 13. In-bin steeping and cooling (dryeration).

Hot grain enters the cooling bin throughout the day and steeps with the cooling fans off. After the first hot grain delivered to the bins has steeped, the cooling fan is turned on while additional hot grain enters the bin. Set the cooling fans to start in the evening if hot grain is first delivered to the bin in the morning.

On the second morning, the dryer discharge switches to the second dryeration bin and cooling is completed in the first dryeration bin. Finally the grain moves into storage. Alternate this cooling process from bin to bin on successive days.

Large-capacity cooling bins can safely accumulate more grain than dries in one day. So if a system includes only one cooling bin, make it large enough to hold several days' drying capacity. Initially check and test the specific cooling rate for the fan-and-bin system. Use a 24-h timer or a 1–2-h percentage timer to control the operation of the cooling fan. These controllers allow operators to adjust the operating time of the fan to any percentage of the total period.

For dryeration, force the air upward through the bin so that it is exhausted at the top. In most cases, the cooling fan operates while the heated-air dryer continues to deliver hot grain to the bin. With upward airflow, the heat and moisture removed from the last grain delivered in the upper portion of the bin do not affect the grain in the lower part of the bin. Upward airflow causes heavy condensation on the roof and upper portions of the bin walls, particularly in cold weather. Nonetheless, when the cooled grain passes from the bin, the small quantity of wet grain around the walls blends with the remaining grain in the bin so that no storage problems result.

Design drying systems for easy management. In particular, the system requires two essential maintenance checks. First, operators must monitor the moisture content of the grain before and after cooling. Second, they must regularly measure the temperatures of hot grain discharged from the dryer and of cooled grain in the bins.

Provide a probe thermometer to monitor the cooling progress in the bin. Use cables to monitor temperatures in bins of 500 m^3 or larger. An indoor–outdoor thermometer with one bulb located in the top air exhaust helps follow temperatures as cooling progresses. Remember, though, a low reading at the top of the bin does not necessarily mean the bin is cool; the grain in the top centre of the bin cools last. Check the grain in the centre of the bin as well with a probe thermometer. Do not stop the fan if the bin contains any warm grain.

Exercise caution when inspecting bins during cooling of hot grain. The hot, moist air coming off the grain can be hazardous to breathe. Do not climb into the bin under these conditions. Be careful even when looking through the door into the bin because metal surfaces may be slippery and protective eyeglasses may fog up, creating a dual hazard.

3.25 In-bin cooling and drying

In this system, heated-air drying in one facility precedes in-storage cooling and natural-air or low-temperature drying in another. The heated-air drying phase of the two-stage system removes less moisture compared with single-stage drying; however, in-bin cooling and drying requires less propane or natural gas. Total savings depend on the moisture content level at which the grain discharges from the heated-air dryer. On the other hand, electrical energy requirements for the two-stage system increase as a result of fan operation. But overall, in-bin cooling and drying systems require substantially less energy than systems using heated-air dryers for both drying and cooling functions.

The drying capacity of the heated-air dryer operating in an in-bin cooling and drying system is significantly increased. Less moisture is removed in the dryer, as compared with other drying systems. In a continuous-flow dryer the cooling section of the dryer can be equipped with a propane burner to provide even more drying capacity. In-bin cooling and drying systems can realize capacity increases up to 300% for heated-air dryers.

3.26 *Managing in-bin cooling and drying systems* Do not exceed suggested moisture content levels for discharge from the heated-air dryer to the bin for cooling and drying. During the first year of operation, reduce the moisture content to 20% or less in the heated-air dryer until operators gain experience, especially at measuring the moisture content of the warm, moist grain.

The moisture content of warm grain is difficult to measure accurately. Take grain samples from the cooled grain to establish the control parameters for the bin. With the airflow rates used in natural-air drying, grain normally cools 1 or 2 h after it reaches the bin.

Start in-storage drying fans as soon as hot grain enters. This action prevents undesirable condensation build-up on the walls of the bin. During in-bin cooling, the hot, moist air discharged from the grain condenses on the bin's roof and eaves. Condensation becomes a problem if water collects, runs along roof supports, and deposits in one place.

The downspout to the bin may be a potential source of problems because moist air rising in it cools and condenses, and water returns into the bin. Close the entrance to the downspout at the bin to prevent air from traveling up the spout. Spring-loaded covers that automatically close when grain stops flowing are available but they require regular service. Ventilating the space above the grain with a supplementary roof-mounted exhaust also controls condensation but this solution requires additional air inlets on the underside of the bin roof.

Besides these few special management procedures, in-bin cooling and drying systems require essentially the same practices as natural-air drying and low-temperature drying systems, including setting airflow rates, operating fans, and monitoring grain conditions (see section 3.24).

3.27 Fan selection and system design

Proper component selection and design, proper installation, and good management assure the satisfactory performance of a system for cooling and drying grain. Before designing the system, know the crop to be stored and the storage bin dimensions. These data, along with additional information on specific applications, permit sizing or selection of fans, ducts, bin vents, and transitions. It also helps determine the necessary sizes of perforated floor areas. References cited at the end of this manual contain application information.

In particular, establish values for these design criteria:

- airflow rate
- fan capacity
- static pressure

Set the airflow rate according to the crop and the bin volume. Use the values listed in Tables 3–8.

Tables 3–8 illustrate the level of risk taken in selecting an airflow rate for a particular set of conditions. For a given crop and moisture content, the rate of spoilage depends entirely on climatic conditions.

For example, Table 6 reflects the actual climatic conditions recorded over 12 years, from 1962 to 1973. Each year differed from the others in the rate at which corn dried in natural air, and the rate at which corn spoiled in ambient conditions. The designation "2nd worst year" indicates that grain dried before it spoiled in all but 1 of the 12 years with an airflow rate as shown in the table. The designation "worst year" identifies the airflow rate required to prevent spoilage in all 12 years.

Tables 3–8 also list data for determining airflow requirements.

The static pressure against which the fan must operate, and hence the pressure drop (Δp) across the grain, depends on the resistance to airflow, the grain depth (H_g), the effects of using a grain spreader (K_s), and the effects of the head loss caused by a perforated area less than the total floor area of the storage (K_p).

The velocity of the air traveling through the grain and the grain type affect the resistance to airflow. The velocity is simply the total airflow rate (measured in litres per second) divided by the cross-sectional area of the bin (measured in metres). Fig. 14 lists the pressure drop (Δp) for several grains. The data in this figure refer to airflow resistance for Argentine canola, a large seed. The resistance to airflow for smaller varieties of canola is approximately 60% of that predicted for Argentine canola (Jayas and Sokhansanj 1985).

The effects of a grain spreader in increasing the resistance can be expressed as a constant (K_s) for each grain type.

Grain	K_s
Barley	1.5
Corn	2.0
Flax	1.0
Canola	2.2
Sunflowers	1.5
Wheat	1.3

Sources: Friesen and Huminicki (1986) and Jayas and Sokhansanj (1985).

A partially perforated floor also increases the resistance to airflow by a constant amount (K_p) for each type of grain.

% of floor perforated	K_p for wheat, barley, sunflowers, flax, corn, and canola
100	1.0
40	1.1
25	1.3
15	1.5

The total static pressure of the system (p_s) is represented by this equation:

$$p_s = \Delta p \times H_g \times K_s \times K_p$$

Size the ducts and transitions to conform with the following standard principles defined by the American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE).

- The duct velocity should not exceed 7.5 m/s (7500 (L/s)/m^2) to minimize head loss and noise.
- Transitions from the fan discharge to the supply duct should not create abrupt changes in dimension. An expansion of 15–20° is preferred. As well, do not create restrictions in the cross-sectional area of the ducts.

Calculate the required duct area in square metres. Divide the total airflow rate (litres per second) by 7500 (L/s)/m^2.

Size the perforated area required in relation to the total airflow. The desired face velocity (the airflow per unit area of grain surface in the bin) depends on the percentage of perforated flooring and on the type of grain. The maximum recommended velocity can be generalized this way:

- cereals 200 mm/s
- canola 75 mm/s

Note that the units mm/s are equivalent to and used in place of (L/s)/m^2 in most applications.

Size the bin vents to yield an outlet velocity of less than 5000 (L/s)/m^2. This value minimizes flow restriction. For louvered vents, use the area of the actual discharge opening (unrestricted area) to calculate the outlet velocity.

Positive ventilation of the airspace above the grain, if provided, should exceed the airflow through the grain. Provide access for the excess airflow to prevent roof collapse and size the ducts for an outlet velocity less than 5000 (L/s)/m^2.

3.28 Sample problems

3.29 *Aeration system parameters* Calculate the system parameters for a load of wheat to be aerated in a bin with a diameter of 7.3 m and an eave height of 6.7 m. Use a grain spreader to load the bin. Choose the maximum common airflow rate for aeration from Table 11 and refer to Fig. 14.

Level depth of grain (H_g)

= 6.7 m

Airflow requirement

= common airflow rate × grain depth

= 2 (L/s)/m^3 × 6.7 m

= 13.4 (L/s)/m^2

Airflow rate

= airflow requirement × grain surface area

= 13.4 (L/s)/m^2 × π × (7.3 /4) m^2

= 561 L/s

Minimum recommended perforated floor area for an aeration system from Table 11 is 15%. The airflow resistance factor (K_p) for a 15% perforated floor is 1.5.

Static pressure required (p_s)

$= \Delta p \times H_g \times K_p \times K_s$

= 54 Pa/m × 6.7 m × 1.5 × 1.3

= 706 Pa

Table 11 Basic design recommendations for various drying and cooling methods

Process	Percentage above dry	Common airflow rates (L/s·m^3)	Minimum perforated floor area (%)	Transfer for final storage
Aeration	0	1–2	15	no
Natural-air drying	3–6	10–30	100	no
Dryeration	2–3	5–10	40	yes
			100	no
In-storage cooling	1	5–10	40	no

Note: Select the airflow rates and perforated floor areas based on local environmental conditions, initial moisture content, crop value, and economic constraints.

Source: Friesen and Huminicki (1986).

where Δp = pressure drop across the grain
= 54 Pa/m with airflow of 13.4 (L/s)/m^2 based on the data in Fig. 14

H_g = bin depth (m)

K_p = airflow resistance factor for a 15% perforated floor

K_s = 1.3 because the design calls for a spreader

Minimum duct area

= airflow rate × maximum duct velocity

= 561 L/s / 7500 (L/s)/m^2

= 0.075 m^2

Minimum bin vent area

= airflow rate × maximum outlet velocity

= 561 L/s / 5000 (L/s)/m^2

= 0.11 m^2

3.30 *Barley cooled in storage* Calculate the system parameters for a load of barley to be cooled in storage in a bin with a diameter of 5.8 m and an eave height of 4.7 m. From Table 11, choose 8 (L/s)/m^3 as the common airflow rate for in-storage cooling.

Level depth of grain (H_g)

= 4.7 m

Airflow requirement

= common airflow rate × grain depth

= 8 (L/s)/m^3 × 4.7 m

= 37.6 (L/s)/m^2

Airflow rate

= airflow requirement × grain surface area

= 37.6 (L/s)/m^2 × π × (5.8 /4) m^2

= 993 L/s

Minimum recommended perforated floor area for an in-bin cooling system is 40% (Table 11). The airflow resistance factor (K_p) for a 40% perforated floor is 1.1.

Static pressure required (p_s)

= $\Delta p \times H_g \times K_p \times K_s$

= 146 Pa/m × 4.7 m × 1.1 × 1.0

= 755 Pa

where Δp = pressure drop across the grain
= 146 Pa/m for barley with airflow of 37.6 (L/s)/m^2 based on the data in Fig. 14

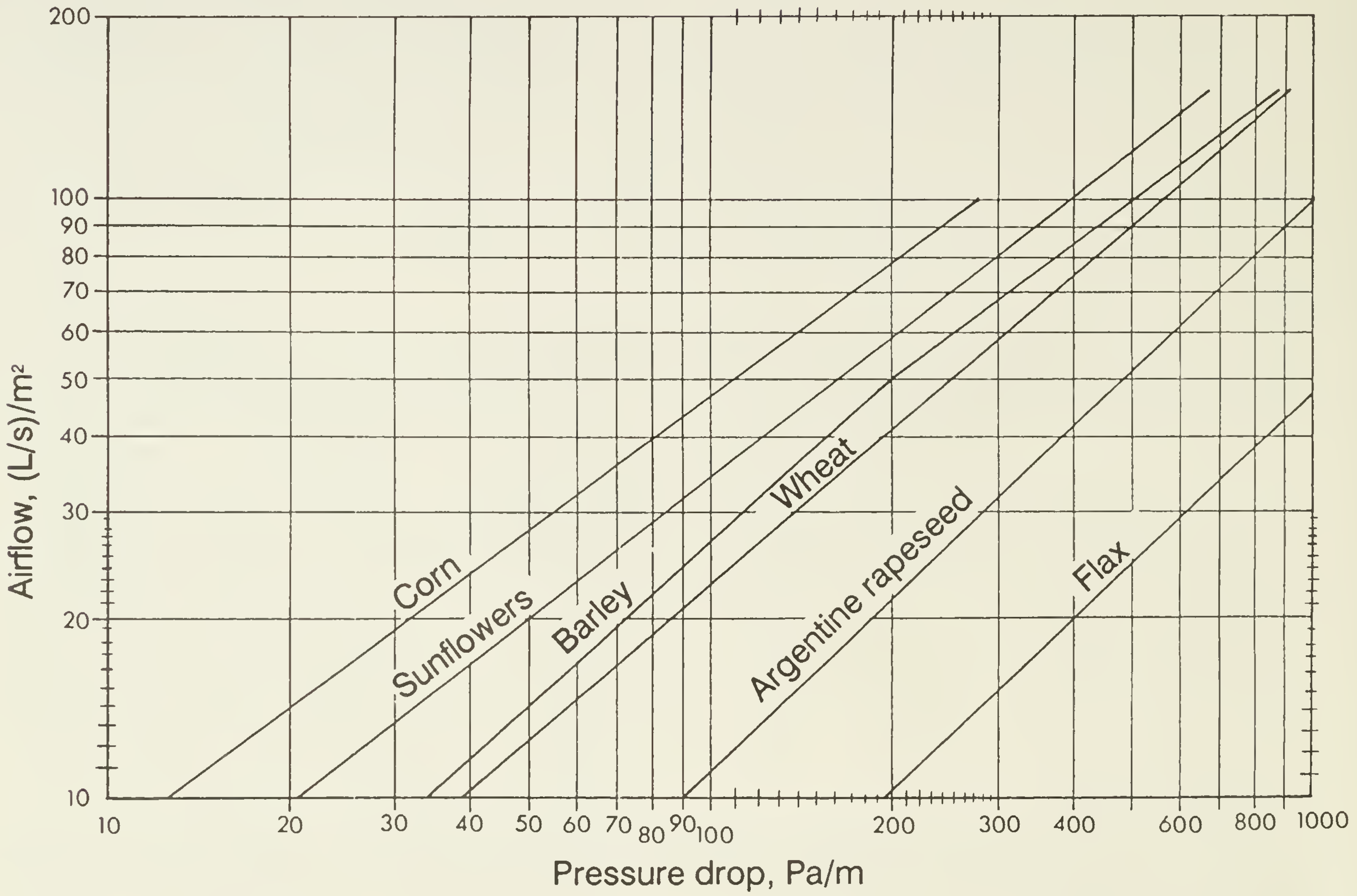


Fig. 14. Resistance of grains and oilseeds to airflow.

H_g = bin depth (m)

K_p = head loss because the perforated area is less than the total floor area

K_s = 1.0 because a spreader is not used

Minimum duct area

= 993 L/s / 7500 (L/s)/m²

= 0.13 m²

Minimum bin vent area

= 993 L/s / 5000 (L/s)/m²

= 0.20 m²

3.31 *Natural-air drying of wheat* Calculate the system parameters for a load of wheat to be natural-air dried from an initial moisture content of 18% in a bin with a diameter of 6.7 m and an eave height of 6.1 m. The wheat was harvested 15 September in Swift Current, Sask.

Table 5 indicates a recommended airflow rate of 4.4 (L/s)/m³ for wheat with a moisture content of 18%. However, Table 11 suggests a common airflow rate of 10–30 (L/s)/m³ for natural-air drying. Base the system design decisions on an anticipated range of grain moisture contents, for example 16–20%. So choose a system airflow rate of 13 (L/s)/m³.

Level depth of grain (H_g)

= 6.1 m

Airflow requirement

= common airflow rate × grain depth

= 13.0 (L/s)/m³ × 6.1 m

= 79.3 (L/s)/m²

Airflow rate

= airflow requirement × grain surface area

= 79.3 (L/s)/m² × 35.3 m²

= 2796 L/s

Minimum recommended perforated floor area for natural-air drying is 100% (Table 11). The airflow resistance factor (K_p) for a 100% perforated floor is 1.0.

Static pressure required (p_s)

$= \Delta p \times H_g \times K_p \times K_s$

= 420 Pa/m × 6.1 m × 1.0 × 1.0

= 2562 Pa

where Δp = pressure drop across the grain

= 420 Pa/m for wheat with airflow of 79.3 (L/s)/m³ based on the data in Fig. 14

H_g = bin depth (m)

K_p = head loss because the perforated area is less than the total floor area

K_s = 1.0 because a spreader is not used

Minimum duct area

= airflow rate × maximum duct velocity

= 2796 L/s / 7500 (L/s)/m²

= 0.37 m²

Minimum bin vent area

= airflow rate × maximum outlet velocity

= 27965 L/s / 5000 (L/s)/m²

= 0.56 m²

3.32 *Corn cooled by dryeration* Calculate the system parameters for a load of corn cooled by dryeration in a bin with a diameter of 7.3 m and an eave height of 6.5 m. Use a grain spreader in the system and transfer the corn to final storage following cooling. Choose a common airflow rate of 10 (L/s)/m³ (Table 11).

Level depth of grain (H_g)

= 6.5 m

Airflow requirement

= common airflow rate × grain depth

= 10 (L/s)/m³ × 6.5 m

= 65 (L/s)/m²

Airflow rate

= airflow requirement × grain surface area

= 65 (L/s)/m² × 41.9 m²

= 2725 L/s

Minimum perforated floor area is 40% for dryeration when the grain is transferred to final storage for cooling. The airflow resistance factor (K_p) for a 40% perforated floor is 1.1.

Static pressure required (p_s)

$= \Delta p \times H_g \times K_p \times K_s$

= 157 Pa/m × 6.5 m × 1.1 × 2.0

= 2245 Pa

where Δp = pressure drop across the grain

= 157 Pa/m for corn with airflow of 65 (L/s)/m³ based on the data in Fig. 14

H_g = bin depth (m)

K_p = head loss because the perforated area is less than the total floor area

K_s = 2.0 because the design calls for a spreader

Minimum duct area

= airflow rate × maximum duct velocity

= 2725 L/s / 7500 (L/s)/m^2

= 0.36 m^2

Minimum bin vent area

= airflow rate × maximum outlet velocity

= 2725 L/s / 5000 (L/s)/m^2

= 0.55 m^2

4 SYSTEM SELECTION CRITERIA

Four interdependent units make up grain storage and conditioning systems:

- storage
- drying
- interface of drying and storage
- materials handling

Several value judgments go into the decisions involved in selecting system components. The information presented in the first three parts of this manual should help in understanding how those decisions are made. Use this section of the manual to aid in selecting the actual components for a complete grain storage and conditioning system.

4.1 Storage

First establish volume requirements. Industrial facilities normally gauge the storage volume required according to their strategic requirements. As a minimum they provide storage sufficient to maintain stock that permits uninterrupted plant operation during inclement weather or holidays. Storage capacity beyond this permits the industry to take advantage of cyclical prices or grain availability.

Commercial facilities generally base their storage requirements on the anticipated annual throughput divided by the number of turnovers of stock required to render the facility economically viable. Turnovers usually occur 7.5–10 times per year on new construction of inland facilities. The gross volume is divided into the number of bins required to service the crops and grades produced in the area. The number of crops and grades generally vary from 15 to 35. Productivity of the area and reasonable transportation distances by truck dictate the anticipated annual throughput. Capacity typically ranges from 3500 to 5000 t for inland facilities and from 25 000 to 75 000 t for terminals.

The productivity of farms and the marketing inclinations of the operators determine farm storage requirements.

If the grain is marketed through the quota system or for feeding livestock, the system must include storage for nearly the entire crop. Cash crops or crops grown on contract do not require storage because they are normally taken directly from field to market.

The crop type and the volume requirements together set the number of bins required. The crop type largely dictates the bin depth because this parameter affects product degradation during filling. The need to force air through the bin during storage also constrains bin depth. Limitations in bin depth then dictate the required total cross-sectional area of bins. Finally, the practical horizontal dimension of the bin along with the number of crop varieties and grades normally grown in the area establishes the minimum number of bins.

The smallest number of bins that satisfies the above criteria represents the most economical storage possible for a given situation.

Storage facilities are normally constructed of wood, concrete, or steel. The natural insulating properties of wood provide the advantage of reduced moisture and related problems in storage. Wooden granaries are, however, relatively expensive for small volumes and are susceptible to rodents and fire.

For multibin storage facilities larger than 3500 t the decision is whether to use steel or concrete bins. Smaller concrete bins require repetitive form work thus increasing initial construction costs. Concrete's natural thermal buffering reduces the need for aeration in storage. Nevertheless, aeration is required where crops are stored for long periods. Include temperature-monitoring equipment to detect the onset of spoilage. However, the advantages of concrete, particularly for deep bins, disappear when easily damaged crops are to be stored.

Farm operations most commonly rely on steel storage bins because of several characteristics of steel: low capital cost, quick erection, and wide range of sizes. Steel bins lack the thermal buffering and insulating traits of concrete and wood but lend themselves to modular development and system expansion.

Steel storage bins are normally cylindrical for maximum structural efficiency in hoop tension. Square bins are only cost effective where space is limited, for example, for working bins that service a secondary process operation. Round bins over 4 m in diameter are corrugated to provide sectional stability with a minimum of steel.

For deep bins, the thickness of the wall increases from the top to the bottom of the bin to withstand the increasing load. Shallow bins, however, rely totally on the sectional stability of the wall material to resist crushing. As the bin depth increases, the vertical load exerted by material friction on the walls also increases substantially. Because of these large vertical forces, use stiffeners or mini-columns bolted to the bin wall to increase the vertical load capacity. The structural integrity of the bin also requires adequate fastening of the wall panels to these columns plus support at the bottom of the columns. Follow the supplier's instructions for fastening and supporting the bin elements.

Although stiffeners significantly increase the maximum depth of storage bin possible from light-gauge steel, they add significantly to the cost. Yet they offer a very cost-effective means of increasing the long-term reliability of the storage, thus reducing the total cost of a storage system. They limit bin shrinkage, or compression of the corrugated panels over time. Unstiffened bins commonly suffer from these problems. Stiffeners also reduce the risk of nonuniform panel compression, which results from slightly off-centre loading or unloading of the bin.

A significantly reduced cost for the materials-handling equipment particularly illustrates the savings attributable to use of bin stiffeners. Because stiffeners allow construction of higher bins, fewer bins require filling. Likewise, the system requires fewer conveyors and discharge equipment. The savings are especially evident if portable augers are not used to load and unload the storage bins.

Despite the advantages of deep bins, weigh their use against the increased resistance to airflow that the deeper bins produce.

Of critical importance, the bin wall-to-foundation connection affects both the performance of the bin as a structure and its ability to maintain grain quality. To preserve the structure and to accept the uniform loads transmitted by the bin wall, this connection must be level and uniform. Lack of bearing uniformity at this connection concentrates the vertical loads in the bin wall and predisposes that area to crushing. At the extreme, a poorly designed wall connection causes bin failure. A rigid, monolithic foundation maximizes bin longevity.

Fluctuations in temperature and load from stored grain cause the connection between the foundation and the bin wall to shift constantly. Maintain the seal annually to prevent moisture from migrating into the bottom of the bin. This seal permits some differential movement and prevents escape of air supplied under a fully perforated floor. The pressure of the air may open the seal or identify a fault in the bin-to-foundation connection. Inspect the seal annually prior to filling the bin and again after the air supply system is started up in bins with fully perforated floors.

Place the interior floor above the bin-to-foundation connection to reduce migration of moisture into the bin. Sloping the foundation exterior to the bin away from the bin wall also assists in moisture control.

Various arrangements of ducts and perforated floors are available as well. Some of the most common include a single perforated duct across the bin floor, a cross-shaped duct, a V-shaped duct arrangement, and a rectangular perforated area in the centre of the bin. Take care to provide sufficient cross-sectional area of duct around the central unloading bin well.

Ducts also provide a conduit for the unloading screw. Seal around the conveyor at the point of egress from the bin to prevent undesirable leakage of air. Refer to section 3.26 for information on duct sizing. Ensure at least 15% of the bin floor area is perforated in bins up to 6 m high.

Flat grain-storage bins are more difficult than conventional round bins to aerate effectively. The shallow, flat bins allow grain to collect in piles of various depths. Increased airflow relieves some of the problems created by poor air distribution in the shallow bins, so use airflow rates of 2–3 (L/s) per cubic metre of bin space. Duct arrangement also enhances successful aeration of flat storage bins.

Fig. 15 shows some typical duct arrangements for flat bins. Arrangement *A* permits only a portion of the building to be used for storage or aeration during a protracted unloading period. Uncovered air ducts are blocked off. Arrangement *B* requires that the single air duct be covered from the beginning to the end of the aeration process.

Duct arrangements perform well if they are correctly sized and the ducts are properly spaced. Keep the longest air path from the duct to the grain surface no more than 1.5 times the shortest air path. Fig. 16 shows the number

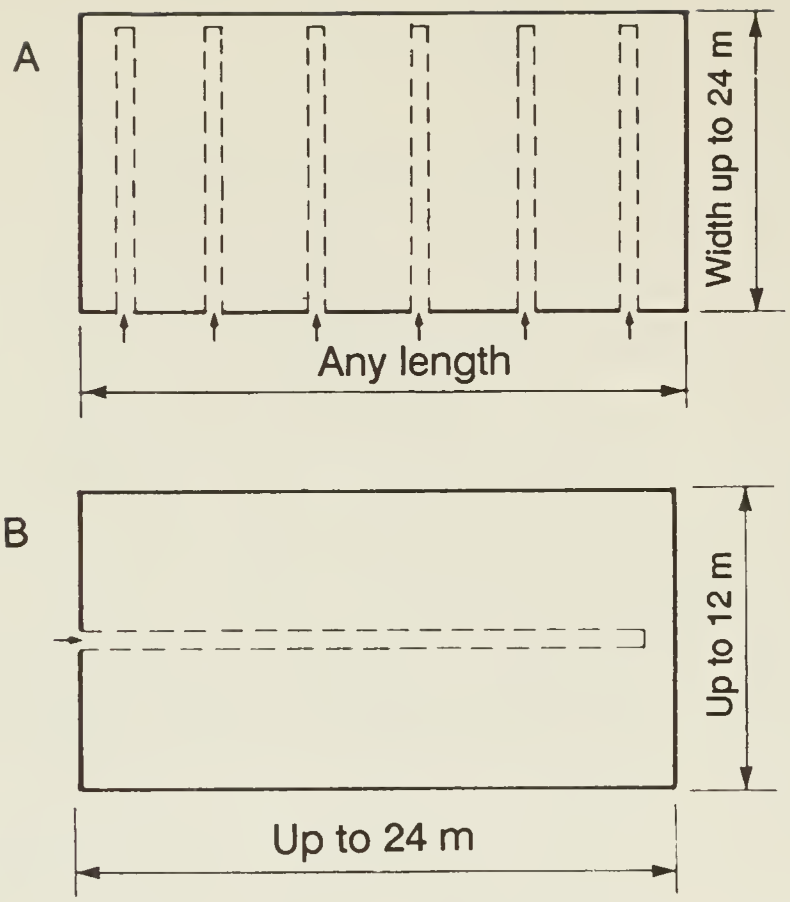


Fig. 15. Aeration duct arrangements for flat storage bins.

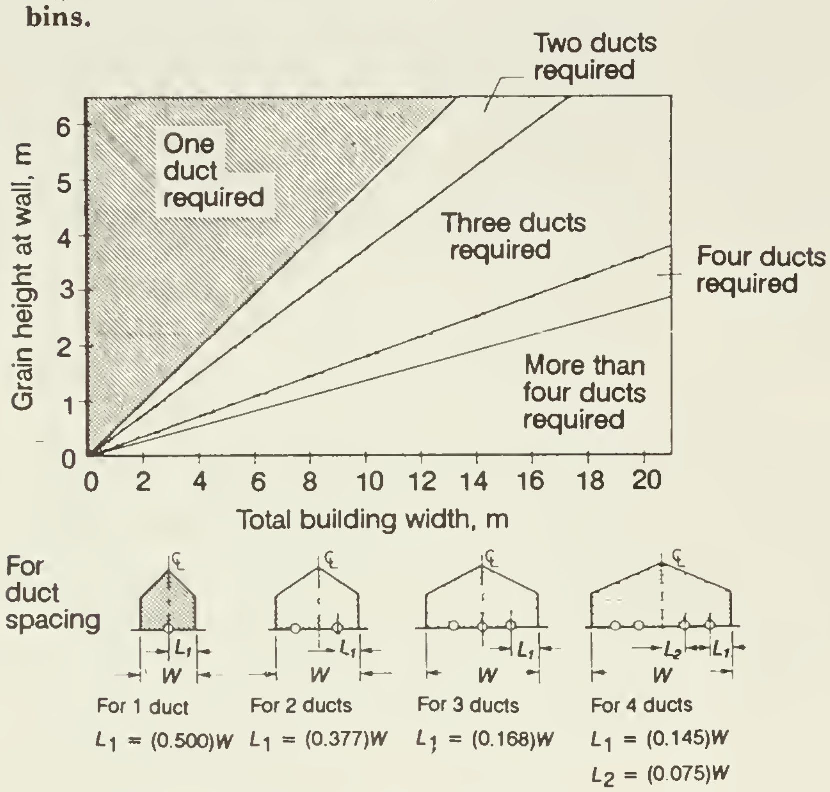


Fig. 16. Lengthwise duct spacing for rectangular buildings.

and spacing of the ducts. For level-filled flat storage bins, the duct spacing equals the grain depth.

Equip all storage systems with at least two bins having totally perforated floors. Use them for any of the purposes discussed previously in this manual, or simply for holding problem lots of grain until remedial measures can be taken, for example, for holding wet grain until a high-temperature dryer is available. The flexibility and safety provided by moving 10–30 (L/s) of ambient air through each cubic meter of grain in a perforated bin represents the cheapest means of avoiding losses in grain quality or quantity. Use these same storage units, as well, for natural-air or low-temperature drying, or to increase dryer capacity through combination drying.

4.2 *Storage bin size* When selecting the bin size for a particular operation, keep these factors in mind:

- the crops normally grown in the area
- the average size of field seeded with a single crop and the yield normally expected for each crop
- resistance to airflow demonstrated by the stored grains

From a materials-handling standpoint, settle on a single bin size for a particular operation. Incorporating two or three bin sizes in a single storage system simply adds complexity.

Consider the susceptibility to damage of the crops grown in an area. Dicotyledonous crops, such as peas or beans, cannot tolerate long drops into deep storage bins. Long drops damage corn more than wheat. For fragile crops, install shallow bins with large diameters; or use pea ladders to reduce the negative effect of long drops into deep bins.

The average size of a seeded field multiplied by the average yield of the crop with the smallest harvest offers an economic compromise by which to select bin size.

For example, consider wheat growing in fields averaging 65 ha. The fields provide an average yield of 2.5 t/ha.

Bin size

$= 65\ \text{ha} \times 2.5\ \text{t/ha} \times 1.3\ \text{m}^3/\text{t}$

$= 211\ \text{m}^3$

Select a bin size of 200 m^3.

If the 65-ha fields contained flax instead of wheat, the harvested crop would only fill half the 200-m^3 bin. And if the crop were corn, two 200-m^3 bins would be needed.

Another farm raising soybeans on fields averaging 20 ha might require a bin of 100 m^3. Two bins would be needed to store corn harvested from the same field. Alternately two bin sizes of 100 and 200 m^3 could handle both crops.

The airflow resistance of stored grains dictates the diameter of the bin. The fan performance characteristics of commercial or light industrial fans limit the usable bin depth.

As an aid in determining bin sizes, estimate the air pressure and flow required to aerate the grain (see section 3.26 and Tables 3–8) and understand the characteristics of fans commercially available.

For example, a wheat farm with fields of 65 ha yielding 2.5 t/ha requires 200 m^3 storage bins. If the owner wishes to accommodate natural-air drying of canola, bins of what diameter should be selected?

From Table 11, the required airflow rate is 20 (L/s) per cubic metre of canola.

Fan delivery

= 20 (L/s)/m^3 × 200 m^3

= 4000 L/s

For this airflow rate a centrifugal fan operating at an average 3450 r/min would produce approximately 1000 Pa of static pressure. Based on Fig. 14, a grain depth of 2.3 m would yield this airflow:

Airflow

= 20 (L/s)/m^3 × 2.3 m

= 46 (L/s)/m^2

A pressure drop of 420 Pa/m results (Fig. 14).

Actual pressure loss

= 420 Pa/m × 2.3 m

= 966 Pa

From these calculations, a bin 2.3 m deep offers the most practical option for drying canola using the natural-air method.

Perform similar calculations to determine maximum practical bin depths for any other operating scenario. For example, a grain depth of 6 m may be acceptable if the grain was aerated instead of natural-air dried. Alternatively, based on the requirement for a storage volume of 200 m^3 in a bin with an eave height of 2.3 m, select a bin 11 m in diameter to dry canola with natural air or a bin 6.8 m in diameter to aerate it.

In areas of ambient relative humidity less than 60% and where minimal oilseed crops are grown, the crops can usually be harvested dry. Farmers in these areas generally designate a couple of storage bins for natural-air drying. Aeration systems probably equip the other storage bins.

In areas where relative humidity commonly exceeds 75%, natural-air drying systems offer little value because of their drying inefficiency, compared with heated-air drying systems (Mittal and Otten 1982). Size the storage systems, then, for the harvest volumes required and equip the storage bins with aeration devices to cool the grain and maintain uniform temperatures.

4.3 Drying systems

Two factors figure prominently in the design of grain-drying systems:

- the reasons for drying
- the operational priorities

Reasons for drying grain relate to the crops grown, and the geographic and climatic conditions.

Access to drying facilities is especially important if an operator grows crops that must be harvested wet because of biological factors. For example, farmers normally harvest corn wet and dry it for sale. The fragility of corn in storage and the transportation costs of wet corn make it unsuitable for sale without drying. Sunflowers, too, are normally dried after harvest, before sale. In contrast, corn destined for use as feed can be stored as a high-moisture grain.

For some crops, drying is discretionary; but economics justify it. In many cases, shortage of labor means farmers must harvest continuously. In such cases the dryer becomes a normal part of the harvesting operation. Crops such as canola, peas, and beans, if left to dry in the field, shell during or before combining. A loss of yield results. Shelling losses, particularly with canola, can exceed the cost of early harvest and drying.

Straight combining of many crops is standard practice in areas where climatic conditions do not permit drying in a swath. With straight combining many farmers reduce both the number of operations required in the field and the risk of grade and dry-matter loss in the swath.

Abnormal climatic conditions can force the drying of significant percentages of crops to make them suitable for storage or sale.

The type of drying system appropriate for an individual operation depends on the level of need and the frequency of use. Some situations justify specialty drying equipment, for example, when high volumes of only one or two crops are harvested and dryers are used annually.

Alternatively, operations drying a wide variety of crops with an even wider variety of moisture contents and grain quality conditions demand drying flexibility. Commercial facilities offering custom drying services fall into this category. They contend with a wide variety of crops in various quantities and conditions.

Other operations call for simplicity and low capital cost. The dryer may be required rarely, or a high-temperature dryer would only supplement the mainstay of natural-air drying in storage. Many commercial facilities maintain equipment to dry grain that they have purchased. This grain has been tough, damp, or degraded in storage. Drying facilities receiving such materials require simple operations. They normally handle high volumes of relatively dry grain.

Fuel efficiency sits high on the priority list of many operators. Energy conservation and recovery systems, and alternate fuel systems, have yet to demonstrate cost effectiveness. The capital costs are too high for most drying facilities that do not operate for long periods, that is, for more than one crop or commercially. Industrial applications can recover some return on investment for heat recovery systems where the system operates longer than in normal farm use. Systems offering more predictable and significant fuel savings include natural-air drying, especially in areas of low humidity, and combination drying. As well, recycling the cooling air from a continuous-flow dryer can also yield fuel savings of 10–15%.

In selecting a dryer, consider these five factors:

- the dryer's ability to dry grain without quality loss
- fuel efficiency
- the dryer's ability to accommodate the full range of crop varieties and moisture contents expected
- the rate at which the dryer removes moisture
- the rate at which grain can move through the dryer

Set the moisture removal rate for the dryer according to the grain supply expected in a 24-h period. Daily drying capacity should equal the amount of water contained in the wettest quantity of grain that the operator is likely to harvest during that time.

Calculate the quantity of moisture to be removed this way:

$$q = \left[m_f \times \frac{(1 - M_f)}{(1 - M_i)} \right] - m_f$$

where q = quantity of water removed (kg)

m_f = mass of grain at final moisture content (kg)

M_f = final moisture content

M_i = initial moisture content

For example, an operator harvests corn at a dry-corn rate of 10 t/h, for 8 h/day. Initially the harvested corn has a moisture content of 30%. Calculate the moisture removal rate if the corn is dried to 14.4% moisture content.

$$q = \left[1000\text{ kg} \times \frac{(1 - 0.144)}{(1 - 0.30)} \right] - 1000\text{ kg}$$

$$= 223\text{ kg/t}$$

This calculation indicates 223 kg of water is removed from 1 t of corn with an initial moisture content of 30% and a final moisture content of 14.4%.

The rate of moisture removal

$$= (223\text{ kg/t}) \times (10\text{ t/h}) \times \frac{(8\text{ h/day})}{24\text{ h/day}}$$

$$= 740\text{ kg of water per hour}$$

Manufacturers often specify dryer capacities in tonnes per hour of "dry-hot" and "dry-cool" grain at 10% moisture removal. Yellow dent corn is the most common crop dried in commercial dryers. Consequently, manufacturers of drying systems generally publish comparative performance data for removal of 10% of the moisture from this crop.

Drying rates vary with grain moisture content, dryer operating temperature, and grain type. Dryer capacity also varies with these factors. However, three additional important issues enter into the design decisions surrounding dryer selection.

First, grain moisture content is designated on a wet basis rather than a dry basis. Therefore, the quantity of water contained in a tonne of grain increases with the grain moisture content; that is, more water is removed in drying grain to a moisture content of 25% from 30% than in drying the same grain to 15% moisture from 20%. So design the drying system to handle the maximum expected rate of moisture removal.

Second, evaporating the last kilogram of moisture from dry grain requires more energy and time than evaporating the first kilogram. Ensure the drying system can dry the grain to a moisture content of 14% from an initial 24%.

Finally, two factors significantly influence dryer capacity:

- the ability to move air through the drying crop
- the rate at which each crop releases moisture

Do not select a dryer on the basis of its rated capacity for a single crop. Consider, also, the other possible uses for the dryer.

An operator drying corn at a rate that removes 223 kg of moisture per tonne wants to know the average moisture removal rate for the system.

The average amount of moisture removed per percentage point

= 223 kg/t / (30 – 14.4)%/t

= 14.3 kg/%

The average moisture removed over 10 percentage points

= 14.3 kg × 10

= 143 kg/t

Performance data for removing 10% of the moisture from crops is commonly stated.

The dryer capacity rating required for 10% moisture removal equals the total moisture to be removed per hour divided by the moisture removal rate per tonne across 10 percentage points

= 740 kg/h / 143 kg/t

= 5.2 t/h of dry grain

Note, however, this dryer capacity rating varies significantly for different crops.

As mentioned earlier, dryer capacity represents the average capacity of the dryer. For continuous-flow dryers, capacity is a steady-state condition. For batch dryers, however, capacity also reflects the time in which no drying is taking place, that is, during loading, cooling, and emptying.

4.4 Dryer loading and unloading systems

Besides the dryer, a drying system also consists of:

- a surge bin for loading wet grain
- an unloading system that discharges the dry grain into storage

Do not overlook either component in designing a total drying system.

The surge bin holds the wet grain until the dryer can receive it. In some cases the truck box serves this function but it makes a relatively expensive holding bin. Instead, use a hopper-bottom bin for temporary holding. Flat-bottom bins, equipped with airflow sufficient to delay spoilage, also offer alternative storage capacity.

Size the surge bin in relation to the dryer capacity and the harvesting rate. In the example involving corn harvested at 10 t/h and dried from 30% moisture to 14.4%, the capacity required is the harvesting rate minus the actual drying rate. Determine the actual drying rate by multiplying the average rate of moisture removal by the dryer capacity and dividing the result by the actual moisture removal rate per tonne.

Drying rate

= 143 kg/t × 5.2 t/h / 223 kg/t

= 3.3 t/h

to dry the crop from a moisture content of 30% to 14.4%.

The surge bin capacity required

= (10 – 3.3) t/h × 8 h

= 53.6 t

For batch dryers, locate a surge bin directly above the dryer. This configuration virtually eliminates loading time and thereby increases dryer capacity. It also permits topping up the dryer during drying without having to start a fully loaded conveyor.

Loading a continuous-flow dryer promptly initiates the drying operation quickly. It is also desirable to be able to operate a continuous-flow dryer in a recirculating batch mode during start-up, until the grain approaches dry. Then switch the system to continuous mode.

Augers or bucket elevators, controlled by level sensors in the top of the dryer, generally supply wet grain to a continuous-flow dryer. The sensors control either the auger filling the dryer or the slide gate (or conveyor) discharging grain from the wet surge bin into a bucket elevator filling the dryer.

Batch dryers are normally designed with high unloading capacity to maximize their drying capacity. To accommodate this feature, the drying system requires high-capacity conveyors to transfer the grain into cooling bins or storage. Alternatively, mount batch dryers above dry surge bins to use gravity for fast dumping of the dried grain. This arrangement increases dryer capacity and reduces the requirements for conveyor capacity.

Some continuous-flow dryers suffer from inadequate discharge capacity when drying grain that requires minimal moisture removal. The dryer unloads slower than the grain dries. Check the dryer discharge rate prior to purchase, especially for applications that require the dryer be used for a wide range of activities.

Many operators select the unloading and transfer conveyors for the dryer according to their primary requirements. If, for example, the system has primarily been assembled to dry corn with an initial moisture content of 25–35%, then a continuous-flow dryer can discharge the grain relatively slowly.

Small conveyors or a pneumatic system offer the least expensive methods for transferring grain to several storage bins. However, these options may lack the capacity to accommodate other drying operations.

Use a surge bin for dry grain between the main dryer-unloading conveyor and the distribution conveyors to minimize the need for auxiliary transfer equipment to unload the batch dryers. As well, use a surge bin for dry grain with continuous-flow dryers that rely on a common bucket elevator to receive both wet and dry grain.

Base the size of the surge bin for dry grain on one of two criteria.

- The volume of the surge bin must at least equal the volume of the batch dryer.
- The bin capacity must handle the amount of grain that can be dried by the continuous-flow dryer during unloading an incoming truck.

4.5 Electrical supply

The availability of energy to support storage and drying facilities is frequently a major design constraint. The operation of fans and conveyors can rarely be sequenced to reduce the demand load. As well, annual peak energy use often lasts only a couple of weeks or months.

Three-phase power offers a significant cost reduction and an increase in the starting torque capability of motors without high current demands. Servicing a site with three-phase power, however, may be costly, particularly when the utility's monthly demand charges must be paid. Consider using a standby generator to supplement or operate the facility during periods of peak loading. Three other means of reducing demand include power factor control, peak shaving, and load shedding. Whatever the choice, though, eliminating the demand charges remains the most effective cost-saving measure.

As the relative humidity levels increase to near 75%, the airflow required to prevent spoilage while drying the grain increases dramatically. Fans must operate for extended periods, to the point where the total electrical energy required to dry the grain with natural air exceeds the energy required to dry it in a high-temperature dryer. Nonetheless, the offsetting advantage for natural-air drying remains the lack of capital costs.

Frequently, the choice of drying system pivots on the cost of electrical energy. Climatic conditions, crop varieties, and crop yield strongly affect dryer usage and, therefore, directly influence energy consumption. Consequently, those three factors often figure in rationalizing the approach to grain drying.

4.6 Materials-handling systems

For systems relying primarily on high-temperature dryers (and not simply using them as backup to contend with abnormal climatic conditions), incorporate the dryers as a part of the storage system and in convenient locations where they can be easily used. If the drying system is not easy to use, chances are it will be underused. An underutilized drying system fails to generate the expected income benefits despite the operator incurring significant capital cost and depreciation on the equipment.

A materials-handling system offers several benefits:

- reduction in the labor required for harvest
- reduction in quantity losses because of shelling and wildlife
- reduction in dry matter loss
- reduction in grade losses because of inclement weather
- increase in the crop volume that can be harvested by existing equipment
- possibility of earlier harvest, leaving more time for necessary field operations after harvest

However, these benefits are frequently insufficient to defray the cost of a materials-handling drying system. So operators often additionally use the system to:

- enhance the timeliness of marketing by improving accessibility to storage through inclement weather and snow
- blend similar grains to improve the market value of a larger percentage of the crop
- support secondary processing and feed applications such as feed preparation, grain cleaning, custom storage, or custom drying

The materials-handling equipment for a drying system basically consists of storage loading and storage unloading components.

4.7 *Loading* An inclined auger or a bucket elevator serving a horizontal conveyor above the storage bins makes up the loading system. The horizontal conveyor permits single-point discharge of grain into storage. Generally the loading system receives grain directly from trucks, surge bins, or dryers.

If both trucks and continuous-flow dryers serve a single conveyor, ensure it is either a chain conveyor or a screw conveyor fitted with hanger bearings. Partially loaded screw conveyors without hanger bearings wear rapidly and may cause significant grain damage.

Low-capacity pneumatic and chain-drag conveyors, using augers or bucket elevators, can also transport grain from continuous-flow dryers to storage bins. These conveyors offer a less-costly alternative to augers and elevators; however, because of their low capacity, their loading flexibility is limited. This restriction eliminates the ability to receive grain from a truck at high capacity. As well, loading systems built around low-capacity pneumatic and chain-drag conveyors cannot dry grain efficiently when only small amounts of moisture are to be removed, since this operation requires high flow rates.

High-capacity pneumatic and chain-drag conveyors are available. However, they are not cost-effective for farm use.

To clean out the horizontal conveyor, for example, in seed growing operations, use a U-trough chain-drag or pneumatic conveyor. Excessive velocity or head loss (because of trough elbows or length) in pneumatic systems may reduce the germination of seed grain. Velocity may also worsen the stress cracking of the grain created by inappropriate dryer or combine operation.

Provide U-trough chain drags with adequate discharge opening areas to permit complete emptying at the desired location. Alternatively, use a low chain speed to compensate for undersized discharge openings. Unfortunately, this action simultaneously reduces capacity. Equipment suppliers should recommend appropriate discharge configurations.

4.8 *Unloading* Unloading systems normally consist of an under-floor or inclined auger fed by gravity or a bin sweep. A secondary transport conveyor may consist of either an inclined auger feeding a truck or a horizontal collection conveyor servicing several bins. Hopper-bottomed bins that need no mechanical equipment for unloading offer a storage alternative, but they are expensive.

The elevation of the unloading conveyor dictates the elevation of the secondary transport conveyor. If the elevation of the primary unloading conveyor discharge is inadequate or the foundation settles, excavation to install the transport conveyor becomes essential. Remember, though, excavations present drainage and maintenance problems, so avoid them if possible. Instead, elevate the foundation well above the adjacent grade. This arrangement permits good surface drainage away from the storage facilities.

The design of the discharge transition between an overhead filling conveyor and the bin roof must also accommodate settling of the foundations. Anticipating differential movement at this location saves costly remedial repair work.

5 STORAGE AND CONDITIONING OF HAY

Hay stores safely when the moisture content reaches 15% or less. This moisture content prevents mold growth in the hay if it is used within 12 months.

In areas where weather conditions permit, dry the crop in the field before baling. Simply leave the cut hay exposed to the sun until it has dried sufficiently to store safely. To speed the field drying process, crimp or roll the hay at cutting. These actions break the stems, increase the release of moisture to the air, reduce drying time by approximately 50%, and significantly improve hay quality.

Both the rate and duration of field drying (also called curing) greatly influence the quality and quantity of hay harvested. Lengthy curing periods increase dry matter losses and diminish the nutritive value and palatability of the hay. Rain or poor drying weather (such as cloudy skies, high humidity, or still air) delays drying.

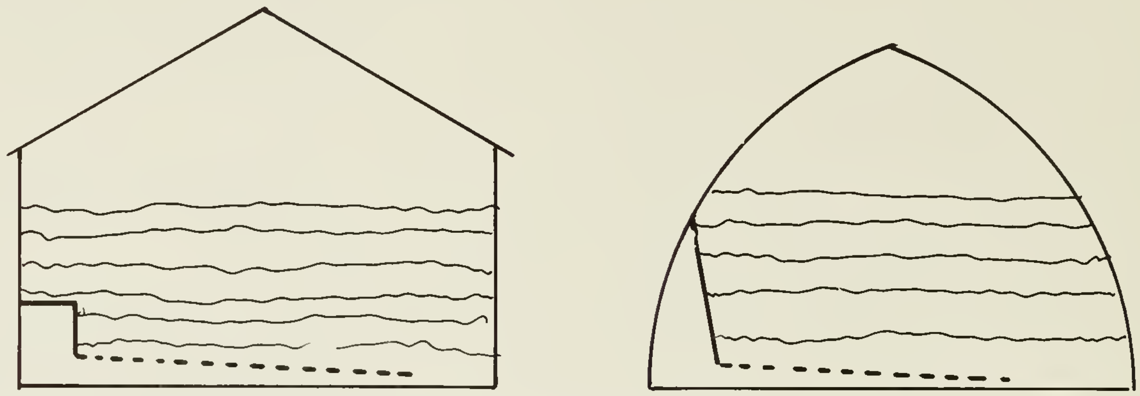
In the case of legume hay such as alfalfa or clover, the leaves contain most of the nutrient value. However, as the hay dries, the leaves tend to separate from the stem and are readily lost during harvesting. Losses of 4–5% protein content can occur. Retaining the feed value of these crops requires either faster drying or reliance on a harvesting method that ensures leaves and stems remain intact.

Hay may be harvested at a moisture content above 15% and dried in storage rather than cured in the field. This approach reduces risks to product quality and dry matter from losses caused by inclement weather.

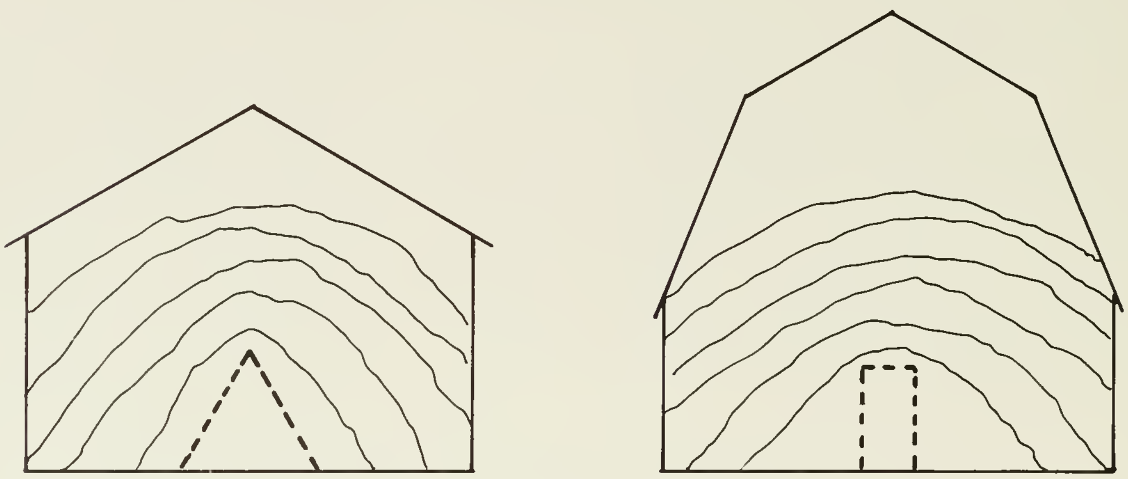
5.1 Drying hay in storage

To dry hay in storage, use an air delivery system designed for uniform distribution of air. Size the ducts to provide a face velocity of air moving outward from the duct into the hay at a rate of 260 mm/s. Ensure a duct velocity of 5 m/s or less.

Duct layout normally centres on a primary distribution duct running the length of the storage. Lateral distribution ducting may accompany the main duct. Use a single, perforated central duct without lateral passages for storage structures up to 10 m wide. Add lateral ducting to the primary supply duct for larger structures. Figs. 17 and 18 illustrate common duct cross sections.



Main duct at side of mow for shallow hay storage



Main duct at centre of mow for deep hay storage

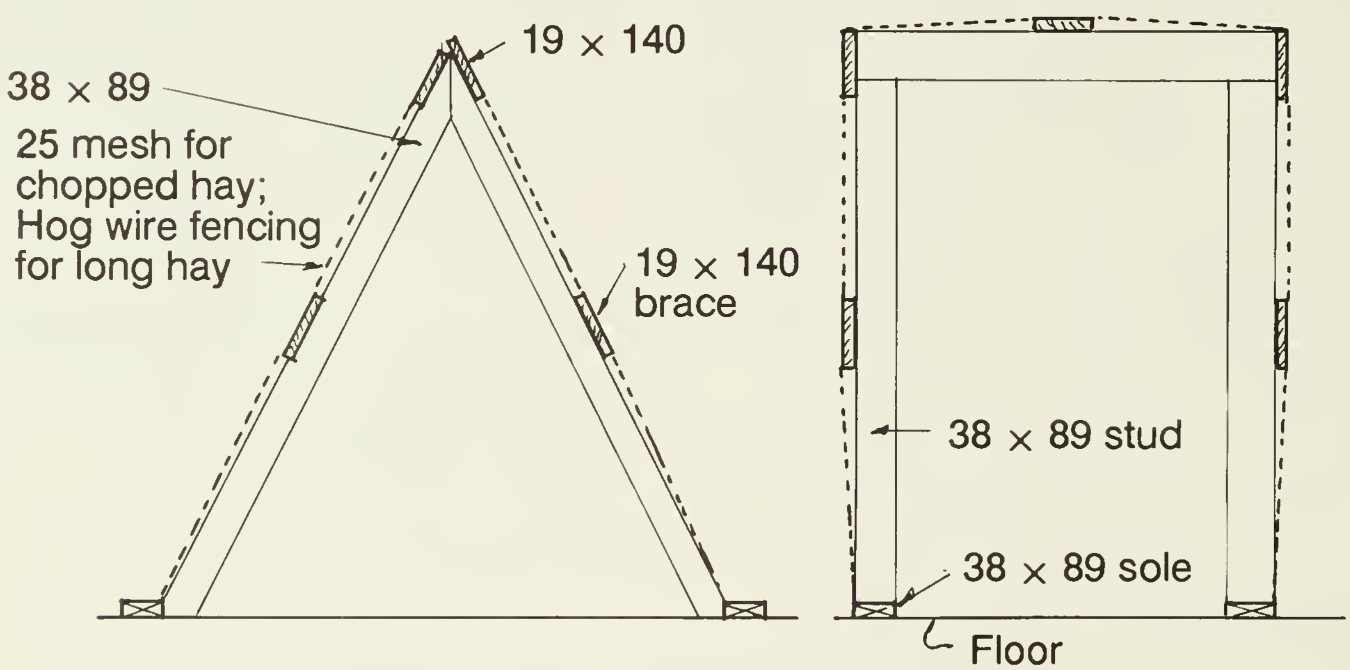


Fig. 17. Unlined primary distribution ducts. All measurements are expressed in millimetres.

5.2 *Safe storage requirements: airflow and static pressure* Hay generally enters storage during the warm summer weather when natural-air drying is reliable in most areas. Properly designed natural-air drying systems require no supplementary heat under these conditions.

In some circumstances, however, the storage system requires supplementary heat provided through the use of a heat exchanger:

- when the initial moisture content of the hay is too high for natural-air drying
- when normal climatic conditions do not allow rapid moisture removal by natural air circulation

Compared with heat exchangers, direct-fired heaters offer a more efficient drying alternative; but beware of the high fire risk that accompanies their use.

The rate of hay spoilage increases with air temperature. Supplementary heat sufficient to reduce slightly the relative humidity of the supply air is safer than high-temperature drying, and the same airflow rate as natural-air drying may be used.

In most cases, hay must be dried to a moisture content of less than 20% within 3.5 days of cutting to prevent visible mold growth. Determine the quantity of water to be removed from the hay using a method similar to that for drying grain.

Recall this equation:

$$q = \left[m_f \times \frac{(1 - M_f)}{(1 - M_i)} \right] - m_f$$

where q = quantity of water removed (kg)

m_f = mass of grain at final moisture content (kg)

M_f = final moisture content

M_i = initial moisture content

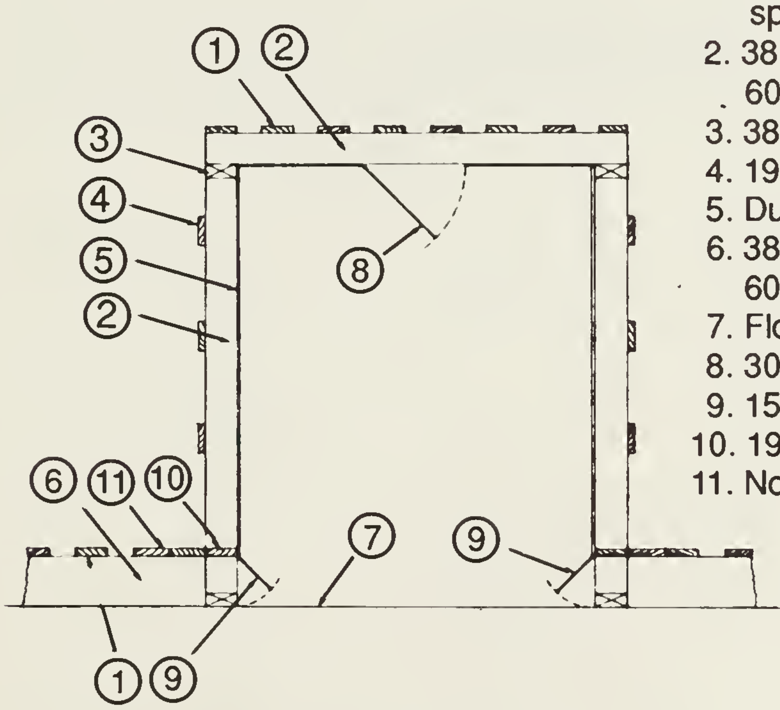
See section 4.3 for more details.

The moisture-removal capacity of the air being blown through the hay limits the drying rate expected from a natural-air dryer. Other more controllable factors influencing the drying rate include airflow rate and uniformity of air distribution. Decreasing the humidity of the supply air increases the capability of the ventilation air to remove moisture.

Select the airflow rate according to the required rate of moisture removal. The average temperature and relative humidity levels in the area during hay drying, in turn, influence the rate of moisture removal. Use local climatic data and basic psychrometrics to calculate the theoretical airflow rate required. Assume the relative humidity of the discharge air from the dryers averages around 85% with constant enthalpy through the dryer.

Base the airflow rate on the anticipated moisture content of the hay to be dried (Table 12). Increase the airflow rate with increasing initial moisture content.

No consistent information exists that correlates static pressure with airflow rate and hay quality, in terms of either genetic or physical configuration (legumes or grasses; baled or loose). Set the static pressure for the system in the range of 125–375 Pa; commonly 250 Pa is used.



1. 19 x 89 mm slats spaced 75 mm apart
2. 38 x 89 mm spaced 600 mm on centre
3. 38 x 89 mm plate
4. 19 x 89 mm slats
5. Duct lining
6. 38 x 140 mm joists spaced 600 mm on centre
7. Floor
8. 300 mm air control door
9. 150 mm air control door
10. 19 x 89 mm blocking
11. No spacing first 300 mm

Fig. 18. Lined rectangular distribution ducts.

Table 12 Airflow related to dryer area and hay moisture content

Moisture content of hay (%)	Airflow rate	
	Floor area (L/s·m2)	Amount of hay (L/s·t)
20–25	40	77
25–30	75	155
30–35	125	260

Several characteristics of hay operations help explain the variability in static pressure that can be achieved.

Because the fibers shrink, chopped hay settles by 10–15% during drying and increases pressure by an amount roughly equal to the volume decrease. Baled hay, on the other hand, does not demonstrate the same effect on pressure.

Tightly stacked bales of hay do not permit air to flow through fast enough to dry the crop before it spoils. Consequently, keep the specific density of baled hay as low as possible, yet maintain the integrity of the bale in handling.

Bales stacked on edge have a lower resistance to airflow than bales stacked on the flat. In the dryer, place the square bales together on edge. To prevent short-circuiting airflow, do not leave spaces between the bales.

The static pressure directly relates to the velocity of air traveling through the hay and the depth of hay between the duct and free airspace. Table 13, adapted from a Hydro Quebec publication, provides a useful reference for estimating the air velocity and static pressure required for a drying system.

5.3 *Air distribution systems* Design the air distribution system for a hay dryer to ensure a uniform airflow rate to the entire dryer area. Size the duct work to conform with good engineering practices and with the criteria given in the previous section. Define both the minimum cross-sectional area of all ducts and the minimum net open area of duct surface in contact with the hay.

Locate a primary air-delivery duct longitudinally, either in the centre of the dryer or along one side. A duct located centrally provides adequate air distribution for dryers up to 10 m wide. To maintain uniform air distribution, however, the depth of hay above the top of the duct must equal the distance from the duct to the edge of the dryer. Inadequate depths of hay above the duct causes the air to move through the hay directly above the duct, taking the path of least resistance.

Choose any configuration for the primary duct. Figs. 17 and 18 illustrate the most common configurations: triangular and rectangular. Line the ducts to permit manual directional control of the air. Or leave them unlined for uniform air discharge over their entire length.

Unlined ducts require that the entire duct be uniformly covered with hay prior to starting the flow of air. Lined ducts, on the other hand, permit effective use of only a portion of the dryer at one time. Use lined ducts where the volume to be dried does not fill the dryer or where only portions of the storage are to be dried.

Size the lined primary ducts to ensure easy access by the operator. The operator is then

Table 13 Fan air velocity and static pressure for drying hay in storage

Thickness of hay (m)	Baled hay*		Chopped hay*	
	Air velocity (mm/s)	Static pressure (Pa)	Air velocity (mm/s)	Static pressure (Pa)
1.83	76	190	76	250
2.30	76	190	76	250
2.75	76	250	76	250
3.20	76	250	76	250
3.70	76	250	86	310
4.10	86	250	97	310
4.60	97	250	112	375
5.30	112	310	127	375
5.80	122	375	137	440

* At 40% moisture content.

more likely to properly adjust the doors controlling air direction.

Lateral ducts connected to a primary supply duct extend the practical width of a hay dryer. Lateral ducts can take two forms: a slatted floor over floor joists, or a series of small lateral ducts on one or both sides of the primary supply duct.

Arrange the duct system so that all air paths through the hay are equivalent. For example, the distance from the end of the duct to the side of the dryer should equal the distance from the end of the duct to the top of the hay surface when the dryer is fully loaded.

To ensure uniform air distribution, observe the following:

- Install airtight dryer floors to prevent the escape of air intended for the hay. Tongue-and-groove or concrete flooring, or earth, are adequately airtight. Cover other floors with 150 μm polyethylene before assembling the duct work.
- Eliminate routes for air escape. Structural columns in the dryer may permit leakage of air that is intended to go through the hay. Reduce this short-circuiting by inserting an impermeable layer such as plastic, extending at least 0.6 m from the column in all directions on the surface of the floor.
- Ensure that the lateral ducting within 0.3 m of the primary distribution duct is not perforated. Primary distribution ducts should not be perforated within 2 m of the fan.

Check the structural adequacy of the floor of the hay dryer before its use. Hay with a moisture content of 35% weighs 25–30% more than the equivalent volume of field-dried hay. Dry, baled hay has a density of around 0.13 t/m^3. The density of dry, chopped hay is around 0.08 t/m^3.

5.4 Drying hay

A hay-drying operation involves four stages:

- field drying
- arranging hay in the dryer
- operating the dryer
- terminating drying

5.5 *Field drying* Allow the hay to field dry to a moisture content of 35% before baling. This step reduces both the risk of mold growth in the hay as well as field and harvest losses.

Set the twine tension for wet hay the same as for dry hay. This string tension maintains bale integrity while permitting adequate airflow through the bales. A bale length of 0.85 m improves manual handling characteristics and tightness of hand stacking. Bales 0.6 m long allow improved stack density and bale durability when bales are stacked randomly in the dryer.

5.6 *Arranging hay in the dryer* How the hay is arranged in the dryer depends on whether the hay is baled or chopped.

Follow these guidelines for baled hay:

- For central duct systems, cover the duct in even layers of hay. Gradually work upward and outward to keep hay depths equal in all directions.
- In a slatted-floor system, mound the first layer over the duct and slightly past the end of the slatted floor. Place each successive layer on as a blanket, eventually reaching the edge of the dryer.
- When using a lined, primary distribution duct with a slatted floor system, start loading with the doors in the top of the main duct closed and the bottom doors open. When the hay is 1–1.2 m over the top of the floor, open the top doors. When the hay is 3–4 m over the duct, close the bottom doors leaving the top doors open.
- Pack long bales tightly and on edge with alternate layers at 90° to each other. This arrangement reduces the chances of air short-circuiting. Randomly dump short bales into the dryer, providing the moisture content is 25% or less. Plug any gaps in the packing by stacking some bales by hand.
- Use baled hay to create mini-ducts in a central lined duct that has no slatted floor. Space the first two or three bales outward from the duct with 150–200 mm between them.

Follow these guidelines for chopped hay:

- Cut chopped hay to 50 mm or longer. This length prevents excessive density and resistance to airflow.
- Use a blower or other conveyor to put chopped hay in place.
- Do not tramp wet hay or concentrate it in one area of the dryer. Move the discharge pipe frequently.
- Cover the drying floor to a uniform depth to encourage even air distribution.

5.7 *Operating the dryer* The drying front moves through the hay in the direction of airflow. Hay on the top of the dryer does not dry until the hay below it has dried. Consequently, pile only as much wet hay in the dryer as permits the drying front to pass through in time to prevent mold growth: 3.5 days for hay of 20% moisture content, 4–6 days for 15% moisture content.

The depth that wet hay can be stacked in a dryer varies directly with the dryer airflow and the climatic conditions for the area. Experience, therefore, dictates the normal operation for a given installation. However, as a general rule, set the initial loading to 1.5 m deep. Then add 1 m/day to fill the dryer.

The drying front moves through the hay regardless of fluctuations in ambient air quality. So operate the fan continuously until the hay dries. Interrupting fan operation delays drying and allows the hay to heat. With increasing hay temperature, the risks of dry matter losses and fire increase, as does the rate of mold growth.

5.8 *Terminating dryer operation* When all the hay appears dry, turn off the fan for 8–12 h. Then restart the fan and monitor the exhaust air. If the exhaust air temperature exceeds the ambient air temperature, run the fan for several more days and recheck the air temperatures. Consider the hay dry after three such checks reveal no further temperature rises. Shut down the dryer.

5.9 Supplementary heat drying

Heated-air day dryers are operated in one of three temperature ranges:

- low-temperature dryers operating at 5–10°C above ambient air temperatures
- medium-temperature dryers operating at 10–200°C above ambient air temperatures
- high-temperature dryers operating 300–800°C above ambient air temperatures

Low-temperature dryers increase drying rate by increasing the capacity to hold the moisture of the air blown through the hay. Increasing the temperature of the supply air reduces the relative humidity of the air, thus enhancing its drying potential. Drying hay this way ultimately requires less air, as compared with natural-air drying.

Some operators use the heat of respiration of the hay to provide additional heat to dry the hay and reduce the fan operating time. This arrangement entails operating the fan intermittently and allowing the hay to heat between periods of fan operation. However, the heat obtained in this manner costs 4–5% of the dry matter of the hay being dried, a value exceeding the energy costs saved. As well, heat captured this way also poses a safety hazard. Consequently, intermittent fan operation is not recommended.

Install fans to minimize noise. As well, consider solar heat gain on the south side of buildings. See Fig. 19.

Fig. 20 illustrates the correlation between the time required for visible mold growth to appear and hay temperature. Since mold growth depends on both temperature and moisture, this curve shifts to the right as the hay dries.

Medium-temperature dryers are much less common than low-temperature dryers. Medium-temperature dryers demonstrate high capital costs in their construction and they need elaborate firing units. As well, the faster drying rate demands more intense involvement from operators because of faster turnover rates in the dryers. Moreover, should drying not proceed quickly, the risk of spoilage is high.

Design medium-temperature dryers with an airflow rate, temperature, and hay depth combination that allows moisture to leave the hay fast enough to prevent mold formation. Only qualified designers should make design decisions concerning the thermodynamics and psychrometrics related to medium-temperature drying.

High-temperature dryers that raise the temperature of the hay sufficiently high to kill the microorganisms that cause spoilage require heat-tolerant construction. These dryers involve high-cost facilities. Choose them only where continuous operation permits spreading the capital cost over many thousands of tonnes of hay. Commercial dryers normally operate with supply-air temperatures of 370–750°C for hay of a moisture content ranging from 40 to 70%. Hay with higher moisture contents need drying at higher temperatures. Discharge air temperatures usually measure 65–120°C.

With heated-air drying, the hay retains its nutritional value better than with other drying methods. Higher carotene concentrations, superior palatability, and dry matter conservation all result from faster curing or drying. Still, the benefits of speeding the drying process with supplementary heat may be less significant where objectives other than hay quality must also be met. Carefully examine the economics of using supplementary heat before beginning the detailed design of a system.

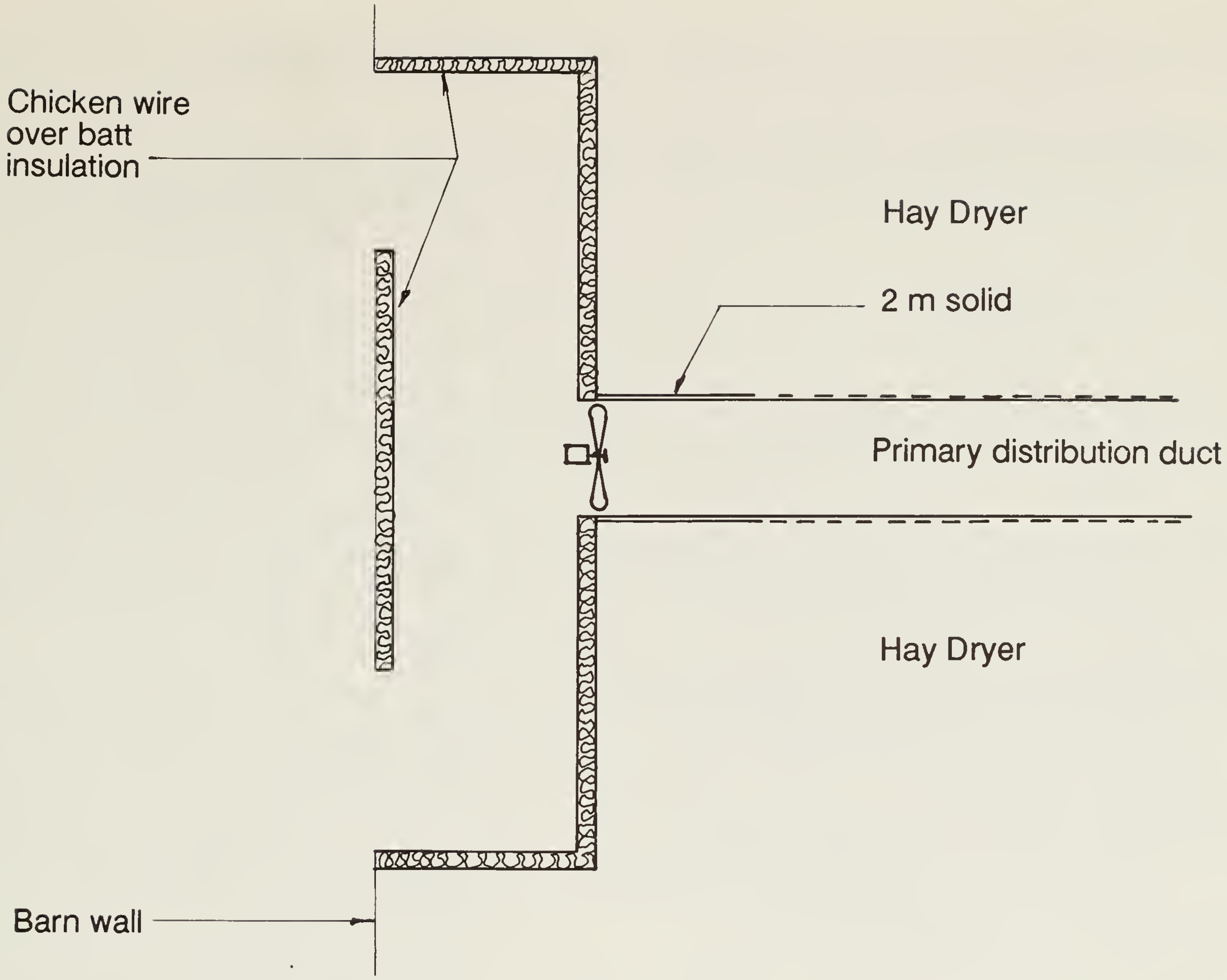


Fig. 19. **Fan installation for sound absorption.**

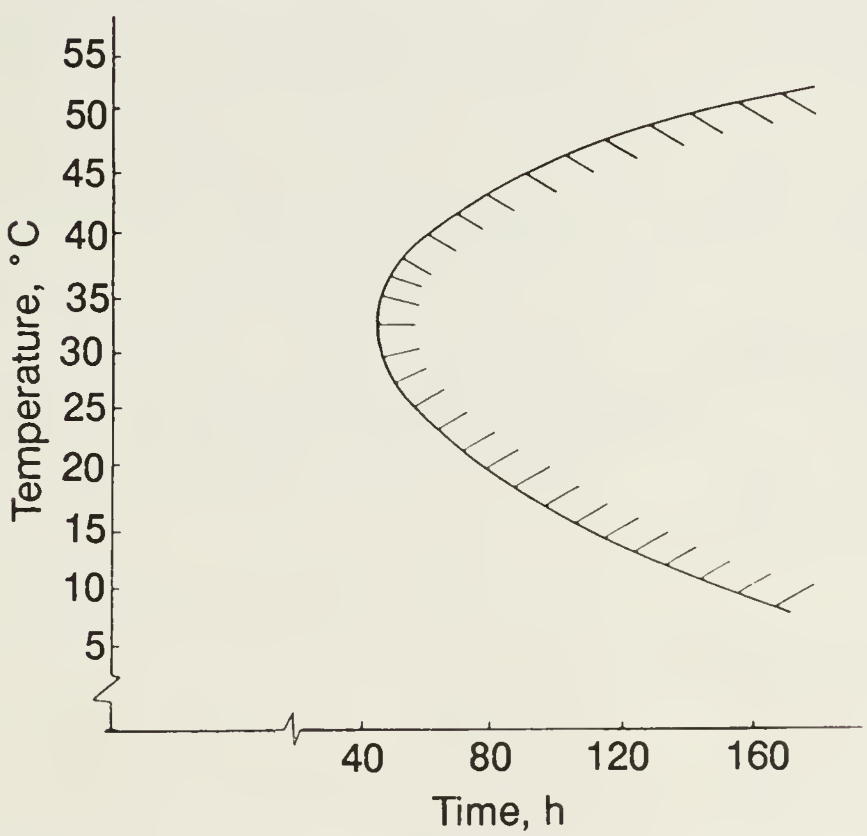


Fig. 20. **Relationship of temperature and time to mold formation on high-moisture hay.**

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